INTERNATIONAL ATOMIC ENERGY AGENCY

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I N D C INTERNATIONAL NUCLEAR DATA COMMITTEE

WORKSHOP

ON NUCLEAR STRUCTURE AND DECAY DATA:

THEORY AND EVALUATION

MANUAL – PART 1

Editors: A.L.Nichols and P.K.McLaughlin
IAEA Nuclear Data Section
Vienna, Austria

November 2004

IAEA NUCLEAR DATA SECTION, WAGRAMER STRASSE 5, A-1400 VIENNA

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WORKSHOP
ON NUCLEAR STRUCTURE AND DECAY DATA: THEORY AND EVALUATION

MANUAL – PART 1

ICTP Trieste, Italy

17 – 28 November 2003

Edited by

A.L. Nichols and P.K. McLaughlin

IAEA Nuclear Data Section

Vienna, Austria

Abstract

A two-week Workshop on Nuclear Structure and Decay Data was organized and administrated by the IAEA Nuclear Data Section, and hosted at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy from 17 to 28 November 2003. The aims and contents of this workshop are summarized, along with the agenda, list of participants, comments and recommendations. Workshop materials are also included that are freely available on CD-ROM (all relevant PowerPoint presentations and manuals along with appropriate computer codes):

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January 2004

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ON NUCLEAR STRUCTURE AND DECAY DATA: THEORY AND EVALUATION

Summary

ICTP Trieste, Italy

17 – 28 November 2003

Prepared by

A.L. Nichols

IAEA Nuclear Data Section

Vienna, Austria

Abstract

Basic aspects of a two-week Workshop on Nuclear Structure and Decay Data: Theory and Evaluation are outlined in this short note for the record. The aims and contents of this workshop are summarized, along with the agenda, list of participants, comments and recommendations. Much was achieved and one aim will be to hold this specific workshop at various time intervals for training purposes (with agreed changes and regular modifications) on the advice of the International Nuclear Data Committee (INDC) and Network of Nuclear Structure and Decay Data Evaluators.

January 2004

1. OBJECTIVES

The International Atomic Energy Agency organised a two-week Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation" at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste from 17 to 28 November 2003. This workshop was conceived and directed by A.L. Nichols (IAEA Nuclear Data Section), J. Tuli (NNDC, Brookhaven National Laboratory, USA) and A. Ventura (ENEA, Bologna, Italy).

The primary objective of the ICTP-hosted workshop was to familiarize nuclear physicists and engineers from both developed and developing countries with

- (i) modern nuclear models;
- (ii) relevant experimental techniques;
- (iii) statistical analyses procedures to derive recommended data sets;
- (iv) evaluation methodologies for nuclear structure and decay data;
- (v) international efforts to produce the Evaluated Nuclear Structure Data File (ENSDF).

Reliable nuclear structure and decay data are important in a wide range of nuclear applications and basic research. Participants were introduced to both the theory and measurement of nuclear structure data, and the use of computer codes to evaluate decay data.

Detailed presentations were given by invited lecturers, along with computer exercises and workshop tasks. Participants were also invited to contribute their own thoughts and papers of direct relevance to the workshop.

2. PROGRAMME

The workshop programme is listed in Section 2.1 of this brief summary, based on a one-week pilot workshop in November 2002 (1) and subsequent debate between the workshop directors.

2.1 Agenda

MONDAY, 17 November 2003

09:00 – 10:30	Registration & Coffee
10:30 – 12:30	Opening Session
	Welcome (Alan Nichols (IAEA) and Jag Tuli (BNL))
	Aims (Jag Tuli)
	NSDD – general features (Jag Tuli)
	IAEA-NDS – NSDD network and recent relevant CRPs (Alan Nichols)
12:30 – 14:00	Lunch
14:00 – 15:30	Introduction
	ICTP computer facilities (ICTP staff/Kevin McLaughlin)
15:30 – 15:45	Coffee break
15:45 – 17:30	Introduction (cont.)
	Web capabilities (Tom Burrows and Alan Nichols)
	Bibliographic databases (Tom Burrows)

TUESDAY, 18 November 2003

09:00 – 10:30	Nuclear theory (Piet Van Isacker)
10:30 – 10:45	Coffee break
10:45 – 12:30	ENSDF format (Jag Tuli)
12:30 – 14:00	Lunch
14:00 – 15:30	ENSDF programs (Tom Burrows)
15:30 – 15:45	Coffee break
15:45 – 17:30	Students' presentations

WEDNESDAY, 19 November 2003

09:00 – 10:30	Nuclear theory (Piet Van Isacker and Ashok Jain)
10:30 – 10:45	Coffee break
10:45 – 12:30	ENSDF - decay (Eddie Browne)
12:30 – 14:00	Lunch
14:00 – 15:30	Model exercise – format (lead by Jag Tuli)
15:30 – 15:45	Coffee break
15:45 – 17:30	Students' presentations

THURSDAY, 20 November 2003

09:00 – 10:30	Nuclear theory (Dario Vretenar)
10:30 – 10:45	Coffee break
10:45 – 12:30	ENSDF - reaction (Coral Baglin)
12:30 – 14:00	Lunch
14:00 – 15:30	Model exercise – decay (lead by Eddie Browne)
15:30 – 15:45	Coffee break
15:45 – 17:30	Students' presentations

FRIDAY, 21 November 2003

09:00 – 10:30	Nuclear theory (Dario Vretenar)
10:30 – 10:45	Coffee break
10:45 – 12:30	Model exercise- reaction (lead by Coral Baglin)
12:30 – 14:00	Lunch
14:00 – 15:30	Theory (Ashok Jain)
15:30 – 15:45	Coffee break
15:45 – 17:30	ENSDF programs (Tom Burrows)

Saturday, 22 November 2003
Sunday, 23 November 2003

MONDAY, 24 November 2003

09:00 – 10:30	ENSDF – evaluation policies (Jag Tuli)
10:30 – 10:45	Coffee break
10:45 – 12:30	ENSDF - adopted levels and gammas (Coral Baglin)
12:30 – 14:00	Lunch

14:00 – 15:30	Model exercise – programs (lead by Tom Burrows)
15:30 – 15:45	Coffee break
15:45 – 17:30	Workshop activities (JT, TB, CB, EB, KMc)

TUESDAY, 25 November 2003

09:00 – 10:30	Model exercise - adopted levels and gammas (Coral Baglin)
10:30 – 10:45	Coffee break
10:45 – 12:30	Workshop activities (JT, TB, CB, EB, KMc)
12:30 – 14:00	Lunch
14:00 – 15:30	Workshop activities (JT, TB, CB, EB, KMc)
15:30 – 15:45	Coffee break (JT, TB, CB, EB, KMc)
15:45 – 17:30	Workshop activities (JT, TB, CB, EB, KMc)

WEDNESDAY, 26 November 2003

09:00 – 10:30	Experimental techniques (Peter von Brentano)
10:30 – 10:45	Coffee break
10:45 – 12:30	Experimental techniques (Peter von Brentano)
12:30 – 14:00	Lunch
14:00 – 15:30	Workshop activities (TB, CB, EB, KMc)
15:30 – 15:45	Coffee break
15:45 – 17:30	Workshop activities (TB, CB, EB, KMc)

THURSDAY, 27 November 2003

09:00 – 10:30	Statistical analyses (Desmond MacMahon)
10:30 – 10:45	Coffee break
10:45 – 12:30	Statistical analyses (Desmond MacMahon)
12:30 – 14:00	Lunch
14:00 – 15:30	Workshop activities (TB, EB, KMc)
15:30 – 15:45	Coffee break
15:45 – 17:30	Workshop activities (TB, EB, KMc)

FRIDAY, 28 November 2003

09:00 – 10:30	Workshop activities (TB, EB, KMc)
10:30 – 10:45	Coffee break
10:45 – 12:30	Review of workshop (Eddie Browne, Tom Burrows and Alan Nichols)
12:30 – 14:00	Lunch

2.2 Participants

Twenty-four participants (predominantly from developing countries) with full or partial support from the IAEA were selected to attend the workshop in November 2003. Selection was undertaken by Nuclear Data Section staff in association with the workshop directors.

<u>First row, sitting from left to right</u>:
Thomas W. BURROWS (USA), Edgardo BROWNE-MORENO (USA), Dario VRETENAR (Croatia), Jagdish K. TULI (USA), Alan NICHOLS (IAEA), Ashok Kumar JAIN (India), Coral M. BAGLIN (USA), Andrea SCHERBAUM (IAEA).

Second row, standing from left to right:
Elsayed M.K. Ahmed ELMAGHRABY (Egypt), Reza NAZARI (Iran), Gopal MUKHERJEE (India), Nagappa M. BADIGER (India), Houshyar NOSHAD (Iran), Suresh Kumar PATRA (India), Kevin MCLAUGHLIN (IAEA), Youssef ABDEL-FATTAH (Egypt), A.K.M. HARUN-AR-RASHID (Bangladesh), Alejandro ALGORA (Hungary), Maitreyee NANDY (India), Mohini GUPTA (India), Sham S. MALIK (India), Guilherme Soares ZAHN (Brazil), Hai NGUYEN (Vietnam), Guillermo V. MARTI (Argentina), Zhimin WANG (China), Young Ae KIM (Korea), Jing QIAN (China), Elena LITVINOVA (Russia), Vitaly PRONSKIKH (Russia).

<u>Unavailable</u>:
Kripamay MAHATA (India), Luc PERROT (France), Prakash Kumar SAHU (India), Renju George THOMAS (India).

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3. PRESENTATIONS AVAILABLE IN ELECTRONIC FORM ON CD-ROM

Presentations by Lecturers

Aims of the Workshop - General features of NSDD, J. Tuli

Nuclear Theory:
Nuclear Shell Model, P. Van Isacker
Interacting Boson Model, P. Van Isacker
Geometrical Symmetries in Nuclei – An Introduction, A. Jain
Geometrical Symmetries in Nuclei, A. Jain
Lectures on Geometrical Symmetries in Nuclei, A. Jain
Hartree-Foch-Bogoliubov Method, D. Vretenar
Self-consistent Mean-field Models – Structure of Heavy Nuclei, D. Vretenar

Experimental Nuclear Spectroscopy:
Introduction, P. Von Brentano
Lecture I – Nuclear Shapes, P. Von Brentano
Lecture II – Measurement of Lifetimes, P. Von Brentano

Statistical Analyses:
Evaluation of Discrepant Data I, D. MacMahon
Evaluation of Discrepant Data II, D. MacMahon
Convergence of Techniques for the Evaluation of Discrepant Data: D. MacMahon, A. Pearce, P. Harris
Techniques for Evaluating Discrepant Data, M.U. Rajput, D. MacMahon
Possible Advantages of a Robust Evaluation of Comparisons, J.W. Muller (presented by D. MacMahon)

ENSDF:
Evaluated Nuclear Structure Data Base, J.K. Tuli
Evaluations – A Very Informal History, J.K. Tuli
Evaluated Nuclear Structure Data File – A Manual for Preparation of Data Sets, J.K. Tuli
Guidelines for Evaluators, M.J. Martin, J.K. Tuli
Bibliographic Databases, T.W. Burrows
ENSDF Analysis and Utility Codes, T.W. Burrows:

- Their Descriptions and Uses, T.W. Burrows
- FMTCHK (Format and Syntax Checking), T.W. Burrows
- PowerPoint presentations, T.W. Burrows
- LOGFT (Calculates log *ft* for beta decay), T.W. Burrows
- GTOL (Gamma to Level), T.W. Burrows
- HSICC (Hager-Seltzer Internal Conversion Coefficients), T.W. Burrows

ENSDF – Decay Data, E. Browne
Model Exercises – Decay, E. Browne
ENSDF – Reaction Data, C. Baglin
ENSDF – Adopted Levels and Gammas, C. Baglin
ENSDF – Examples 1, 2, 3, 4 and 5, C. Baglin

Additional Material:
IAEA: NSDD Network, Recent Relevant CRPs and Other Activities (PowerPoint presentation), A.L. Nichols
IAEA: NSDD Network, Recent Relevant CRPs and Other Activities (draft paper), A.L. Nichols
Nuclear Structure and Decay Data: Introduction to Relevant Web Pages (draft paper), T.W. Burrows, P.K. McLaughlin, A.L. Nichols

Presentations by Participants

Study of Isomers in Heavy Nuclei, G. Mukherjee
Optimisation of the Performance of the ETRR-2 Facilities, A. Fattah-Youssef
Target/Projective Structure Dependence in Transfer Reactions, P.K. Sahu
Comparison of Thomas-Fermi and Rotating Finite Range Model Fission Barriers, K. Mahata
Use of Nuclear Reaction Modeling Codes at Low and Intermediate Energies, M. Nandy
Fission of ^{209}Bi and ^{197}Au Nuclei Induced by 30 MeV Protons, H. Noshad
γ-γ Studies of β^- decay ^{193}Os $\rightarrow$ ^{193}Ir, G. Zahn
Neutron Cross Sections of Er Isotopes, A.K.M. Harun-ar-Rashid
Nuclear Reaction Analysis Using Pre-developed Programs – EMPIRE and Abarax, E. Elmaghraby
ETFFS Calculations of the Low-lying Dipole Strength in Ca Isotopes, E. Litvinova
Bremsstrahlung in the Optical Region, N. Badiger
^{152}Gd Excited States – Preliminary Discussion, V. Pronskikh
Beta-decay Studies Using Total Absorption Spectroscopy, A. Algora
A = 193 Mass Chain Evaluation, G. Marti

4. OTHER WORKSHOP MATERIALS ON CD-ROM

Atomic Masses
Access to ENSDF Codes and Tools
Isotope Explorer
PCNuDat
Access to NSDD Resources

NNDC Online Data Service Manual and Data Citation Guidelines

1.Introduction to International Nuclear Structure and Decay Data Network
Contact names and addresses

Access to ENSDF Format Summary and Examples

Nuclear Structure Manuals

5. RECOMMENDATIONS AND CONCLUSIONS

A number of important points can be made concerning the workshop:

1. Twenty-four participants were selected and attended a two-week workshop that covered nuclear theory and modeling, relevant experimental techniques, statistical analyses, and the philosophy and methodology for comprehensive mass chain evaluations. Support materials and information were also provided on the network of international nuclear structure and decay data evaluators and the most relevant CRPs undertaken through the IAEA Nuclear Data Section.

2. Workshop participants were introduced to mass chain evaluations through group and individual PC/computing activities (50% of agenda of second week) CD-ROM and hardcopy materials were provided by IAEA staff for all students/lecturers.

3. Administrative functions leading up to and during the course of the workshop worked smoothly, including visa arrangements, travel and subsistence payments to students and lecturers, additional banking transactions, and hotel/guest-house accommodation – as an ICTP-hosted workshop many of the administrative details for these functions were organized by IAEA staff.

4. Specific participants were identified for future involvement in NSDD and mass chain evaluations.

5. Lessons were learnt by the IAEA staff involved in this ICTP-hosted event, and much experience was gained in ensuring future success in the organization of such "at-distance" workshops. This particular workshop ran extremely smoothly, and all participants were able to attend (i.e., 100% success with visas). Students were given the opportunity to review the workshop through a written questionnaire and direct discussions (on 28 November). Their major recommendations are as follows:

(a) provide exercises as homework beyond normal workshop hours;
(b) provide sample questions and answers (answers also to be worked out during the course of individual lectures);
(c) increase PC activities within the main body of the workshop, and their introduction much earlier during the first week.
(d) establish stronger links between ENSDF and nuclear theory lectures (i.e., between ENSDF nuclear parameters (and those data used to derive such parameters) and topics to be discussed within nuclear theory).

Combination of Thursday questionnaire and Friday face-to-face review session produced constructive feedback. The overall opinion of all of the students was that they had thoroughly enjoyed the 2-week workshop, made useful new contacts with lecturers, IAEA-NDS staff and other students, and learnt much about nuclear structure and decay data; all of the primary objectives of the workshop were successfully achieved.

REFERENCE

1. PRONYAEV, V.G., NICHOLS, A.L., Summary Report on Workshop on Nuclear Structure and Decay Data Evaluation, 18-22 November 2002, INDC(NDS)-439, January 2003.

Workshop on
Nuclear Structure and Decay Data: Theory and Evaluation

17-28 November 2003

ICTP, Miramare - Trieste, Italy

Introduction

The International Atomic Energy Agency (IAEA, Vienna, Austria) in co-operation with the Abdus Salam International Centre for Theoretical Physics (ICTP, Trieste, Italy) and the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA, Bologna, Italy) organized a *"Workshop on Nuclear Structure and Decay Data: Theory and Evaluation"* at the ICTP in Trieste from 17 to 28 November 2003. This workshop was co-directed by Drs. A. Ventura (ENEA, Bologna), A.L. Nichols (IAEA, Vienna) and J.K. Tuli (Brookhaven National Laboratory, USA).

The workshop constituted a unique opportunity for scientists to gain extensive and up-to-date training on the evaluation of nuclear structure and decay data, as developed for the Evaluated Nuclear Structure Data File (ENSDF) and *Nuclear Data Sheets* for the nuclear physics community. Reliable evaluated nuclear structure and decay data are of vital importance in a large number of nuclear applications such as power generation, material analysis, dosimetry and medical diagnostics, as well as basic nuclear physics and astrophysics. Important features of these needs are satisfied by the work undertaken by the international Nuclear Structure and Decay Data Evaluators' Network (NSDD). The main products of this worldwide network are the recommended data files and evaluated decay data.

ENSDF is an enormous source of nuclear data and information for basic research and applications. Both the maintenance and further developments of these files are vitally important, and require continuing scientific effort. While the input to ENSDF from developing countries has been limited in the past, the time has come for scientists from these countries to make a significant contribution to these on-going efforts. The workshop represented the initiation of a suitable mechanism to achieve this aim by focusing on advances in nuclear structure physics and evaluation methodologies through practical training.

Aims

The primary objective of the workshop was to familiarize nuclear physicists from both developing and developed countries with:

(i) new data that characterize the decay properties of nuclei and their nuclear structure;
(ii) nuclear models;
(iii) evaluation methodologies for nuclear structure and decay data.

Participants were introduced to the rigorous criteria adopted to evaluate nuclear structure data, and how these data are entered into ENSDF. Important aspects of the workshop included the use of computer codes to evaluate the nuclear structure and decay data, and the construction of data files for ENSDF. Presentations were given by invited lecturers, along with well-defined exercises involving the use of the relevant computer codes. Participants were also be invited to contribute their own thoughts of direct technical relevance to the workshop.

The workshop programme included coverage of the following topics:
review of modern nuclear models and new data obtained at experimental installations;
ENSDF and related bibliographic databases;
computer codes used for NSDD evaluations;
computer exercises with real NSDD evaluations and preparation of the data sets for inclusion in ENSDF;
network of NSDD evaluators, their products and communication links;
participants' presentations of their own work in NSDD.
Scientists attended from countries that are members of the United Nations, UNESCO or IAEA. Although the main purpose of the ICTP is to help scientists from developing nations through a programme of training activities within a framework of international cooperation, applicants from developed countries were also encouraged to attend.

Workshop manual

Significant quantities of written material were prepared for the workshop. Their accumulation in various forms acted as aid to the participants in their understanding of nuclear theory, measurement techniques, data analysis and ENSDF mass-chain evaluations, representing an important combination of technical information for future reference and other NSDD workshops. Therefore, a relatively large fraction of these presentations, background papers and manuals have been assembled in the form of this document for further use.

Our intention is to use and develop this material in the years to come, particularly for other workshops of this type. Another aim is to ensure that such presentations are not lost, and can be readily at hand for new mass-chain and decay-data evaluators to assist them in their preparation of recommended data for the ENSDF files.

Acknowledgements

I wish to thank my fellow co-directors of the NSDD Workshop for their support leading up to November 2003, and particularly the lecturers (all experts in their fields) for their enthusiasm during the workshop and provision of the various technical input to this document. Administrative aspects of the workshop were considerable leading up to and during the course of November 2003 – as an ICTP-hosted activity, all such features and problems were handled by Ms Andrea Scherbaum (IAEA Nuclear Data Section), and her efforts were much appreciated. Finally, none of the lectures and associated materials would have been delivered without the enthusiastic involvement of all participants at this workshop and an equivalent one-week pilot course in November 2002 (INDC(NDS)-439. January 2003).

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30 April 2004

Evaluations:
A Very Informal History

J. Tuli

NNDC, BNL

E-mail: tuli@bnl.gov

Nuclear Structure and Decay Data Evaluations - an informal history

Jagdish K. Tuli
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BROOKHAVEN NATIONAL LABORATORY

Informal Evaluation History

Webster's Dictionary defines "to compile" as

"to put together, in a new form, out of materials already existing"

In scientific fields: to compact and serve as a convenient source of detailed information - a good "compilation" always involves "evaluation"

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Informal Evaluation History – cont.

First compilation of known nuclides was published by Giorgio Fea in 1935:

Tabelle Riassunitive E Bibliografia delle Transmutazioni Artificiali,

Nuovo Cimento 6, 1 (1935)

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Informal Evaluation History – cont.

First evaluation as "Table of Isotopes" published by J.J. Livingwood and G. T. Seaborg,

Rev Mod Phys 12, 30 (1940)

Evaluation limited to artificially produced nuclear species – immediate use in identification and radiotracers

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Informal Evaluation History – cont.

Subsequent editions of "Table of Isotopes" included all nuclear species:

- G.T. Seaborg, Rev Mod Physics 16, 1 (1944)
- G.T. Seaborg, I. Perlman, *ibid*., 20, 585 (1948)
- J. M. Hollander, I. Perlman and G. T. Seaborg, *ibid*., 25, 469 (1953)
- D. Strominger, J.M. Hollander and G.T. Seaborg, *ibid.,* 30, 585 (1958)

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Informal Evaluation History – cont.

Subsequent editions of "Table of Isotopes" published by John Wiley:

6th Edition: C. M. Lederer, J. M. Hollander and I. Perlman

7th Edition: C. M. Lederer, V. S. Shirley, Editors; E. Browne, J.M. Dairiki, R.E. Doebler, Principal Authors; A.A. Shihab-Eldin, L.J. Jardine, J.K. Tuli, A.B. Buyrn, Authors

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Informal Evaluation History – cont.

8th (and last) edition of “Table of Isotopes” was also published by John Wiley in two volumes, ~ 3000 pages + CD ROM:

R.B. Firestone, V.S. Shirley, Editor
C.M. Baglin, S.Y. Chu, J. Zipkin, Assistant Editors

Unlike previous editions, 8th edition is derived, and not an independent evaluation

Informal Evaluation History – cont.

An Editor of “Table of Isotopes” observed in 1941

“The rate at which radioactivities are discovered may be reduced very considerably and the table would itself become stable.”

That clearly did not happen!

Informal Evaluation History – cont.

There were other parallel evaluation efforts
Some of these were:

T. Lauritsen (and later F. Ajzenberg-Selove) (1948-on)

B.S. Dzhelepov (and later with L. Peker and others) in USSR (1950-on)

P. M. Endt (and later with C. van der Leun)
(1954 – on)

Informal Evaluation History – cont.

Wall Chart

Emilio Segre (as part of Enrico Fermi's group) introduced first chart, with Z along the x-axis and N along the Y axis.

Segre's chart was published in 5/1945 as Los Alamos report with classified data omitted!

1948: G. Friedlander and M. Perlman (GE Research Lab) created the first GE chart with Z and N reversed. Sixteen editions have since been published by Knolls Atomic Power Lab

Informal Evaluation History – cont.

Nuclear Data Sheets

Katherine Way as part of Manhattan Project working at Clinton Lab (later renamed ORNL) began collecting nuclear data.

1948: Way headed the Nuclear Data Project at US National Bureau of Standards (later renamed US National Institute of Standards and Technology)

Informal Evaluation History – cont.

"Nuclear Data" report was published in 1950.

Data included measured values with references of isotopic abundances, methods of production, n cross sections, half-lives, decay modes, energies and intensities of radiations, conversion coefficients, and some reaction data and decay schemes. No recommended values or uncertainties were given.

Informal Evaluation History – cont.

1953: Nuclear Data Project moved under the control of the US National Academy of Sciences-National Research Council in Washington, DC

Published data (AEC reports) now also included coincidence, mass assignments, n,p separation energies, total disintegration energies, spins, magnetic and electric moments. Uncertainties were given with a single decay scheme for all isobars and given A.

Data were in form of loose leaf pages called "NUCLEAR DATA SHEETS"

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Informal Evaluation History – cont.

1964: Nuclear Data Project under the leadership of Katherine Way moved back to Oak Ridge National Lab, where her effort had originally started in 1948.

Nuclear Data Sheets were once again to be published in book form by Academic Press, rather than as single sheets of data.

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Informal Evaluation History – cont.

Nuclear Data Sheets

February 1966: Nuclear Data Sheets started as section B of the journal Nuclear Data, and later as simply Nuclear Data Sheets published by Academic Press

December 1965: Section A of Nuclear Data was started as Atomic Data Tables.

August 1973: Two journals (Atomic Data and Atomic Data A) merged as Atomic and Nuclear Data Tables, with K. Way as Editor

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Informal Evaluation History – cont.

Evaluations limited to NDP-ORNL effort

Time lag in evaluations (1970-71)

Employment situation was not good for Ph.D.students

NSF/NAS joined forces to ensure that evaluations became more current:

- created three-year NIRA program
- recruited two sets of 12 young Ph.Ds for two-year terms
- some stayed in the evaluation business at the end of the program (1971-74)

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Informal Evaluation History – cont.

Hand-written data sheets. Draftsman were drawing the decay schemes

Bruce Ewbank at ORNL was instrumental in computerization of recent references (NSR)

Computerization of various drawings

Common input format for tables and drawing

Evaluated Nuclear Structure Data File

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Informal Evaluation History – cont.

Subsequent to the completion of NIRA program, proposed in 1975 that the evaluation activity be decentralized with international involvement under the auspice of IAEA, Nuclear Data Section.

Evaluation responsibility was divided amongst various data centers within and outside the US.

NNDC at BNL coordinated the national and international effort for US/DOE.

Lead role in editing and processing evaluations continued at NDP/ORNL.

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Informal Evaluation History - cont

1980: change of production responsibility to NNDC, when ORNL management support for the activity declined.

1981: NNDC became responsible for production of Nuclear Data Sheets and computerized the process. Photo-ready copy of the journal has since been supplied to the publisher.

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Informal Evaluation History – cont.

ORNL and NNDC edited the journal jointly until June 1998 when Murray Martin retired (started evaluation work with Katherine Way and served as the Editor-in-Chief of the journal while working at the Nuclear Data Project, ORNL).

With Murray's retirement the editing responsibility shifted completely to the National Nuclear Data Center, BNL.

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Nuclear Structure and Decay Data Network

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Nuclear Structure and Decay Data Network

US Network (~ 6 FTE)

BNL
INEEL
LBNL
McMaster, Canada
ORNL
TUNL

BROOKHAVEN NATIONAL LABORATORY

Nuclear Structure and Decay Data Network

Non-US Contributors

Belgium
Canada
China
France
Japan
Kuwait
Russia
Sweden

Nuclear Structure and Decay Data Network

WHAT DO WE DO?

Primary mission:

Evaluate (or compile) structure and decay data, A = 1-293, for inclusion in ENSDF (or XUNDL) database.

Other responsibilities:

- Maintenance of checking and evaluation software
- Peer review of evaluations
- Dissemination of data

Nuclear Structure and Decay Data Network

OUR PRINCIPAL DATABASES

Web accessible from NNDC or mirror sites; http://www.nndc.bnl.gov links you to them

- **NSR** - Nuclear Science References
- **ENSDF** - Evaluated Nuclear Structure Data File
- **XUNDL** - Unevaluated data compiled from recently published literature

BROOKHAVEN NATIONAL LABORATORY

Nuclear Theory:
The Nuclear Shell Model

P. Van Isacker

GANIL, France

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Nuclear Shell Model

Context and assumptions of the model

Symmetries of the shell model:

Racah's SU(2) pairing model

Wigner's SU(4) symmetry

Elliott's SU(3) model of rotation

Overview of nuclear models

- *Ab initio* methods: description of nuclei starting from the bare nn and nnn interactions
- Nuclear shell model: nuclear average potential + (residual) interaction between nucleons
- Mean-field methods: nuclear average potential with global parametrization (+ correlations)
- Phenomenological models: specific nuclei or properties with local parametrization

Ab initio methods

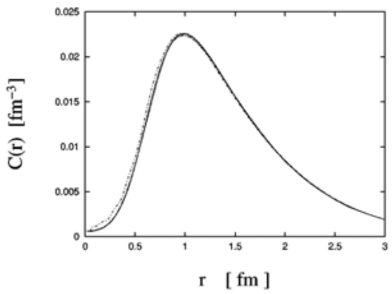
- Faddeev-Yakubovsky: A ≤ 4
- Coupled-rearrangement-channel Gaussian-basis variational: A ≤ 4 (higher with clusters)
- Stochastic variational: A ≤ 7
- Hyperspherical harmonic variational: A ≤ 4
- Green's function Monte Carlo: A ≤ 7
- No-core shell model: A ≤ 12
- Effective interaction hyperspherical: A ≤ 6

Benchmark calculation for *A* = 4

- Test calculation with realistic interaction: all methods agree

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
CRCGV	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

$$\langle \Psi | \sum_{k<l}^{4} \delta(r - r_{kl}) | \Psi \rangle$$



But E_{expt} = -28.296 MeV ⇒ need for three-nucleon interaction

- **Basic symmetries**

- Non-relativistic Schrödinger equation:

$$H = \sum_{k=1}^{A} \frac{p_k^2}{2m_k} + \sum_{k<l}^{A} W_2(\xi_k, \xi_l) + \sum_{k<l<m}^{A} W_3(\xi_k, \xi_l, \xi_m) + \cdots$$

$$\left[\xi_k \equiv \{\vec{r}_k, \vec{\sigma}_k, \vec{\tau}_k\}, \vec{p}_k = -i\hbar\vec{\nabla}_k\right]$$

- Symmetry or invariance under:

— translations ⇒ linear momentum ***P***

— rotations ⇒ angular momentum ***J***=***L***+***S***

— space reflection ⇒ parity π

— time reversal

Nuclear shell model

- Separation in mean field + residual interaction:

$$H = \sum_{k=1}^{A} \frac{p_k^2}{2m_k} + \sum_{k<l}^{A} W(\xi_k, \xi_l)$$

$$= \underbrace{\sum_{k=1}^{A} \left[\frac{p_k^2}{2m_k} + V(\xi_k)\right]}_{\text{mean field}} + \underbrace{\left[\sum_{k<l}^{A} W(\xi_k, \xi_l) - \sum_{k=1}^{A} V(\xi_k)\right]}_{\text{residualinteraction}}$$

- Independent-particle assumption - choose *V* and neglect residual interaction:

$$H \approx H_{\mathrm{IP}} = \sum_{k=1}^{A} \left[\frac{p_k^2}{2m_k} + V(\xi_k)\right]$$

Independent-particle shell model

- Solution for one particle:

$$\left[\frac{p_k^2}{2m_k}+V(\xi_k)\right]\phi_i(k)=E_i\phi_i(k) \qquad [\phi_i(k)\equiv\phi_i(\vec{r}_k,\vec{\sigma}_k,\vec{\tau}_k)]$$

- Solution for many particles:

$$\Phi_{i_1i_2\ldots i_A}(1,2,\ldots,A)=\prod_{k=1}^{A}\phi_{i_k}(k)$$

$$H_{\mathrm{IP}}\Phi_{i_1i_2\ldots i_A}(1,2,\ldots,A)=\left(\sum_{k=1}^{A}E_{i_k}\right)\Phi_{i_1i_2\ldots i_A}(1,2,\ldots,A)$$

Independent-particle shell model

- Antisymmetric solution for many particles (Slater determinant):

$$\Psi_{i_1i_2\ldots i_A}(1,2,\ldots,A)=\frac{1}{\sqrt{A!}}\begin{vmatrix}\phi_{i_1}(1) & \phi_{i_1}(2) & \ldots & \phi_{i_1}(A)\\ \phi_{i_2}(1) & \phi_{i_2}(2) & \ldots & \phi_{i_2}(A)\\ \vdots & \vdots & \ddots & \vdots\\ \phi_{i_A}(1) & \phi_{i_A}(2) & \ldots & \phi_{i_A}(A)\end{vmatrix}$$

- Example for $A=2$ particles:

$$\Psi_{i_1i_2}(1,2)=\frac{1}{\sqrt{2}}\left[\phi_{i_1}(1)\phi_{i_2}(2)-\phi_{i_1}(2)\phi_{i_2}(1)\right]$$

Hartree-Fock approximation

- Vary ϕ_i (*i.e., V*) to minize the expectation value of H in a Slater determinant:

$$\delta \frac{\int \Psi^*_{i_1 i_2 \ldots i_A}(1,2,\ldots,A) H \Psi_{i_1 i_2 \ldots i_A}(1,2,\ldots,A) d\xi_1 d\xi_2 \ldots d\xi_A}{\int \Psi^*_{i_1 i_2 \ldots i_A}(1,2,\ldots,A) \Psi_{i_1 i_2 \ldots i_A}(1,2,\ldots,A) d\xi_1 d\xi_2 \ldots d\xi_A} = 0$$

- Application requires choice of H - many global parametrizations (Skyrme, Gogny…) have been developed

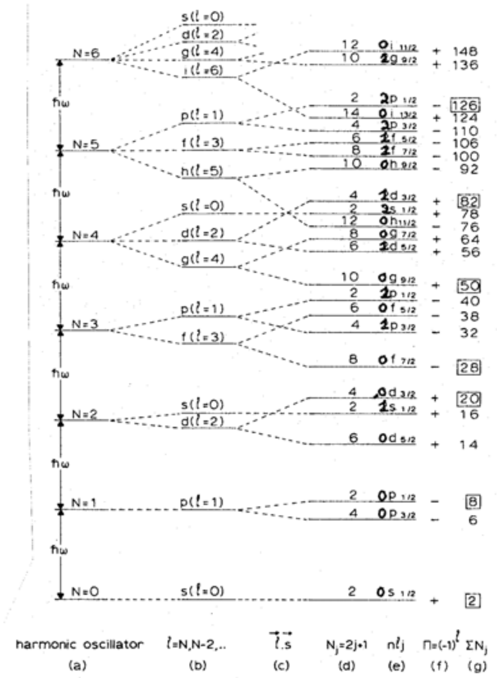
Poor man's Hartree-Fock

- Choose a simple, analytically solvable V that approximates the microscopic HF potential:

$$H_{\mathrm{IP}} = \sum_{k=1}^{A} \left[\frac{p_k^2}{2m} + \frac{1}{2} m\omega^2 r_k^2 - \zeta_{\mathrm{ls}} \vec{l}_k \cdot \vec{s}_k - \zeta_{\mathrm{ll}} l_k^2 \right]$$

- Contains
  - — Harmonic oscillator potential with constant ω
  - — Spin-orbit term with strength $\zeta_{\mathbf{ls}}$
  - — Orbit-orbit term with strength $\zeta_{\mathbf{ll}}$
  - — Adjust ω, $\zeta_{\mathbf{ls}}$ and $\zeta_{\mathbf{ll}}$ to best reproduce HF

Energy levels of harmonic oscillator



Typical parameter values:

$$\hbar\omega \approx 41A^{-1/3}\text{MeV}$$
$$\zeta_{ls}\hbar^2 \approx 20A^{-2/3}\text{MeV}$$
$$\zeta_{ll}\hbar^2 \approx 0.1\text{MeV}$$
$$\therefore b \approx 1.0A^{1/6}\text{fm}$$

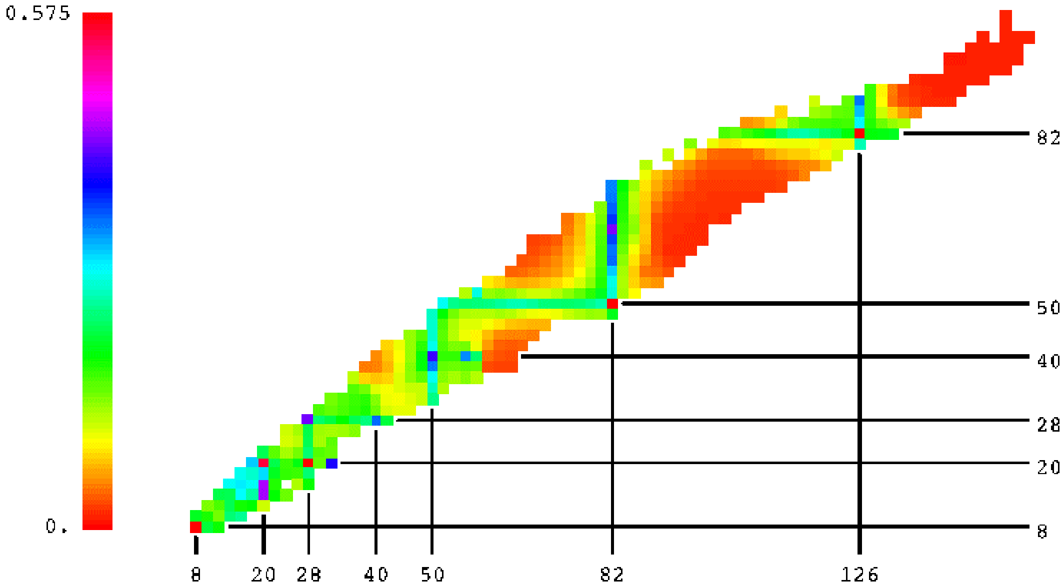
'Magic' numbers at 2, 8, 20, 28, 50, 82, 126, 184,…

Evidence for shell structure

- Evidence for nuclear shell structure from
  - — Excitation energies in even-even nuclei
  - — Nucleon-separation energies
  - — Nuclear masses
  - — Nuclear level densities
  - — Reaction cross sections
- Is nuclear shell structure modified away from the line of stability?

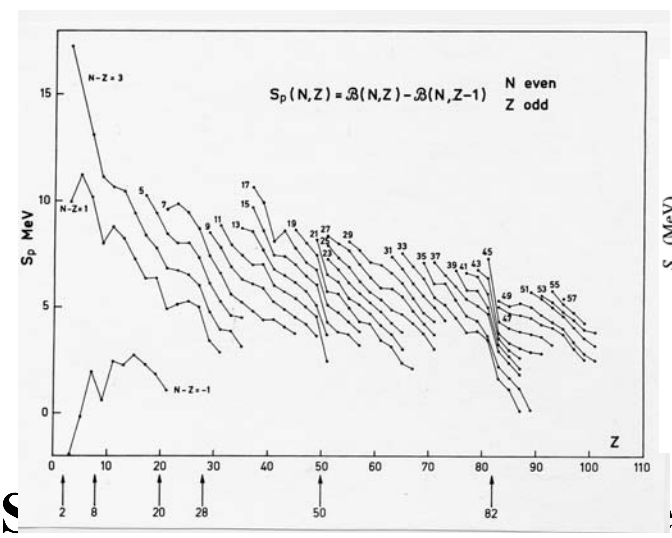
Shell structure from $E_x(2_1)$

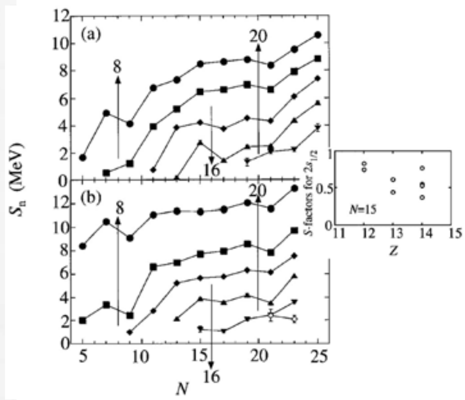
High $E_x(2_1)$ indicates stable shell structure:



Shell structure from S_n or S_p

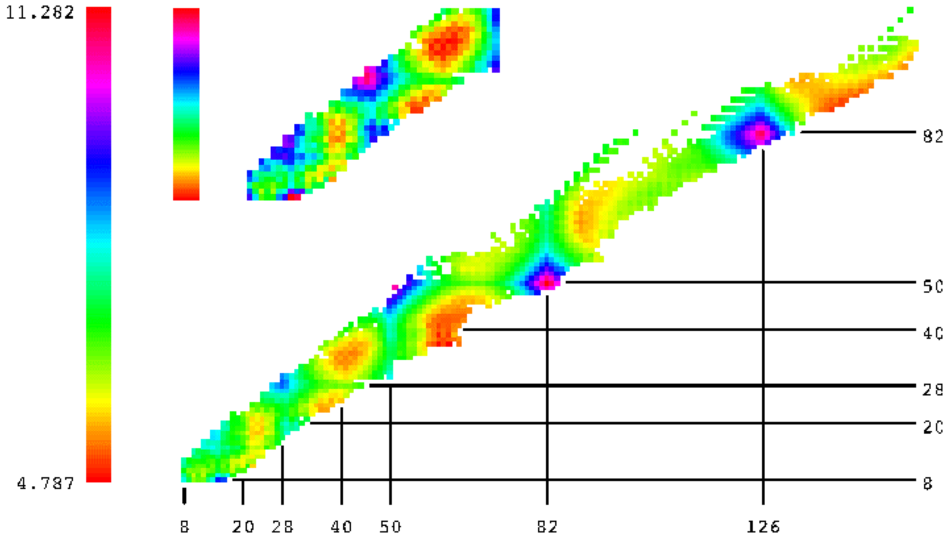
- Change in slope of S_n (S_p) indicates neutron (proton) shell closure (constant N-Z plots):





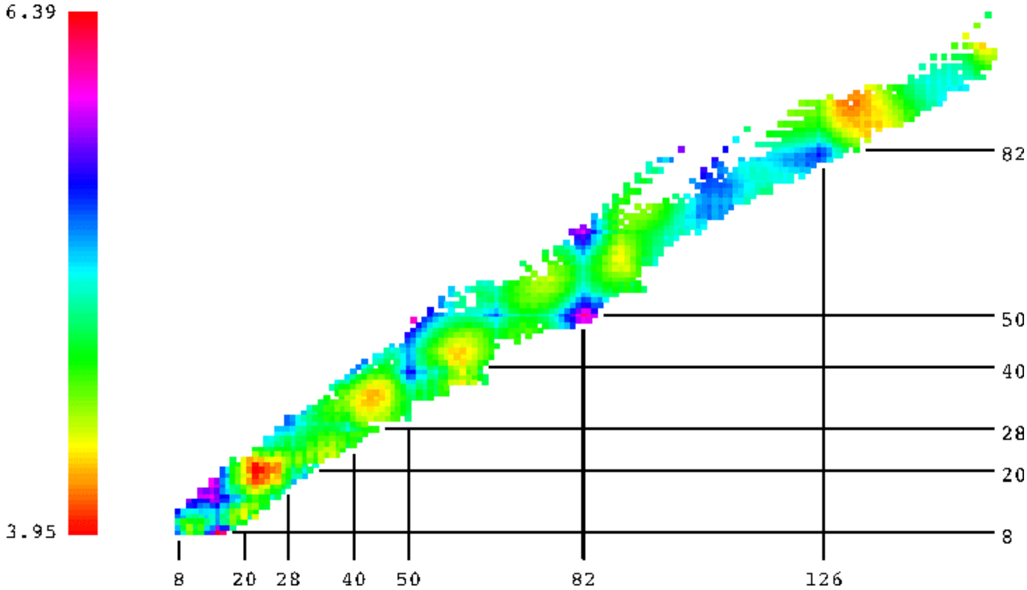
Shell structure from masses

- Deviations from Weizsäcker mass formula:



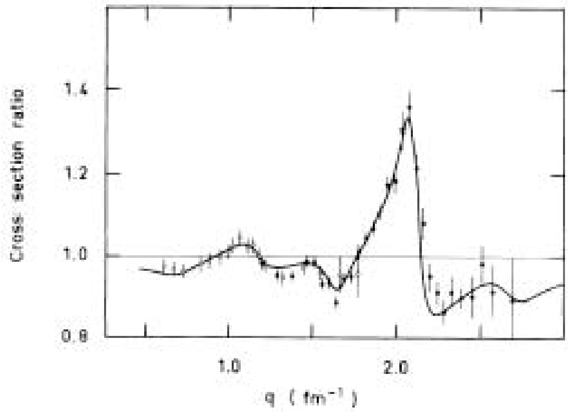
Shell structure from masses

- Deviations from improved Weizsäcker mass formula that includes $n_\nu n_\pi$ and $n_\nu + n_\pi$ terms:



Validity of SM wave functions

- Example: Elastic electron scattering on ^{206}Pb and ^{205}Tl, differing by a 3s proton
- Measured ratio agrees with shell-model prediction for 3s orbit with modified occupation



Nuclear shell model

- The full shell-model Hamiltonian:

$$H = \sum_{k=1}^{A} \left[\frac{p_k^2}{2m} + V(\xi_k) \right] + \sum_{k<l}^{A} V_{\mathrm{RI}}(\xi_k, \xi_l)$$

- Valence nucleons: neutrons or protons that are in excess of the last, completely filled shell
- Usual approximation: consider the residual interaction V_{RI} among valence nucleons only
- Sometimes include selected core excitations ('intruder' states)

The shell-model problem

- Solve the eigenvalue problem associated with the matrix (*n* active nucleons):

$$\left\langle i'_1 \ldots i'_n \left| \sum_{k<l}^{n} V_{\mathrm{RI}}(\xi_k,\xi_l) \right| i_1 \ldots i_n \right\rangle \qquad \left[\langle 1 \ldots n | i_1 \ldots i_n \rangle \equiv \Psi_{i_1 \ldots i_n}(1 \ldots n) \right]$$

- Methods of solution:

— Diagonalization (Strasbourg-Madrid): 10^9

— Monte-Carlo (Pasadena-Oak Ridge):

— Quantum Monte-Carlo (Tokyo):

— Group renormalization (Madrid-Newark): 10^{120}

Residual shell-model interaction

- Four approaches:

— Effective: derive from free nn interaction taking account of the nuclear medium

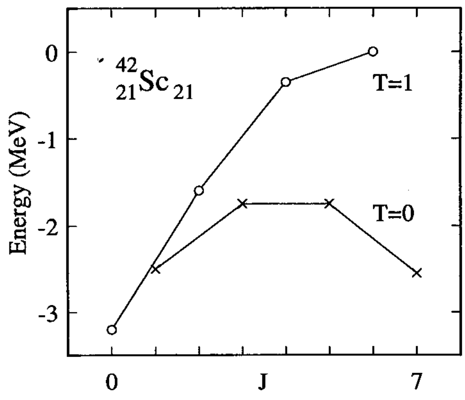
— Empirical: adjust matrix elements of residual interaction to data; examples: p, sd and pf shells

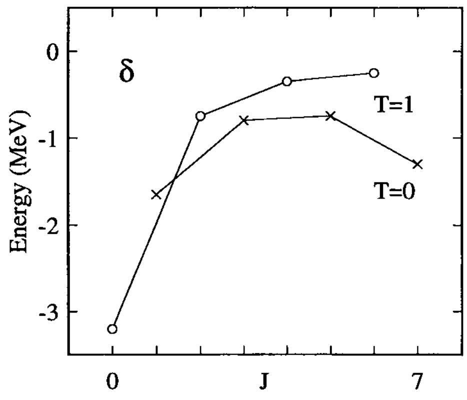
— Effective-empirical: effective interaction with some adjusted (monopole) matrix elements

— Schematic: assume a simple spatial form and calculate its matrix elements in a harmonic-oscillator basis; example: δ interaction

Schematic short-range interaction

- Delta interaction in harmonic-oscillator basis.
- Example of $^{42}Sc_{21}$ (1 active neutron + 1 active proton):





Symmetries of the shell model

- Three bench-mark solutions:

— no residual interaction ⇒ IP shell model

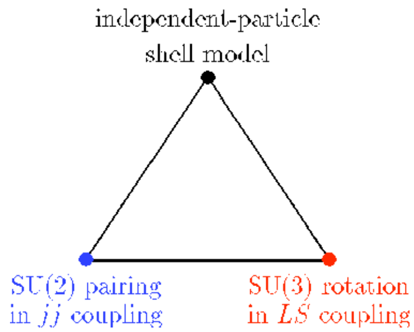
— pairing (in *jj* coupling) ⇒ **Racah**'s SU(2)

— quadrupole (in *LS* coupling) ⇒ **Elliott**'s SU(3)

- Symmetry triangle:

$$H_{\mathrm{IP}} = \sum_{k=1}^{A}\left[\frac{p_k^2}{2m} + \frac{1}{2}m\omega^2 r_k^2 - \zeta_{\mathrm{ls}}\vec{l}_k\cdot\vec{s}_k - \zeta_{\mathrm{ll}}l_k^2\right]$$

$$+\sum_{k<l}^{A}V_{\mathrm{RI}}(\xi_k,\xi_l)$$



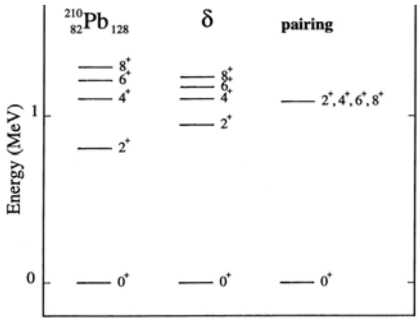
Racah's SU(2) pairing model

- Assume large spin-orbit splitting ζ_{ls} which implies a *jj* coupling scheme

- Assume pairing interaction in a single-*j* shell:

$$\left\langle j^2 JM_J \middle| V_{\text{pairing}} \middle| j^2 JM_J \right\rangle = \begin{cases} -\frac{1}{2}(2j+1)g, & J=0 \\ 0, & J \neq 0 \end{cases}$$

- Spectrum of ^{210}Pb:



Solution of pairing Hamiltonian

- Analytic solution of pairing hamiltonian for identical nucleons in a single-*j* shell:

$$\left\langle j^n \upsilon J \middle| \sum_{k<l}^{n} V_{\text{pairing}}(\xi_k, \xi_l) \middle| j^n \upsilon J \right\rangle = -\tfrac{1}{4} G(n-\upsilon)(2j-n-\upsilon+3)$$

- Seniority υ (number of nucleons not in pairs coupled to $J=0$) is a good quantum number

- Correlated ground-state solution (*cf.* super-fluidity in solid-state physics)

Pairing and superfluidity

- Ground states of a pairing Hamiltonian have *superfluid* character:

  — even-even nucleus ($\upsilon=0$): $\left(S_+\right)^{n_j/2}|o\rangle$

  — odd-mass nucleus ($\upsilon=1$): $a_j^+\left(S_+\right)^{n_j/2}|o\rangle$

- Nuclear superfluidity leads to

  — constant energy of first 2^+ in even-even nuclei

  — odd-even staggering in masses

  — two-particle (2n or 2p) transfer enhancement

Superfluidity in semi-magic nuclei

- Even-even nuclei:

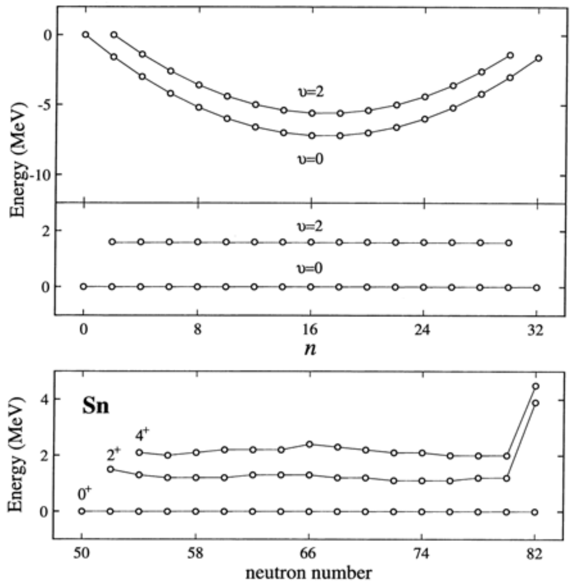
  — ground state has $\upsilon=0$.

  — first-excited state has $\upsilon=2$.

  — pairing produces constant energy gap:

$$E_x\left(2_1^+\right)=\tfrac{1}{2}\left(2j+1\right)g$$

- Example of Sn nuclei:



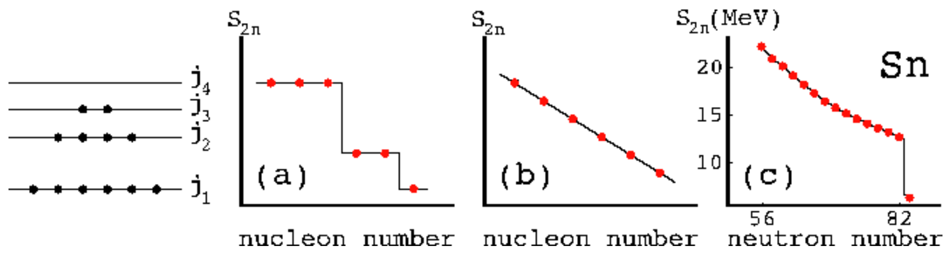
Two-nucleon separation energies

- Two-nucleon separation energies S_{2n}:

  (a) shell splitting dominates over interaction

  (b) interaction dominates over shell splitting

  (c) S_{2n} in tin isotopes



Generalized pairing models

- Trivial generalization from a single-j shell to several degenerate j shells:

$$S_+ \propto \frac{1}{2}\sum_j \sqrt{2j+1}\left(a_j^+ \times a_j^+\right)_0^{(0)}$$

- Pairing with neutrons and protons:

  — $T=1$ pairing: SO(5).

  — $T=0$ and $T=1$ pairing: SO(8)

- Non-degenerate shells:

  — Talmi's generalized seniority

  — Richardson's integrable pairing model

Pairing with neutrons and protons

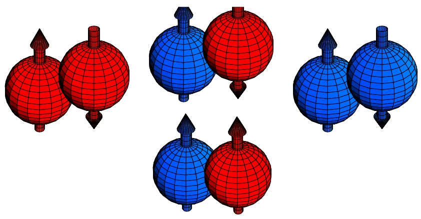
- For neutrons and protons *two* pairs, and hence *two* pairing interactions are possible:

— Isoscalar ($S=1,T=0$):

$$-S_+^{10} \cdot S_-^{10}, \quad S_+^{10} = \sqrt{l+\tfrac{1}{2}}\left(a^+_{l\frac{1}{2}\frac{1}{2}} \times a^+_{l\frac{1}{2}\frac{1}{2}}\right)^{(010)}, \quad S_-^{10} = \left(S_+^{10}\right)^+$$

— Isovector ($S=0,T=1$):

$$-S_+^{01} \cdot S_-^{01}, \quad S_+^{01} = \sqrt{l+\tfrac{1}{2}}\left(a^+_{l\frac{1}{2}\frac{1}{2}} \times a^+_{l\frac{1}{2}\frac{1}{2}}\right)^{(001)}, \quad S_-^{01} = \left(S_+^{01}\right)^+$$



Superfluidity of *N*=*Z* nuclei

- Ground state of a $T=1$ pairing Hamiltonian for identical nucleons is superfluid, $(S_+)^{n/2}|\mathrm{o}\rangle$

- Ground state of a $T=0$ and $T=1$ pairing Hamiltonian with equal number of neutrons and protons has *different* superfluid character:

$$\left(\cos\theta S_+^{10} \cdot S_+^{10} - \sin\theta S_+^{01} \cdot S_+^{01}\right)^{n/4}|\mathrm{o}\rangle$$

- $\Rightarrow$ Condensate of α s (θ depends on g_0/g_1)

- Observations:

— isoscalar component in condensate survives only in $N\sim Z$ nuclei, if anywhere at all

— spin-orbit term *reduces* isoscalar component

Wigner's SU(4) symmetry

- Assume the nuclear Hamiltonian is invariant under spin *and* isospin rotations:

$$\left[H_{\text{nucl}}, S_\mu\right] = \left[H_{\text{nucl}}, T_\nu\right] = \left[H_{\text{nucl}}, Y_{\mu\nu}\right] = 0$$

$$S_\mu = \sum_{k=1}^{A} s_\mu(k), \quad T_\nu = \sum_{k=1}^{A} t_\nu(k), \quad Y_{\mu\nu} = \sum_{k=1}^{A} s_\mu(k) t_\nu(k)$$

- Since $\{S_\mu, T_\nu, Y_{\mu\nu}\}$ form an SU(4) algebra:

— H_{nucl} has SU(4) symmetry

— total spin ***S***, total orbital angular momentum ***L***, total isospin ***T*** and SU(4) labels $(\lambda\mu\nu)$ are conserved quantum numbers

Physical origin of SU(4) symmetry

- SU(4) labels specify the separate spatial and spin-isospin symmetry of the wavefunction:

particle number	spatial symmetry	L	spin–isospin symmetry	$(\lambda\mu\nu)$	(S,T)
2	□□ (S)	$0^2, 2^2, 4$	□/□ (A)	(010)	(0,1) (1,0)
	□/□ (A)	1, 2, 3	□□ (S)	(200)	(0,0) (1,1)

- Nuclear interaction is short-range attractive and hence *favours maximal spatial symmetry*

Breaking of SU(4) symmetry

- Breaking of SU(4) symmetry as a consequence of
  - — spin-orbit term in nuclear mean field
  - — coulomb interaction
  - — spin-dependence of residual interaction
- Evidence for SU(4) symmetry breaking from
  - — masses: rough estimate of nuclear BE from

$$B(N,Z) \propto a + bg(\lambda\mu\nu) = a + b\langle\lambda\mu\nu|C_2[\mathrm{SU}(4)]|\lambda\mu\nu\rangle$$

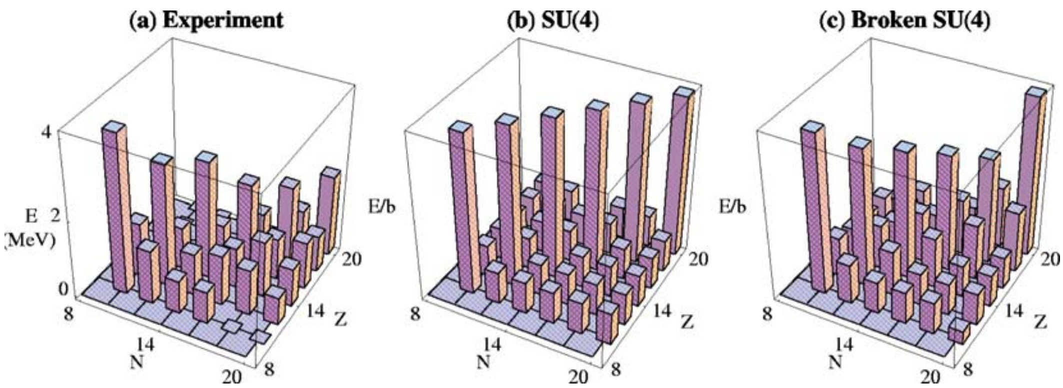
  - — β decay: Gamow-Teller operator $Y_{\mu,\pm 1}$ is a generator of SU(4) ⇒ selection rule in ($\lambda\mu\nu$)

SU(4) breaking from masses

- Double binding energy difference δV_{np}

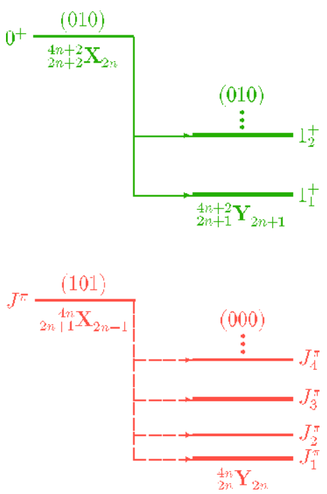
$$\delta V_{\mathrm{np}}(N,Z) = \tfrac{1}{4}[B(N,Z) - B(N-2,Z) - B(N,Z-2) + B(N-2,Z-2)]$$

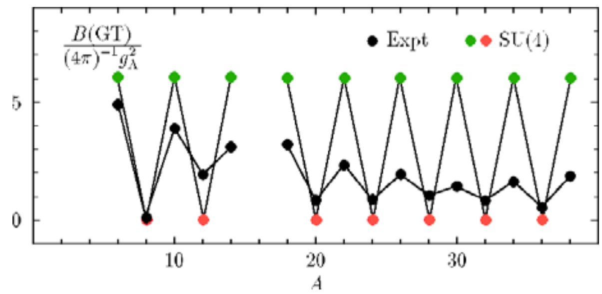
- δV_{np} in *sd*-shell nuclei:



SU(4) breaking from β decay

- Gamow-Teller decay into odd-odd or even-even N=Z nuclei:





Elliott's SU(3) model of rotation

- Harmonic oscillator mean field (*no* spin-orbit) with residual interaction of quadrupole type:

$$H = \sum_{k=1}^{A} \left[\frac{p_k^2}{2m} + \frac{1}{2} m \omega^2 r_k^2 \right] - \kappa Q \cdot Q,$$

$$Q_\mu = \sqrt{\frac{4\pi}{5}} \left(\sum_{k=1}^{A} r_k^2 Y_{2\mu}(\hat{r}_k) + \sum_{k=1}^{A} p_k^2 Y_{2\mu}(\hat{p}_k) \right)$$

Importance and limitations of SU(3)

- Historical importance:

  — bridge between the spherical shell model and the liquid droplet model through mixing of orbits

  — spectrum generating algebra of Wigner's SU(4) supermultiplet

- Limitations:

  — *LS* (Russell-Saunders) coupling, *not jj* coupling (zero spin-orbit splitting) ⇒ beginning of *sd* shell

  — *Q* is the *algebraic* quadrupole operator ⇒ no major-shell mixing

Generalized SU(3) models

- How to obtain rotational features in a *jj*-coupling limit of the nuclear shell model?

- Several efforts since Elliott:

  — pseudo-spin symmetry

  — quasi-SU(3) symmetry (Zuker)

  — effective symmetries (Rowe)

  — FDSM: fermion dynamical symmetry model

  — etc.

Nuclear Theory:
The Interacting Boson Model

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The interacting boson model (IBM)

Dynamical symmetries of the IBM

Neutrons, protons and *F*-spin (IBM-2)

T=0 and *T=1* bosons: IBM-3 and IBM-4

Overview of collective models

- Pure collective models:
  - (rigid) rotor model
  - (harmonic quadrupole) vibrator model
  - liquid-drop model of vibrations and rotations
  - interacting boson model
- With inclusion of particle degrees of freedom:
  - Nilsson model
  - particle-core coupling model
  - interacting boson-fermion model

Rigid rotor model

- Hamiltonian of quantum mechanical rotor in terms of 'rotational' angular momentum ***R***:

$$\hat{H}_{\mathrm{rot}} = \frac{\hbar^2}{2}\left[\frac{R_1^2}{\Im_1} + \frac{R_2^2}{\Im_2} + \frac{R_3^2}{\Im_3}\right] = \frac{\hbar^2}{2}\sum_{i=1}^{3}\frac{R_i^2}{\Im_i}$$

- nuclei have an additional intrinsic part H_{intr} with 'intrinsic' angular momentum ***J***

- total angular momentum is ***I***=***R***+***J***

Modes of nuclear vibration

- nucleus is considered as a droplet of nuclear matter with an equilibrium shape - vibrations are modes of excitation around that shape

- character of vibrations depends on symmetry of equilibrium shape. Two important cases in nuclei:

  – spherical equilibrium shape

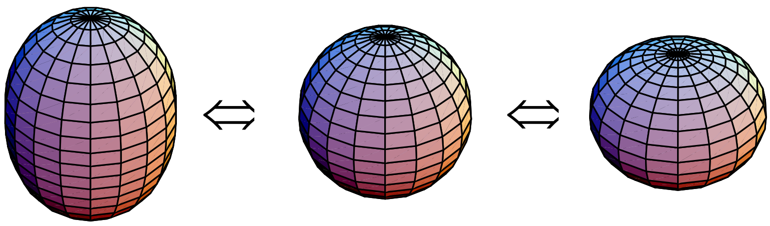
  – spheroidal equilibrium shape

Vibrations about a spherical shape

- Vibrations are characterized by a multipole quantum number λ in surface parametrization:

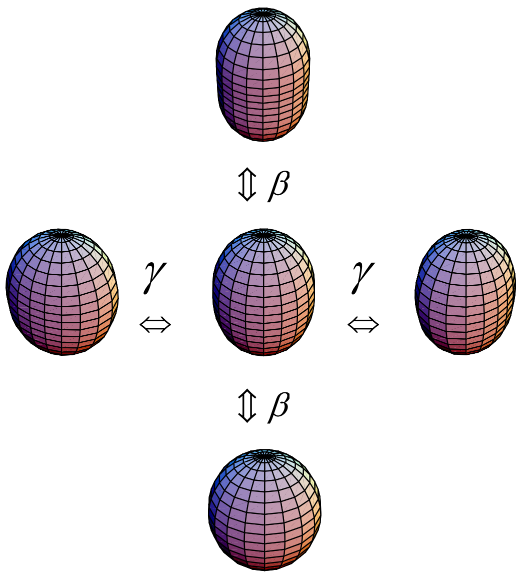
$$R(\theta,\varphi) = R_0\left(1 + \sum_{\lambda}\sum_{\mu=-\lambda}^{+\lambda}\alpha_{\lambda\mu}Y^*_{\lambda\mu}(\theta,\varphi)\right)$$

  - $\lambda = 0$: compression (high energy)
  - $\lambda = 1$: translation (not an intrinsic excitation)
  - $\lambda = 2$: quadrupole vibration



Vibrations about a spheroidal shape

- Vibration of a shape with axial symmetry is characterized by $a_{\lambda\nu}$
- Quadrupolar oscillations:
  - $\nu = 0$: along the axis of symmetry (β)
  - $\nu = \pm 1$: spurious rotation
  - $\nu = \pm 2$: perpendicular to axis of symmetry (γ)



Interacting boson model (IBM)

- Nuclear collective excitations are described in terms of *N s* and *d* bosons

- Spectrum generating algebra for the nucleus is U(6) - all physical observables (Hamiltonian, transition operators…) are expressed in terms of the generators of U(6)

- Formally, nuclear structure is reduced to solving the problem of *N* interacting *s* and *d* bosons

Justifications for IBM

- Bosons are associated with *fermion pairs* which approximately satisfy Bose statistics:

$$S^+ = \sum_j \alpha_j \left(a_j^+ \times a_j^+\right)_0^{(0)} \to s^+,\ D_m^+ = \sum_{jj'} \alpha_{jj'} \left(a_j^+ \times a_{j'}^+\right)_m^{(2)} \to d_m^+$$

- Microscopic justification: IBM is a truncation and subsequent bosonization of the *shell model* in terms of *S* and *D* pairs

- Macroscopic justification: in the classical limit ($N \to \infty$) the expectation value of the IBM Hamiltonian between coherent states reduces to a *liquid-drop* Hamiltonian

IBM Hamiltonian

- Rotational invariant Hamiltonian with up to N-body interactions (usually up to 2):

$$H_{\mathrm{IBM}} = \varepsilon_s n_s + \varepsilon_d n_d + \sum_{ijklJ} \upsilon^L_{ijkl} \left(b_i^+ \times b_j^+\right)^{(L)} \cdot \left(\tilde{b}_k \times \tilde{b}_l\right)^{(L)} + \cdots$$

- For what choice of single-boson energies ε_s and ε_d and boson-boson interactions $\upsilon^L{}_{ijkl}$ is the IBM Hamiltonian solvable?

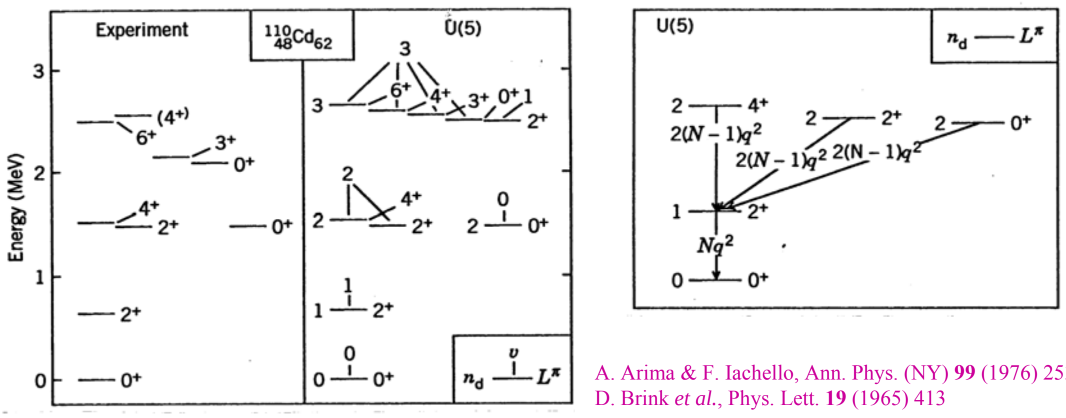
- This problem is equivalent to the enumeration of all algebras G that satisfy

$$\mathrm{U}(6) \supset G \supset \mathrm{SO}(3) \equiv \left\{ L_\mu = \sqrt{10}\left(d^+ \times \tilde{d}\right)^{(1)}_\mu \right\}$$

U(5) vibrational limit

- Spectrum of an anharmonic oscillator in 5 dimensions associated with the quadrupole oscillations of a droplet's surface

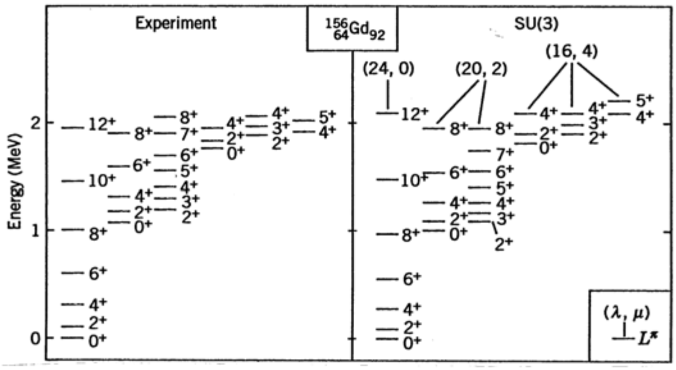
- Conserved quantum numbers: n_d, υ, L



A. Arima & F. Iachello, Ann. Phys. (NY) **99** (1976) 253
D. Brink *et al.*, Phys. Lett. **19** (1965) 413

SU(3) rotational limit

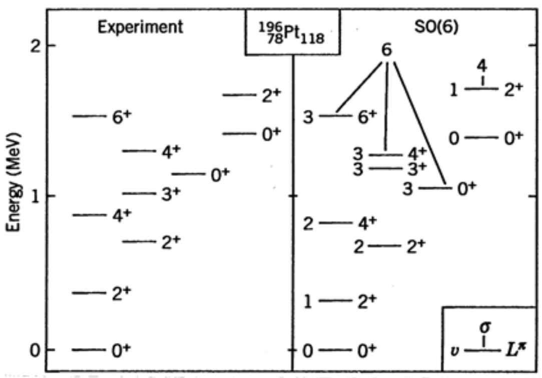
- Rotation-vibration spectrum with β- and γ-vibrational bands
- Conserved quantum numbers: (λ,μ), L

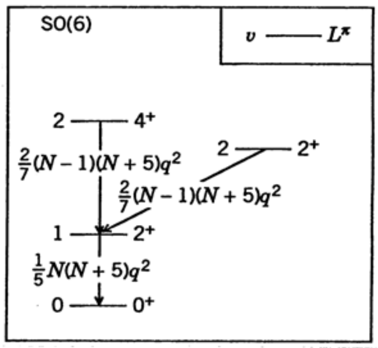


A. Arima & F. Iachello, Ann. Phys. (NY) **111** (1978) 201
A. Bohr & B.R. Mottelson, Dan. Vid. Selsk. Mat.-Fys. Medd. **27** (1953) No 16

SO(6) γ-unstable limit

- Rotation-vibration spectrum of a γ-unstable body
- Conserved quantum numbers: σ, υ, L

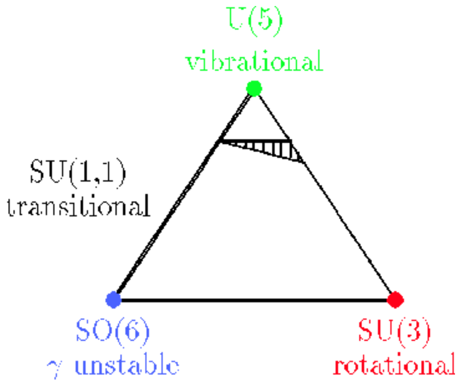




A. Arima & F. Iachello, Ann. Phys. (NY) **123** (1979) 468
L. Wilets & M. Jean, Phys. Rev. **102** (1956) 788

Synopsis of IBM symmetries

- Symmetry triangle of IBM:
  - three standard solutions: U(5), SU(3), SO(6)
  - SU(1,1) analytic solution for U(5) →SO(6)
  - hidden symmetries (parameter transformations)
  - deformed-spherical coexistent phase
  - partial dynamical symmetries
  - critical-point symmetries?

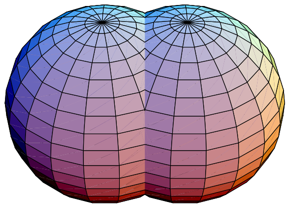


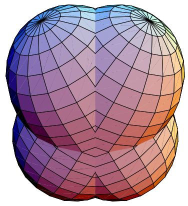
Extensions of IBM

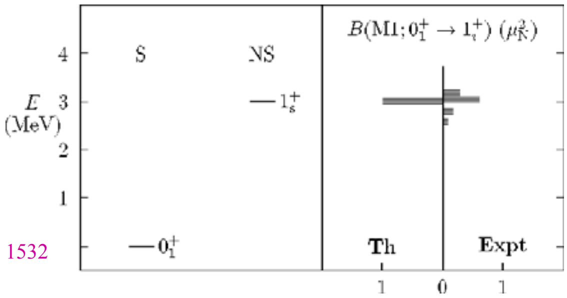
- Neutron and proton degrees freedom (IBM-2):
  - *F*-spin multiplets ($N_\nu + N_\pi$ = constant)
  - scissors excitations
- Fermion degrees of freedom (IBFM):
  - odd-mass nuclei
  - supersymmetry (doublets and quartets)
- Other boson degrees of freedom:
  - isospin *T=0* and *T=1* pairs (IBM-3 and IBM-4)
  - higher multipole (*g*…) pairs

Scissors excitations

- Collective displacement modes between neutrons and protons:
  - *linear* displacement (giant dipole resonance): $\boldsymbol{R}_\nu\text{-}\boldsymbol{R}_\pi \Rightarrow E1$ excitation
  - *angular* displacement (scissors resonance): $\boldsymbol{L}_\nu\text{-}\boldsymbol{L}_\pi \Rightarrow M1$ excitation



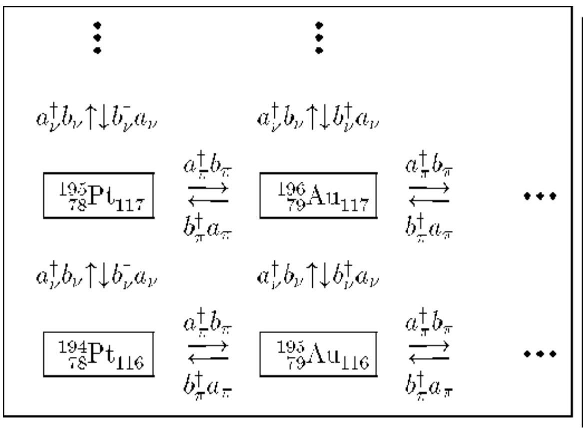




N. Lo Iudice & F. Palumbo, Phys. Rev. Lett. **41** (1978) 1532
F. Iachello, Phys. Rev. Lett. **53** (1984) 1427
D. Bohle *et al.*, Phys. Lett. B **137** (1984) 27

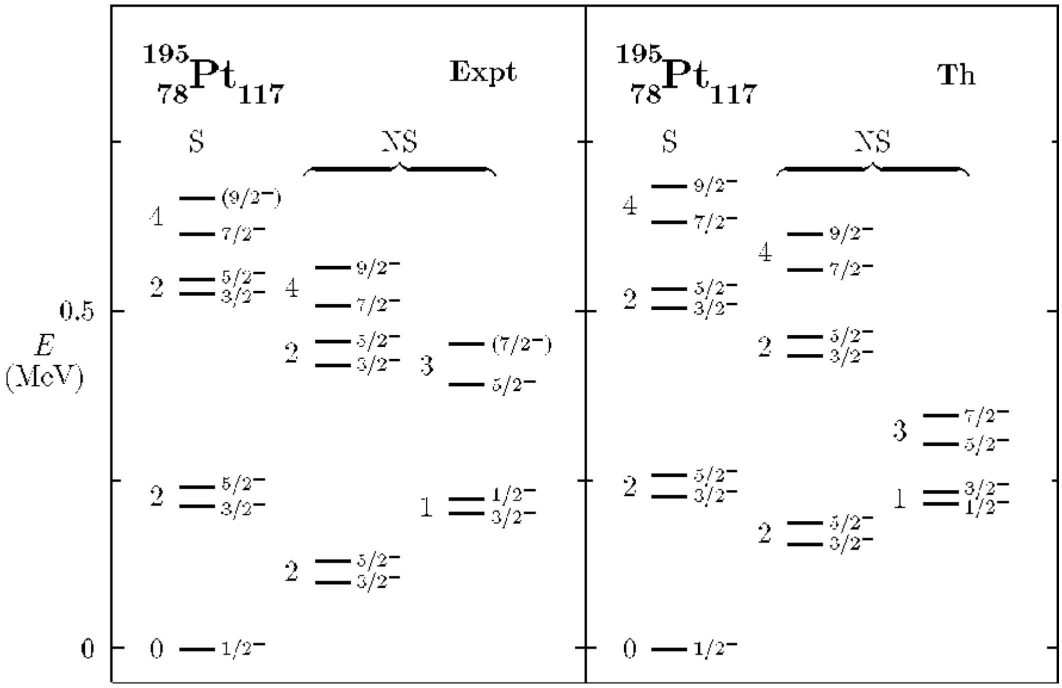
Supersymmetry

- Simultaneous description of even- and odd-mass nuclei (*doublets*) or of even-even, even-odd, odd-even and odd-odd nuclei (*quartets*)
- Example of ^{194}Pt, ^{195}Pt, ^{195}Au and ^{196}Au:

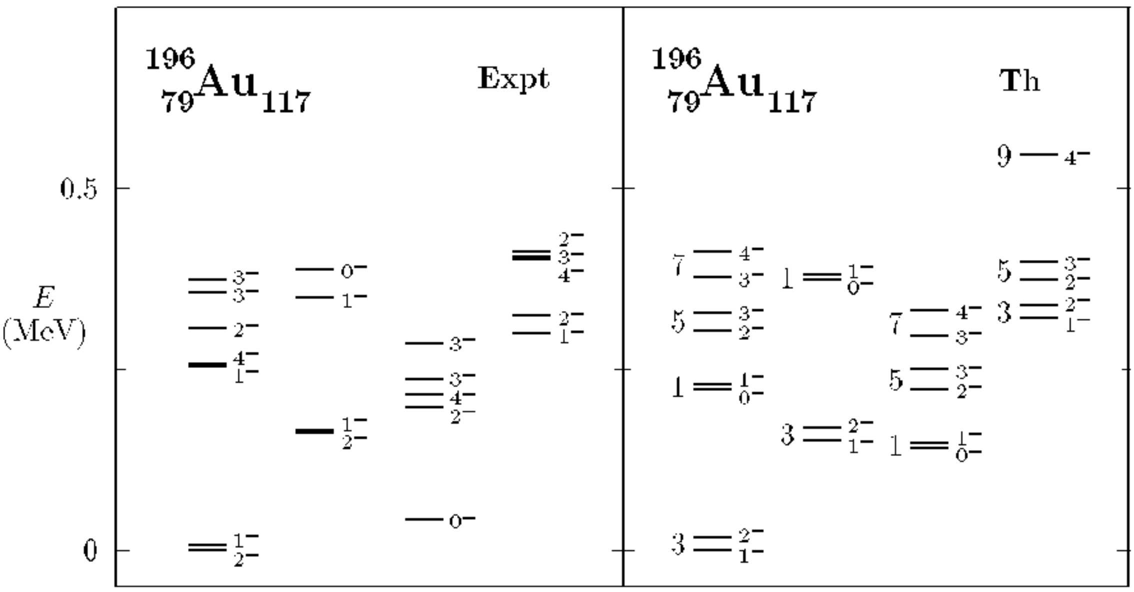


F. Iachello, Phys. Rev. Lett. **44** (1980) 772
P. Van Isacker *et al.*, Phys. Rev. Lett. **54** (1985) 653
A. Metz *et al.*, Phys. Rev. Lett. **83** (1999) 1542

Example of ^{195}Pt



Example of ^{196}Au



Isospin invariant boson models

- Several versions of IBM depending on the fermion pairs that correspond to the bosons:
  - IBM-1: single type of pair
  - IBM-2: $T=1$ nn ($M_T=-1$) and pp ($M_T=+1$) pairs
  - IBM-3: full isospin $T=1$ triplet of nn ($M_T=-1$), np ($M_T=0$) and pp ($M_T=+1$) pairs
  - IBM-4: full isospin $T=1$ triplet and $T=0$ np pair (with $S=1$)
- Schematic IBM-*k* has only S ($L=0$) pairs, full IBM-*k* has S ($L=0$) and D ($L=2$) pairs

IBM-4

•Shell-model justification in *LS* coupling:

particle number	spatial symmetry	L	spin–isospin symmetry	$(\lambda\mu\nu)$	(S,T)
2	$\square\square$ (S)	$0^2, 2^2, 4$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$ (A)	(010)	(0,1) (1,0)
	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$ (A)	$1, 2, 3$	$\square\square$ (S)	(200)	(0,0) (1,1)

- Advantages of IBM-4:
  - boson states carry L, S, T, J and $(\lambda\mu\nu)$
  - mapping from the shell model to IBM-4 ⇒ shell-model test of the boson approximation
  - includes np pairs ⇒ important for N~Z nuclei

IBM-4 with *L=0* bosons

- Schematic IBM-4 with bosons
  - $L=0, S=1, T=0 \Rightarrow J=1$ (p boson, $\pi=+1$)
  - $L=0, S=0, T=1 \Rightarrow J=0$ (s boson, $\pi=+1$)
- Two applications:
  - microscopic (but schematic) study of the influence of spin-orbit coupling on the structure of the superfluid condensate in $N = Z$ nuclei
  - phenomenological mass formula for $N \sim Z$ nuclei

Boson mapping of SO(8)

- Pairing Hamiltonian in non-degenerate shells,

$$H = \sum_j \varepsilon_j n_j - g_0 S_+^{10} \cdot S_-^{10} - g_1 S_+^{01} \cdot S_-^{01}$$

is non-solvable in general but can be treated (numerically) via a boson mapping

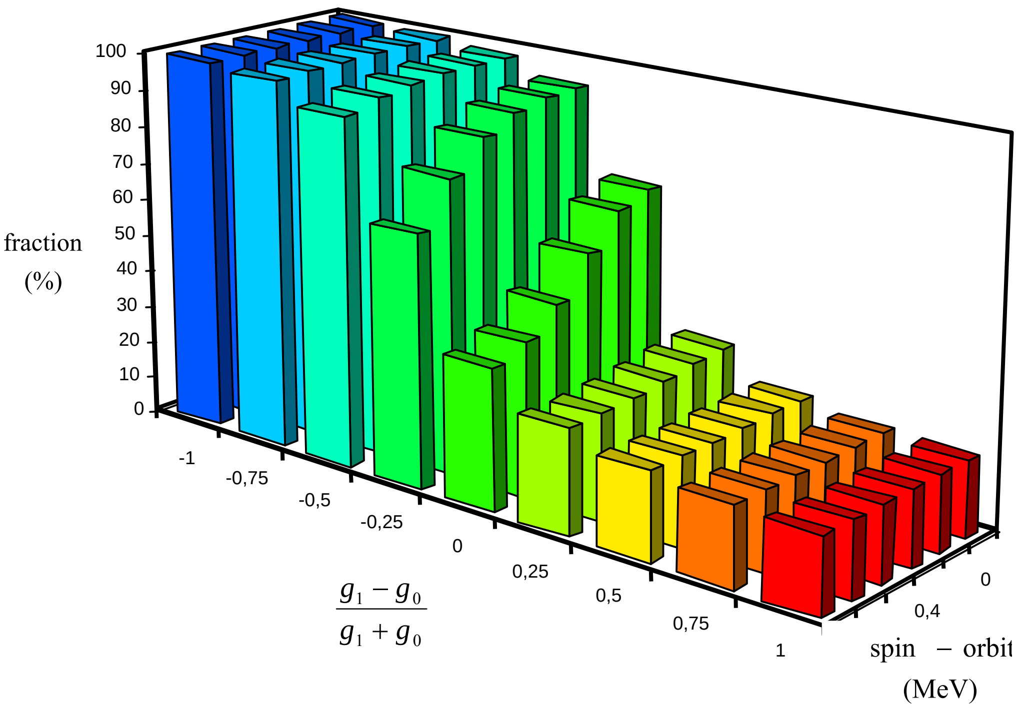
- Correspondence $S_+^{10} \rightarrow p^+$ and $S_+^{01} \rightarrow s^+$ leads to a schematic IBM-4 with $L=0$ bosons

- Mapping of shell-model pairing Hamiltonian completely determines boson energies and boson-boson interactions (*no* free parameters)

P. Van Isacker *et al.*, J. Phys. G **24** (1998) 1261

Pair structure and spin-orbit force

- Fraction of p bosons in the lowest $J=1$, $T=0$ state for $N = Z = 5$ in the pf shell:



O. Juillet & S. Josse, Eur. Phys. A **2** (2000) 291

Mass formula for $N \sim Z$ nuclei

- Schematic IBM-4 with $L = 0$ bosons has U(6) algebraic structure

- Symmetry lattice of the model:

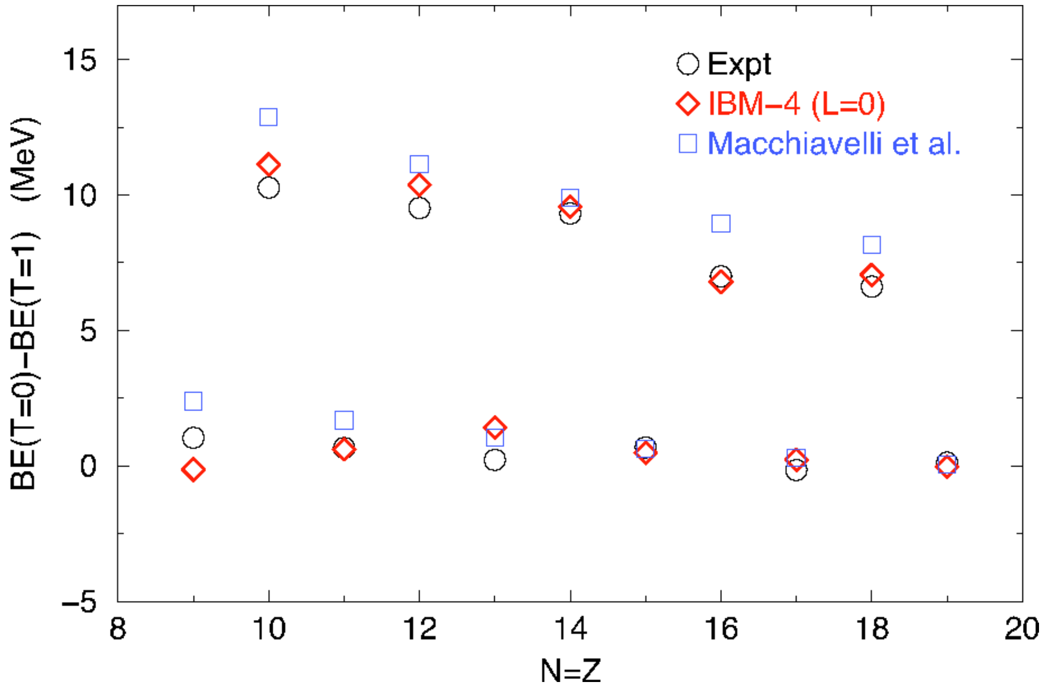
$$\mathrm{U}(6) \supset \left\{ \begin{matrix} \mathrm{U}_S(3) \otimes \mathrm{U}_T(3) \\ \mathrm{SU}(4) \end{matrix} \right\} \supset \mathrm{SO}_S(3) \otimes \mathrm{SO}_T(3)$$

- Simple IBM-4 Hamiltonian suggested by microscopy with *adjustable* parameters:

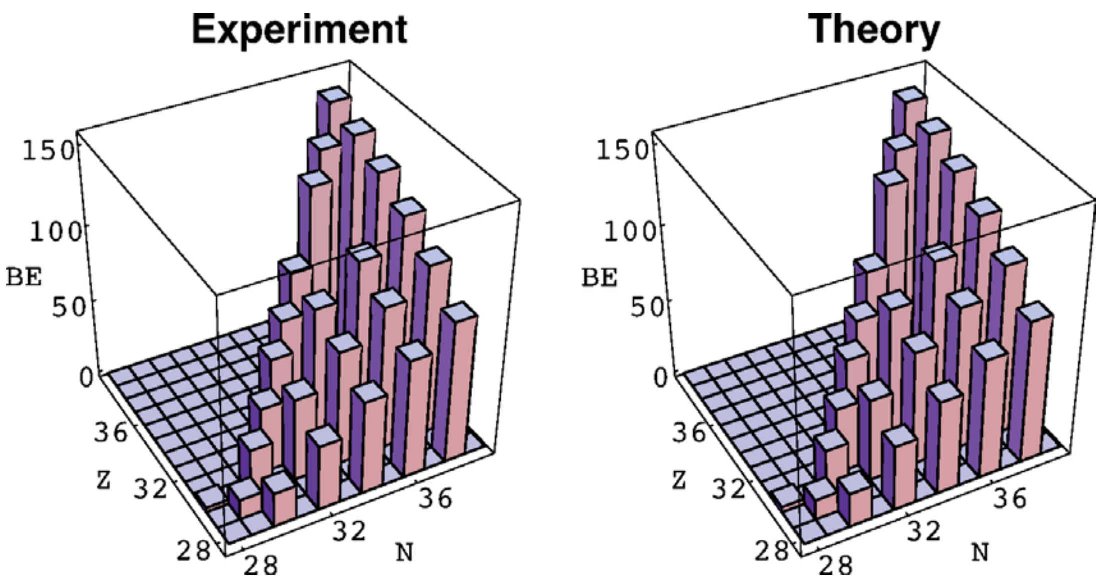
$$H = aC_1[\mathrm{U}(6)] + bC_2[\mathrm{U}(6)] + cC_2[\mathrm{SO}_T(3)] + dC_2[\mathrm{SU}(4)] + eC_2[\mathrm{U}_S(3)]$$

E. Baldini-Neto *et al.*, Phys. Rev. C **65** (2002) 064303

Binding energies of *sd* $N = Z$ nuclei



Binding energies of *pf*-shell nuclei



Algebraic many-body models

- Integrability of any quantum many-body (bosons and/or fermions) system can be analyzed with algebraic methods
- Two nuclear examples:
  - pairing *vs.* quadrupole interaction in the nuclear shell model
  - spherical, deformed and γ-unstable nuclei with *s,d*-boson IBM

$$\mathrm{U}(6) \supset \left\{ \begin{array}{c} \mathrm{U}(5) \supset \mathrm{SO}(5) \\ \mathrm{SU}(3) \\ \mathrm{SO}(6) \supset \mathrm{SO}(5) \end{array} \right\} \supset \mathrm{SO}(3)$$

Other fields of physics

- Molecular physics:
  - U(4) vibron model with *s,p*-bosons

$$\mathrm{U}(4) \supset \left\{ \begin{array}{c} \mathrm{U}(3) \\ \mathrm{SO}(4) \end{array} \right\} \supset \mathrm{SO}(3)$$

  - coupling of many SU(2) algebras for polyatomic molecules
- Similar applications in hadronic, atomic, solid-state, polymer physics, quantum dots…
- Use of *non-compact* groups and algebras for scattering problems

Nuclear Theory:

Self-consistent Mean-field Models
Structure of Heavy Nuclei

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The Hartree-Fock-Bogoliubov Method

1. Basics of a mean-field description

The basic building block of any mean-field model is a set of single-nucleon wave functions:

$$\{\psi_i(\mathbf{x}), i = 1, \ldots, N_{\mathrm{wf}}\}, \quad \mathbf{x} = (\mathbf{r}, \sigma, \tau)$$

- the number of single-particle wave functions (N_{wf}) is larger than number of nucleons A = Z + N.

$$\hat{a}_i^+ = \int d^3r \sum_{\sigma t} \psi_i(\mathbf{x})\, \hat{a}_x^+$$

Creation operator for a nucleon in a single-particle state i

Creation operator for eigenstates of position

Independent single-particle model: state of a nucleus is described by a Slater determinant:

$$|\Phi\rangle \equiv \det\{\psi_i(\mathbf{x}), i=1, \ldots, A\}$$

$\hat{a}_i^+|\Phi\rangle = 0$ for occupied states $1 \leq I \leq A$

$\hat{a}_i|\Phi\rangle = 0$ for unoccupied states $(i > A)$

Pairing correlations ⇒ concept of independent quasi-particles defined by the Bogoliubov transformation

$$\hat{b}_n^+ = \sum_i (U_{in}\,\hat{a}_i^+ + V_{in}\,\hat{a}_i)$$

- Ground state of the system is given by the condition defined as the quasi-particle vacuum:

$$\hat{b}_n|\Phi\rangle = 0$$

- quasi-particle wave functions in coordinate space:

$$\phi_n = \begin{pmatrix} \phi_n^{(U)}(\mathbf{x}) \\ \phi_n^{(V)}(\mathbf{x}) \end{pmatrix} = \begin{pmatrix} \sum_i U_{in}\psi_i(\mathbf{x}) \\ \sum_i V_{in}\psi_i(\mathbf{x}) \end{pmatrix}$$

one-body density → $\rho_{ij} = \langle\Phi|\hat{a}_j^+\hat{a}_i|\Phi\rangle = (V^*V^T)_{ij} = \rho_{ji}^*$

pair tensor → $\kappa_{ij} = \langle\Phi|\hat{a}_j\hat{a}_i|\Phi\rangle = (V^*U^T)_{ij} = -\kappa_{ji}$

$$\mathcal{R} = \begin{pmatrix} \rho & \kappa \\ -\kappa^* & 1\!\!1 - \rho^* \end{pmatrix}$$

Generalized density matrix: eigenvalues either 0 or 1

Coordinate space representation

$$\rho(\mathbf{x},\mathbf{x}') = \langle\Phi|\hat{a}_{x'}^+\hat{a}_x|\Phi\rangle \equiv \sum_n \phi_n^{(V)}(\mathbf{x})\phi_n^{(V)^*}(\mathbf{x}')$$

$$\kappa(\mathbf{x},\mathbf{x}') = \langle\Phi|\hat{a}_{x'}\hat{a}_x|\Phi\rangle \equiv \sum_n \phi_n^{(U)}(\mathbf{x})\phi_n^{(V)^*}(\mathbf{x}')$$

2. Hartree-Fock-Bogoliubov equation

Ground state |Φ› of HFB is obtained by minimization of the total energy:

$$E = \langle \Psi | \hat{H} | \Psi \rangle = E[\rho, \kappa, \kappa^*]$$

with constraints on the proton and neutron numbers $\langle \Psi | \hat{N}_q | \Psi \rangle = N_q$

- Minimization of the total Routhian: $E^\lambda = E - \lambda_q \langle \Psi | \hat{N}_q | \Psi \rangle$ ⇒

HFB equation

$$\mathcal{H} \begin{pmatrix} U_n \\ V_n \end{pmatrix} = e_n \begin{pmatrix} U_n \\ V_n \end{pmatrix} \quad \text{with} \quad \mathcal{H} = \begin{pmatrix} h - \lambda & \Delta \\ -\Delta^* & -h^* + \lambda \end{pmatrix}$$

- Mean-field Hamiltonian and the pairing field:

$$h_{ij} = \frac{\delta E}{\delta \rho_{ji}} = h^*_{ji} \qquad \Delta_{ij} = \frac{\delta E}{\delta \kappa^*_{ij}} = -\Delta_{ji}$$

$$h_{ij} = T_{ij} + \sum_{kl} V_{ikjl}\, \rho_{lk} \qquad \Delta_{ij} = \frac{1}{2} \sum_{kl} V_{ijkl}\, \kappa_{kl}$$

1. Quasiparticle basis Φ_n → diagonalizes the generalized one-body matrix *R*
2. Canonical basis ψ_i → diagonalizes the one-body density p
3. Hartee-Fock basis → diagonalizes the mean-field Hamiltonian *h*

3. Symmetries and Constraints

i) symmetries related to the shape of the nucleus – spherical, axial quadrupole, triaxial quadrupole, octupole
ii) time reversal symmetry – for even-even non-rotating nuclei - creation of a quasiparticle or rotation of the nucleus breaks time-reversal symmetry

- Landscape of the energy as a function of a shape degree of freedom is explored with the help of constraints

  Equations of motion are obtained by minimization of a Routhian:

$$E = \langle \hat{H} \rangle - \sum_{q=p,n} \lambda_q \langle \hat{N}_q \rangle - \sum_\alpha \lambda_\alpha \langle \hat{Q}_\alpha \rangle$$

  constraint on the expectation value: $\langle \hat{Q}_\alpha \rangle \equiv \langle \Psi | \hat{Q}_\alpha | \Psi \rangle = Q_\alpha$

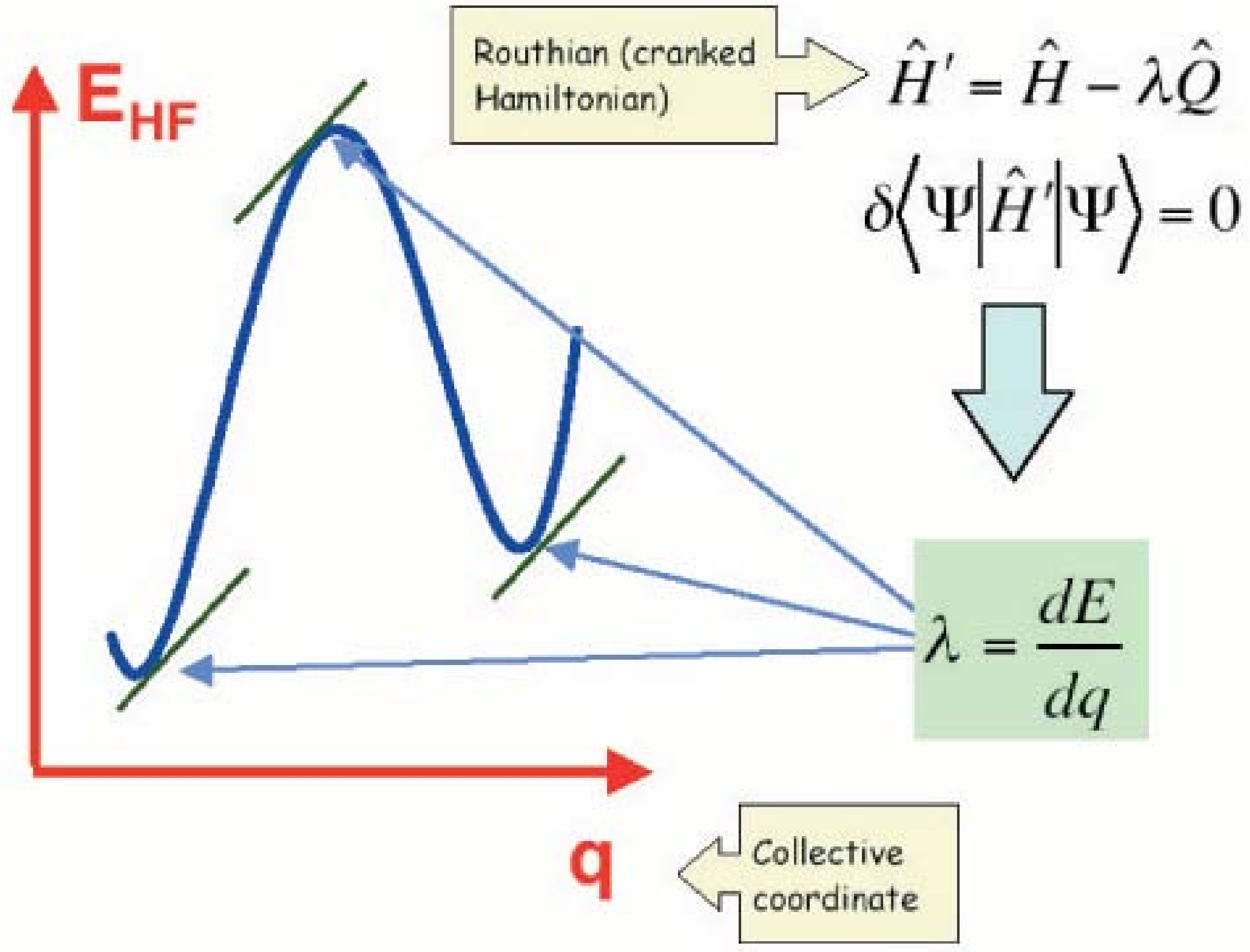
- Quadratic constraint:

$$E = \langle \hat{H} \rangle - \sum_{q=p,n} \lambda_q \langle \hat{N}_q \rangle + \frac{1}{2} \sum_\alpha C_\alpha \left(\langle \hat{Q}_\alpha \rangle - \mu_\alpha \right)^2$$

Constant (→ C_α)

Desired value of the Operator expectation (→ μ_α)

$$\delta\left\langle \Psi \middle| \hat{H} \middle| \Psi \right\rangle = 0 \quad \text{at a fixed value of} \quad q = \left\langle \Psi \middle| \hat{Q} \middle| \Psi \right\rangle$$



4. BCS approximation

- well defined only in the case of time-reversal invariance $\longrightarrow$ Kramer's degeneracy of single-particle states:

$$\epsilon_n = \epsilon_{\bar{n}} \quad \text{for time-conjugate partners} \quad \varphi_n, \varphi_{\bar{n}}$$

$$h = \begin{pmatrix} h & 0 \\ 0 & \tilde{h}^* \end{pmatrix} \qquad \Delta = \begin{pmatrix} 0 & d \\ -d^T & 0 \end{pmatrix}$$

- BCS approximation: forces the pairing potential to be diagonal on the basis of the eigenstates of the mean-field potential

$$d_{n\bar{m}} = \delta_{nm} d_{n\bar{m}} \qquad \hat{h}\varphi_n = \varepsilon_n \varphi_n$$

Pairing problem reduces to the determination of occupation amplitudes by solving the gap equation:

$$\boxed{(\varepsilon_n - \lambda)(u_n^2 - v_n^2) + 2 d_{n\bar{n}} u_n v_n = 0}$$

Density matrices become
One-body density: $\rho(\mathbf{x}, \mathbf{x}') = 2 \sum_{n>0} v_n^2 \, \varphi_n(\mathbf{x}) \varphi_n^*(\mathbf{x}')$
Pair density: $\tilde{\rho}(\mathbf{x}, \mathbf{x}') = -2 \sum_{n>0} u_n v_n \, \varphi_n(\mathbf{x}) \varphi_n^*(\hat{\mathbf{x}}')$

5. Local densities and Currents

Full density matrix can be decomposed into four separate spin-isospin terms:

$$\begin{aligned}\rho(\mathbf{r}\sigma\tau,\mathbf{r}'\sigma'\tau') &= \frac{1}{4}\Big\{\Big[\rho_{00}(\mathbf{r},\mathbf{r}')\,\delta_{\sigma\sigma'} + \mathbf{s}_{00}(\mathbf{r},\mathbf{r}')\cdot\boldsymbol{\sigma}_{\sigma'\sigma}\Big]\,\delta_{\tau\tau'} \\ &+ \sum_{\alpha=-1}^{+1}\Big[\rho_{1\alpha}(\mathbf{r},\mathbf{r}')\,\delta_{\sigma\sigma'} + \mathbf{s}_{1\alpha}(\mathbf{r},\mathbf{r}')\cdot\boldsymbol{\sigma}_{\sigma'\sigma}\Big](\boldsymbol{\tau}_{\tau'\tau})_\alpha\Big\}\end{aligned}$$

where $\boldsymbol{\sigma}_{\sigma'\sigma} = (\sigma'|\hat{\boldsymbol{\sigma}}|\sigma)$ $\quad$ $\boldsymbol{\tau}_{\tau'\tau} = (\tau'|\hat{\boldsymbol{\tau}}|\tau)$

- For pure proton and neutron states, only $\alpha = 0$ components of the isovector densities contribute

- There are six local densities and currents that can be derived from the full density matrix.

Omit the second index in the densities and, with T = 0 or 1, local densities and currents:

T = 0 density:

$$\rho_0(\mathbf{r}) = \rho_0(\mathbf{r},\mathbf{r}) = \sum_{\sigma\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma\tau)$$

T = 1 density:

$$\rho_1(\mathbf{r}) = \rho_1(\mathbf{r},\mathbf{r}) = \sum_{\sigma\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma\tau)\,\tau$$

T = 0 spin density:

$$\mathbf{s}_0(\mathbf{r}) = \mathbf{s}_0(\mathbf{r},\mathbf{r}) = \sum_{\sigma\sigma'\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma'\tau)\,\boldsymbol{\sigma}_{\sigma'\sigma}$$

T = 1 spin density:

$$\mathbf{s}_1(\mathbf{r}) = \mathbf{s}_1(\mathbf{r},\mathbf{r}) = \sum_{\sigma\sigma'\tau} \rho(\mathbf{r}\sigma\tau;\mathbf{r}\sigma'\tau)\,\boldsymbol{\sigma}_{\sigma'\sigma}\,\tau$$

Current:

$$\mathbf{j}_T(\mathbf{r}) = \frac{i}{2}(\nabla' - \nabla)\,\rho_T(\mathbf{r},\mathbf{r}')\Big|_{\mathbf{r}=\mathbf{r}'}$$

Spin-current tensor:

$$\mathcal{J}_T(\mathbf{r}) = \frac{i}{2}(\nabla' - \nabla) \otimes \mathbf{s}_T(\mathbf{r},\mathbf{r}')\Big|_{\mathbf{r}=\mathbf{r}'}$$

Kinetic density:

$$\tau_T(\mathbf{r}) = \nabla \cdot \nabla'\,\rho_T(\mathbf{r},\mathbf{r}')\Big|_{\mathbf{r}=\mathbf{r}'}$$

Kinetic spin-density:

$$\mathbf{T}_T(\mathbf{r}) = \nabla \cdot \nabla'\,\mathbf{s}_T(\mathbf{r},\mathbf{r}')\Big|_{\mathbf{r}=\mathbf{r}'}$$

CHOICES FOR THE EFFECTIVE INTERACTION

A. MEAN-FIELD EFFECTIVE INTERACTIONS

1. Gogny interaction: sum of two Gaussians with space, spin and isospin exchange mixtures - also a density-dependent interaction plus a spin-orbit term:

parameters

$$\hat{v}_{\rm Gogny}(\mathbf{r}_{12}) = \sum_{j=1}^{2} e^{-(\mathbf{r}_{12}/\mu_j)^2}\left(W_j + B_j\hat{P}_\sigma - H_j\hat{P}_\tau - M_j\hat{P}_\sigma\hat{P}_\tau\right)$$

parameters

$$+t_3\left(1 + x_0\hat{P}_\sigma\right)\delta(\mathbf{r}_{12})\,\rho^\alpha\left(\frac{\mathbf{r}_1+\mathbf{r}_2}{2}\right)$$

$$+\mathrm{i}W_{ls}(\hat{\sigma}_1 + \hat{\sigma}_2)\cdot\hat{\mathbf{k}}^\dagger \times \delta(\mathbf{r}_{12})\,\hat{\mathbf{k}}$$

Exchange operators:

$$\hat{P}_\sigma = \frac{1}{2}(1 + \hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2) \qquad \hat{P}_\tau = \frac{1}{2}(1 + \hat{\tau}_1 \cdot \hat{\tau}_2)$$

$$\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2 \qquad \mathbf{k} = -\frac{\mathrm{i}}{2}(\nabla_1 - \nabla_2)$$

- Finite-range Gogny interaction is used simultaneously in both the mean-field and pairing channels

2. Skyrme interactions

Skyrme Hartree-Fock approach: total binding energy is given by the sum of kinetic energy, Skyrme energy functional that models the effective interaction between nucleons, Coulomb energy, pair energy and corrections for spurious motions:

$$E = E_{\text{kin}} + \int d^3r\, \mathcal{E}_{\text{Sk}} + E_{\text{Coul}} + E_{\text{pair}} - E_{\text{corr}}$$

The Skyrme energy functional $\mathcal{E}_{\text{Sk}} = \sum_{T=0,1} \left(\mathcal{E}_T^{\text{even}} + \mathcal{E}_T^{\text{odd}} \right)$

Density-dependent coefficients

Contains only time-even dens.

Dependences on time-odd currents

$$\mathcal{E}_T^{\text{even}} = C_T^{\rho} \rho_T^2 + C_T^{\Delta\rho} \rho_T \Delta \rho_T + C_T^{\tau} \rho_T \tau_T + C_T^{J} \mathcal{J}_T^{\in} + C_T^{\nabla J} \rho_T \nabla \mathbf{J}_T$$

$$\mathcal{E}_T^{\text{odd}} = C_T^{s} \mathbf{s}_T^2 + C_T^{\Delta s} \mathbf{s}_T \cdot \Delta \mathbf{s}_T + C_T^{sT} \mathbf{s}_T \cdot \mathbf{T}_T + C_T^{\nabla s} (\nabla \cdot \mathbf{s}_T)^2 + C_T^{j} \mathbf{j}_T^2 + C_T^{\nabla j} \mathbf{s}_T \cdot \nabla \times \mathbf{j}_T$$

Does not contribute in stationary calculations of even-even nuclei

Single-particle Hamiltonians

Contribution from Skyrme interaction to the single-particle Hamiltonian:

$$\hat{h}_q = U_q - \nabla \cdot B_q \nabla - \frac{i}{2}\{\mathcal{W}_q, \nabla\sigma\} + \mathbf{S}_q \cdot \hat{\boldsymbol{\sigma}} - \nabla \cdot (\hat{\boldsymbol{\sigma}} \cdot \mathbf{C}_q)\nabla - \frac{i}{2}\{\mathbf{A}_q, \nabla\}$$

where $\{\mathcal{W}_q, \nabla\sigma\} = \sum_{ij}\{W_{ij}, \nabla_i \hat{\sigma}_j\}$ (q = p, n)

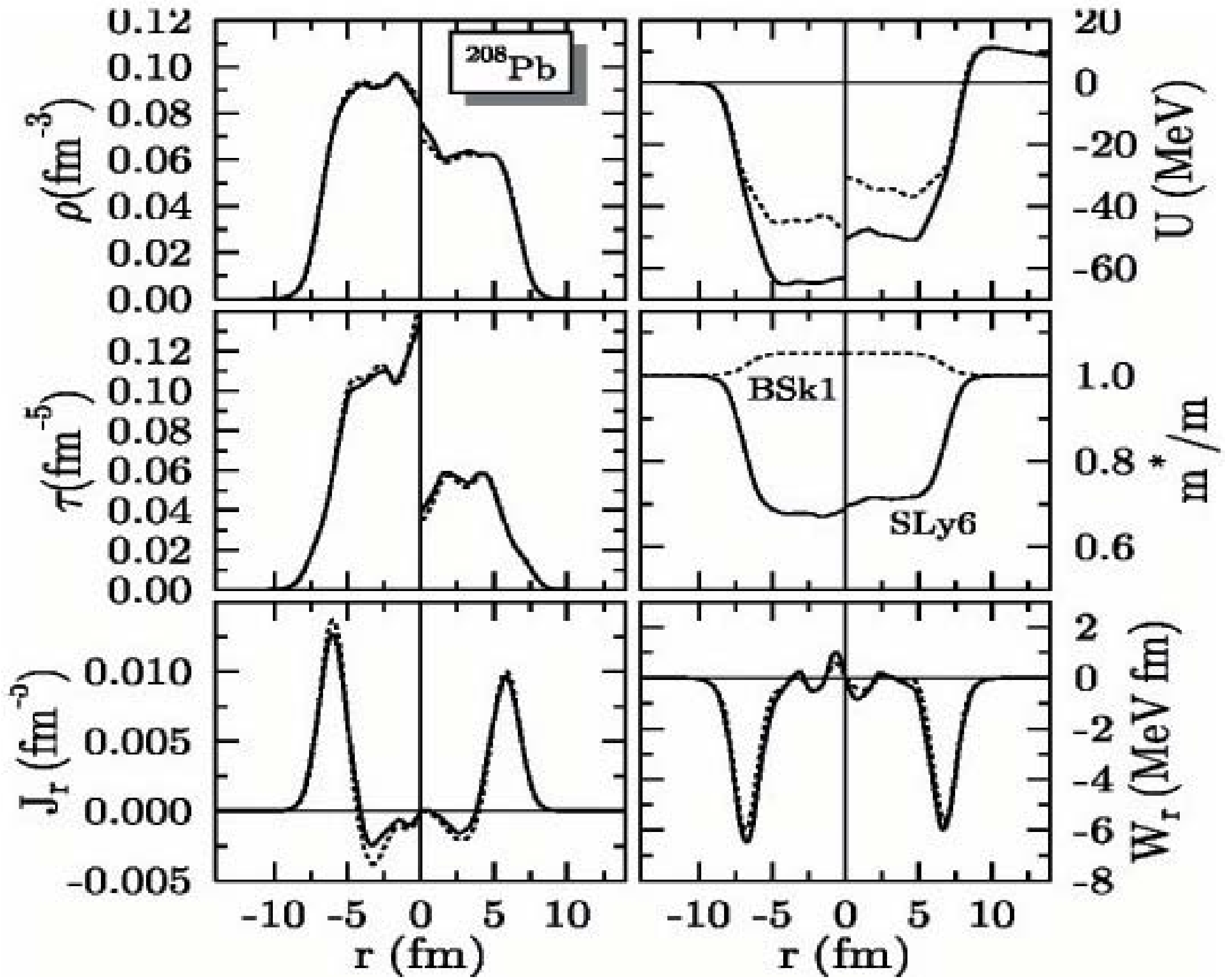
- Local potentials are calculated from:

$$\text{time-even}: \quad U_q = \frac{\delta E}{\delta \rho_q}, \quad B_q = \frac{\delta E}{\delta \tau_q}, \quad \mathcal{W}_q = \frac{\delta E}{\delta \mathcal{J}_q},$$

$$\text{time-odd}: \quad \mathbf{A}_q = \frac{\delta E}{\delta \mathbf{j}_q}, \quad \mathbf{S}_q = \frac{\delta E}{\delta \mathbf{s}_q}, \quad \mathbf{C}_q = \frac{\delta E}{\delta \mathbf{T}_q}$$

Time-odd fields:

Time-odd fields **A**, **C**, and **S** contribute to the single-particle Hamiltonian only when the intrinsic time-reversal symmetry is broken and the Kramer's degeneracy of single-particle levels is removed



Time-even densities and potentials in ^{208}Pb, for neutrons (left) and protons (right), calculated with Skyrme interactions SLy6 (solid lines) and BSk1 (dotted lines)

Choices for coupling constants

1. Energy functional is derived from the Hartree-Fock expectation value

$$\mathcal{E}_{\mathsf{Sk}}^{\mathsf{HF}} = \langle \mathsf{HF} | \hat{v}_{\mathsf{Sk}} | \mathsf{HF} \rangle$$

of the zero-range momentum dependent two-body force introduced by Skyrme:

$$\begin{aligned} \hat{v}_{\mathsf{Sk}}(\mathbf{r}_{12}) = \; & t_0 (1 + x_0 \hat{P}_\sigma)\, \delta(\mathbf{r}_{12}) \\ & + \tfrac{1}{2} t_1 (1 + x_1 \hat{P}_\sigma) \left(\hat{\mathbf{k}}^{\dagger 2}\, \delta(\mathbf{r}_{12}) + \delta(\mathbf{r}_{12})\, \hat{\mathbf{k}}^2 \right) \\ & + t_2\, (1 + x_2 \hat{P}_\sigma)\, \hat{\mathbf{k}}^{\dagger} \cdot \delta(\mathbf{r}_{12})\, \hat{\mathbf{k}} \\ & + \tfrac{1}{6} t_3 (1 + x_3 \hat{P}_\sigma)\, \delta(\mathbf{r}_{12})\, \rho^{\alpha} \left(\tfrac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right) \\ & + \mathrm{i} W_0 (\hat{\boldsymbol{\sigma}}_1 + \hat{\boldsymbol{\sigma}}_2) \cdot \hat{\mathbf{k}}^{\dagger} \times \delta(\mathbf{r}_{12})\, \hat{\mathbf{k}} \end{aligned}$$

2. Energy functional is parameterized directly without reference to an effective two-body force - contains systematically all possible bilinear terms in the local densities and currents up to second order in the derivatives which are invariant with respect to parity, time-reversal, rotational, translational and isospin transformations

B. PAIRING CORRELATIONS

- Pairing-energy functional:

$$E_{\text{pair}} = \sum_{q=p,n} \frac{V_q}{4} \int d^3r \left[1 - \left(\frac{\rho(\mathbf{r})}{\rho_c}\right)^{\beta}\right] \tilde{\rho}_q^2(\mathbf{r})$$

corresponds to the density-dependent two-body zero-range local pairing force:

$$v_{\text{pair}} = \frac{V_0}{2}(1 - \hat{P}_\sigma) \left[1 - \left(\frac{\rho(\mathbf{r}_1)}{\rho_c}\right)^{\beta}\right] \delta(\mathbf{r}_1 - \mathbf{r}_2)$$

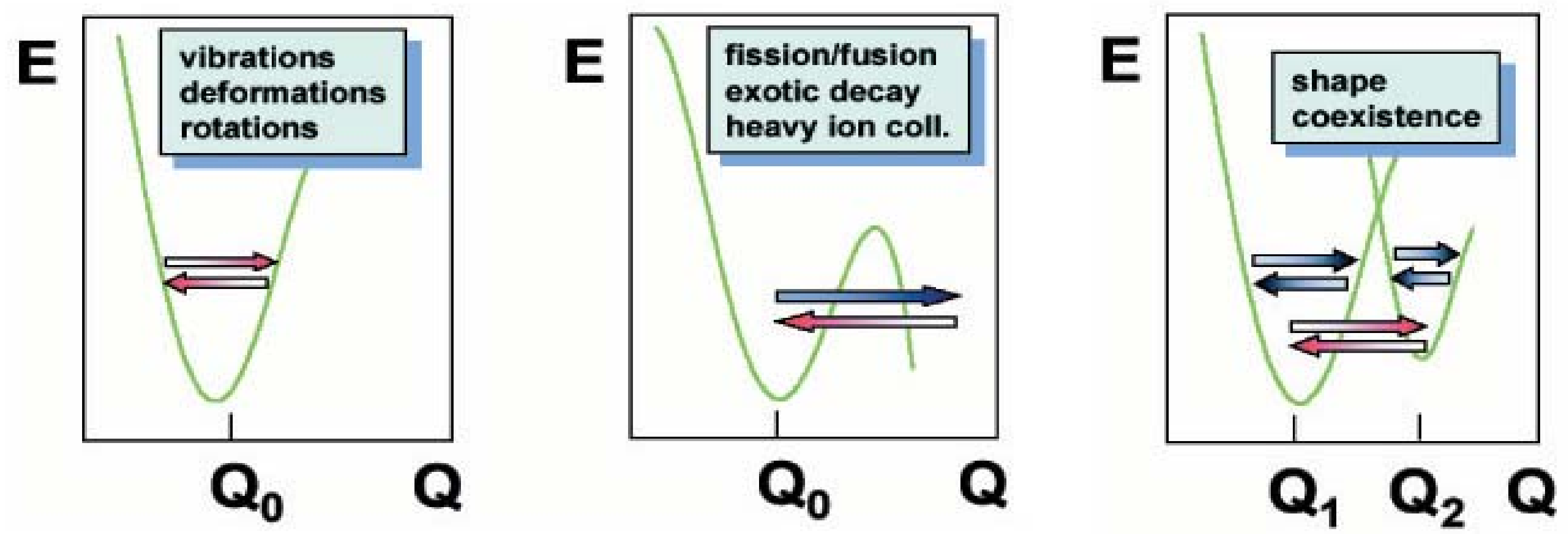
Volume pairing: $\rho_c \to \infty$

Surface pairing: $\rho_c \approx \rho_{nm}$

- Pairing strengths $V_{p,n}$ are adjusted phenomenologically to reproduce the odd-even staggering of energies in selected chains of nuclei

- Pairing-active space of single-particle states ⟸ Cutoff recipe ?

CORRELATIONS BEYOND THE STATIC MEAN-FIELD APPROACH: CONFIGURATION MIXING



Most important correlation effects in nuclear structure stem from large amplitude collective motion. Low-lying excited states are mixed into the calculated mean-field ground state that can be removed by configuration mixing: superposition of several mean-field states

Includes nuclear surface vibrations related to low-lying excitation spectra and zero-energy modes (translation, rotation ...) associated with restoration of symmetries broken by the mean-field ground state

Generator Coordinate Method

- Determines approximate eigenstates of Hamiltonian H:

$$|\Psi_k\rangle = \int dq \, |\Phi(q)\rangle \, f_k(q)$$

Weight functions

Generator coordinate (collective variable)

Intrinsic (e.g. HFB) wave functions

- Requires expectation value $E_k = \frac{\langle \Psi_k | \hat{H} | \Psi_k \rangle}{\langle \Psi_k | \Psi_k \rangle}$ to be stationary with respect to an arbitrary variation δf_k ⟹ Hill-Wheeler equation

$$\int dq' \left[\mathcal{H}(q,q') - E_k \mathcal{I}(q,q') \right] f_k(q') = 0$$

Hamiltonian kernel
$\mathcal{H}(q,q') = \langle \Phi(q) | \hat{H} | \Phi(q') \rangle$

Overlap kernel
$\mathcal{I}(q,q') = \langle \Phi(q) | \Phi(q') \rangle$

- Collective wave functions for the variable ***q*** $g_k(q) = \int dq' \, \mathcal{I}^{1/2}(q,q') \, f_k(q')$
- Matrix element of any operator O between two GCM states can be expressed in terms of the gk values as:

$$\langle \Psi_k | \hat{O} | \Psi_l \rangle = \iint dq \, dq' \, g_k^*(q) \, \tilde{\mathcal{O}}(q,q') \, g_l(q')$$

$$\tilde{\mathcal{O}}(q,q') = \iint dq'' \, dq''' \, \mathcal{I}^{1/2}(q,q'') \, \mathcal{O}(q'',q''') \, \mathcal{I}^{1/2}(q''',q')$$

- GCM energies $\mathbf{E_k}$ and functions $\mathbf{g_k}$ are the eigenvalues and eigenvectors of the hermitian integral operator

$$\int dq' \, \tilde{\mathcal{H}}(q,q') \, g_k(q') = E_k g_k(q)$$

Gaussian Overlap Approximation: overlap kernel is replaced by a Gaussian function of the form:

$$\mathcal{I}(q,q') \simeq \mathcal{I}_G(q,q') = \exp\left\{-\frac{1}{2}\left[\frac{(q-q')}{a(\bar{q})}\right]^2\right\}$$

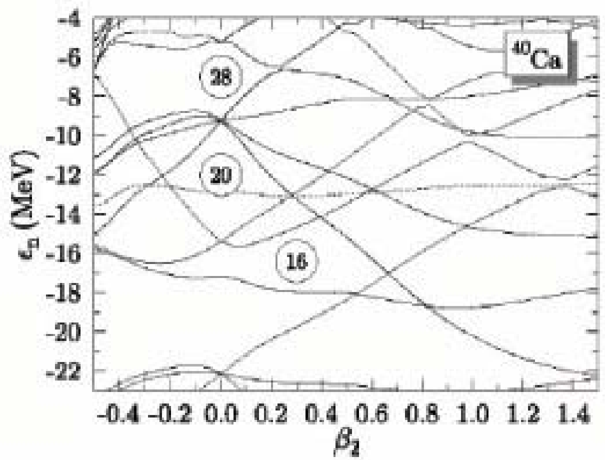
based on the rapid decrease of the matrix elements between wave functions corresponding to different values of the collective variable

Choice of the collective coordinate

1. RESTORATION OF BROKEN SYMMETRIES: family of wave functions $|\Phi(q)>$ is generated by the symmetry operations: rotation in coordinate space for angular momentum, rotation in gauge space for particle number - generating function $\mathbf{f_k(q)}$ is a priori determined by the properties of the symmetry operator.

2. SHAPE DEGREES OF FREEDOM: collective space is generated by constrained mean-field calculations - the generating function is unknown and has to be determined by diagonalization of the Hill-Wheeler equation.

Example: Projected GCM+HF+BCS



M.Bender, H.Flocard, P.-H. Heenan
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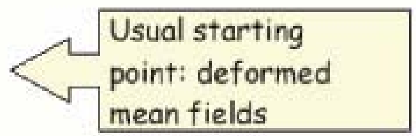
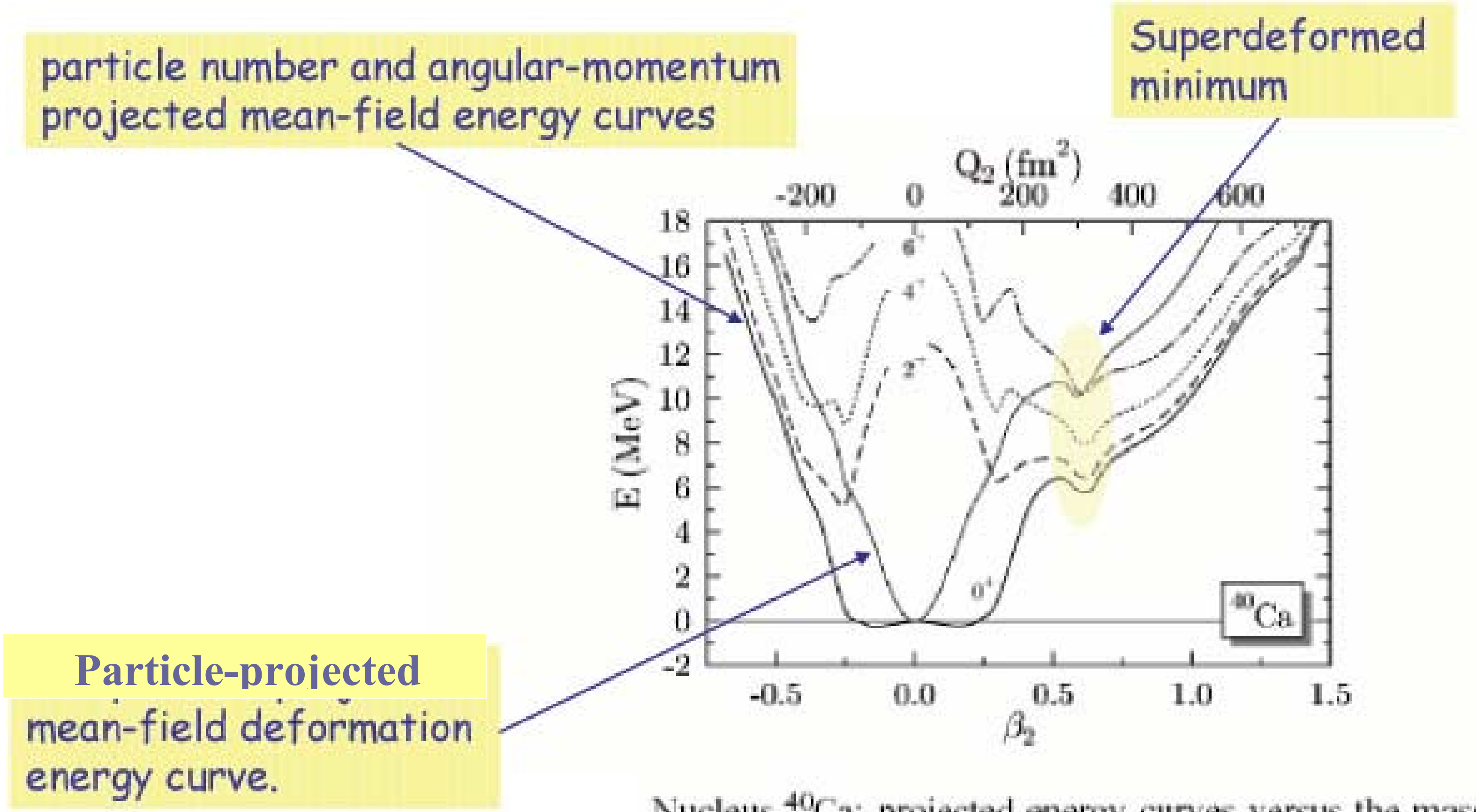
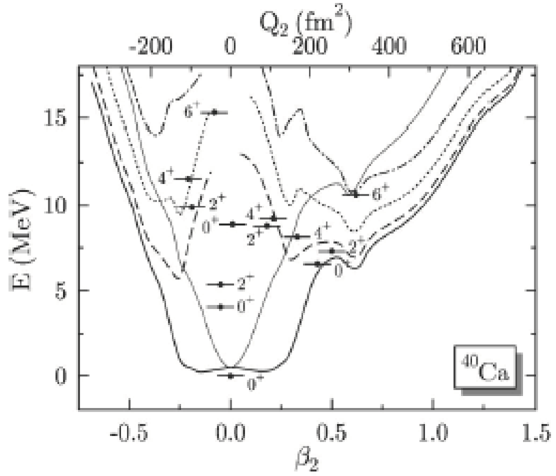




Nucleus ^{40}Ca; projected energy curves versus the mass deformation (β_2 and Q_2). The thin solid curve gives $\langle\beta_2|\hat{H}|\beta_2\rangle$ (MF), while the thick solid, dashed, dotted, and dash-dotted curves correspond to $\langle J,\beta_2|\hat{H}|J,\beta_2\rangle$ (PMF) for the values J=0, 2, 4, and 6, respectively. The energy origin is taken at $\langle\beta_2=0|\hat{H}|\beta_2=0\rangle$.

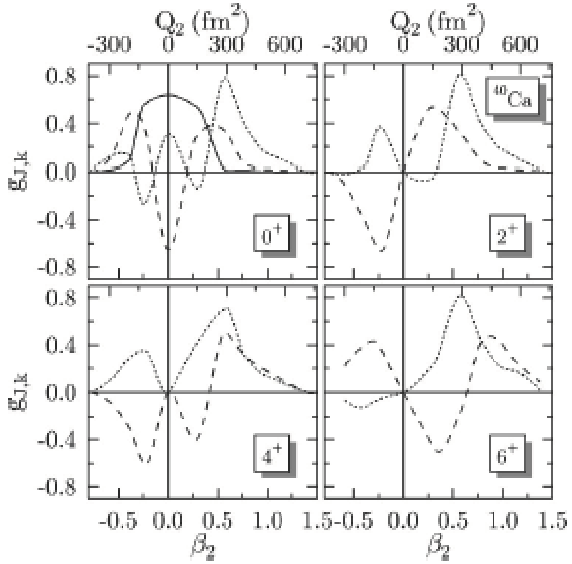
The Hamiltonian is diagonalized within each of the collective subspaces of the nonorthogonal bases |J, $\boldsymbol{\beta_2}$ > by using GCM.

PES and GCM eigenstates



Nucleus ^{40}Ca; MF $\langle \beta_2|\hat{H}|\beta_2\rangle$ (thin solid) and PMF $\langle J,\beta_2|\hat{H}|J,\beta_2\rangle$ (thick solid) deformation energy curves. The ordinates of short horizontal segments give the energy $E_{J,k}$ of the GCM states [Eq. (5)]. The abscissa of the black points indicates the mean deformation $(\bar{\beta}_2)$ of the corresponding collective wave function $g_{J,k}$ [Eq. (6)]. The energy origin is taken at $E_{0,1}$.

Collective wave functions



Collective GCM wave functions $g_{J,k}$ for low-spin states of ^{40}Ca. The ground-state 0^+ wave function is drawn with a thick solid line. The wave functions of the ND and SD bands are drawn with dashed and dotted lines, respectively.

CORRELATIONS BEYOND THE STATIC MEAN-FIELD APPROACH: SYMMETRY RESTORATION

Necessarily, a self-consistent mean-field (SCMF) wave function breaks several symmetries of the nuclear Hamiltonian. Any SCMF solution is degenerate with respect to the SCMF wave functions created by the symmetry operation which is broken. One must superpose all these equivalent wave functions to restore symmetry.

1. Particle-number projection   BCS (or HFB) states are not eigenstates of the particle-number operator

an eigenstate $|\Phi(N,Z)]\}>$ of the particle-number operators with N neutrons and Z protons acts on any wave SCMF function $|\Psi>$ with projection operators:

$|\Phi(N,Z)\rangle = \hat{P}_N \hat{P}_Z |\Psi\rangle$ where $\hat{P}_N = \frac{1}{2\pi} \int_0^{2\pi} d\phi_N \, e^{i\phi_N(\hat{N}-N)}$

Variation before or after projection

PAV: $$E_k = \frac{\langle \Phi(N,Z)|\hat{H}|\Phi(N,Z)\rangle}{\langle \Phi(N,Z)|\Phi(N,Z)\rangle}$$

2. Angular-number projection

Deformed mean-field states are not eigenstates of the total angular momentum.
An eigenstate with eigenvalue J is obtained by projecting the mean-field wave function |Ψ›

$$|\Phi, JM\rangle = \frac{\sum_K g_K \hat{P}^J_{MK}|\Psi\rangle}{\sqrt{\sum_K |g_K|^2 \langle\Psi|\hat{P}^J_{KK}|\Psi\rangle}}$$

where the projector is given by $\hat{P}^J_{MK} = \frac{2J+1}{8\pi^2} \int d\Omega \, D^{J*}_{MK}(\Omega) \, \hat{R}(\Omega)$

(Euler angles: Ω; rotation operator: $\hat{R}(\Omega)$)

- Rotational Correction as approximate projection: $E_{\text{rot}} = -\frac{\langle \hat{\mathbf{J}}^2 \rangle}{2\mathcal{J}}$

3. Center-of-mass projection

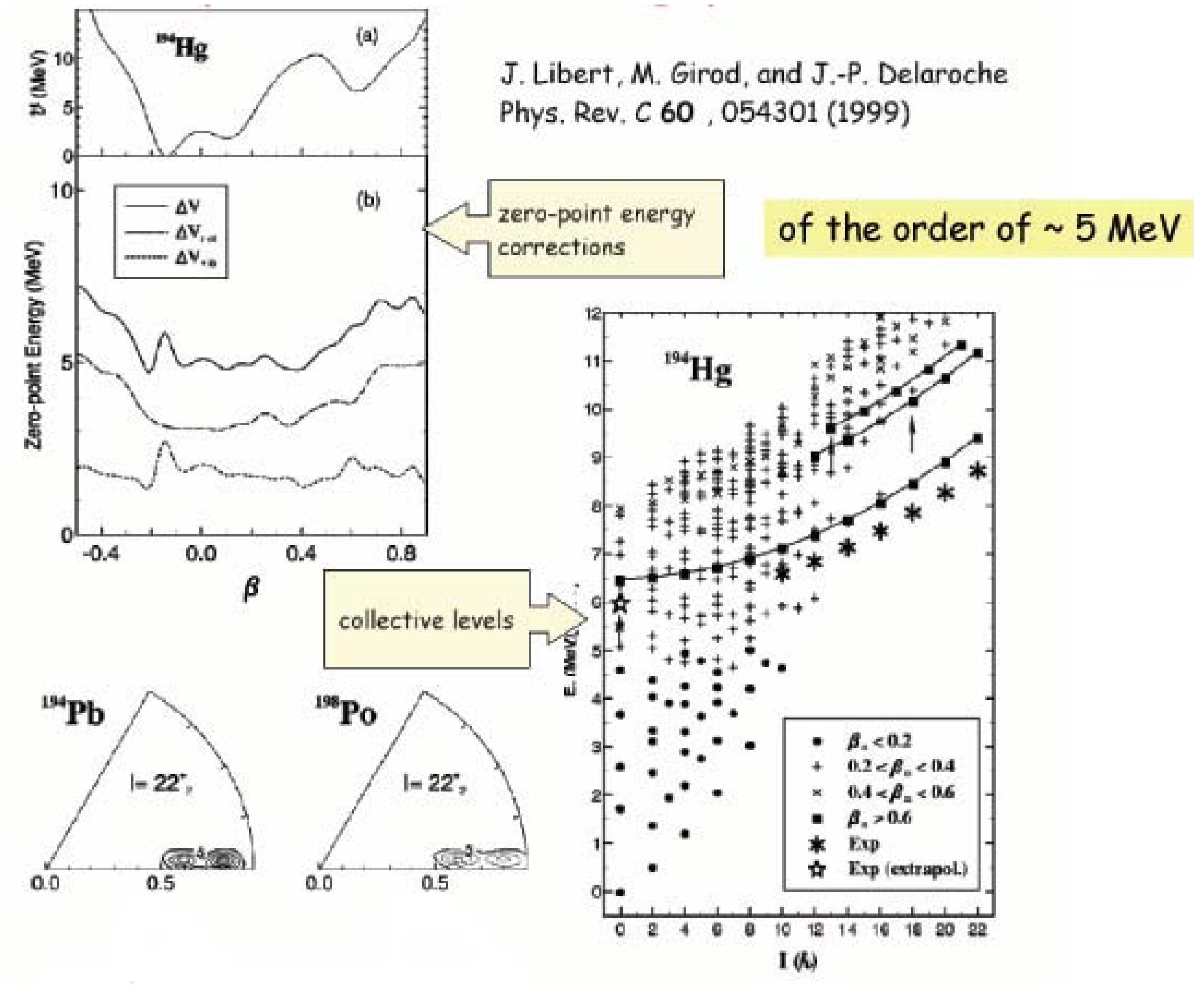
Mean field is localized in space, violating translational invariance which has to be restored by projection onto good centre-of-mass momentum zero

$$|\Phi(\mathbf{P}_{\text{cm}} = 0)\rangle = \int d^3R \exp(-i\mathbf{R} \cdot \hat{\mathbf{P}}_{\text{cm}})|\Psi\rangle$$

- Exact projection is numerically expensive – a simple expression for a center-of-mass correction to the energy and second order in $\mathbf{P}_{\text{cm}}$

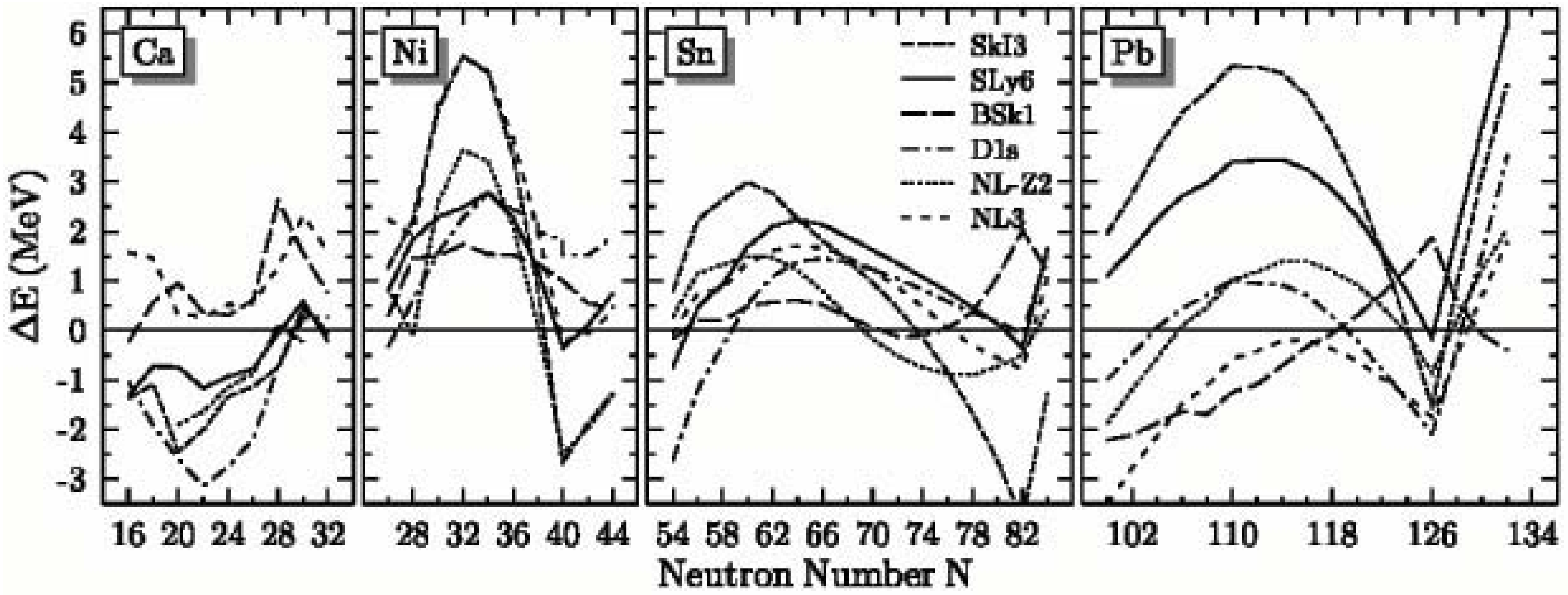
$$E_{\text{cm}} = -\frac{\langle \hat{\mathbf{P}}^2_{\text{cm}} \rangle}{2mA}$$

Example: GOA + HF(B) Gogny calculations

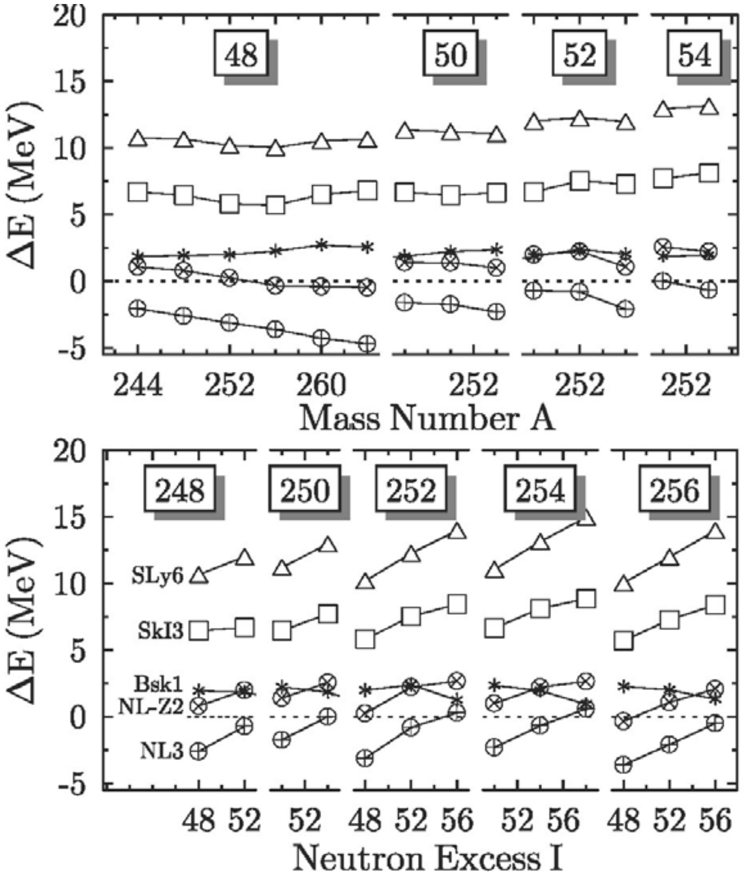


Applications

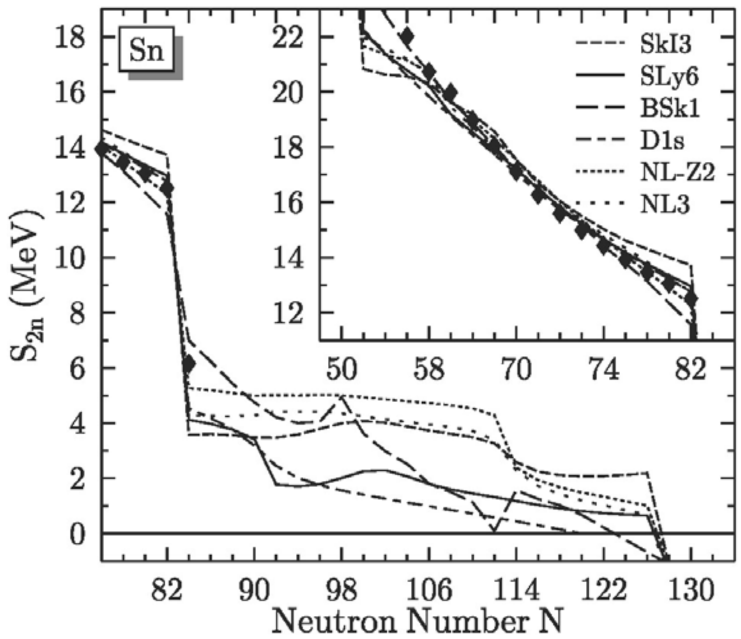
1. Binding Energies



Error on the total binding energy for the isotopic chains and forces as indicated - positive (negative) **ΔE** denote underbound (overbound) nuclei with respect to experiment (results obtained by spherical mean-field calculations)

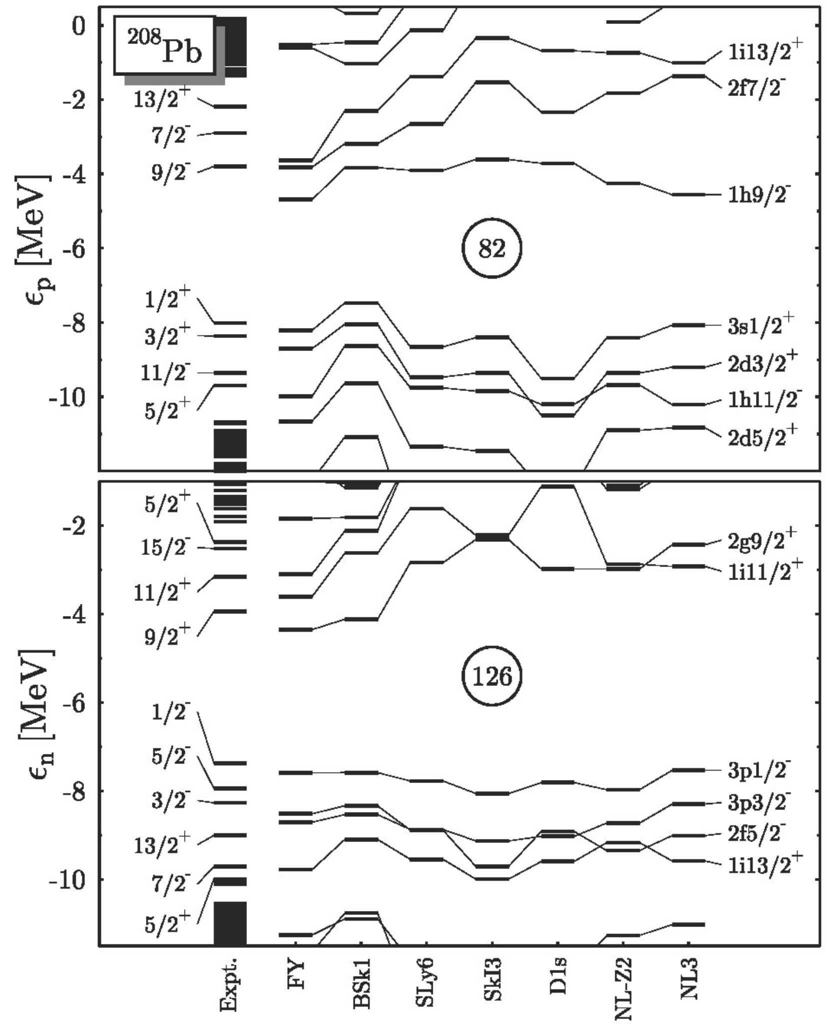


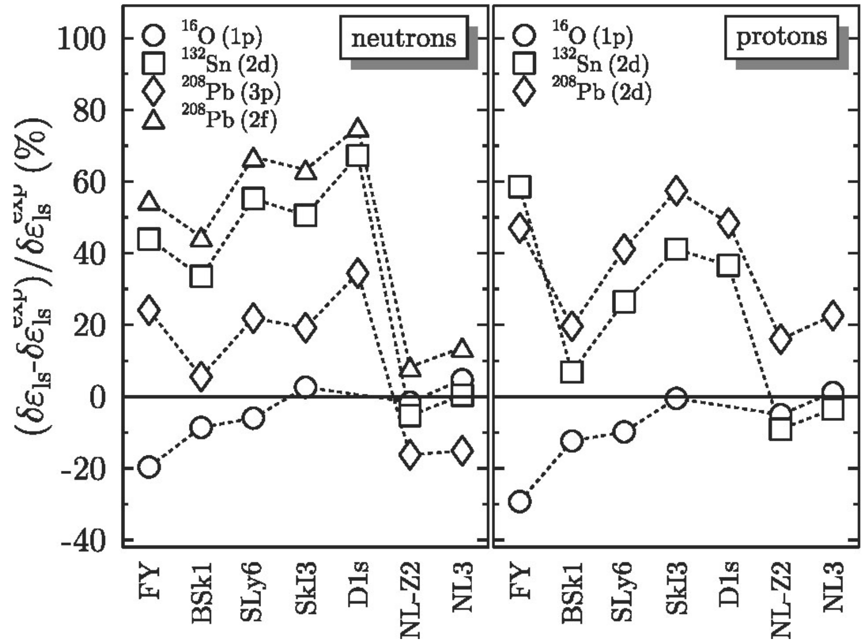
Error on the binding energy for the heaviest nuclei whose experimental mass is known: calculations include quadrupole axial deformations



Two-neutron separation energy for the chain of Sn isotopes

2. Shell structure

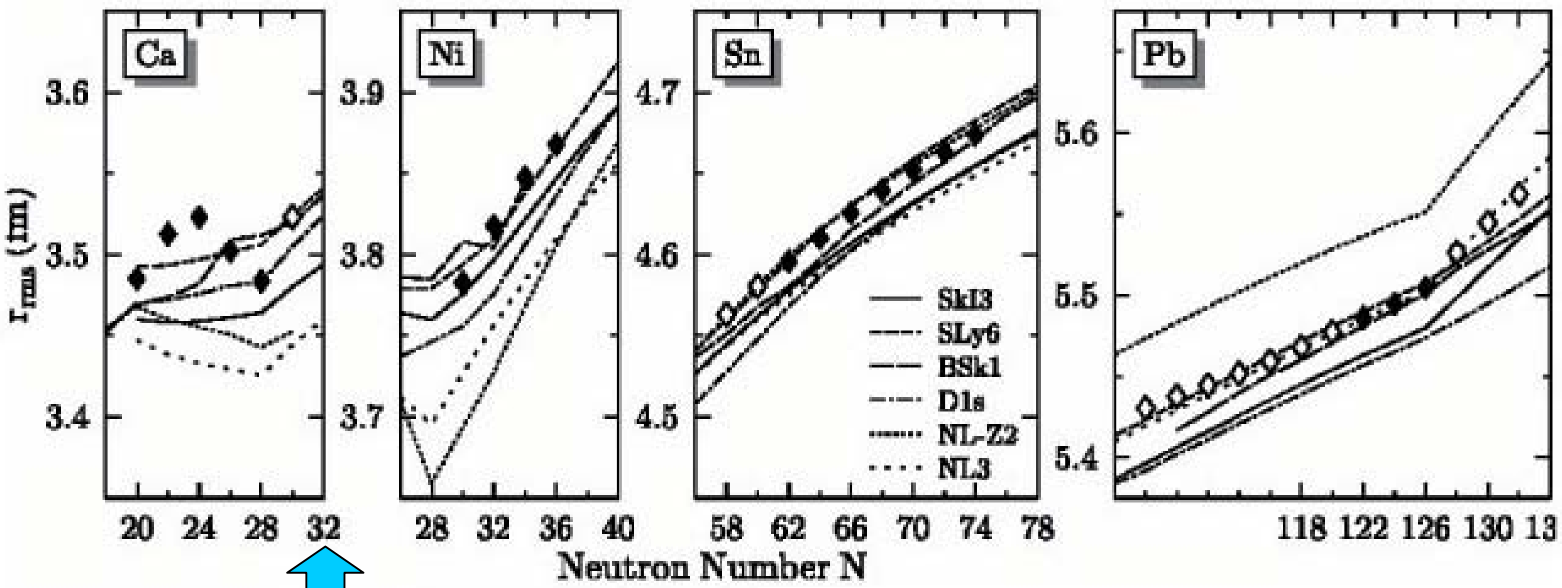




Relative error on spin-orbit
Splitting in doubly-magic nuclei

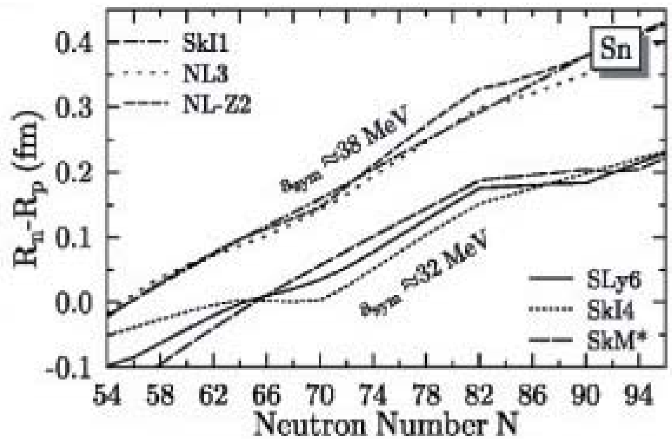
Eigenvalues ε_k of the single-particle Hamiltonian for neutrons in ^{208}Pb and ^{132}Sn calculated with Skyrme forces BSk1, SLy6 and SkI3, Gogny force D1S, and RMF forces NL3 and NL-Z2; results obtained with Folded-Yukawa model (FY) used in mic-mac models are shown for comparison

3. Observables of the Density Distribution



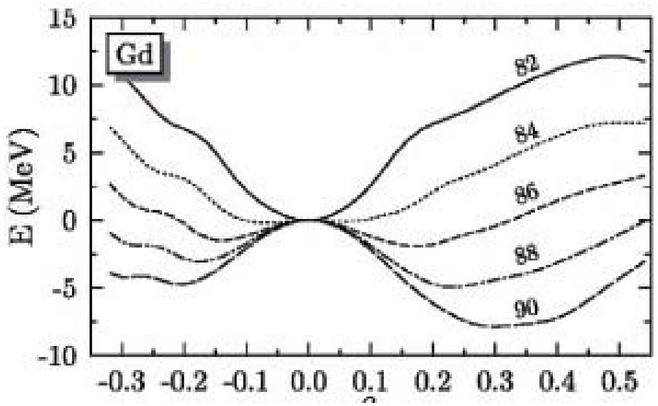
Comparison of rms radii of charge distributions from spherical mean-field calculations

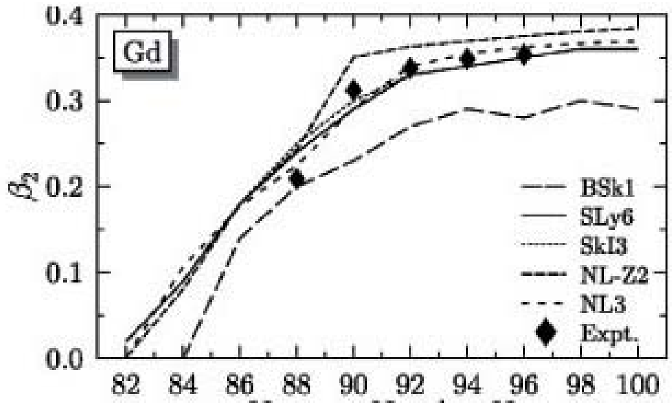
- ◆ direct radius measurements;
- ◊ measurements of isotopic shifts



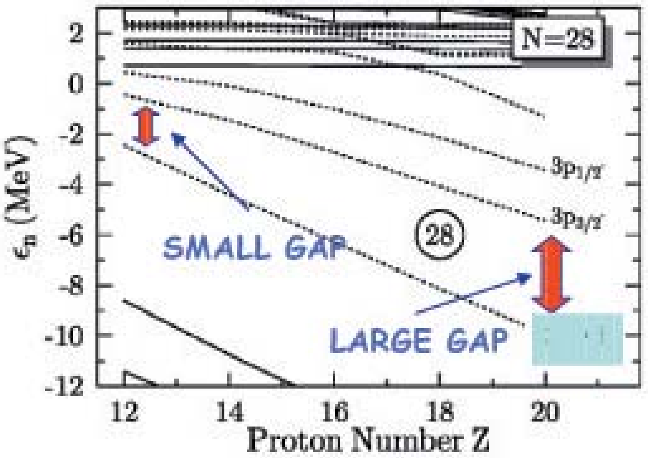
Neutron skin **Rn-Rp** along the chain of Sn isotopes: results are shown for two groups of forces, one with low and one with high asymmetry energy

4. Deformations



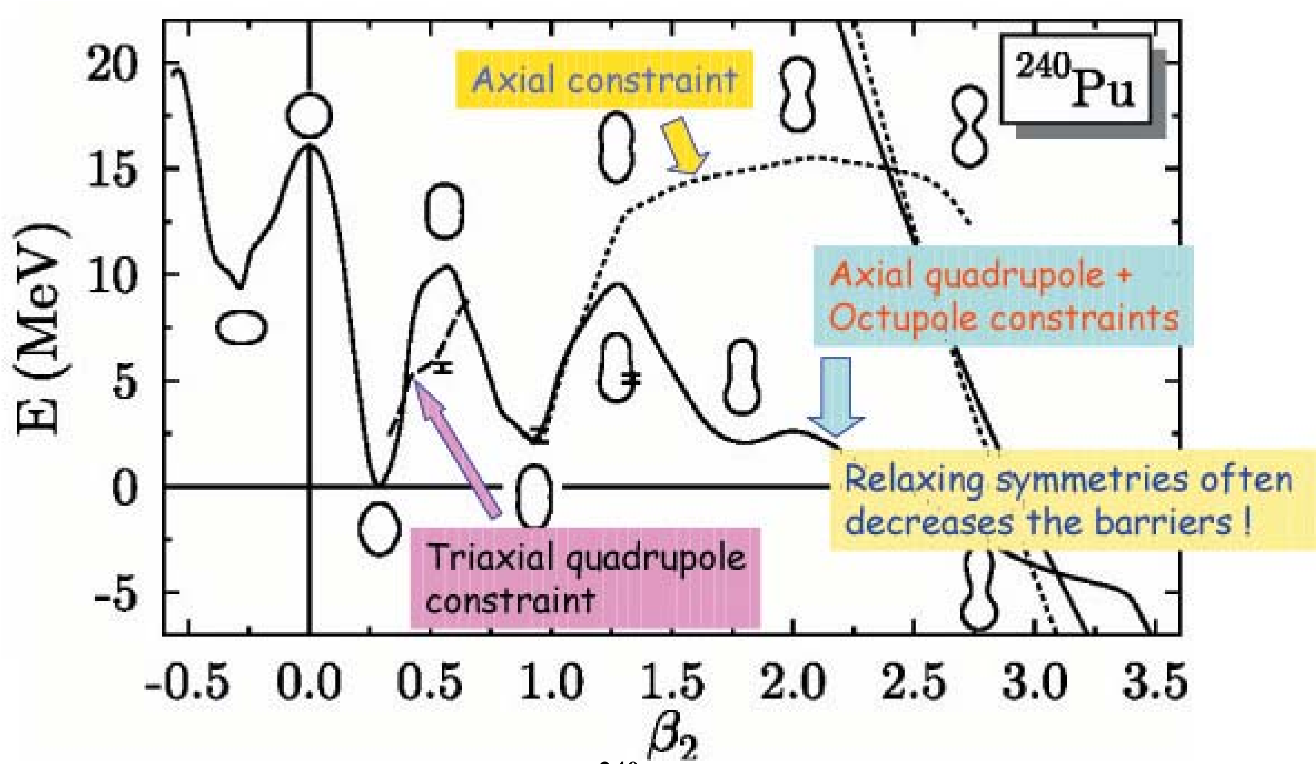


Transition from spherical to deformed shapes in the chain of Gd isotopes
Left panel: HF+BCS PES for Gd isotopes with 82 < N < 90 (SLy6 interaction)
Right panel: Ground state deformation of Gd isotopes with several forces



Disappearance of spherical N = 28 shell
in neutron-rich nuclei; neutron single-particle energies at spherical shape for N = 28 isotones

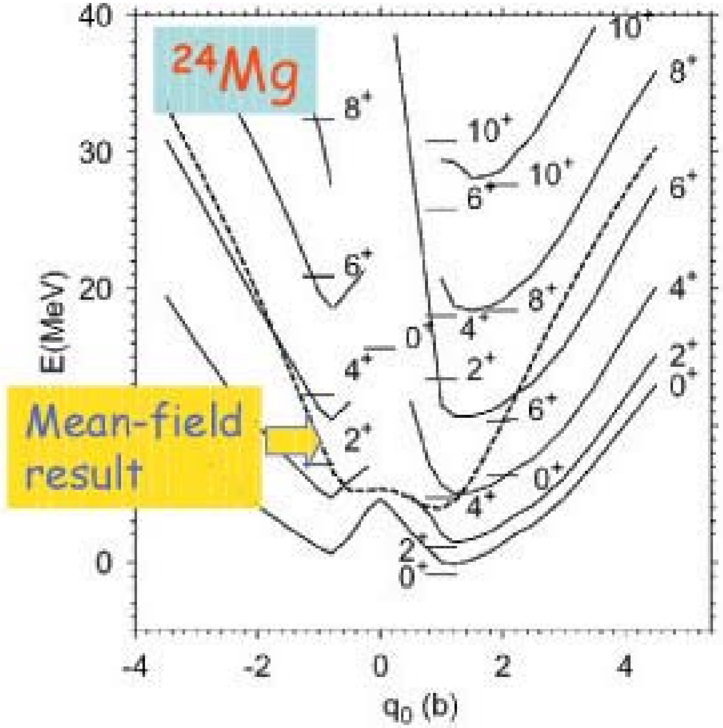
Fission Barriers



Paths in the deformation energy landscape of ^{240}Pu calculated with the SkI4 force

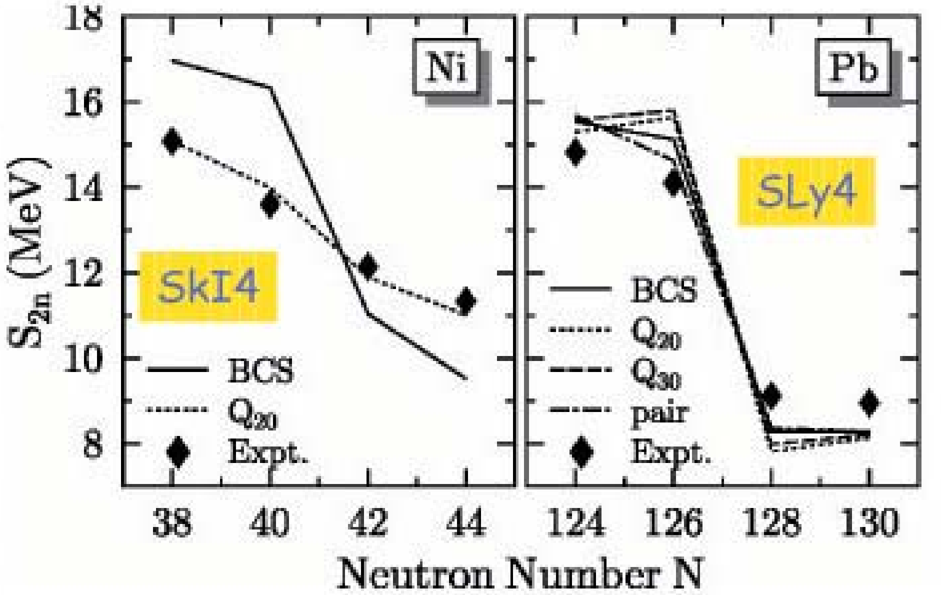
- solid line corresponds to axial quadrupole and octupole (reflexion asymmetric) constraints
- dashed line corresponds to triaxial quadrupole constraints
- dotted line corresponds to axial quadrupole constraint only
- two steep lines correspond to the symmetric (dotted line) and asymmetric(full line) fusion paths

5. Excitations



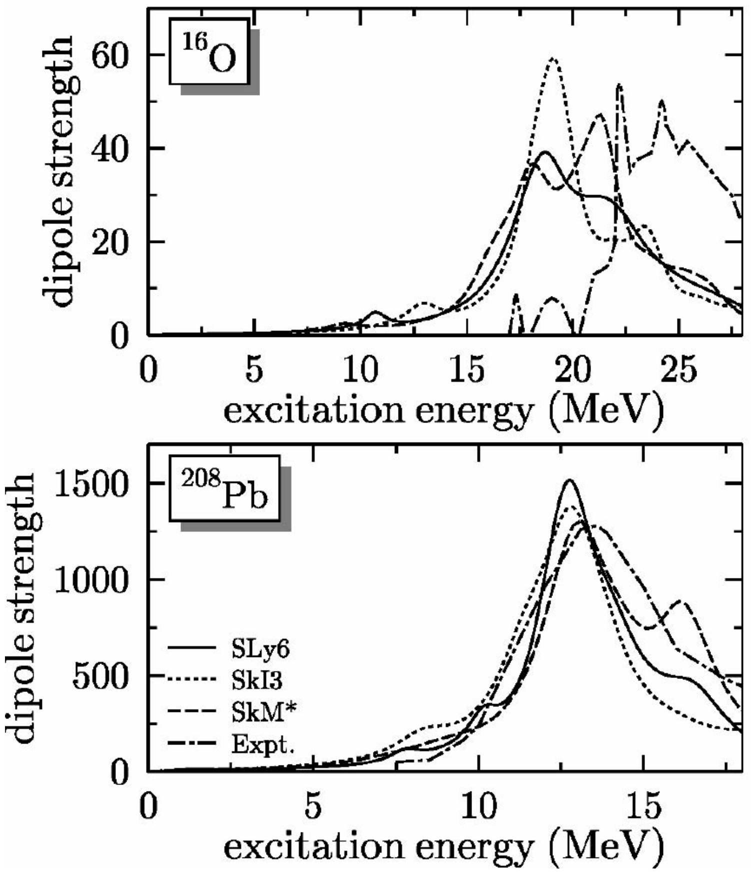
Projected ^{24}Mg PES for angular momentum J = 0 to 10, as a function of the axial quadrupole moment q_0 of the state projected.
First three energies obtained for each J in a GCM calculation: horizontal bars at the value of q_0 where the respective collective wave functions are maximum.

Ground-state correlations and mass sytematics



Influence of ground-state correlations on S_{2n} mean-field Skyrme-HF+BCS+LN calculations . Correlations beyond mean-field are included in both cases.
Ni: GOA approximation of the GCM
Pb: particle-number projected GCM calculations

Giant Resonances



RPA results for the dipole strength distribution in ^{16}O and ^{208}Pb for various interactions. Discrete RPA spectra are folded with a Lorenzian of width 1 MeV to account roughly for escape width and collision broadening.

The peak positions of giant resonances in ^{208}P computed with RPA for various forces and compare with experimental values (all energies are given i MeV).

	$L=1,T=1$	$L=2,T=0$	$L=0,T=0$
Expt.	13.6	11.2	14.2
SIII	14.1	12.0	17.5
SkM*	13.0	11.6	14.0
SkP	12.5	10.3	13.2
SLy6	12.8	12.5	14.5
SkI3	12.7	13.7	15.3
SkI4	12.7	13.0	15.1
MSk5	11.4	10.3	14.1
SkT6	14.5	12.4	9.9
NL3	12.9	11.3	13.8

Nuclear Theory:

Self-consistent Relativistic Mean-Field Models
Structure of Heavy Nuclei

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Self-consistent Relativistic Mean-Field Models

Quantum Hadrodynamics → low-energy, large-distance, effective field theory (EFT) representation of **QCD**

- models based on QHD provide a microscopic description of the nuclear many-body problem that is consistent with:

quantum mechanics

special relativity

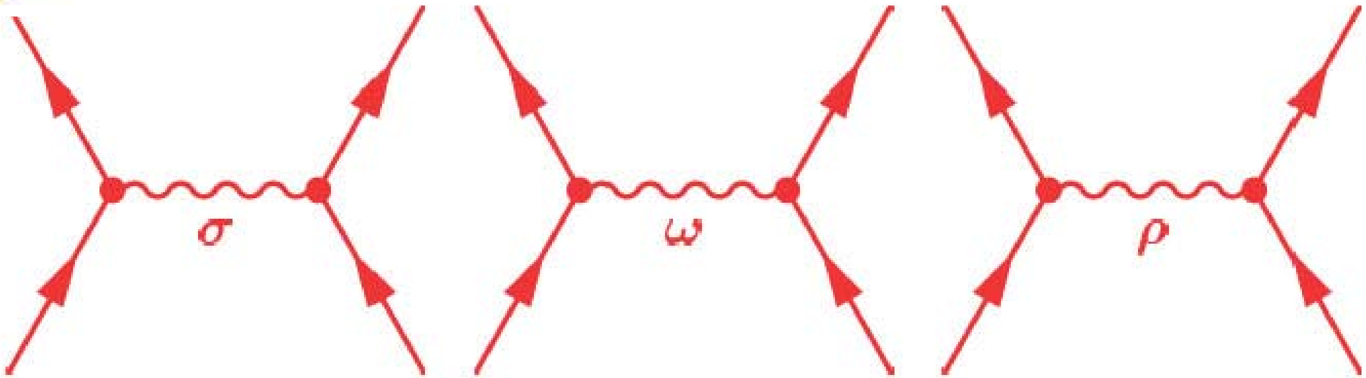
unitarity and causality

symmetries of QCD →

Lorentz invariance
parity consevation
isospin symmetry
spontaneously broken chiral symmetry

1. MODELS WITH NON-LINEAR SELF-INTERACTIONS

system of Dirac nucleons coupled to the exchange mesons and the photon field through an effective Lagrangian



$(J_\pi,T)=(0+,0)$	$(J_\pi,T)=(1-,0)$	$(J_\pi,T)=(1-,1)$
Sigma-meson: attractive Scalar field	Omega-meson: short-range repulsive field	Rho-meson: isovector field

Model defined by the Lagrangian density:

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$$

- Lagrangian of the free nucleon $\mathcal{L}_N = \bar{\psi}\left(i\gamma^\mu \partial_u - m\right)\psi$

- Lagrangian of the free meson fields and the electromagnetic field:

$$\begin{aligned}\mathcal{L}_m &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ &\quad -\frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\end{aligned}$$

$$\begin{aligned}\Omega_{\mu\nu} &= \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \\ \vec{R}_{\mu\nu} &= \partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu.\end{aligned}$$

- minimal set of interaction terms:

$$\mathcal{L}_{int} = -\bar{\psi}\Gamma_\sigma\sigma\psi - \bar{\psi}\Gamma_\omega^\mu\omega_\mu\psi - \bar{\psi}\vec{\Gamma}_\rho^\mu\vec{\rho}_\mu\psi - \bar{\psi}\Gamma_e^\mu A_\mu\psi.$$

with vertices

$$\Gamma_\sigma = g_\sigma, \quad \Gamma_\omega^\mu = g_\omega\gamma^\mu, \quad \vec{\Gamma}_\rho^\mu = g_\rho\vec{\tau}\gamma^\mu, \quad \Gamma_e^m = e\tfrac{1-\tau_3}{2}\gamma^\mu$$

Simple linear model does not provide a quantitative description of complex nuclear systems. Effective density dependence is introduced through a non-linear potential:

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{g_2}{3}\sigma^3 + \frac{g_3}{4}\sigma^4$$

From the Lagrangian-density model, the classical variation principle leads to the equations of motion:

time-dependent Dirac equation for the nucleon:

$$[\gamma^\mu(i\partial_\mu + V_\mu) + m + S]\,\psi = 0$$

Neglecting retardation effects for the meson fields, a self-consistent solution is obtained when the time-dependent mean-field potentials:

$$S(\mathbf{r},t) = g_\sigma\sigma(\mathbf{r},t)$$
$$V_\mu(\mathbf{r},t) = g_\omega\omega_\mu(\mathbf{r},t) + g_\rho\vec{\tau}\vec{\rho}_\mu(\mathbf{r},t) + eA_\mu(\mathbf{r},t)\frac{(1-\tau_3)}{2}$$

are calculated at each step in time from the solution of the stationary Klein-Gordon equations

$$-\Delta\phi_m + U'(\phi_m) = \pm\left\langle\bar{\psi}\Gamma_m\psi\right\rangle$$

Mean-field approximation:
meson field operators are replaced by their expectation values

No-sea approximation:
no contributions from the Dirac sea of negative energy states

Pairing correlations and relativistic Hartree-Bogoliubov theory

- Description of ground-state properties of exotic nuclei far from stability

  ⇨ unified description of mean-field and pairing correlations

- relativistic Hartree-Bogoliubov (RHB) equations:

$$\begin{pmatrix} \hat{h}_D - m - \lambda & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D + m + \lambda \end{pmatrix} \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix}$$

Pairing field
Quasiparticle energy
Dirac Hamiltonian
nucleon mass
chemical potential

RHB equations are solved self-consistently, with potentials determined in the mean-field approximation from solutions of static Klein-Gordon equations:

$$\begin{aligned} \left[-\Delta + m_\sigma^2\right] \sigma(\mathbf{r}) &= -g_\sigma \rho_s(\mathbf{r}) - g_2 \sigma^2(\mathbf{r}) - g_3 \sigma^3(\mathbf{r}) \\ \left[-\Delta + m_\omega^2\right] \omega^0(\mathbf{r}) &= g_\omega \rho_v(\mathbf{r}) \\ \left[-\Delta + m_\rho^2\right] \rho^0(\mathbf{r}) &= g_\rho \rho_3(\mathbf{r}) \\ -\Delta A^0(\mathbf{r}) &= e \rho_p(\mathbf{r}) \end{aligned}$$

Source terms are sums of bi-linear products of nucleon amplitudes:

$$\rho_s(\mathbf{r}) = \sum_{k>0} V_k^\dagger(\mathbf{r})\gamma^0 V_k(\mathbf{r}) \qquad \rho_3(\mathbf{r}) = \sum_{k>0} V_k^\dagger(\mathbf{r})\tau_3 V_k(\mathbf{r})$$

$$\rho_v(\mathbf{r}) = \sum_{k>0} V_k^\dagger(\mathbf{r}) V_k(\mathbf{r}) \qquad \rho_{\mathrm{em}}(\mathbf{r}) = \sum_{k>0} V_k^\dagger(\mathbf{r})\frac{1-\tau_3}{2} V_k(\mathbf{r})$$

no-sea approximation

- Gogny pairing interaction:

$$V^{pp}(1,2) = \sum_{i=1,2} e^{-((\mathbf{r}_1-\mathbf{r}_2)/\mu_i)^2} \left(W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau\right)$$

EFFECTIVE INTERACTIONS

model parameters: meson masses m_σ, m_ω, m_ρ, meson-nucleon coupling constants g_σ, g_ω, g_ρ, nonlinear self-interactions coupling constants g_2, g_3 ...

- mean-field model does not contain explicit correlation effects – parameters are determined from the properties of nuclear matter (symmetric and asymmetric) and bulk properties of finite nuclei (binding energies, charge radii, neutron radii, surface thickeness ...)

Least-squares adjustment to empirical nuclear matter properties and experimental data on ground-state properties of spherical nuclei constrains only six or seven parameters in the general expansion of an effective Lagrangian

Minimization of

calculated values — exp. data

$$\chi^2 = \sum_i \frac{(O_i^{th} - O_i^{expt})^2}{(\Delta O_i)^2}$$

assumed errors

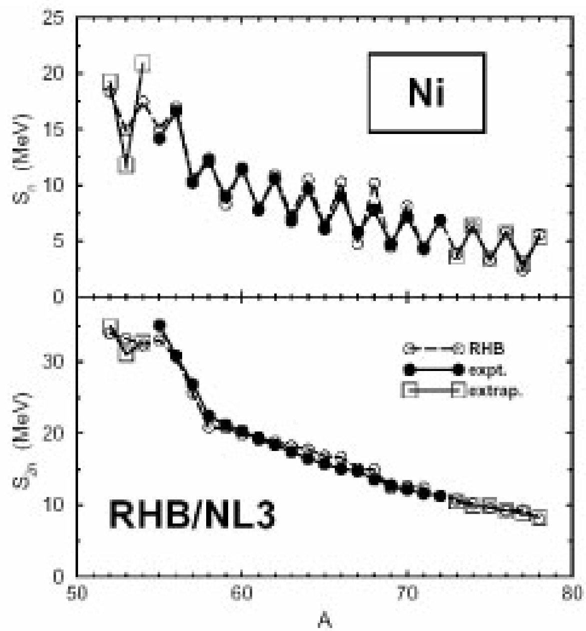
- Uncorrelated error of a parameter is the allowed variation of that isolated parameter (while all other parameters are kept fixed) which enhances χ^2 just by a value of 1

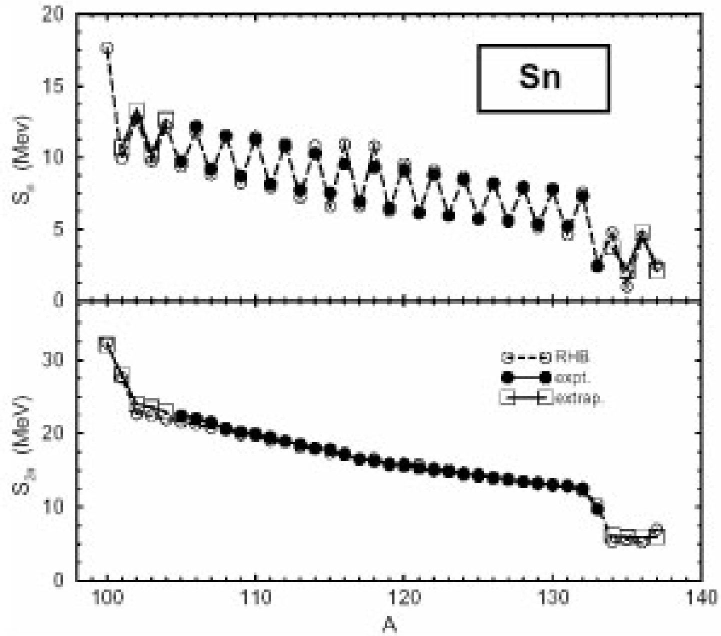
- Correlated error of a parameter is the allowed change of that parameter, i.e. within χ^2+1, if all the other parameters are readjusted

Correlated and uncorrelated error of a particular parameter would be the same if that parameter was completely independent from all other parameters

Ground-state properties of Ni and Sn isotopes

Combination of the NL3 effective interaction for the RMF Lagrangian, and the Gogny interaction with the parameter set D1S in the pairing channel

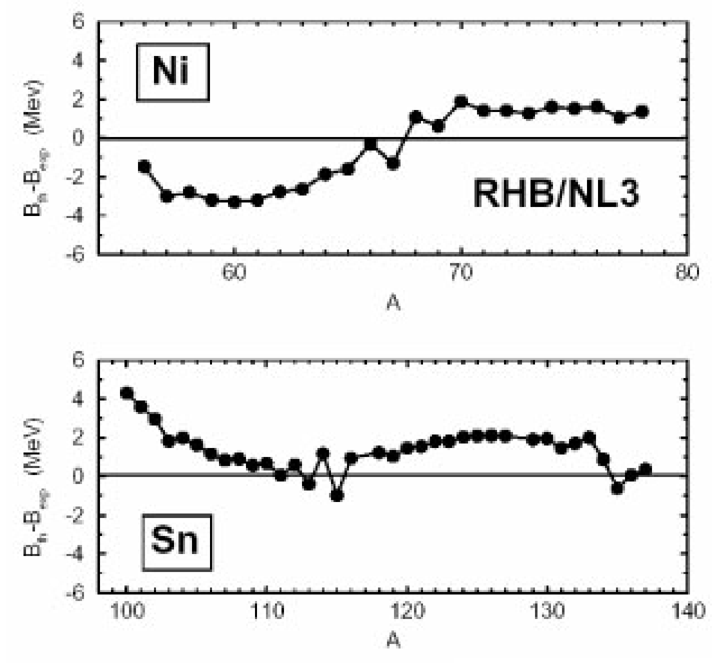




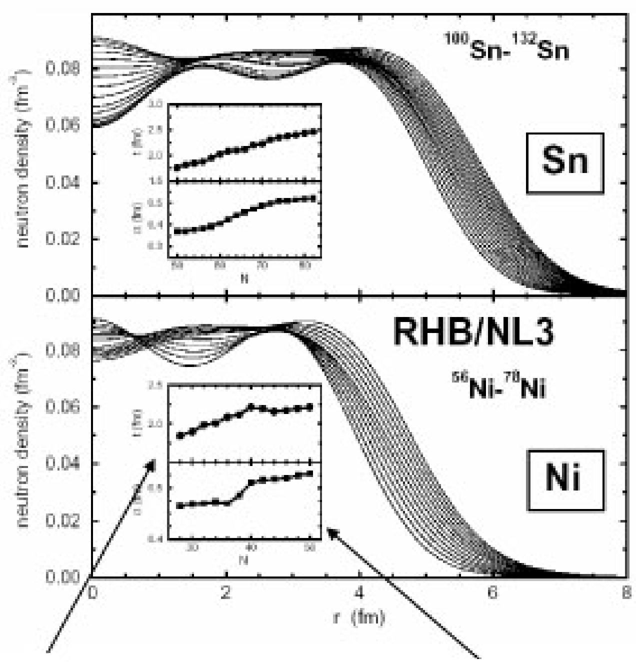
One- and two-neutron separation energies

$$S_n(Z,N) = B_n(Z,N) - B_n(Z,N-1)$$
$$S_{2n}(Z,N) = B_n(Z,N) - B_n(Z,N-2)$$

Differences between RHB model and experimental binding energies for Ni and Sn isotopes



Self-consistent RHB single-neutron density distributions



surface thickness

surface diffuseness α

$$\rho(r) = \rho_0\left(1 + exp(\frac{r-R_0}{\alpha})\right)^{-1}$$

Reduction of the spin-orbit potential in neutron-rich nuclei

Spin-orbit potential originates from the addition of two large fields - field of the vector mesons (short range repulsion), and scalar field of the sigma meson (intermediate attraction)

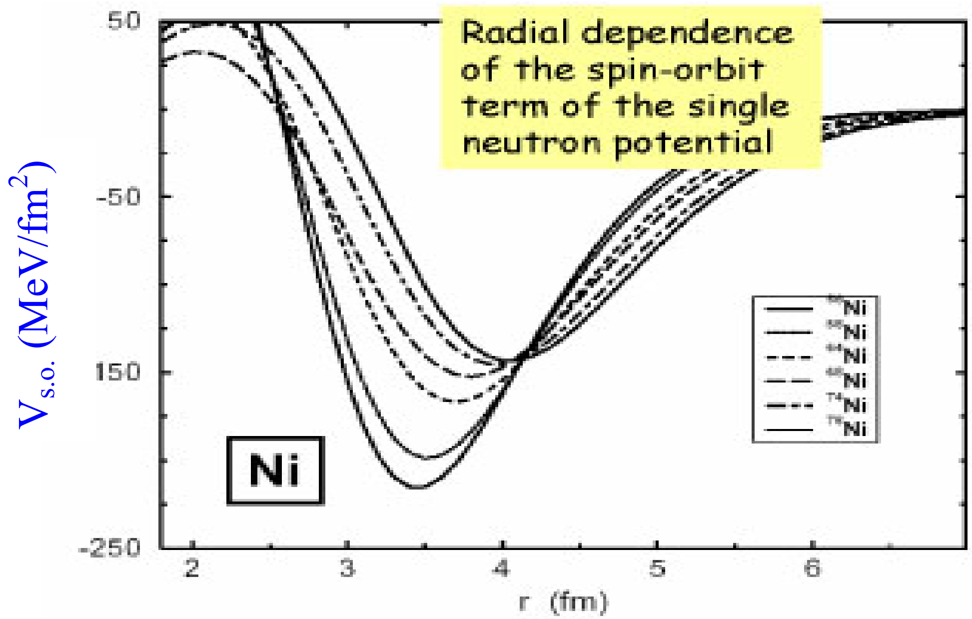
First order approximation, and assuming spherical symmetry: spin-orbit term can be written as

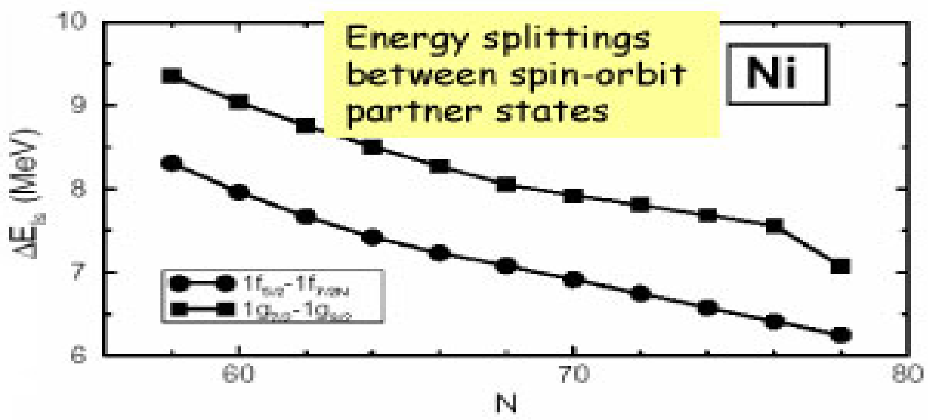
$$V_{s.o.} \approx \frac{1}{r}\frac{\partial}{\partial r}V_{ls}(r)$$

$$V_{ls} = \frac{m}{m_{eff}}(V - S)$$

Weakening of the effective single-neutron spin-orbit potential in neutron-rich isotopes is reflected in the calculated energy spacings between spin-orbit

$$\Delta E_{ls} = E_{n,l,j=l-1/2} - E_{n,l,j=l+1/2}$$





2. MODELS WITH DENSITY-DEPENDENT MESON-NUCLEON COUPLINGS

A. LAGRANGIAN

$$\begin{aligned}\mathcal{L} \;=\; & \bar{\psi}\,(i\gamma\cdot\boldsymbol{\partial}-m)\,\psi \;+\; \frac{1}{2}(\partial\sigma)^2-\frac{1}{2}m_\sigma\sigma^2 \\ & -\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu}+\frac{1}{2}m_\omega^2\omega^2 \;-\; \frac{1}{4}\vec{\mathrm{R}}_{\mu\nu}\vec{\mathrm{R}}^{\mu\nu}+\frac{1}{2}m_\rho^2\vec{\rho}^{\,2} \;-\; \frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} \\ & -\; g_\sigma\bar{\psi}\sigma\psi \;-\; g_\omega\bar{\psi}\gamma\cdot\omega\psi \;-\; g_\rho\bar{\psi}\gamma\cdot\vec{\rho}\vec{\tau}\psi \;-\; e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi\end{aligned}$$

B. DENSITY DEPENDENCE OF THE COUPLINGS

Meson-nucleon couplings g_σ, g_ω, g_ρ $\longrightarrow$ functions of Lorentz-scalar bi-linear forms of the nucleon operators; simplest choice

a) functions of the vector density $\rho_v = \sqrt{j_\mu j^\mu}$ $\qquad j_\mu = \bar{\psi}\gamma_\mu\psi$

b) functions of the scalar density $\rho_s = \bar{\psi}\psi$

a) is a more natural choice.
$\int \rho_v \, d^3r$ = baryon number (conserved quantity)
ρ_s is a dynamical quantity (determined by the selfconsistency condition $\partial\,\varepsilon/\partial M^* = 0$ in nuclear matter)

C. MESON FIELD EQUATIONS

$$
\begin{aligned}
(-\Delta + m_\sigma)\sigma(\mathbf{r}) &= -g_\sigma(\rho_v)\rho_s(\mathbf{r}) \\
(-\Delta + m_\omega)\omega(\mathbf{r}) &= g_\omega(\rho_v)\rho_v(\mathbf{r}) \\
(-\Delta + m_\rho)\rho_3(\mathbf{r}) &= g_\rho(\rho_v)(\rho_n(\mathbf{r}) - \rho_p(\mathbf{r}))
\end{aligned}
$$

D. SINGLE-NUCLEON DIRAC EQUATION

Variation of the Lagrangian: $\frac{\delta \mathcal{L}}{\delta \bar{\psi}} = \frac{\partial \mathcal{L}}{\partial \bar{\psi}} + \frac{\partial \mathcal{L}}{\partial \rho_v}\frac{\delta \rho_v}{\delta \bar{\psi}}$

Second term produces rearrangement contributions to the vector self-energy:

$$\frac{\delta \rho_v}{\delta \bar{\psi}} = \frac{j_\mu \gamma^\mu}{\rho_v}\psi \qquad\qquad \frac{\partial \mathcal{L}}{\partial \rho_v} \Rightarrow \frac{\partial g_\sigma}{\partial \rho_v}, \frac{\partial g_\omega}{\partial \rho_v}, \frac{\partial g_\rho}{\partial \rho_v}$$

$$[\gamma^\mu(i\partial_\mu - \Sigma_\mu) - (m - \Sigma)]\,\psi = 0$$

nucleon self-energies: $\Sigma = g_\sigma \sigma$

$$\Sigma_\mu = g_\omega \omega_\mu + g_\rho \vec{\tau} \cdot \vec{\rho}_\mu + e\frac{(1-\tau_3)}{2} A_\mu + \Sigma_\mu^R$$

inclusion of the rearrangment self-energy:

$$\Sigma_\mu^R = \frac{j_\mu}{\rho_v}\left(\frac{\partial g_\omega}{\partial \rho_v}\bar{\psi}\gamma^\nu \psi \omega_\nu + \frac{\partial g_\rho}{\partial \rho_v}\bar{\psi}\gamma^\nu \vec{\tau}\psi \cdot \vec{\rho}_\nu + \frac{\partial g_\sigma}{\partial \rho_v}\bar{\psi}\psi\sigma\right)$$

Essential for:

a) energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$

b) thermodynamic consistency of the model $\rho_B^2 \frac{\partial}{\partial \rho_B}\left(\frac{\varepsilon}{\rho_B}\right) = \frac{1}{3}\sum_{i=1}^{3} T^{ii}$

requires equality of the pressure obtained from the thermodynamic definition and from the energy-momentum tensor ($\varepsilon = T^{00}$, $\rho B = (2/3\pi^2)\, k_F^3$)

E. PARAMETERIZATION OF THE DENSITY DEPENDENCE

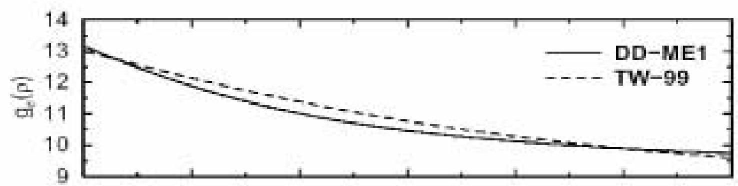
MICROSCOPIC: Dirac-Brueckner calculations of nucleon self-energies in symmetric and asymmetric nuclear matter

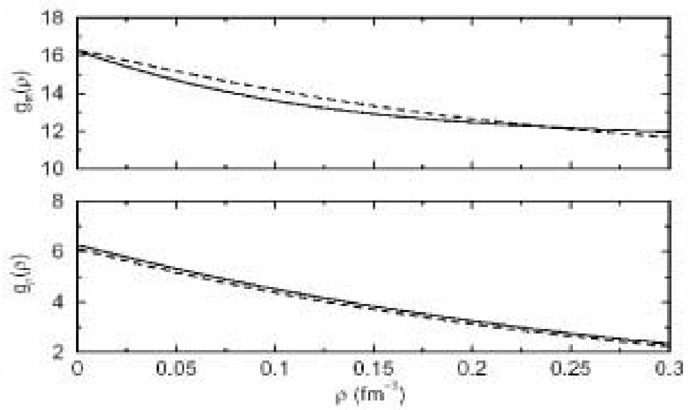
PHENOMENOLOGIC:

$$g_i(\rho) = g_i(\rho_{sat}) f_i(x) \quad f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2} \quad i = \sigma, \omega$$

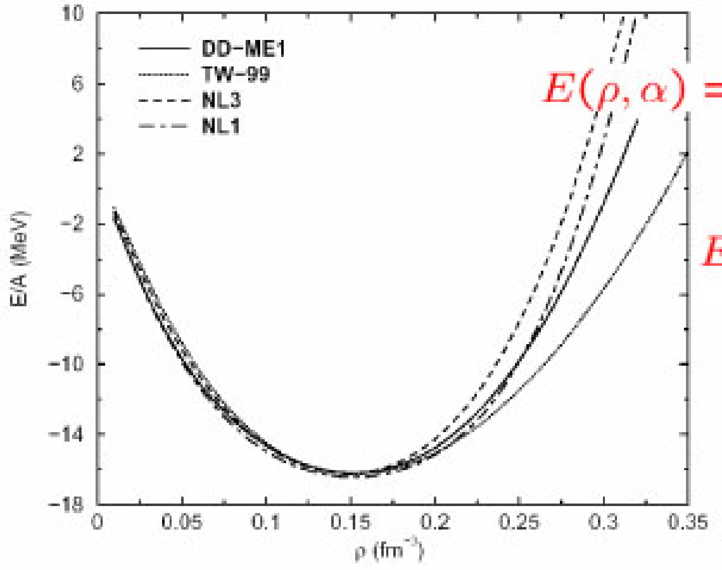
$$g_\rho(\rho) = g_\rho(\rho_{sat}) \exp\left[-a_\rho(x-1)\right] \quad x = \rho/\rho_{sat}$$

Density dependence of the couplings of σ-, ω- and ρ-meson





NUCLEAR MATTER EQUATION OF STATE: Binding energy per nucleon for symmetric nuclear matter as a function of the baryon density

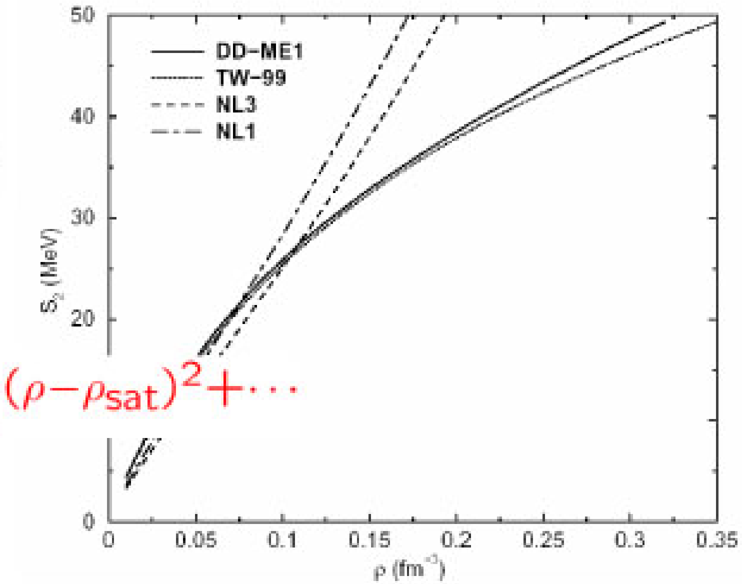


$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + S_4(\rho)\alpha^4 + \cdots$$

$$\alpha \equiv \frac{N-Z}{N+Z}$$

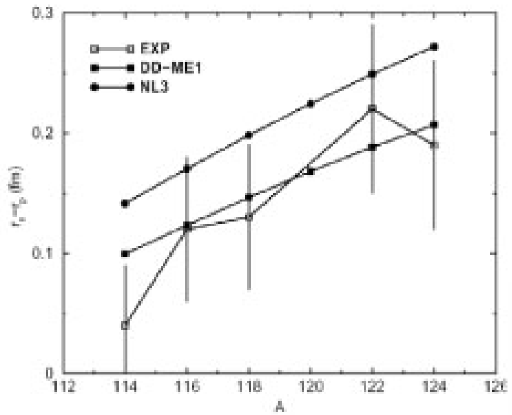
$$E(\rho,0) = -a_v + \frac{K_0}{18\rho_{sat}^2}\,(\rho-\rho_{sat})^2 + \ldots$$

ASYMMETRIC ENERGY



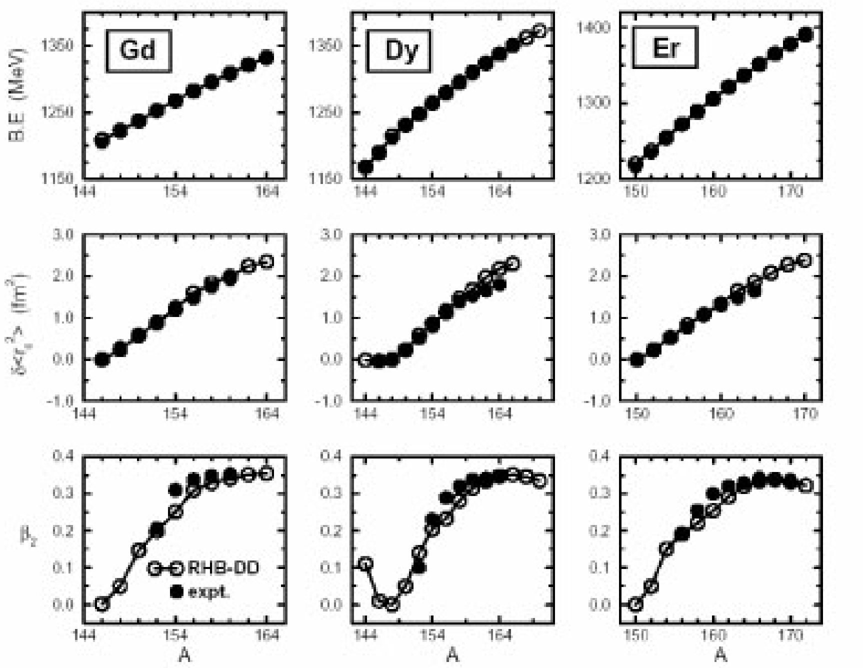
$$S_2(\rho) = a_4 + \frac{p_0}{\rho_{sat}^2}\,(\rho-\rho_{sat}) + \frac{\Delta K_0}{18\rho_{sat}^2}\,(\rho-\rho_{sat})^2 + \cdots$$

F. GROUND-STATE PROPERTIES OF FINITE NUCLEI

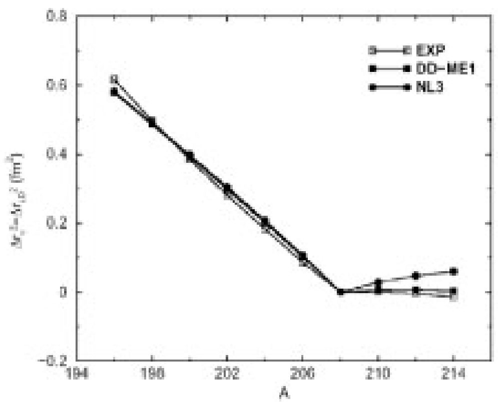


Differences between neutron and proton radii of ground-state distributions of Sn isotopes

Binding energies, charge isotope shifts and quadrupole deformations of Gd, Dy and Er isotopes

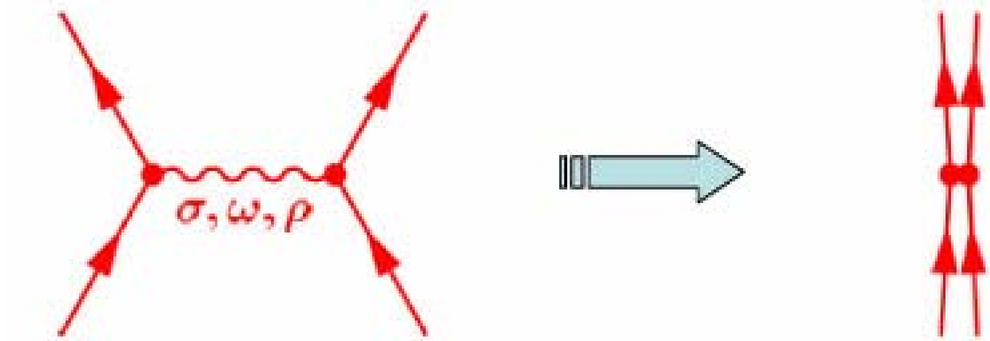


Charge isotope shifts in even-A Pb isotopes



3. RELATIVISTIC POINT-COUPLING MODELS

Is the explicit meson-exchange representation of QHD necessary for a quantitative description of finite nuclei ?



FINITE RANGE

CONTACT INTERACTION

A. Lagrangian

Elementary building blocks of the point-coupling vertices are two-fermion terms of the general type

$$\bar{\psi}\mathcal{O}_\tau\Gamma\psi \quad \mathcal{O}_\tau \in \{1, \tau_i\} \quad \Gamma \in \{1, \gamma_\mu, \gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

10 building blocks characterized by their transformation character in isospin and spacetime; interactions $\longrightarrow$ products of the elementary building blocks to a given order, and derivative terms in the Lagrangian simulate to some extent the effect of finite range

Four-fermion vertices:

isoscalar-scalar: $(\bar\psi\psi)^2$ isovector-scalar: $(\bar\psi\vec\tau\psi)\cdot(\bar\psi\vec\tau\psi)$

isoscalar-vector: $(\bar\psi\gamma_\mu\psi)(\bar\psi\gamma^\mu\psi)$ isovector-vector: $(\bar\psi\vec\tau\gamma_\mu\psi)\cdot(\bar\psi\vec\tau\gamma^\mu\psi)$

higher-order terms: $(\bar\psi\psi)^3$ $(\bar\psi\psi)^4$ $[(\bar\psi\gamma_\mu\psi)(\bar\psi\gamma^\mu\psi)]^2$

Lagragian of the point-coupling model:

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}^{\text{free}} + \mathcal{L}^{\text{4f}} + \mathcal{L}^{\text{hot}} + \mathcal{L}^{\text{der}} + \mathcal{L}^{\text{em}} \\
\mathcal{L}^{\text{free}} &= \bar\psi(\mathrm{i}\gamma_\mu\partial^\mu - m)\psi \\
\mathcal{L}^{\text{4f}} &= -\frac{1}{2}\alpha_{\mathrm{S}}(\bar\psi\psi)(\bar\psi\psi) - \frac{1}{2}\alpha_{\mathrm{V}}(\bar\psi\gamma_\mu\psi)(\bar\psi\gamma^\mu\psi) \\
&\quad -\frac{1}{2}\alpha_{\mathrm{TS}}(\bar\psi\vec\tau\psi)\cdot(\bar\psi\vec\tau\psi) - \frac{1}{2}\alpha_{\mathrm{TV}}(\bar\psi\vec\tau\gamma_\mu\psi)\cdot(\bar\psi\vec\tau\gamma^\mu\psi) \\
\mathcal{L}^{\text{hot}} &= -\frac{1}{3}\beta_{\mathrm{S}}(\bar\psi\psi)^3 - \frac{1}{4}\gamma_{\mathrm{S}}(\bar\psi\psi)^4 - \frac{1}{4}\gamma_{\mathrm{V}}[(\bar\psi\gamma_\mu\psi)(\bar\psi\gamma^\mu\psi)]^2 \\
\mathcal{L}^{\text{der}} &= -\frac{1}{2}\delta_{\mathrm{S}}(\partial_\nu\bar\psi\psi)(\partial^\nu\bar\psi\psi) - \frac{1}{2}\delta_{\mathrm{V}}(\partial_\nu\bar\psi\gamma_\mu\psi)(\partial^\nu\bar\psi\gamma^\mu\psi) \\
&\quad -\frac{1}{2}\delta_{\mathrm{TS}}(\partial_\nu\bar\psi\vec\tau\psi)\cdot(\partial^\nu\bar\psi\vec\tau\psi) \\
&\quad -\frac{1}{2}\delta_{\mathrm{TV}}(\partial_\nu\bar\psi\vec\tau\gamma_\mu\psi)\cdot(\partial^\nu\bar\psi\vec\tau\gamma^\mu\psi) \\
\mathcal{L}^{\text{em}} &= -eA_\mu\bar\psi[(1-\tau_3)/2]\gamma^\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}
\end{aligned}$$

Interaction terms in the Lagrangian are expressed in terms of the local densities (mean-field and no-sea approximations):

isoscalar-scalar:

$$\rho_S(\vec{r}) = \sum_\alpha \bar{\phi}_\alpha(\vec{r})\phi_\alpha(\vec{r})$$

isoscalar-vector:

$$\rho_V(\vec{r}) = \sum_\alpha \bar{\phi}_\alpha(\vec{r})\gamma_0\phi_\alpha(\vec{r})$$

isovector-scalar:

$$\rho_{TS}(\vec{r}) = \sum_\alpha \bar{\phi}_\alpha(\vec{r})\tau_3\phi_\alpha(\vec{r})$$

isovector-vector:

$$\rho_{TV}(\vec{r}) = \sum_\alpha \bar{\phi}_\alpha(\vec{r})\tau_3\gamma_0\phi_\alpha(\vec{r})$$

B. Equations of Motion

$$\gamma_0\varepsilon_\alpha\phi_\alpha = (i\vec{\gamma}\cdot\vec{\partial} + m + V_S + V_V\gamma_0 + V_{TS}\tau_3 + V_{TV}\tau_3\gamma_0 + V_C\frac{1-\tau_3}{2}\gamma_0)\phi_\alpha$$

$$V_S = \alpha_S\rho_S + \beta_S\rho_S^2 + \gamma_S\rho_S^3 + \delta_S\Delta\rho_S \qquad V_{TS} = \alpha_{TS}\rho_{TS} + \delta_{TS}\Delta\rho_{TS}$$

$$V_V = \alpha_V\rho_V + \gamma_V\rho_V^3 + \delta_V\Delta\rho_V \qquad V_{TV} = \alpha_{TV}\rho_{TV} + \delta_{TV}\Delta\rho_{TV}$$

C. Relation to meson-exchange finite range models

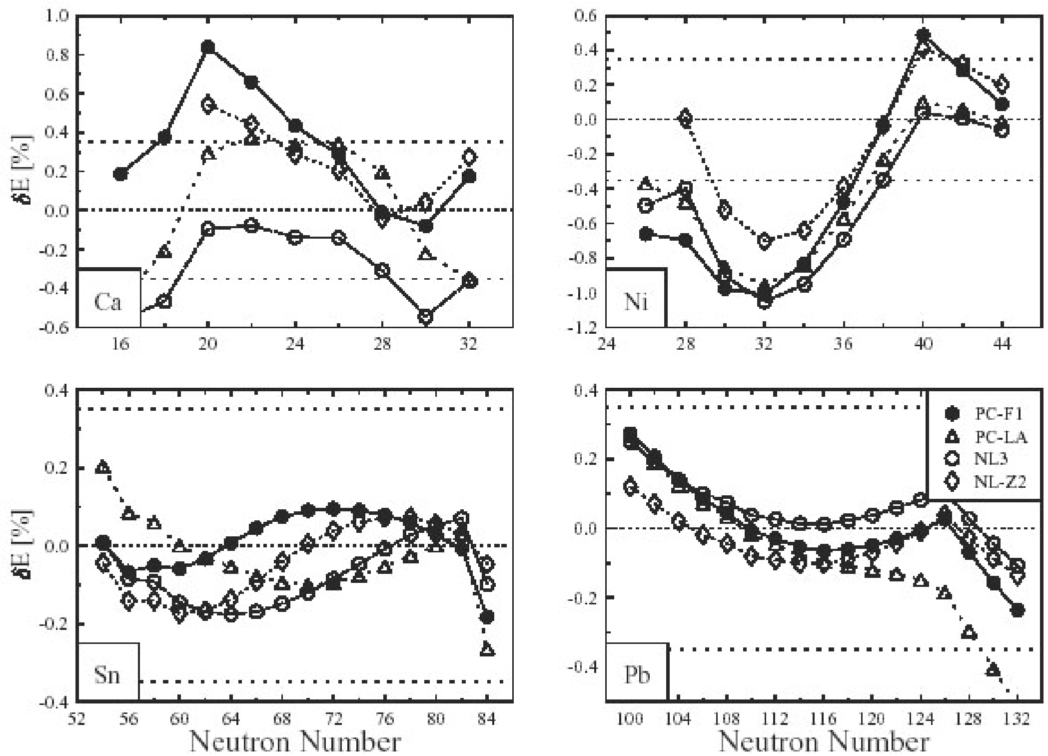
$$(-\Delta + m_\sigma^2)\sigma = -g_\sigma\rho_S \quad \Rightarrow \quad V_\sigma = g_\sigma\sigma$$

$$\frac{-g_\sigma^2}{-\Delta+m_\sigma^2}\rho_S \approx \underbrace{\frac{-g_\sigma^2}{m_\sigma^2}}_{\alpha_S}\rho_S + \underbrace{\frac{-g_\sigma^2}{m_\sigma^4}}_{\delta_S}\Delta\rho_S \quad \Longrightarrow \quad \begin{aligned} m_\sigma^2 &= \alpha_S/\delta_S \\ g_\sigma^2 &= -\alpha_S^2/\delta_S \end{aligned}$$

Bulk properties of nuclear matter: point-coupling and meson-exchange interactions

	PC–F1	PC–LA	NL-Z2	NL3
ρ_0 (fm^{-3})	0.151	0.148	0.151	0.148
E/A (MeV)	-16.17	-16.126	-16.07	-16.24
m^*/m	0.61	0.575	0.583	0.595
K (MeV)	270	264	172	272
a_{sym} (MeV)	37.8	37.194	39.0	37.4

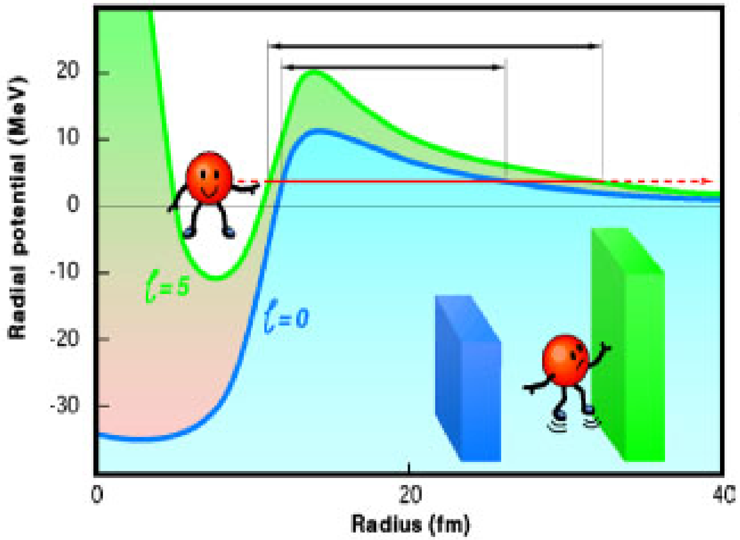
Deviation of the calculated energies from the experimental values: Ca, Ni, Sn and Pb isotopic chains



4. Applications

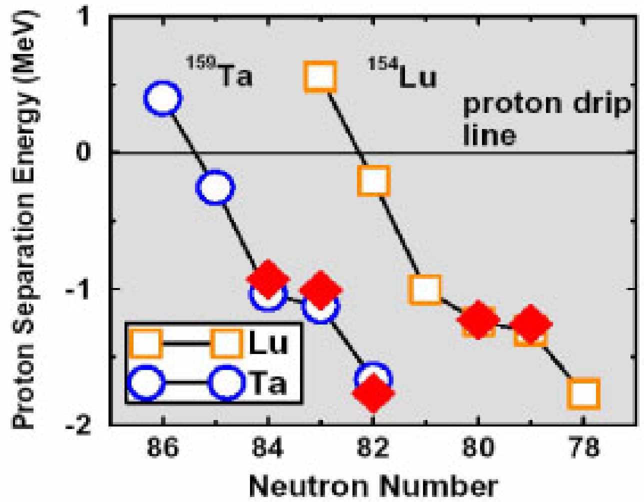
A. Proton-rich nuclei and the proton drip-line

characterized by exotic ground-state decay modes such as the direct emission of charged particles and β-decays with large Q-values; many proton-rich nuclei play an important role in the process of nucleosynthesis by rapid-proton capture

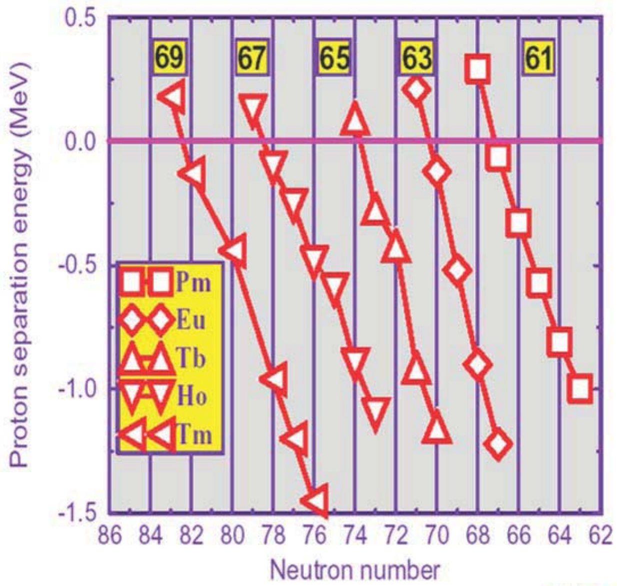


RHB calculation of proton-rich nuclei (NL3+D1S interaction)

Lu and Ta Ground-State Proton Emitters



DEFORMED PROTON EMITTERS



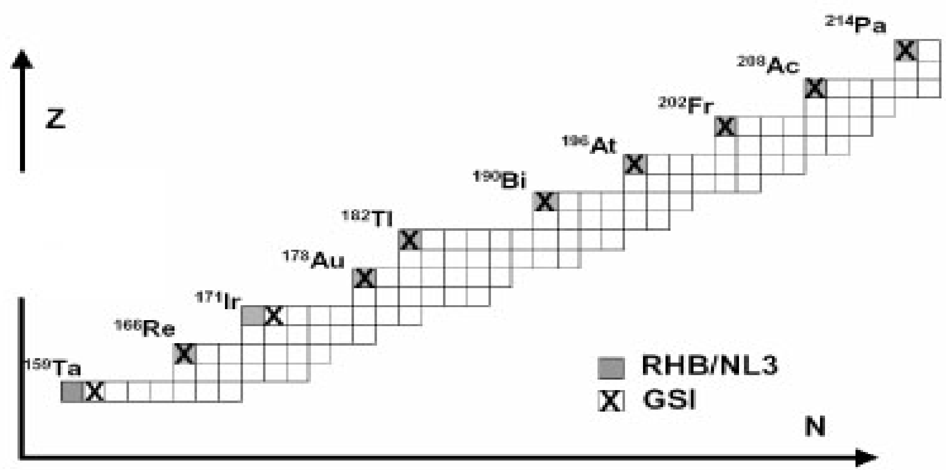
separation energy → S_p; deformation → β_2; odd-proton orbital → p-orbital; spectroscopic factor → u^2

	N	S_p	β_2	p-orbital	u^2	E_p *exp.*
^{124}Pm	63	-1.00	0.35	$5/2^-[532]$	0.72	
^{125}Pm	64	-0.81	0.35	$5/2^-[532]$	0.74	
^{130}Eu	67	-1.22	0.34	$5/2^-[532]$	0.44	
^{131}Eu	68	-0.90	0.35	$5/2^+[413]$	0.44	0.950(8)
^{135}Tb	70	-1.15	0.34	$3/2^+[411]$	0.62	
^{136}Tb	71	-0.90	0.32	$3/2^+[411]$	0.65	
^{140}Ho	73	-1.10	0.31	$7/2^-[523]$	0.61	
^{141}Ho	74	-0.90	0.32	$7/2^-[523]$	0.64	1.169(8)
^{145}Tm	76	-1.43	0.23	$7/2^-[523]$	0.47	1.728(10)
^{146}Tm	77	-1.20	-0.21	$7/2^-[523]$	0.50	1.120(10)
^{147}Tm	78	-0.96	-0.19	$7/2^-[523]$	0.55	1.054(19)

Ground-state properties of probable proton-emitters; results of RHB model calculations (NL3+D1S interaction) are compared with experimental data

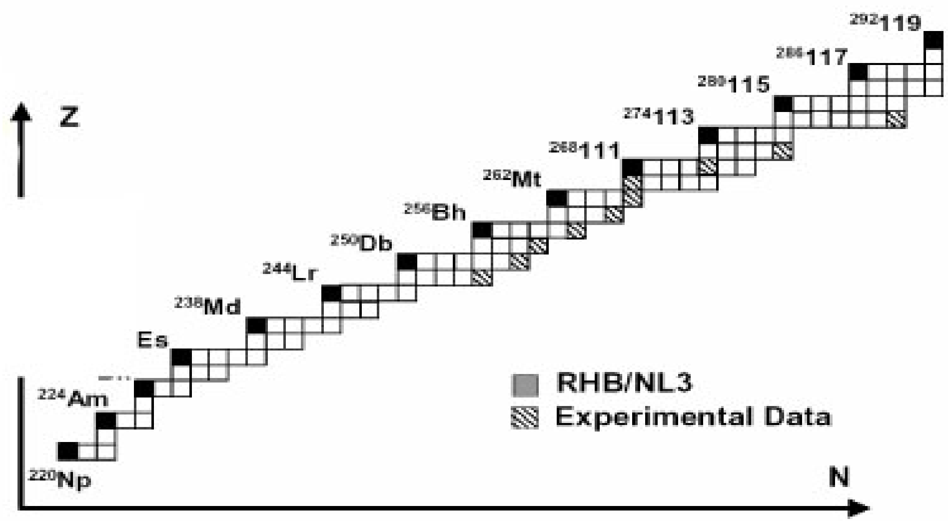
The proton drip-line in the sub-uranium region

Possible ground-state proton emitters in this mass region?



The proton drip-line in the region of superheavy elements

How far is the proton-drip line from the experimentally known superheavy nuclei?

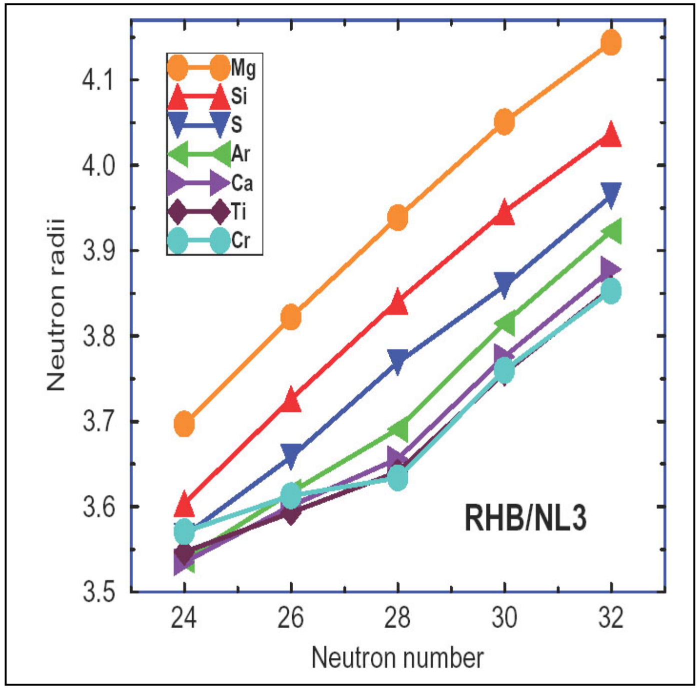


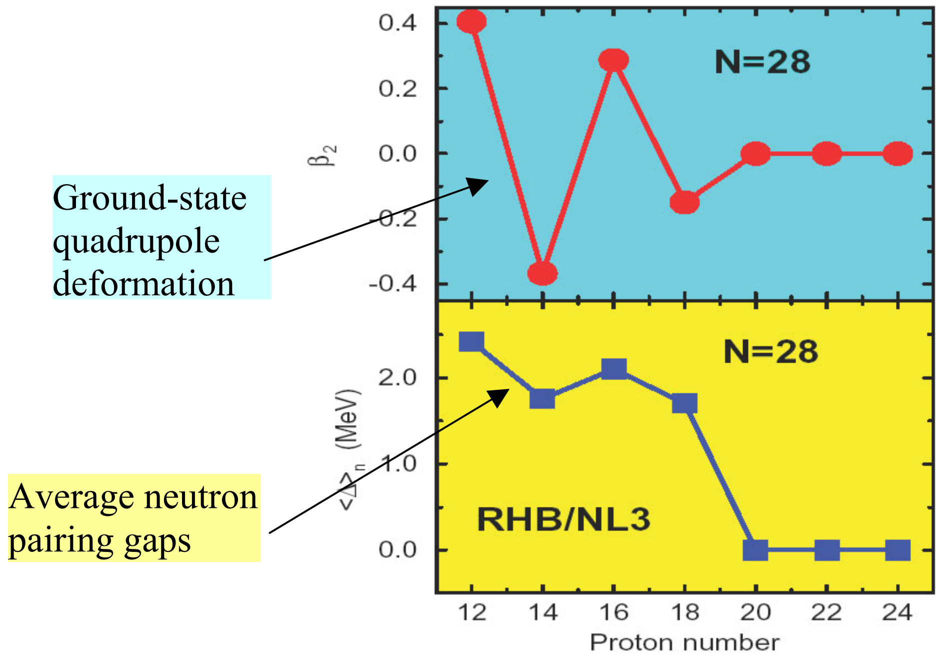
Shape coexistence in the deformed N = 28 region

RHB description of neutron rich N = 28 nuclei; NL3+D1S effective interaction.

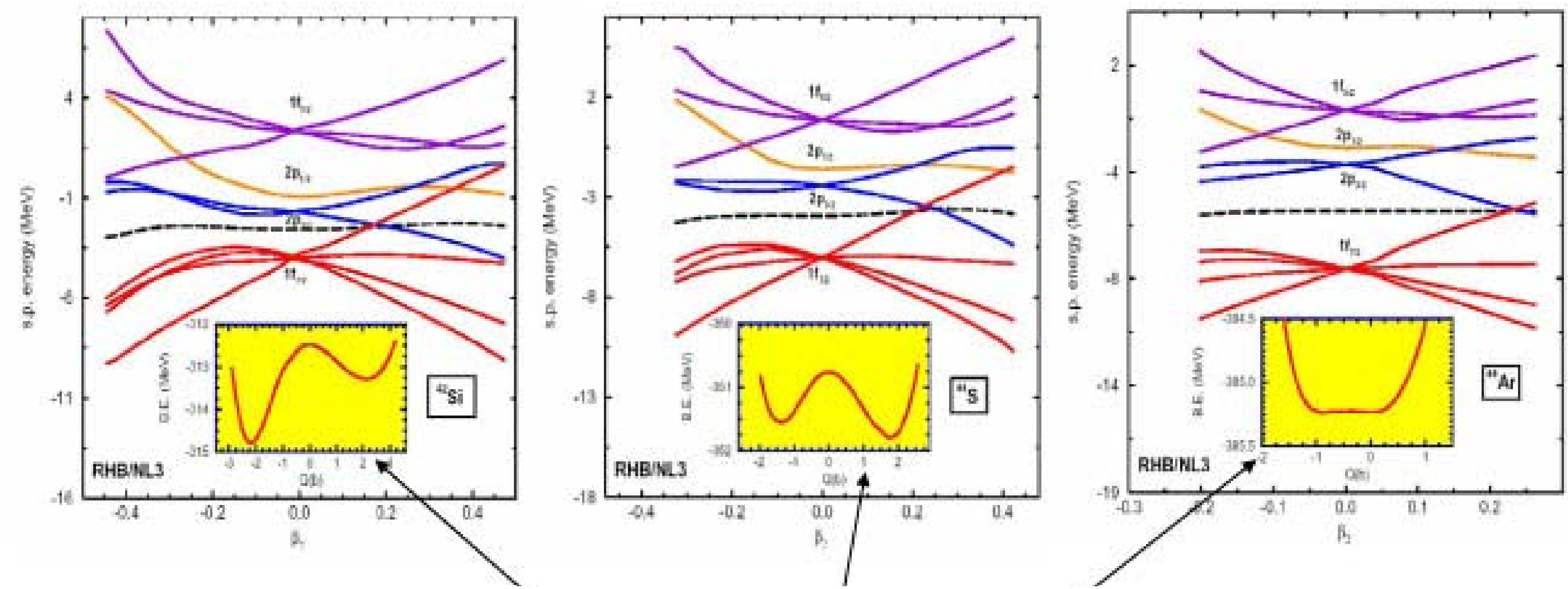
Strong suppression of the spherical N = 28 shell gap.

1f7/2 ➡ fp core breaking ⇨ Shape coexistence





Neutron single-particle levels for ^{42}Si, ^{44}S and ^{46}Ar as functions of the quadrupole deformation. Energies in the canonical basis correspond to ground-state RHB solutions with constrained quadrupole deformation.



Total binding energy curves

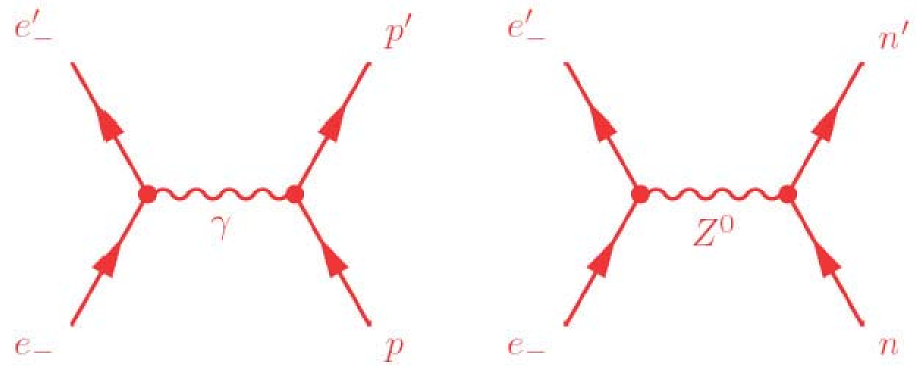
SHAPE COEXISTENCE

Evolution of the shell structure, shell gaps and magicity with neutron number

B. Parity-violating elastic electron scattering and neutron density distributions

Elastic scattering of longitudinally-polarized electrons provides a direct measurement of the neutron distribution

Elastic electron scattering on a spin-zero nucleus:



potential: $\hat{V}(r) = V(r) + \gamma_5 \frac{G_F}{2^{3/2}} \rho_W(r)$

weak-charge density:

$$\rho_W(r) = \int d^3r' G_E(|\mathbf{r}-\mathbf{r}'|)[-\rho_n(r') + (1-4\sin^2\Theta_W)\rho_p(r')]$$

in the limit of vanishing electron mass: $[\alpha \cdot \mathbf{p} + V_\pm(r)]\Psi_\pm = E\Psi_\pm$

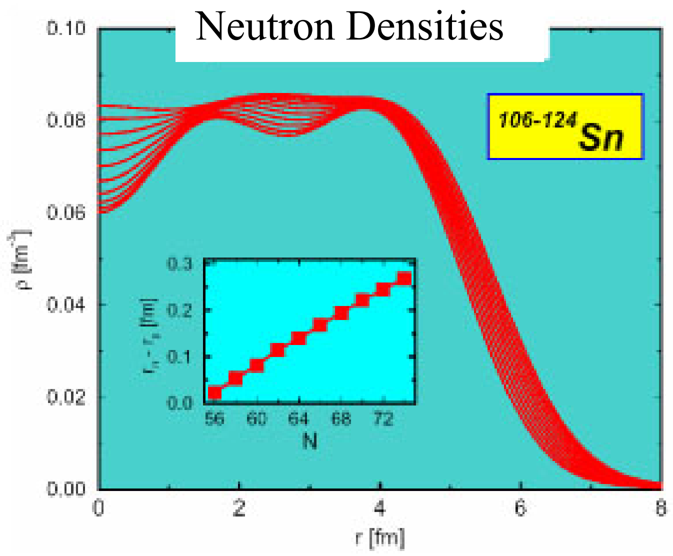
$$\Psi_\pm = \tfrac{1}{2}(1\pm\gamma_5)\Psi \qquad V_\pm(r) = V(r) \pm \frac{G_F}{2^{3/2}}\rho_W(r)$$

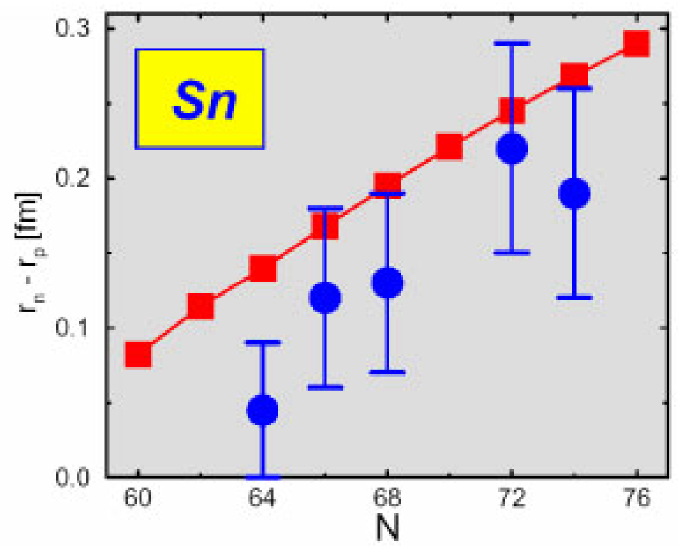
Helicity asymmetry: $$A_l = \frac{d\sigma_+/d\Omega \; - \; d\sigma_-/d\Omega}{d\sigma_+/d\Omega \; + \; d\sigma_-/d\Omega}$$

where +(-) refers to the elastic scattering on the potential $V_{\pm}(r)$. This difference arises from the interference of one-photon and Z^0 exchange between the electron and nucleus.

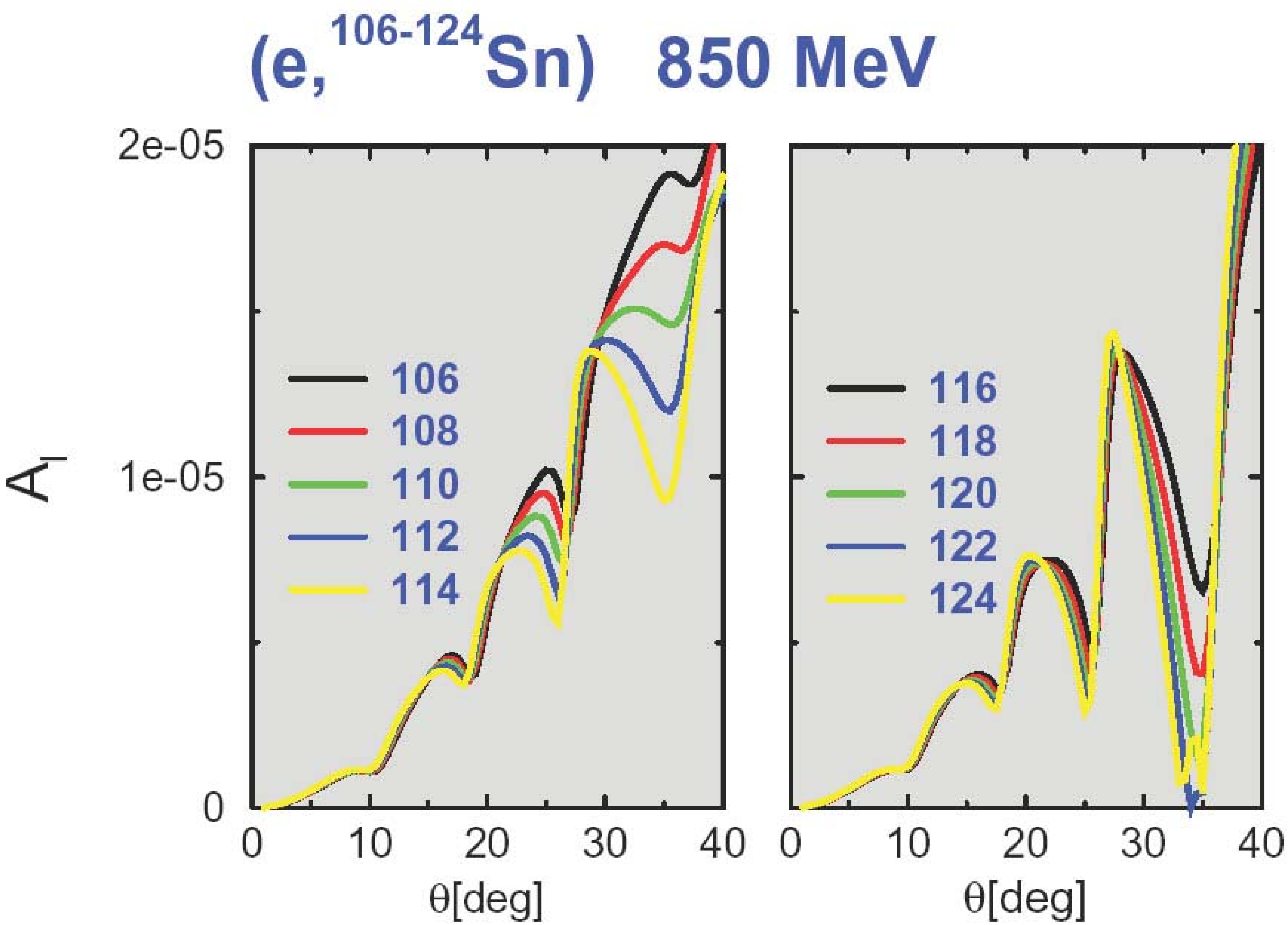
asymmetry parameter $\mathbf{A_l}$ ➡ a direct measurement of the Fourier transform of the neutron density

$$F(q) = \frac{4\pi}{q} \int dr \; r^2 j_0(qr) \rho_n(r)$$

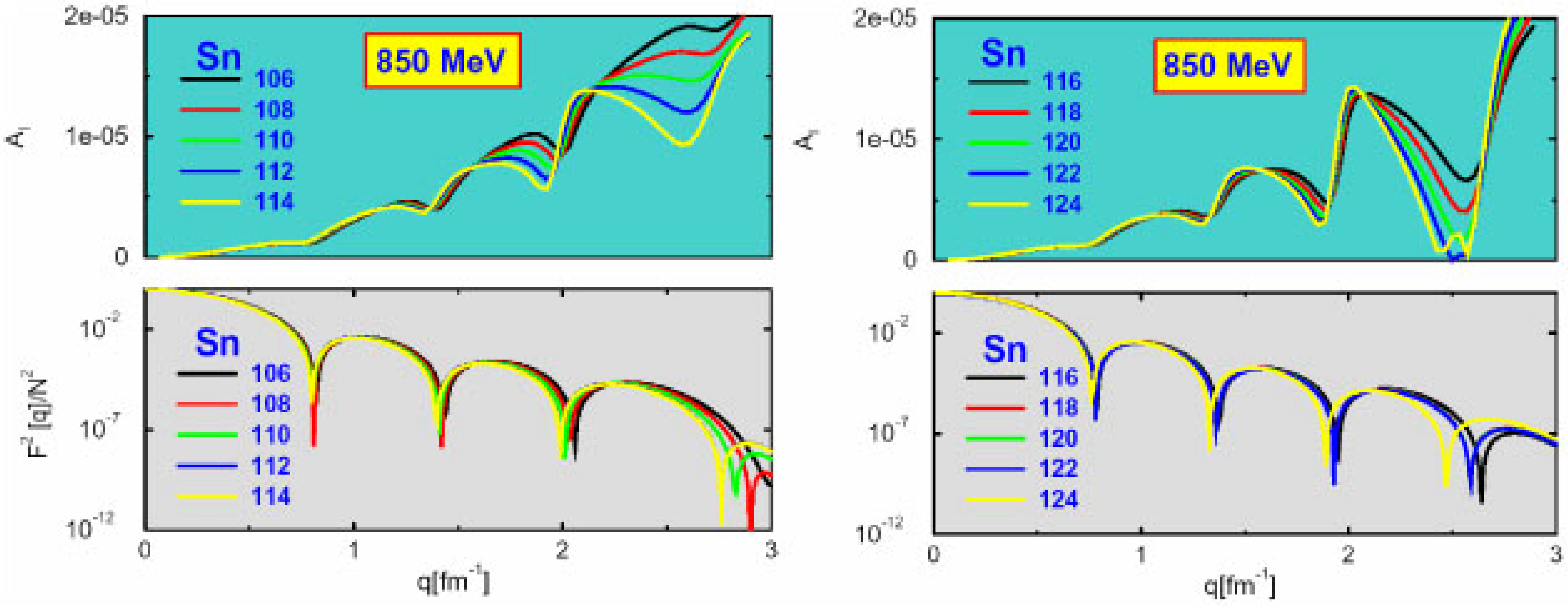




Parity-violating asymmetry parameters A_l for elastic scattering from $^{106\text{-}124}$Sn at 850 MeV



Asymmetry parameters A_l and Fourier transforms of neutron densities, as functions of the momentum transfer q, for (e, $^{106-114}$Sn) at 850 MeV



Differences between the asymmetries can be directly related to the form factors

C. Relativistic quasiparticle random phase approximation

1. Giant resonances in EXOTIC nuclei ⟶ evolution of low-lying dipole strength in nuclei with large neutron excess – **PYGMY RESONANCES**

2. EXOTIC giant resonances in nuclei – **TOROIDAL DIPOLE RESONANCE**

RQRPA ⟶ formulated in the canonical basis of the relativistic Hartree-Bogoliubov model; NL3 mean-field plus Gogny D1S pairing interactions

$$\begin{pmatrix} A^J & B^J \\ B^{*J} & A^{*J} \end{pmatrix} \begin{pmatrix} X^{\nu,JM}_{kk'} \\ Y^{\nu,JM}_{kk'} \end{pmatrix} = \omega_\nu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^{\nu,JM}_{kk'} \\ Y^{\nu,JM}_{kk'} \end{pmatrix}$$

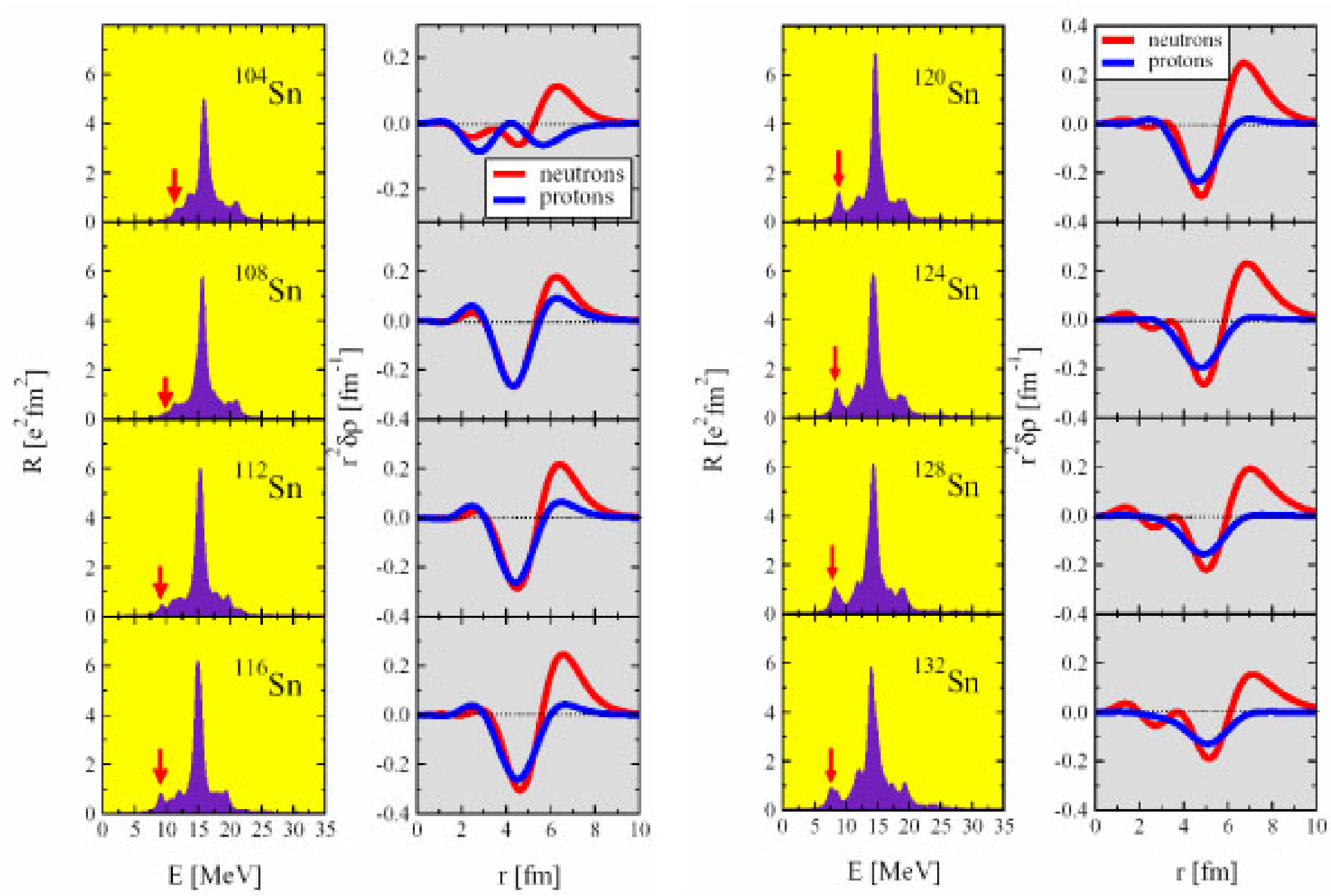
RQRPA equations:

$$\begin{aligned} A^J_{kk'll'} &= H^{11(J)}_{kl}\delta_{k'l'} - H^{11(J)}_{k'l}\delta_{kl'} - H^{11(J)}_{kl'}\delta_{k'l} + H^{11(J)}_{k'l'}\delta_{kl} \\ &\quad + \frac{1}{2}(\xi^+_{kk'}\xi^+_{ll'} + \xi^-_{kk'}\xi^-_{ll'})V^{ppJ}_{kk'll'} + \zeta_{kk'll'}\tilde{V}^{phJ}_{kl'k'l} \\ B^J_{kk'll'} &= \frac{1}{2}(\xi^+_{kk'}\xi^+_{ll'} - \xi^-_{kk'}\xi^-_{ll'})V^{ppJ}_{kk'll'} \\ &\quad + \zeta_{kk'll'}(-1)^{j_l - j_{l'} + J}\tilde{V}^{phJ}_{klk'l'} \\ H^{11}_{kl} &= (u_k u_l - v_k v_l)h^D_{kl} - (u_k v_l + v_k u_l)\Delta_{kl} \end{aligned}$$

Evolution of isovector dipole strength in Sn isotopes

Transition densities

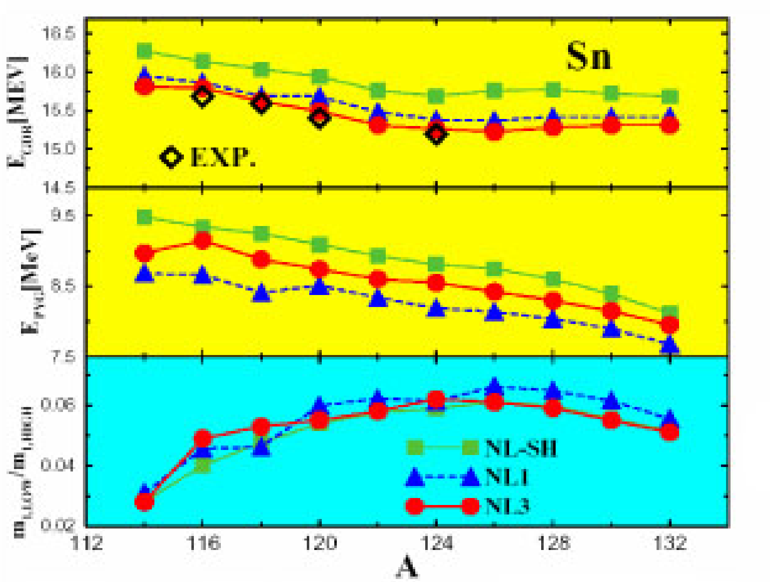
Transition densities



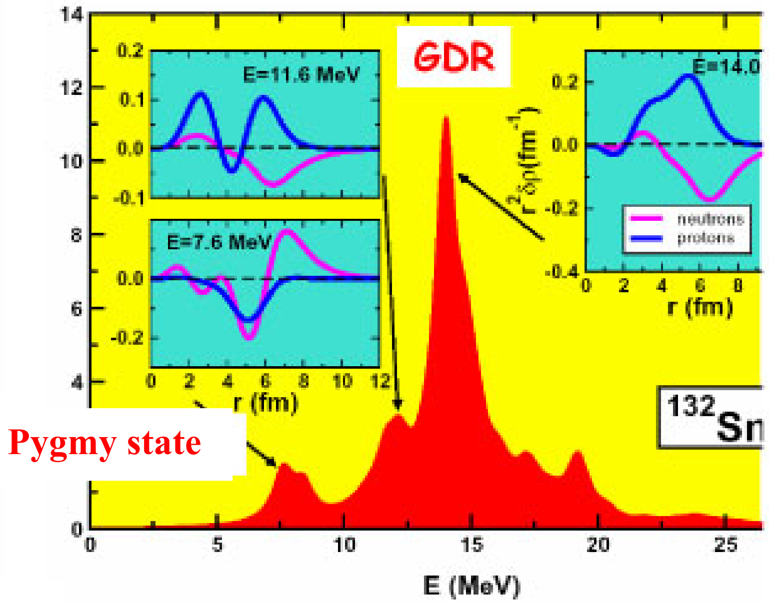
Evolution of isovector dipole strength in neutron-rich nuclei:

Low-lying dipole strength in light nuclei → non-resonant independent single-particle excitations of loosely bound nucleons

Heavier nuclei → among several single-particle transitions, a single collective dipole state is found below 10 MeV



Mass dependence of GDR and pygmy dipole states in Sn isotopes; evolution of low-lying strengths



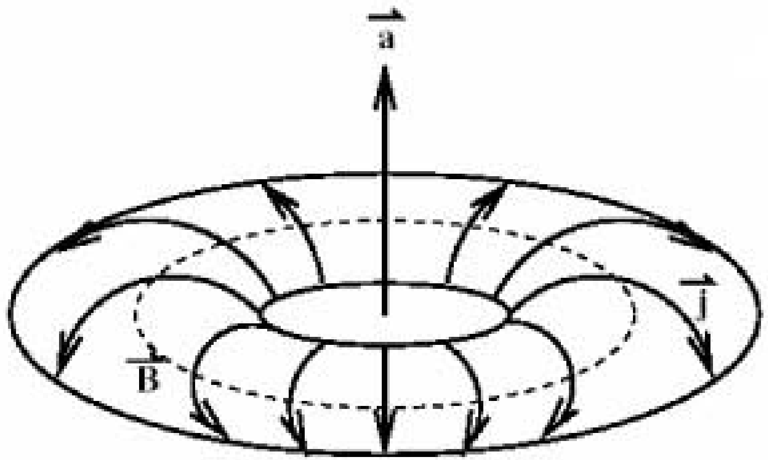
Isovector dipole strength in ^{132}Sn
Proton and neutron transition densities

Toroidal Giant Dipole Resonances

Multipole expansion of a four-current distribution:

- charge moments
- magnetic moments
- electric transverse moments → toroidal moments

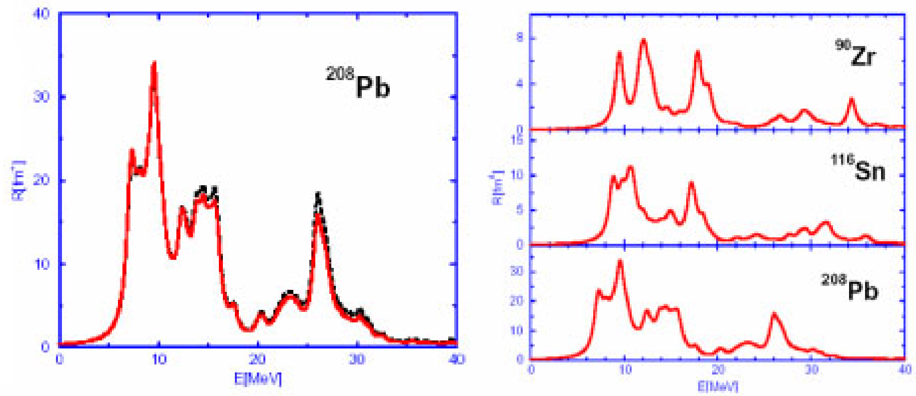
Toroidal dipole moment: poloidal currents on a torus



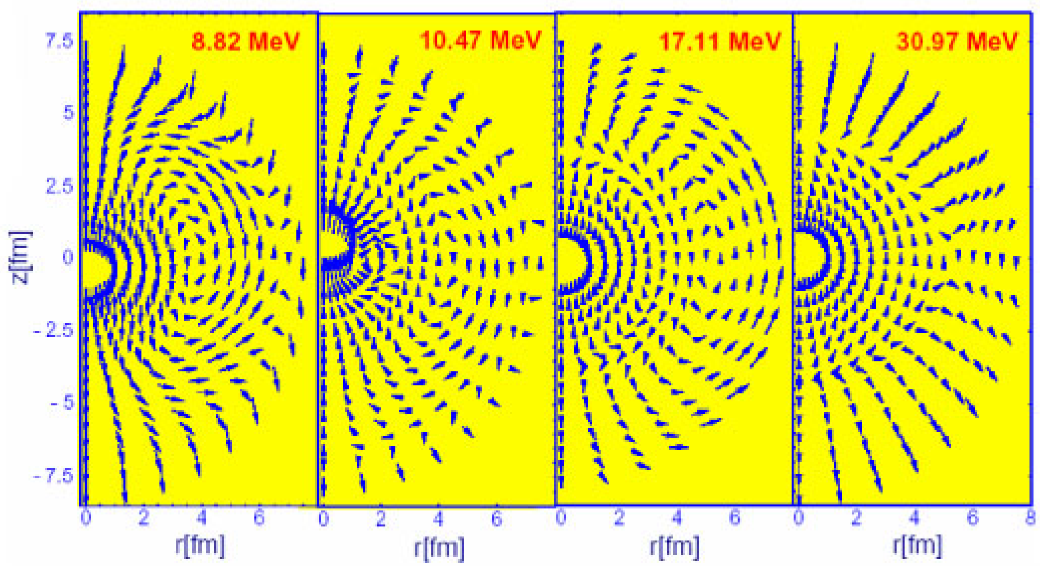
isoscalar toroidal dipole operator

$$\hat{T}^{T=0}_{1\mu} \sim \int [r^2 \left(\vec{Y}^*_{10\mu} + \frac{\sqrt{2}}{5} \vec{Y}^*_{12\mu} \right) - \langle r^2 \rangle_0 \, \vec{Y}^*_{10\mu}] \cdot \vec{J}(\vec{r}) d^3 r$$

Toroidal dipole strength distributions



Velocity distributions in ^{116}Sn



Nuclear Theory

Geometrical Symmetries in Nuclei

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Geometrical Symmetries in Nuclei[1]

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Department of Physics

Indian Institute of Technology Roorkee

India

[1] These lectures are dedicated to my son NamaN, a beautiful soul.

Introduction

Symmetries in nature, art and architecture fascinate us. We are charmed by objects which are symmetric, and therefore beautiful. Most of these symmetries are geometric in nature, and are related to the external appearance. However, we do come across many other types of symmetries in physics that are quite different from the purely geometric, or spatial symmetries.

The theorem of Emmy Noether enunciates that each continuous symmetry is related to a conserved quantity, or a constant of motion. Accordingly, we have constants related to symmetries of translation, rotation and reflection in space and time. Thus, invariance under the time translation leads to the conservation of the total energy of a closed system. Likewise, invariance under space translation and rotation leads to the conservation of linear momentum and angular momentum, respectively. Besides the continuous symmetries, we also come across discrete symmetries like reflection, or inversion of space that leads to conservation of parity. Time reversal invariance can also be added to this list, as manifested by Kramer's degeneracy in single nucleon orbits. Most common among the discrete symmetries are the point-group symmetries used widely in the classification of crystal structure. These symmetries have also found useful application in molecules and nuclei.

Besides these, we have dynamical symmetries and the fundamental gauge symmetries in nature. However, complex systems like atoms, molecules and nuclei have their own set of symmetries which can be geometrical as well as dynamical, and emerge from the complexity of the system. Certain algebraic symmetries related to the various group structures such as U(5), SU(3) and SO(6) have also been identified in complex systems such as nuclei. These result in a characteristic set of patterns of energy levels, and inter related transition patterns. A more recent development along a similar line is the observation of simple behavior in systems at the critical point of quantum phase transitions. This behavior has been interpreted as the occurrence of a dynamical symmetry such as X (5) in ^{152}Sm. Systems lying at the critical point of first and second order phase transitions are being closely scrutinized for similar behaviour. However, we shall not discuss these kinds of symmetries.

Mean Field and Spontaneous Symmetry Breaking

The concepts of mean field and spontaneous breaking of the symmetries of mean field play an important role in explaining the observed band structures. The fundamental nucleon-nucleon interaction can be taken to be a two body force, and should be invariant under all the basic transformations like translation, rotation and inversion in space and time. However, a collection of nucleons as a nucleus give rise to a mean field, and may break one or more of these symmetries even though the fundamental N-N interaction has no such effect. Such symmetry breaking is termed as spontaneous breaking of symmetry, and is crucial in understanding a large variety of characteristic pattern of levels observed in experiments. However, as we shall see, additional varieties of patterns are predicted, and are waiting to be observed.

If nuclei also obeyed the basic symmetries of the N-N interaction, we would miss much of the richness in their band structure. Spontaneous breaking of one or more of these symmetries leads to a rich band structure, and enables us to classify and label the levels into various bands and infer information about the nature of the mean field. For example, the energy levels of ^{168}Er shown in the column on the left of Fig. 1 begin to look meaningful and systematic when classified into bands as on the right hand side.

Symmetry, Unitary Transformation, Degeneracy and Multiplets

A symmetry in quantum mechanics can be represented by a group of unitary transformations Û in the Hilbert space. Operator Q represents an observable, and transforms as

$$Q \rightarrow u^{\dagger} Q u$$

under the unitary transformation u. Since $u^{\dagger} = u^{-1}$ for unitary transformations, invariance of Q under u implies that

$$Q = u^{-1} Q u$$

$$\text{and } [u, Q] = 0,$$

which is a well known result from quantum mechanics. If the unitary operator happens to arise from the Hamiltonian of the quantum system, the operator Q leads to a conserved quantity. Under such circumstances, the unitary operator defined by H is $e^{-i\,t\,H}$, and

$$e^{itH} Q e^{-itH} = Q \text{ for all } t.$$

Thus, a commutation of Q with $u = e^{itH}$ also implies a commutation of Q with H, and Q is conserved.

Note that H is the generator of time translation because

$$\Psi' = e^{itH}\Psi = (1 + itH)\Psi$$

represents a new state obtained by translation in time. Likewise,

$$\Psi' = e^{i\theta J_z}\Psi = (1 + i\theta J_z)\Psi$$

represents a new state obtained by rotation by θ about the z–axis. J_z is the z–component of the angular momentum operator, and is the generator of rotation about the z-axis. If J_z is an invariant operator, we have

$$[H, J_z] = 0.$$

Also, if $H\Psi = E\Psi$, we have

$$H\Psi' = H(1 + i\theta J_z)\Psi = E\Psi'.$$

This expression means that either Ψ is an eigenstate of both H and J_z, or the eigenvalue E has a degeneracy. Thus, both Ψ and Ψ' are eigenstates of H with the same energy eigenvalue E, leading to the concept of degeneracy and multiplets. An energy eigenstate can have n-fold degeneracy if n-fold rotation of Ψ about the z–axis leaves Ψ invariant. An interaction or deformation that violates this symmetry will lift the degeneracy and a multiplet will emerge.

As a simple example, consider a single particle moving in a spherically symmetric central potential and carrying angular momentum $\vec{j}$; the energy of this particle does not depend on j_z, and has (2j+1)-

fold degeneracy, where j is the angular momentum quantum number. However, a slight deformation of the potential splits the degeneracy of the j-multiplet, and a characteristic level pattern is obtained. Such symmetry breaking is witnessed when going from solutions of the spherical shell model to the deformed shell model, or the Nilsson model, as shown in Fig. 2. If the potential has an axial symmetry about the Z-axis, J_z is the only conserved quantity and the corresponding quantum number Ω can be used to label the state.

Discrete Symmetries in Nuclei

Most commonly encountered discrete symmetries in rotating nuclei correspond to parity P, rotation by π about the body-fixed x, y, z axes, $R_x(\pi)$, $R_y(\pi,)$, $R_z(\pi)$, time reversal T, and $TR_x(\pi)$, $TR_y(\pi)$ and $TR_z(\pi)$. All of these symmetries are two fold discrete symmetries, and breaking them causes a doubling of states. Dobaczewski et al. (2000) have carried out a detailed classification of the mean field solutions according to the discrete symmetries of a double point group denoted by D_{2h} (Landau and Lifshitz, 1956), and this includes all the symmetries listed above. We can enunciate the following simple rules to work out the consequences of these symmetries on a rotational band consisting of levels with angular momentum quantum numbers $I, I+1, I+2,$ etc:

1. When P is broken, we observe a parity doubling of states; a sequence such as $I^+, I+1^+, I+2^+,$ ... turns into $I^{\pm}, I+1^{\pm}, I+2^{\pm},$ ... [see Fig. 3(a)].

2. When $R_x(\pi)$ is broken, states of both signatures occur; two sequences $I, I+2,$...etc. and $I+1, I+3,$ ...etc. having different signatures and are shifted in energy with respect to each other, to merge into one sequence like $I, I+1, I+2, I+3$ ... etc. [see Fig. 3(b)].

3. A doubling of states of the allowed angular momentum occurs when $R_y(\pi)$ T is broken. Sequence $I, I+2, I+4,$ ... etc. becomes $2(I), 2(I+2), 2(I+4),$ ..., with each state occurring twice (Chiral doubling) [see Fig. 3(c)].

4. When $P=R_x(\pi)$, the two signature partners will have different parity. Thus states of alternate parity occur, and we obtain a sequence like $I^+, I+1^-, I+2^+,$ ... etc. [see Fig. 3(d)].

Since all these symmetries have a two-fold degeneracy, a breaking of each of them individually doubles the number of states, and Frauendorf (2001) has listed the consequences that are relevant for the two-body rotating Hamiltonian $H=T+V-\omega\vec{j}_x$, as reproduced in Table I. All the possibilities presented in this table can be determined by using these rules either alone or in combination.

Table I: Consequences of spontaneous breaking of one or more of the discrete symmetries of the rotating mean field.

Symmetry No.	**P**	$R_x(\pi)$	$R_y(\pi)T$	*1Level sequence*
1	S	S	S	$I^+, (I+2)^+, (I+4)^+$...............
2	S	D	S	$I^+, (I+1)^+, (I+2)^+$.............
3	S	D	D	$2I^+, 2(I+1)^+, 2(I+2)^+$..........
4	S	S	D	$2I^+, 2(I+2)^+, 2(I+4)^+$..........
5	S	D	$R_x(\pi)$	$I^+, (I+1)^+, (I+2)^+$.............
6	D	S	S	$I^\pm, (I+2)^\pm, (I+4)^\pm$.........
7	D	D	S	$I^\pm, (I+1)^\pm, (I+2)^\pm$......
8	D	S	D	$2I^\pm, 2(I+2)^\pm, 2(I+4)^\pm$..........
9	D	D	$R_x(\pi)$	$I^\pm, (I+1)^\pm, (I+2)^\pm$........
10	$R_x(\pi)$	D	S	$I^+, (I+1)^-, (I+2)^+$........
11	$R_x(\pi)$	D	D	$2I^+, 2(I+1)^-, 2(I+2)^+$........
12	$R_y(\pi)T$	S	D	$I^\pm, (I+2)^\pm, (I+4)^\pm$............
13	$R_y(\pi)T$	D	D	$I^\pm, (I+1)^\pm, (I+2)^\pm$..........
14	$R_x(\pi)$	D	$R_x(\pi)$	$I^+, (I+1)^-, (I+2)^+$.........
15	D	D	D	$2I^\pm, 2\,(I+1)^\pm, 2\,(I+2)^\pm$...........

x is the axis of rotation

D denotes that the mean field changes under the corresponding operation, and S means the mean field remains the same; when another operation is shown, the two are identical

Last column shows the spectrum arising for a given set of conserved/broken symmetries

Although only positive parity is shown in rows 1-5, parity can also be negative (taken from Frauendorf (2001))

Nuclear Shapes

Some basic ideas of nuclear shapes need to be considered before proceeding further. The surface of an arbitrarily deformed body can be expressed by the radius vector along the polar angles θ and ϕ as

$$R(\theta,\phi) = R_0[1 + \sum_{\lambda,\mu} \alpha_{\lambda,\mu} Y^*{}_{\lambda\mu}(\theta,\phi)]$$

where R_0 is the radius of an equivalent volume sphere. Terms $\lambda = 0, 1, 2, 3, 4$ etc. correspond to the monopole, dipole, quadrupole, octupole, hexadecapole etc shapes, and generally we obtain 2^λ-pole deformation for a given λ. These spherical harmonics have definite geometrical symmetries, and may occur in the mean field of the nucleus. Monopole shape oscillation may occur only at very high excitations in nuclei due to the incompressible nature of nuclear matter. The dipole term corresponds simply to a translation of the nucleus and does not have any physical significance. Therefore, the lowest order term of importance is the $\lambda = 2$ quadrupole term. Higher-order terms play a role in specific mass regions of nuclei, but $\lambda = 2$ is the most widespread and globally occurring shape in nuclei.

A permanent non-spherical shape gives rise to the possibility of observing rotational motion. Under these circumstances, the nuclear surface is more conveniently considered in the body-fixed frame rather than the space-fixed frame. The nuclear surface in the body-fixed frame can also be described by the similar relationship:

$$R(\theta,\phi) = R_0[1 + \sum a_{\lambda,\mu} Y^*{}_{\lambda\mu}(\theta,\phi)]$$

where $a_{\lambda\mu}$ have been introduced as the new time-independent parameters in the body-fixed frame, which coincides with the principal axes. Parameters $a_{\lambda\mu}$ are related to $\alpha_{\lambda\mu}$:

$$a_{\lambda\mu} = \sum_{\mu'} D^{\lambda}_{\mu'\mu}(\Omega)\alpha_{\lambda\mu'}$$

The $Y_{2\mu}$ term corresponding to $\lambda = 2$ has five components labeled by $\mu = \pm 2, \pm 1, 0;$ $\mu = 0$ component corresponds to the situation where full rotational symmetry is maintained about one of the three principal axes (say the z-axis) and the other two axes (x- and y-) are equal. Such a shape is called a spheroid. For $x = y < z$, a prolate spheroid is obtained; and for $x = y > z$, an oblate spheroid is derived. The prolate spheroid is found to be the most common shape in nuclei, although the oblate shape is also known to occur near the magic numbers.

The next most commonly observed shape is $\lambda = 4$ hexadecapole shape, which is generally superposed on the quadrupole shape, and is only found with small amplitude. A small $\lambda = 3$ octupole shape is now believed to occur in certain pockets of nuclei, and is also superimposed on the quadrupole shape. Furthermore, much of the experimental evidence favours the occurrence of $\mu = 0$ component of the various multipoles. However, attention has now focused on $\mu \neq 0$ components of the various multipoles and their consequences, corresponding to the introduction of non-axial or axially-asymmetric degrees of freedom. Some common nuclear shapes corresponding to the various multipoles are shown in Fig. 4, while Fig. 5 depicts some extraordinary, or exotic shapes.

Observation of one or more of these varied shapes in nuclei has become a distinct possibility with recent enhancements in our experimental capabilities. While the ground state configurations of nuclei may not support all of these shapes, we now have the possibility of observing high-spin configurations, non-yrast configurations and configurations with abnormal N/Z ratio (nuclei some considerable distance away from the line of stability) which may support one or more of these novel shapes.

Each of these shapes is obtained by distinct symmetry breaking of the mean field, and therefore leaves a characteristic impression on the level pattern due to the lifting of degeneracy. Such operations leave these geometrical shapes invariant when coupled with the time-reversal and space-inversion (parity) operators, and provide a fertile ground for observing nuclear levels with fascinating patterns.

An additional new dimension to the whole scenario has been provided by the realization that rotation is also possible about an axis other than one of the principal axes. This phenomenon is particularly true for the tri-axial shapes where rotation about a tilted axis has successfully explained observed features and phenomena such as magnetic and chiral rotations. Such behaviour leads to additional types of symmetry breakings and ensuing consequences.

Collective Hamiltonian

The collective Hamiltonian for an irrotational flow of fluid can be written as (Bohr and Mottelson (1975); Pal (1982)):

$$H = T + V = \frac{1}{2}\sum_{\lambda,\mu}[B_\lambda \left|\dot{\alpha}_{\lambda\mu}\right|^2 + C_\lambda \left|\alpha_{\lambda\mu}\right|^2],$$

where

$$B_\lambda = \lambda^{-1}\rho_0 R_o^5 = \frac{3}{4\pi}\lambda^{-1} M A R_0^2$$

$$C_\lambda = C_\lambda^5 + C_\lambda^c = R_0^2 S(\lambda-1)(\lambda-2) - \frac{3}{2\pi}\frac{(Ze)^2}{R_0}.\frac{\lambda-1}{2\lambda+1},$$

and ρ_0 is the equilibrium density of nuclear matter. Note that the space-fixed frame and parameters have been used to give a classical Hamiltonian of a vibrator for each (λ, μ) mode, with a classical frequency of vibration given by $\omega_\lambda = \left(\frac{C_\lambda}{B_\lambda}\right)^{\frac{1}{2}}$. Transformation of this Hamiltonian to a body-fixed principal axes frame assumes a particularly simple form given by

$$H = T_{vib} + T_{rot} + V = \frac{1}{2}\sum_{\lambda\mu} B_\lambda \left|\dot{a}_{\lambda\mu}\right|^2 + \frac{1}{2}\sum_{K=1}^{3}\Im_k\, \omega_k^2 + \frac{1}{2}\sum_{\lambda\mu} C_\lambda \left|a_{\lambda\mu}\right|^2.$$

This equation is written in term of parameters $a_{\lambda\mu}$ defined in the body-fixed frame. The first and last terms represent the energies of a vibrator, and the second term corresponds to a rotator with $\Im_k\,(k = x, y, z)$ as the three components of the moment of inertia in the body-fixed frame. The pure vibrator Hamiltonian in the space-fixed frame becomes a vibrator plus a rotator Hamiltonian in the body-fixed frame.

Quadrupole motion $(\lambda = 2)$**:**

Consider only $\lambda = 2$ terms:

$$H = \frac{1}{2}B(\dot{\beta}^2 + \beta^2\dot{\gamma}^2) + \frac{1}{2}\sum_k \Im_k \omega_k^2 + \frac{1}{2}C\beta^2,$$

where β, γ parameters have been used, and

$$a_{20} = \beta\cos\gamma\ ,\ a_{22} = a_{2-2} = \frac{1}{\sqrt{2}}\beta\ Sin\gamma\ ,\ a_{21} = a_{2-1} = 0$$

$$\Im_k = 4B\beta^2 Sin^2\left(\gamma - k\frac{2\pi}{3}\right),$$

$$B = \frac{1}{2}\rho_0 R_0^5\,.$$

Quantization of this Hamiltonian leads to the Schrödinger equation:

$$\left[-\frac{\hbar^2}{2B}\left(\frac{1}{\beta^4}\frac{\partial}{\partial\beta}\beta^4\frac{\partial}{\partial\beta} + \frac{1}{\beta^2 Sin3\gamma}\frac{\partial}{\partial\gamma}Sin3\gamma\frac{\partial}{\partial\gamma}\right)\right.$$
$$\left. + \sum_k \frac{\hbar^2}{2\Im_k}R_k^2 + \frac{1}{2}C\beta^2\right]\psi(\beta,\gamma,\theta_1,\theta_2,\theta_3) = E\psi(\beta,\gamma,\theta_1,\theta_2,\theta_3).$$

which is separable in β- and γ-coordinates:

$$\Psi(\beta,\gamma,\theta_1,\theta_2,\theta_3) = f(\beta)\Phi(\gamma,\theta_1,\theta_2,\theta_3),$$

where $f(\beta)$ satisfies the β-equation:

$$\left(-\frac{\hbar^2}{2B}\frac{1}{\beta^4}\frac{d}{d\beta}\beta^4\frac{d}{d\beta} + \frac{1}{2}C\beta^2 + \frac{\Lambda\hbar^2}{2B}\frac{1}{\beta^2}\right)f(\beta) = Ef(\beta),$$

and $\Phi(\gamma, \theta_1, \theta_2, \theta_3)$ satisfies the rotor plus γ-motion equation:

$$\left(-\frac{1}{\sin 3\gamma}\frac{\partial}{\partial\gamma}Sin3\gamma\frac{\partial}{\partial\gamma} + \frac{1}{4}\sum_k \frac{R_k^2}{\sin^2\left(\gamma - k\frac{2\pi}{3}\right)}\right)\Phi(\gamma,\theta_1,\theta_2,\theta_3) = \Lambda\Phi(\gamma,\theta_1,\theta_2,\theta_3)\,.$$

If the nucleus is rigid for γ-vibration, only the rotational part is left in the rotor plus γ-motion equation, and we obtain:

$$\frac{1}{4}\sum \frac{R_k^2}{Sin^2\left(\gamma - k\frac{2\pi}{3}\right)}\Phi(\theta_1,\theta_2,\theta_3) = \Lambda\Phi(\theta_1\theta_2\theta_3).$$

The operators $R_k, (k \equiv x, y, z)$ are the components of the rotational angular momentum operator $\hat{R}$ along the body-fixed axes *x*, *y*, and *z*. Components of $\hat{R}$ along the space-fixed axes are donated by X, Y, Z, and

$$[R_X, R_Y] = iR_Z, ...etc$$

but

$$[R_x, R_y] = -iR_z, ...etc$$

Also, $\Phi(\theta_1\theta_2\theta_3)$ can be shown to be simply the function $D_{MK}^I(\theta_1\theta_2\theta_3)$, and these terms satisfy the eigenvalue equations:

$$\hat{R}^2 D_{MK}^I = I(I+1)D_{MK}^I,$$
$$R_Z D_{MK}^I = MD_{MK}^I,$$
$$R_z D_{MK}^I = KD_{MK}^I.$$

Spheroidal Shapes

When the ellipsoidal body has an axis of symmetry along one of the principal axes, a spheroid is obtained. Let the *z*-axis be the symmetry axis perpendicular to the *x*- and *y*-axis, and therefore *γ* = 0 and

$$\Im_x = \Im_y, \Im_z = 0,$$

as a consequence of the general rule that there cannot be any rotation about an axis of symmetry. The equation in $\hat{R}$ reduces to

.

$$\frac{1}{3}\left(R_x^2 + R_y^2\right)\Phi(\theta_1\ \theta_2\ \theta_3) = \frac{1}{3}\left(\hat{R}^2 - R^2\right)\Phi(\theta_1\ \theta_2\ \theta_3)$$
$$= \frac{1}{3}\left[I(I+1) - K^2\right]D_{MK}^I(\theta_1\ \theta_2\ \theta_3)$$

$\Im_x \neq \Im_y \neq \Im_z$ for a general ellipsoid, and the coefficients of R_x^2 and R_y^2 are not equal. We can write $R_x^2 = \frac{1}{4}(R_+ + R_-)^2$ and $R_y^2 = -\frac{1}{4}(R_+ - R_-)^2$, where $R_\pm = R_x \pm iR_y$, leading to terms of the type $R_+ R_+$, $R_- R_-$ and $(R_+ R_- + R_- R_+)$. The last operator leaves D_{MK}^I unchanged, while $R_+ R_+$ and $R_- R_-$ change D_{MK}^I to D_{MK-2}^I and D_{MK+2}^I, respectively. Therefore, the eigen functions, become a mixture of D_{MK}^I, with *K* differing by ± *2*.

The equation for rotor plus *γ*-motion can also be solved by using the D_{MK}^I functions, with eigen functions of the type:

$$\Phi^I{}_M(\gamma,\theta_1\ \theta_2\ \theta_3)=\sum_k g^I_K(\gamma)D^I_{MK}(\theta_1\ \theta_2\ \theta_3).$$

where K differ by ± *2*. This equation corresponds to rotor plus γ-motion and is difficult to solve because a chain of coupled differential equations are created.

Constraints on K-values

$\alpha_{2\mu}$ are the shape parameters in space-fixed frame, and define the shape uniquely. When we transform to the body-fixed axes and introduce the parameter $a_{2\mu}$ or *(β,γ) (θ₁ θ₂ θ₃)*, the labeling of the body-fixed frame becomes arbitrary. Body-fixed axes (which coincide with the principal axes of the body) can be chosen in many ways. Restricting to right-handed frames only, there are 24 different ways to choose the body-frame (Pal, 1982), and we obtain different $(\beta, \gamma, \theta_1, \theta_2, \theta_3)$ values for each such choice. However, any change of body-frame which does not change the values of α_μ should leave the wave function invariant, as ensured by considering the effect of the rotation operators R_1, R_2 and R_3 on the wave function (Fig. 6).

All 24 frames can be obtained by application of one or more of the three rotation operators:

$$R_1(0,\pi,0), R_2\left(0,0,\frac{\pi}{2}\right), R_3\left(\frac{\pi}{2},\frac{\pi}{2},\pi\right)$$

where $R(\theta_1,\theta_2,\theta_3)$ denotes an operator consisting of

$$R(\theta_1,\theta_2,\theta_3)=e^{-i\theta_1 J_z}e^{-i\theta_2 J_y}e^{-i\theta_3 J_z}.$$

A combination of these operators can give the 24 different sets of body-fixed axes, which give different $(\beta, \gamma, \theta_1, \theta_2, \theta_3)$ for the same values of a_μ. Therefore, we demand that the wave function remain invariant under these three operations. The three operators affect the functions as follows, while β remains unaffected in all cases.

(i) $R_1^y(0,\pi,0)$: $\gamma\to\gamma$, $\theta_1\to\theta_1$, $\theta_2\to\theta_2+\pi$, $\theta_3\to-\theta_3$

hence

$$\begin{aligned}&\sum_K g^I_K(\gamma)D^I_{MK}(\theta_1,\theta_2,\theta_3)\\&=\sum_{K'} g^I_{K'}(\gamma)D^I_{MK'}(\theta_1,\theta_2+\pi,-\theta_3)\\&=\sum_{K'} g^I_{K'}(\gamma)D^I_{M-K'}(\theta_1,\theta_2,\theta_3)(-1)^{I+K'}\end{aligned}$$

and equating the coefficients of D^I_{MK} on both sides,

$$g^I_K(\gamma)=g^I_{-K}(\gamma)(-1)^{I-K}$$

(ii) $R_2^z\left(0,0,\frac{\pi}{2}\right)$: $\gamma\to-\gamma$, $\theta_1\to\theta_1$, $\theta_2\to\theta_2$, $\theta_3\to\theta_3+\frac{\pi}{2}$

hence

$$\sum_K g_K^I(\gamma) D_{MK}^I(\theta_1,\theta_2,\theta_3)$$

$$= \sum_{K'} g_{K'}^I(\gamma) D_{MK'}^I\left(\theta_1,\theta_2,\theta_3 + \frac{\pi}{2}\right)$$

$$= \sum_{K'} g_{K'}^I(-\gamma) D_{MK'}^I(\theta_1,\theta_2,\theta_3) i^{K'}$$

and equating the coefficients

$$g_K^I(\gamma) = i^K g_K^I(-\gamma).$$

Using this relationship again to replace $g_K^I(-\gamma)$ gives

$$g_K^I(\gamma) = (-1)^K g_K^I(\gamma),$$

restricting K to even-integer values only. Combining the two equations from (i) and (ii), we obtain

$$g_K^I(\gamma) = (-1)^I g_{-K}^I(\gamma),$$

with K as even integers only.

(iii) $R_3\left(\frac{\pi}{2},\frac{\pi}{2},\pi\right): \gamma \to \gamma - \frac{4\pi}{3}$, $\theta_1 \to \theta_1 + \frac{\pi}{2}$, $\theta_2 \to \theta_2 + \frac{\pi}{2}$, $\theta_3 \to \theta_3 + \pi$

therefore

$$\sum_K g_K^I(\gamma) D_{MK}^I(\theta_1,\theta_2,\theta_3)$$

$$= \sum_{KK'} g_{K'}^I(\gamma - 120^0) D_{KK'}^I\left(\frac{\pi}{2},\frac{\pi}{2},\pi\right) D_{MK}^I(\theta_1,\theta_2,\theta_3)$$

and equating the coefficients gives

$$g_K^I(\gamma) = \sum_{K'} g_{K'}^I(\gamma - 120^0) D_{KK'}^I\left(\frac{\pi}{2},\frac{\pi}{2},\pi\right)$$

Incorporating the relationship from (ii), the wave function remains invariant if written as

$$\Phi^I{}_M(\gamma,\theta_1,\theta_2,\theta_3) = \sum_K g_K^I(\gamma)\left[D_{MK}^I + (-1)^I D_{M-K}^I\right],$$

with K restricted to even integers only.

Axial Symmetry – Symmetric Top

If γ-motion is frozen, $g_K^I(\gamma)$ becomes independent of γ, and K *(= Ω)* is a good quantum number for a spheroidal shape (Fig. 7). The summation on K disappears, and therefore:

$$\Phi_{MK}^I(\theta_1,\theta_2,\theta_3) = g_K^I\left[D_{MK}^I + (-1)^I D_{M-K}^I\right]$$

$$= \sqrt{\frac{2I+1}{16\pi^2}}\left[D_{MK}^I + (-1)^I D_{M-K}^I\right]$$

where the normalization condition has been used (remember that K is allowed to have even-integer values only).

Only even integer values of I are allowed for $K = 0$, or the wave function vanishes. Therefore,

$$\Phi_{MK=0}^I = \sqrt{\frac{2I+1}{8\pi^2}} D_{MK=0}^I$$

and only $K = 0$ is allowed in the case of spheroidal symmetry. Consider the action of $R_2(0,0,\phi)$ for rotation by an arbitrary angle ϕ about the z-axis, which is also the symmetry axis:

$$g_K^I(\gamma) = e^{iK\phi} g_K^I(\gamma) = e^{iK(\frac{\pi}{2}+\phi')} g_K^I(\gamma) \quad = e^{iK\phi'} g_K^I(-\gamma)$$

to give

$$g_K^I(\gamma) = e^{i2K\phi'} g_K^I(\gamma)$$

Since this relationship must be valid for any value of ϕ, only $K = 0$ applies.

Even-even Nuclei: *K = 0* Ground State Band, *β*-bands and *γ*-bands

When the axially-symmetric deformed nucleus acquires small oscillations in β and γ, the total energy E of the nucleus can be written as

$$E = \hbar\omega_\beta\left(N_\beta + \frac{5}{2}\right) + \hbar\omega_\gamma$$

$$\left(2n_\gamma + \frac{1}{2}K + 1\right) + \frac{\hbar^2}{2\Im}\left[I(I+1) - K^2\right]$$

where

$$\omega_\beta = \sqrt{\frac{C}{B}}, N_\beta = 2n_\beta + I - 1,$$

$$\omega_\gamma = \sqrt{\frac{C_\gamma}{B}}, N_\gamma = 2n_\gamma + \frac{1}{2}K.$$

The lowest lying band corresponds to no β-phonon ($N_\beta = 0$), and no γ-phonon ($N_\gamma = 0$, $n_\gamma = 0$, $K = 0$) excitation. Since $K = 0$ allows only even angular momentum states, we obtain $K = 0$,
$I = 0, 2, 4 \ldots$, all of even parity for the ground rotational band.

Another rotational band arises for $N_\beta = 0, N_\gamma = 1$ (one γ-phonon), i.e., $n_\gamma = 0, K = 2,$ and this $K = 2$ γ-band can have any integer $I = 2, 3, 4...$ etc.

$K = 0$ β-band arises for $N_\beta = 1, N_\gamma = 0$ and since $K = 0, I = 0, 2, 4$ ... and positive parity. Higher phonon excitations can be constructed by taking more than one β- or/and γ-phonons, and the various possible bands based on $\lambda = 2$ phonon excitations are shown in Fig. 8 (along with an example of these bands in Fig. 9). We also show an example of octupole phonon-excitation and a subsequent band.

Intrinsic Wave Function

The total wave function of a nucleus is most conveniently written as the product of an intrinsic and a rotational component. Odd-A and odd-odd nuclei require the intrinsic wave function which also contains the parity information.

Signature Quantum Number

An important consequence of introducing the intrinsic wave function is the emergence of signature quantum number for a spheroidal shape. Let z be the symmetry and quantization axis. As a consequence of the spheroidal shape, the nucleus has a reflection symmetry in the x-y plane. The total wave-function

$$\Psi^I_{MK} = \chi_\Omega D^I_{MK}$$

must remain invariant under a transformation $R_x(\pi)$ acting on the intrinsic coordinates, and $R_e(\pi)$ acting on the collective coordinates such that

$$R_x(\pi) = R_e(\pi) .$$

For axial symmetry, $K = \Omega$ and χ_Ω becomes χ_K, where $\chi_K = \sum_J C_J \chi_{JK}$.

The intrinsic state for $K = 0$ will re-evolve when operated twice by $R_x(\pi)$, and therefore:

$$R_x(\pi)\chi_{K=0} = r\chi_{K=0},$$
$$R_x^2(\pi)\chi_{K=0} = r^2\chi_{K=0},$$

so that

$$r^2 = 1 \quad \text{and} \quad r = \pm 1 .$$

One may also write these expressions as

$$R_x(\pi)\chi_{K=0} = e^{-i\pi J_x}\chi_{K=0} = e^{-i\pi\alpha}\chi_{K=0}$$

which leads to $\alpha = 0$ and $\alpha = 1$ corresponding to $r = +1$ and $r = -1$, respectively. Both α and r are referred to as the signature quantum number.

$$R_e(\pi)D^I_{MK=0} = e^{-i\pi I}Y^I_M = (-1)^I Y^I_M .$$

and $r = (-1)^I$.

The $K = 0$ rotational band is divided into two domains:

$$\alpha = 0\,,\; r = +1, \quad I = 0, 2, 4..........$$
$$\alpha = 1\,,\; r = -1, \quad I = 1, 3, 5.............$$

An example of *α = 0*, *K = 0* band is shown in Fig. 9; *K = 0* band in an odd-odd nucleus has both *α = 0* and *α = 1* signatures.

For $K \neq 0$, the intrinsic states are two-fold degenerate as a consequence of the invariance with respect to 180^0 rotation about the *x* (or *y*) axis. This operation has the same effect as the time reversal operator in which the time reversed state is denoted by $\overline{K}$ and has a negative eigenvalue of j_z, so that

$$\chi_{\overline{K}} = R_x^{-1} \chi_K \,.$$

Since $\chi_K = \sum_j C_j \chi_{jK}$, we have

$$\chi_{\overline{K}} = e^{i\pi j_x} . \chi_K = \sum_j (-1)^{j+K} . \chi_{j-K}$$

The effect of $R_e(\pi)$ on D^I_{MK} is given by

$$R_e D^I_{MK} = e^{-i\pi I} D^I_{MK} = (-1)^{I+K} D^I_{M-K} \,.$$

A rotationally-invariant wave function can be constructed:

$$\Psi^I_{MK} = \frac{1}{\sqrt{2}}\left(1 + R^{-1}{}_x R_e\right)\left(\frac{2I+1}{8\pi^2}\right)^{\frac{1}{2}} \chi_K D^I_{MK}$$
$$= \left(\frac{2I+1}{16\pi^2}\right)^{\frac{1}{2}}\left[\chi_K D^I_{MK} + (-1)^{I+K} \chi_{\overline{K}} D^I_{M-K}\right]$$

For odd-A nuclei:

$$R_x^2 \chi_K = (-1)^{2j} \chi_{K,}$$

where *2j* is odd.

$$R_x = e^{-i\pi j_x} = e^{-i\pi\alpha}$$

implies that $\alpha = \frac{1}{2}$ for $r = -i$, and $\alpha = -\frac{1}{2}$ for $r = +i$. Similarly,

$$R_e = e^{-i\pi I}$$

implies that $I = \frac{1}{2}$ for $r_e = -i$, and $I = \frac{3}{2}$ for $r_e = +i$.

Also $R_x^{-1} R_e = 1$ requires that

$$I = \frac{1}{2}, \frac{5}{2}, \frac{9}{2}.........., \text{ for } \alpha = \frac{1}{2}, \;\; r = -i,$$

and

$$I = \frac{3}{2}, \frac{7}{2}, \frac{11}{2}..........., \text{ for } \alpha = -\frac{1}{2}, \;\; r = +i \,.$$

Generally:

$$I = (\alpha + even\ number).$$

The favoured signature levels decreases in energy, whereas the unfavoured signature levels are elevated corresponding to the situation shown in the first row of Table I. An example of bands with $\alpha = 1/2$ and $\alpha = -1/2$ signatures is shown in Fig.10, based on $i_{13/2}$ orbital with $K = ½$ in which the $\langle ½ | j_+ | -½ \rangle$ matrix element (defines the decoupling parameter) plays an important role in lowering the energies of the favoured signature levels (decoupling effect). The decoupling effect is so strong that the levels *13/2, 17/2 ...* are the lowest, although *K* is very small, leading to the well known observation of decoupled bands. When the signature is no longer a good quantum number (i.e., R_x (π) is not a conserving operation), we get only one sequence of levels such as $I = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$......... etc., which corresponds to the second row of Table I.

At higher rotational frequencies, the Coriolis force becomes important and leads to significant *K*-mixing. Therefore, the time reversal as well as the full D_2-symmetry are broken. The only good quantum numbers that survive at high spins are signature α and parity π.

Parity

If the intrinsic Hamiltonian preserves parity, the corresponding wave function has fixed parity. Since parity operator *P* commutes with j_z:

$$P\chi_k = \pi\chi_k,\ \ \pi = \pm 1,$$

and all states in a given band have the same parity π. $K = 0$ bands can occur with π and α quantum numbers independent of each other; and therefore $K=0$ bands may have

$$I = 0^+, 2^+, 4^+ ...., \alpha = 0,$$

or $I = 0^-, 2^-, 4^- ...., \alpha = 0,$ and

$$I = 1^-, 3^-, 5^- ...., \ \alpha = 1,$$

or $I = 1^+, 3^+, 5^+ ...., \alpha = 1.$

Ground rotational bands of even-even nuclei are known to exhibit

$$I = 0^+, 2^+, 4^+ ...., \alpha = 0 \text{ band,}$$

and octupole vibrational bands of even-even nuclei display

$$I = 1^-, 3^-, 5^- ...., \ \alpha = 1 \text{ band.}$$

Parity and Time-reversal Violating Terms

Under the parity operation $\hat{P}$, $\vec{r} \rightarrow -\vec{r}$ and $\vec{p} \rightarrow -\vec{p}$, but spin $\vec{s}$ and time *t* remain unchanged. A Hamiltonian that contains terms such as $\vec{r}.\vec{s}$ or $\vec{s}.\vec{p}$ violates parity. Similarly, under the time-reversal operation $\hat{T}$, $t \rightarrow -t$, $\vec{p} \rightarrow -\vec{p}$ and $\vec{s} \rightarrow -\vec{s}$, but $\vec{r}$ remain unchanged. When present in the Hamiltonian, terms like $\vec{r}.\vec{p}$ and $\vec{r}.\vec{s}$ violate time-reversal invariance, leading to a doublet structure in the spectrum as both $\hat{P}$ and $\hat{T}$ correspond to two-fold discrete symmetry. A connection between rotational motion and $\widehat{P}$ and $\widehat{T}$-violating Hamiltonian occurs if the system, while violating $\widehat{R}_x(\pi)$ symmetry, preserves the $\widehat{R}_x\widehat{P}$ or $\widehat{R}_x\widehat{T}$ symmetry (see Table I).

Ellipsoid with D_2 Symmetry – Asymmetric Top

A general ellipsoid does not have axial symmetry, but has full D_2-symmetry, i.e., the system is invariant with respect to the three rotations by 180^0 about each of the three principal axes (tri-axial shape). The nucleus has a finite γ-deformation different from 0^0 or multiples of $2\pi/3$. Even if the γ-motion is frozen, K is not a good quantum number, and the wave function may be of the form:

$$\Phi^I_M(\gamma,\theta_1,\theta_2,\theta_3) = \sum_K g^I_K \left[D^I_{MK} + (-1)^I D^I_{M-K}\right].$$

Since K is allowed to have only even-integer values, values $K = 2, 4$ …… can be adopted; $K = 0$ is not allowed as axial symmetry has been lost. Parity and signature are still good quantum numbers as $P = 1$ and $R_x(\pi) = 1$. Besides these two operations, $R_y(\pi)\ T$ is also conserved (assuming rotation about the x-axis, which is also the long axis of the ellipsoid). A typical rotational band may have I = 2, 4, 6 ……, corresponding to the first row of Table I. This situation is shown in the upper panel of Fig. 11.

Odd-Multipole Shapes: Simplex Quantum Number

An odd-multipole shape such as Y_{30} (octupole deformation) has an axial symmetry, say about the long axis, violating the $\hat{R}_x(\pi)$ and $\hat{P}$ symmetry, but preserving $\hat{R}_x\hat{P}$. The reflection symmetry is broken and two degenerate states with identical shapes arise, corresponding to the two minima in the octupole deformation energy (Fig. 12), i.e., 9th row of Table I. Operation $\hat{R}_x\hat{P}$ corresponds to a reflection in a plane containing the symmetry axis, denoted by

$$\hat{S} = \hat{P}\hat{R}_x^{-1},$$

where $\hat{S}$ acts on the intrinsic variables.

$K = 0$ band: intrinsic states with $K = 0$ are eigenstates of $\hat{S}$ as well as $\hat{T}$, in which

$$\hat{S}\chi_{K=0} = s\chi_{K=0} = e^{-i\sigma\pi}\chi_{K=0}.$$

Since $\hat{P} = \hat{S}\hat{R}_x$ and $\hat{R}_x D^I_{MK=0} = (-1)^I D^I_{MK=0}$, we obtain

$$\pi = s(-1)^I,$$

where π is the eigenvalue of $\hat{P}$. Hence, the $K = 0$ band can be classified as

$$I^\pi = 0^+, 1^-, 2^+, 3^- ...., s = +1,$$

$$\text{or } I^\pi = 0^-, 1^+, 2^-, 3^+ ...., s = -1.$$

For $K \neq 0$, intrinsic states have a two-fold degeneracy with respect to $\hat{T}$ (Kramer's degeneracy), and the band is classified as

$$I = \frac{1}{2}^-, \frac{3}{2}^+, \frac{5}{2}^- ...., s = -i,$$

$$\text{or } I = \frac{1}{2}^{+}, \frac{3}{2}^{-}, \frac{5}{2}^{+} \ldots\ldots\ldots\ldots\ldots, s = +i\,,$$

where only levels with $I \geq K$ occur. Since $\hat{S}\chi_K = \chi_{\bar{K}}$, the positive and negative parity states with the same spin are degenerate, giving rise to the phenomenon of parity doublets.

Examples of Octupole Deformed Nuclei

Shell effects play a major role in stabilizing a given configuration towards a particular nuclear shape. Nuclei lying in a narrow range beyond ^{208}Pb and to a lesser extent the nuclei in the neutron-excess light rare-earths have been found to be prone to octupole deformation of the Y_{30} type. As shown in Fig. 13, appropriate orbitals with $\Delta l = 3$ are observed to be very close together and near the Fermi energy for nuclei just beyond ^{208}Pb. For example, $1j_{15/2}$ and $2g_{9/2}$ neutron orbitals are 1.42 MeV apart in ^{209}Pb, while $1i_{13/2}$ and $2f_{7/2}$ proton orbitals are 1.70 MeV apart in ^{209}Bi. The corresponding orbitals in the rare-earth are $1i_{13/2}$ and $2f_{7/2}$ neutron orbitals and $1h_{11/2}$ and $2d_{5/2}$ proton orbitals, and for the lighter nuclei the $1g_{9/2}$ and $2p_{3/2}$ orbitals come close together near particle number 34. An early review of the experimental systematics that support the octupole deformation appears in Jain et al. (1990), and a detailed account of theory and experiment related to the octupole shapes can be found in Butler and Nazarewicz (1996).

As noted earlier, parity doublets arise of the type $I^{\pi} = 0^{\pm}, 1^{\pm}, 2^{\pm}\ldots\ldots$ in even-even, and $I^{\pi} = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}, \frac{5}{2}^{\pm}\ldots.$ in odd-A nuclei. These parity doublet (PD) bands split into two, if the barrier separating the two octupole minima has a finite height. Due to tunneling between the two mirror octupole shapes, the two bands of opposite parity are displaced in energy with respect to each other, and the even spins are energetically favoured (Fig. 14). A similar situation exists for odd-A nuclei, that is also shown in Fig. 14. Consider *K = 1/2* bands in which the rotational band is further modified by the octupole decoupling parameter $a^{*} = a.\, p$, so that

$$E = E_0 + A\left[I(I+1) + a^{*}(-1)^{I+\frac{1}{2}}(I+\frac{1}{2}) \right],$$

and obviously $a^{*}(p=+1) = -a^{*}(p=-1)$. Thus, the decoupling parameters for *K = 1/2* bands have opposite sign, but nearly same absolute value. The possibility of tunneling along with octupole decoupling further complicates the energies of the *K = 1/2* band as shown in Fig. 14.

An example of a spectrum where PD bands have been observed is given in Fig. 15 (level scheme of ^{225}Ra taken from Gasparo et al. (2000)). The first interpretation of ^{225}Ra in terms of octupole deformation was provided by Sheline et al. (1989), and the experimental studies of Gasparo et al. (2000) further confirm this interpretation in which 5 PD bands can be identified in the observed spectrum. Each pair of PD bands has been assigned a labelling $K(\langle s_z \rangle, \langle \pi \rangle)$, and for *K = 1/2* bands $\langle -j_{+} \rangle$, the octupole decoupling parameter. Value of $\langle \hat{\pi} \rangle$ indicates the degree of parity mixing in the single particle states.

Density Distribution – Two Planes of Symmetry

Axial-symmetry is lost when shapes like $Y_{3\mu}$, $\mu \neq 0$ are considered. The density distribution has only two independent planes of symmetry for μ even, and rotation is possible about the long axis. As well as $R_x(\pi) = 1$, $R_y(\pi)T = P$, and parity doublets of even or odd angular momenta arise. Therefore, we expect a level pattern such as $I = 2^{\pm}, 4^{\pm}$.... etc., or $I = 1^{\pm}, 3^{\pm}, 5^{\pm}$.........etc.
(row 12 in Table I, and the top panel of Fig. 16).

If the axis of rotation is perpendicular to one of the symmetry planes and the rotation axis is denoted as the *x*-axis, we have $\hat{R}_x(\pi) = \hat{P}$ and $\hat{R}_y(\pi)T = \hat{P}$ in which signature is not a good quantum number. A pair of parity doublet bands is obtained such as for axial symmetry: $I = 4^+, 5^-, 6^+$........ and $I = 4^-, 5^+, 6^-$........... (as given in row 13 of Table I). This situation is also shown in the middle panel of Fig. 16, and is discussed below as tetrahedral symmetry.

Density Distribution - Only One Plane of Symmetry

Further symmetry reductions occur if only one plane of symmetry is supported by the nuclear shape; under such circumstances one may also have odd μ components. Fig. 16 depicts such a shape in which rotation is possible along the long axis as well as any one of the short axes. Signature is not a good quantum number in either case, and both even and odd spins will be found in the rotational sequence. Parity is also not conserved, and therefore both parities will occur. When rotation is about the long axis, $\hat{R}_y(\pi)T = \hat{P}$ and four distinct situations can be obtained by the application of $\hat{R}_x(\pi)$ and $\hat{P}$. A sequence such as $I^{\pi} = 4^{\pm}, 5^{\pm}, 6^{\pm}$......... is obtained that represents the situation shown as row 12 of Table I, and is depicted in the top panel of Fig. 17. However, when rotation is about one of the short axes, $\hat{R}_x(\pi) = \hat{P}$, four distinct situations occur through the application of $\hat{R}_x(\pi)$ and $\hat{R}_y(\pi)T$, with the derivation of two nearly-degenerate sequences such as $I^{\pi} = (8^+)^2, (9^-)^2, (10^+)^2$........ The two $\Delta I = 1$ degenerate sequences with alternating parity represent bands that are chiral partners (one left-handed and the other right handed), as defined by row 11 of Table I and in the bottom panel of Fig. 17.

Tetrahedral and Triangle Symmetries in Nuclei

As suggested by Li and Dudek (1994), there is a possibility of observing a four-fold degeneracy in the level patterns of a number of $N \sim 136$ isotones. This symmetry arises as a consequence of the $\lambda = 3, \mu \neq 0$ components in the nuclear shape (see preceeding sections). A tetrahedral symmetry is expected in particular to break both the spherical symmetry and the symmetry by inversion. More specifically, a deformation of $Y_{32}(\theta, \phi)$ is related to the T_d^D symmetry group because of two 2-dimensional and one 4-dimensional irreducible representations. Therefore, three families of multiplets exist: two are doubly degenerate and one is quadruply degenerate.

Theoretical spectra of single particle states as a function of the deformation parameter a_{32} (coefficient of the Y_{32} term) reveal strongly increasing gaps at $Z = 32$, $\Delta E > 2MeV$, at $Z = 40$ with $\Delta E \approx 3MeV$, and a huge gap at $Z = 56, 58$ with $\Delta E \approx 4MeV$ (Fig. 18). Calculations reveal strong tetrahedral-symmetry effects at N, Z = 16, 20, 32, 40, 56-58, 70, 90-94 for both neutrons/protons, and 136/142 for neutrons only. These minima in tetrahedral shapes coincide with oblate and/or prolate minima in energy. A ten-dimensional minimization in energy for $\beta, \gamma, a_{3\mu}(\mu = 0, 1, 2, 3)$, and $a_{4\mu}(\mu = 0, 1, 2, 3, 4)$ shapes leads to tetrahedral equilibrium shapes of $a_{32} = 0.13, 0.13, 0.15$ and 0.11 for ${}^{80}_{40}Zr_{40}$, ${}^{108}_{40}Zr_{68}$, ${}^{160}_{70}Yb_{40}$ and ${}^{242}_{100}Fm_{142}$, respectively. The tetrahedral nuclei also obey the simplex symmetry and lead to parity-doublet bands, but with one important difference: since these nuclei will not have any significant dipole moment, typical E1 transitions of axial octupole nuclei will be absent. We compare the rotational spectrum of an axial-octupole nucleus with a tetrahedral rotor in Fig. 19. A pear-shaped octupole nucleus has considerable dipole moment and hence strong E1 and E2 transitions. On the other hand, a tetrahedral "pyramid" shape rotor with some quadrupole shape has zero dipole moment, and the lowest multipole transitions will be pure E2 type. However, only E3 transitions will be seen in the ideal case of a pure tetrahedral rotor.

Recent calculations of Yamagami et al (2000) suggest the possibility of exotic shapes that break the reflection and axial symmetries in proton rich $N = Z$ nuclei: ${}^{64}Ge$, ${}^{68}Se$, ${}^{72}Kr$, ${}^{76}Sr$, ${}^{80}Zr$ and ${}^{84}Mo$. In particular, the oblate ground state of ${}^{68}Se$ is very soft against Y_{33} triangular deformation, and the low-lying spherical minimum co-existing with the prolate ground state in ${}^{80}Zr$ is extremely soft against the Y_{32} tetrahedral deformation. The Y_{33} triangular deformation has only one plane of symmetry and a rotational spectrum that differs significantly from the Y_{32} tetrahedral shape. There are no known examples of Y_{32} and Y_{33} symmetries so far, although their experimental discovery is a distinct possibility.

Rotation About an Axis Other than the Principal Axis - Tilted Axis Cranking

So far we have considered situations where rotation is always about one of the principal axes of the body. Riemann had pointed out the possibility of having ellipsoidal shapes of equilibrium when the vorticity of internal motion of a non-rigid system leads to uniform rotation about an axis different from the principal axes of the density distribution. Nuclear configurations can occur that support rotation about an axis lying in one of the principal planes (planar-tilted axis cranking), or rotation about an axis lying out of the three principal planes (aplanar-tilted axis cranking).

Consider the effect of planar- and aplanar-tilted axis of rotation for a tri-axial shape. Parity P and $\hat{R}_y(\pi)T$ are conserved for rotation about an axis lying in one of the principal planes. Signature is not a good quantum number; and therefore all spins will be seen with the same parity (e.g., a sequence like $I^{\pi} = 4^{+}, 5^{+}, 6^{+}......$, corresponding to row 2 of Table I, as shown in the middle panel of Fig. 11).

A further doubling of states occurs if the axis of rotation is out of all the principal planes (aplanar TAC), in which only parity is conserved. Four distinct situations are obtained by the operation of $R_x(\pi)$ and $R_y(\pi)T$ to give a rotational sequence of the type $I^{\pi} = (4^{+})^2, (5^{+})^2, (6^{+})^2......$, where each spin occurs twice and is almost degenerate. This situation is defined as row 3 of Table I, and is depicted in the bottom panel of Fig 11.

Consider odd-multipole shapes such as octupole shape in which planar TAC gives rise to a situation, where $R_y(\pi)T = P$. Parity is no longer an invariant operation, and we obtain four distinct situations by the application of $R_x(\pi)$ and P. Two nearly degenerate rotational sequences emerge of $I^{\pi} = 4^{\pm}, 5^{\pm}, 6^{\pm}......$ (identical to the situation specified in row 13 of Table I, and shown in the bottom panel of Fig. 16).

Magnetic Rotation – Magnetic Top

Recent studies have shown that the isotropy of the mean field can be broken in a way other than through an anisotropic charge density distribution. The new kind of anisotropy arises from the net magnetic dipole moment instead of net electric quadrupole moment. Such a situation arises when a higher-lying high-j neutron particle (hole) combines with a high-j proton hole (neutron) at right angles to each other. Therefore, the resultant angular momentum about which the nucleus appears to rotate makes an angle with the principal axes (Fig. 20). Magnetic effects of current anisotropy dominate when the deformation is small. As shown in Fig. 20, a net magnetic dipole moment is generated, and implies current anisotropy. Higher angular momentum states are generated by the closing of the neutron and the proton blades as in a pair of shears, hence the term "shears mechanism" (Frauendorf, 1993). As a consequence, we obtain a "rotation" band, $R_x(\pi)$ symmetry is broken and signature is no longer a good quantum number. A $\Delta I = 1$ band is formed as shown in the example of ^{134}Ce (Fig. 21); consecutive levels of band B5 in ^{134}Ce are connected by strong M1 transitions, with the M1 intensity decreasing as the shears close (Fig. 22) as a result of a decrease in the dipole moment with increasing spin. The first example of MR band would appear to be that of ^{83}Kr, as reported recently by Malik et al., (2004), although a large number of such cases have been discovered that are spread within the A = 80, 110, 130, 190 mass regions (Amita et al., 2000).

Chiral Bands

An aplanar tilt is possible in which the axis of rotation does not coincide with any of the three principal axes, nor lie in any of the principal planes. Such a situation is best visualized in a triaxial odd-odd nucleus. If the configuration is such that the odd-proton alignment is along the short axis, the odd-neutron alignment is along the long axis, and the rotational contribution is along the intermediate axis, we obtain three angular momenta perpendicular to each other and the resultant angular momentum acquires an aplanar tilt. Note that the rotation has been taken along the intermediate axis because the moment of inertia about this axis is maximum and the rotational energy is minimum. While parity is still conserved, such an arrangement breaks the $R_y(\pi)T$ symmetry. The two situations shown in the upper part of this panel have a right-handed sense of rotation; while on the other hand, the two situations shown in the lower part have a left-handed sense of rotation. This breakage of symmetry doubles the number of levels, and we should observe two pairs of identical $\Delta I = 1$ bands with the same parity that are termed chiral bands.

The bands in real nuclei will be shifted in energy because of tunneling between the right-handed and left-handed states. However, the existence of triaxiality and an optimum quadrupole deformation play an important role in breaking chiral symmetry. Dimitrov et al. (2000) presented the first results of an aplanar TAC calculation which support the existence of chiral bands in ^{134}Pr, although recent observations of a chiral pair of bands in an odd-A nucleus ^{135}Nd (Zhu et al. (2003)) have confirmed that chiral rotation is a purely geometric phenomenon and not confined to odd-odd systems alone. The level scheme of ^{135}Nd is shown in Fig. 23, where the A and B bands become chiral partners at higher rotational frequencies. The triaxial shapes shown in the upper part of the figure are labeled by l, s and i-axes which stand for long, short and intermediate axes, respectively. Expressed in the order s-i-l, these axes form a "right-handed" system in the ellipsoid on the left and a "left-handed" system in the ellipsoid on the right to give a chiral doublet. Bands A and B are shown in the level scheme, and come very close to and interlaced with each other at a rotational frequency of about 0.45 MeV. Since the two bands are based on the same configuration $\left[\pi h_{11/2}^{2}, \nu h_{11/2}^{-1}\right]$, there are a significant number of linking transitions. Fig. 24 shows a pair of such bands in ^{135}Ce, which is an odd-A nucleus (Lakshmi et al, unpublished). We observe a two-way connection between the pair of bands for the first time, confirming that the pair of bands have the same configuration. These studies also indicate that the chiral bands are purely a geometrical phenomenon arising out of the special situation of the three vectors.

Conclusions

The basics of geometrical symmetries and their consequences in nuclei have been discussed. Connections between the various shapes and band structures were emphasized, and unusual shapes were also considered. Recent discoveries such as the magnetic rotation and chiral rotation were noted, which involve rotation about a tilted axis rather than the usual principal axis. Efforts have been made to develop a simple guide that will be useful to experimentalists.

Acknowledgements

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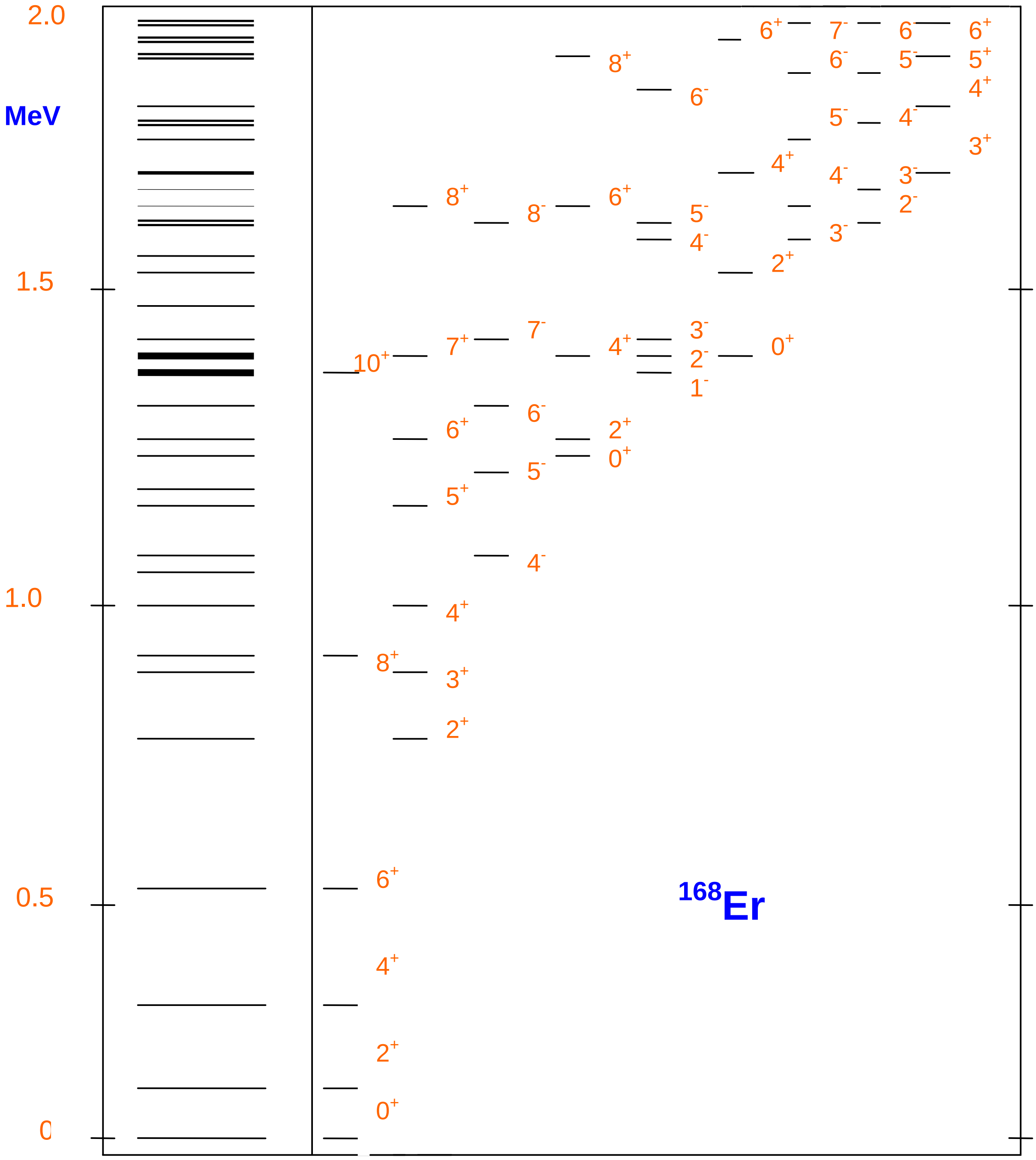

Fig. 1: Level energies shown in the left-hand column exhibit more systematic patterns when grouped into bands.

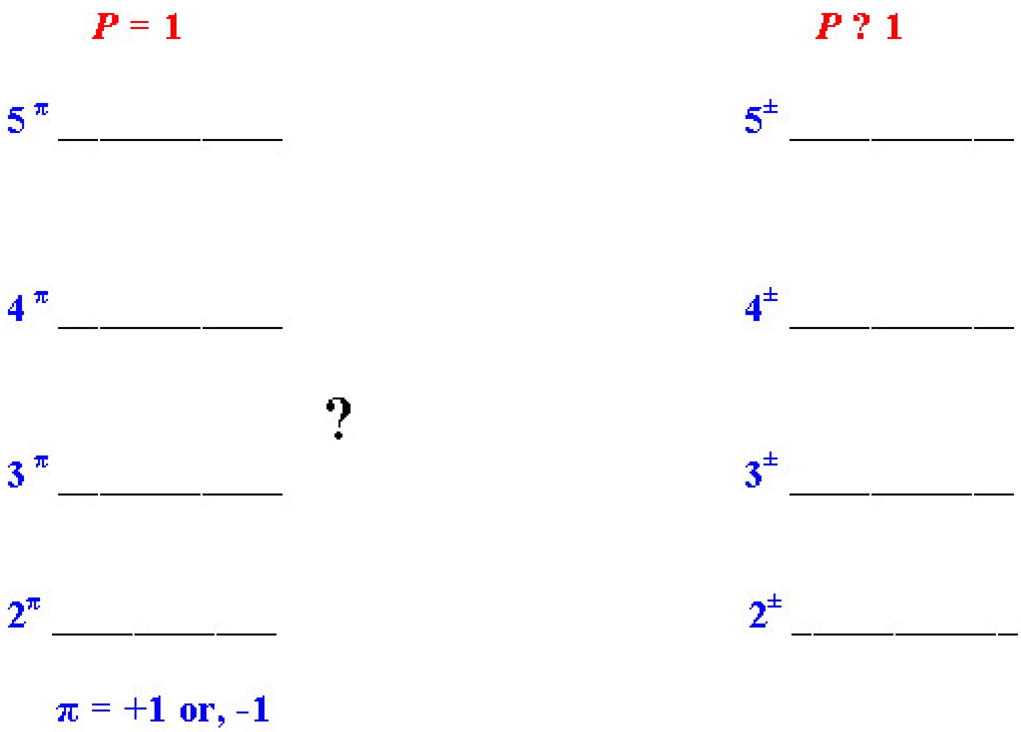

Fig. 2: As deformation increases, the shell model levels evolve into Nilsson model levels, signifying the loss of spherical symmetry.

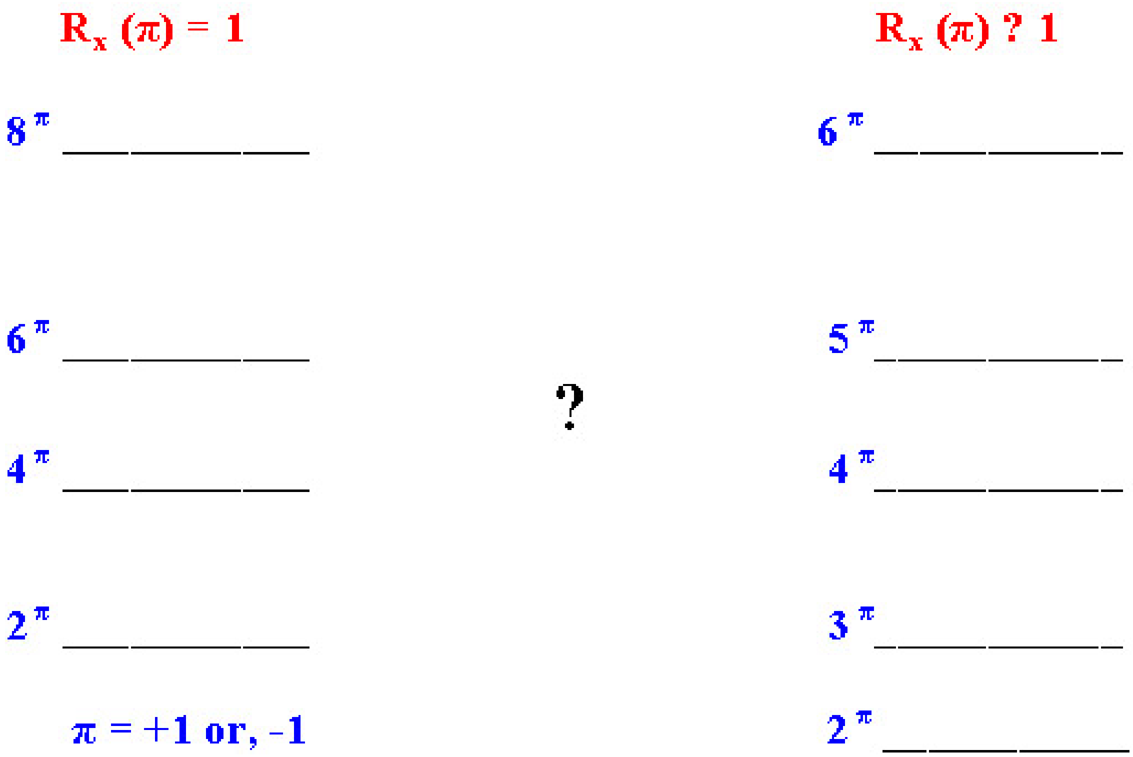

Fig. 3(a): Effect of symmetry breaking due to parity.

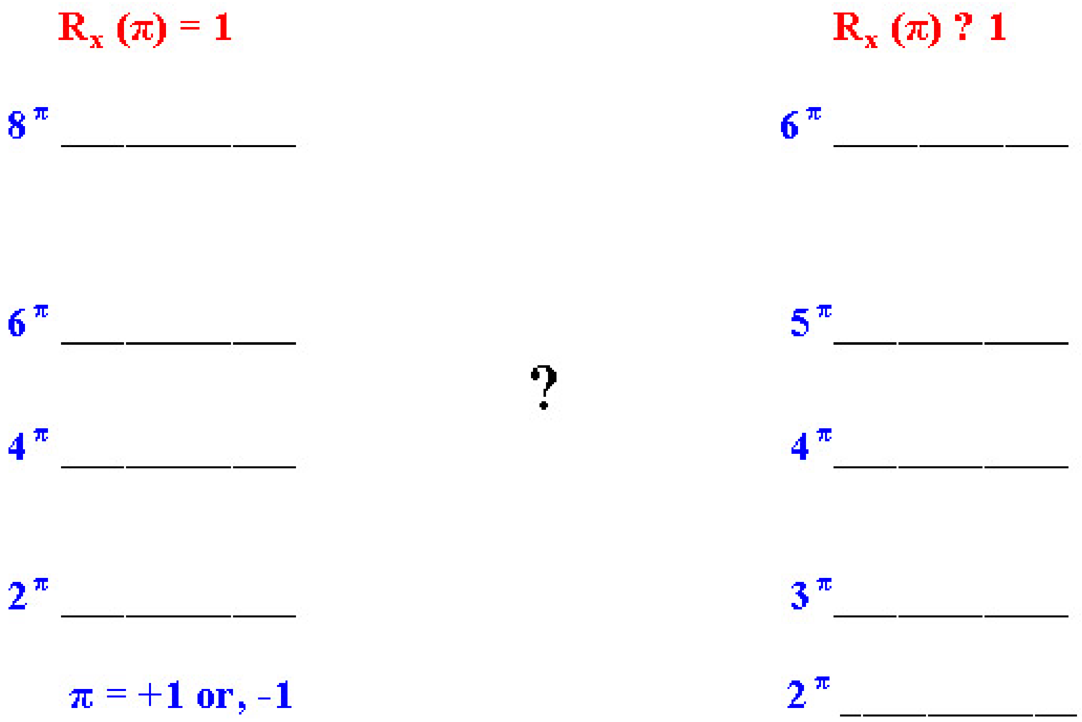

Fig. 3(b): Effect of symmetry breaking due to rotation by π about the *x*-axis $R_x(\pi)$ on a band (signature symmetry breaking).

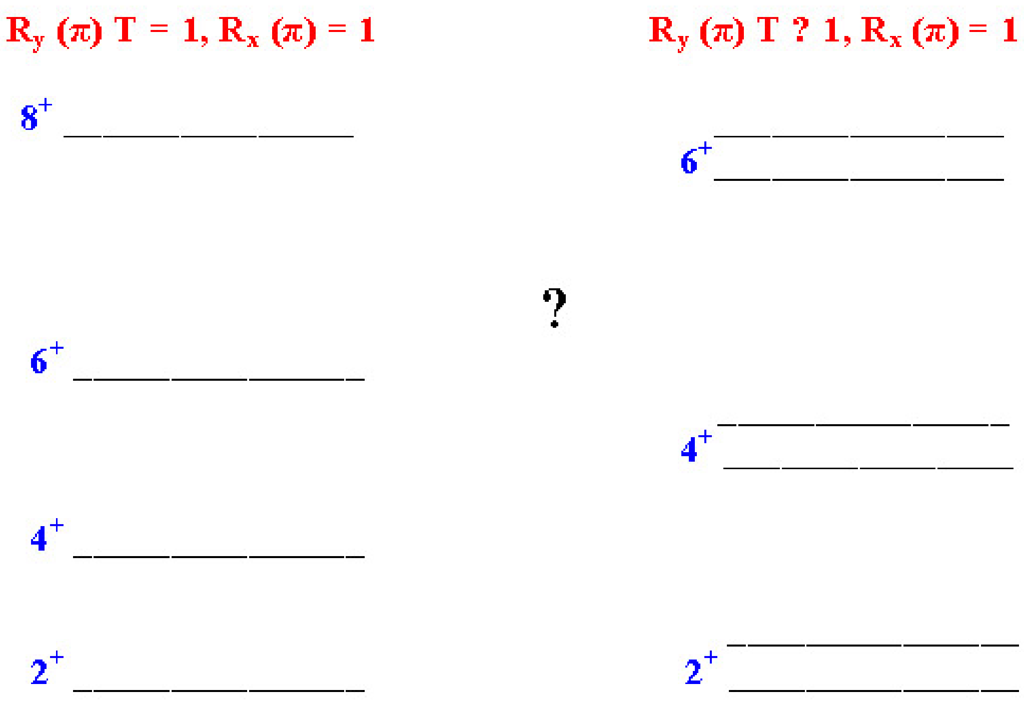

Fig. 3(c-1): Effect of symmetry breaking of $R_y(\pi)T$ on a band with a broken signature; *T* is the time reversal operator.

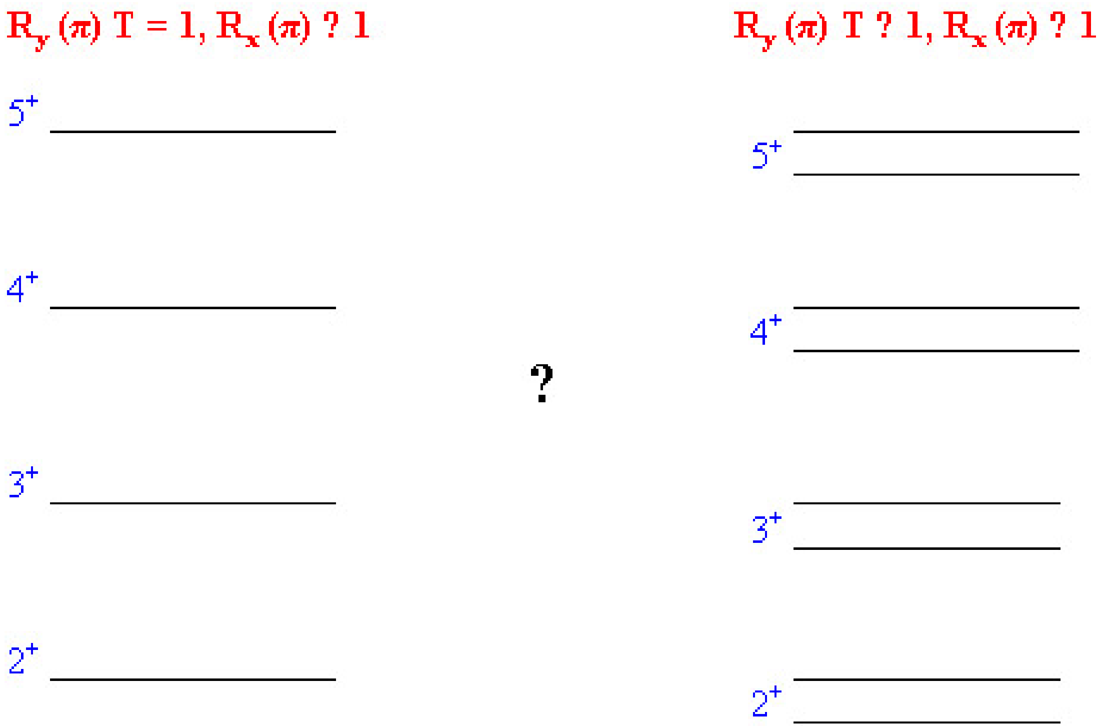

Fig. 3(c-2): Same as Fig 3(c-1), but for a band with a good signature.

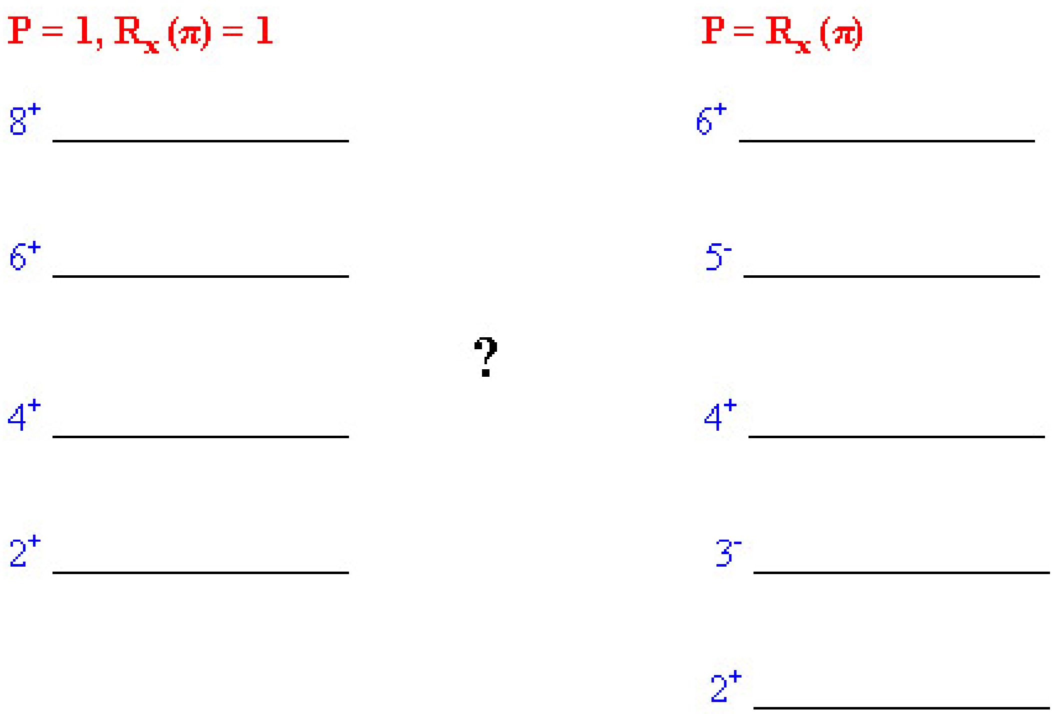

Fig. 3(d): Effect on a band when both parity P and signature $R_x(\pi)$ are broken, but $P = R_x(\pi)$.

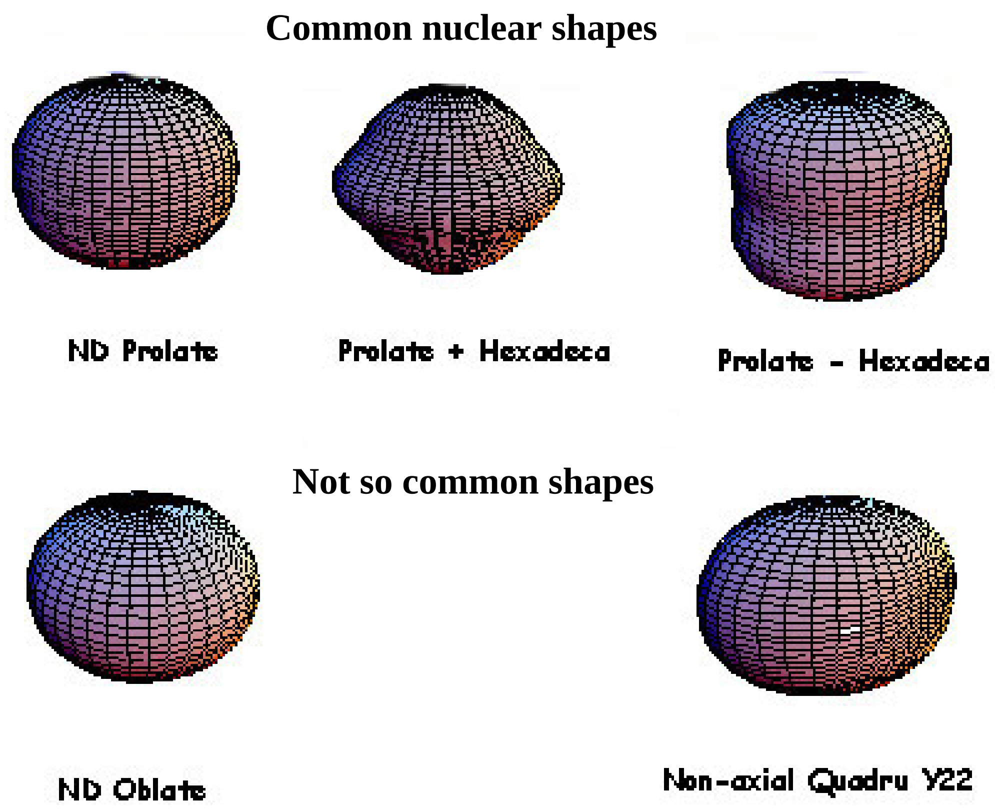

Fig. 4: Nuclear shapes with axial symmetry.

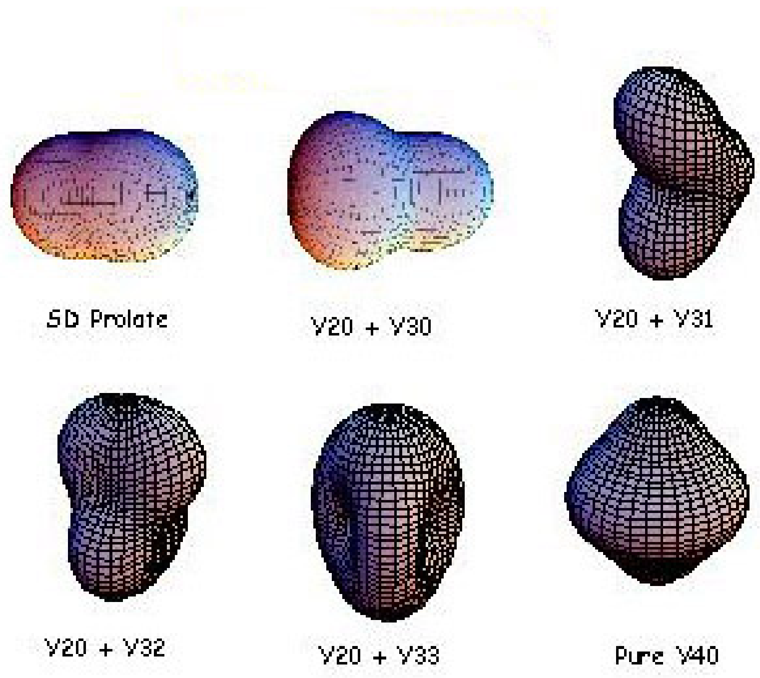

Fig. 5: Exotic nuclear shapes.

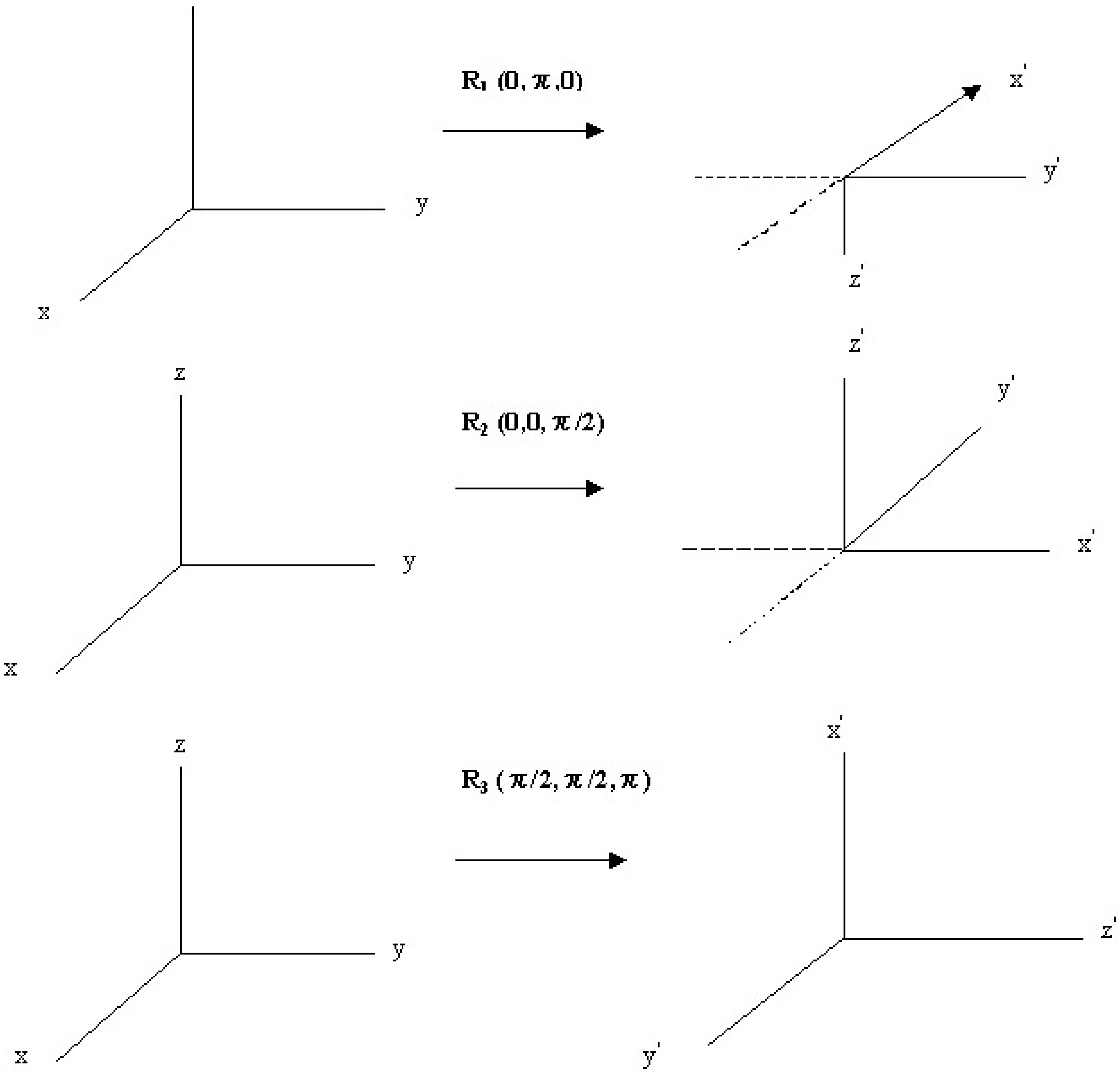

Fig. 6: Effect of the three rotation operators R_1, R_2, R_3 on a frame of reference.

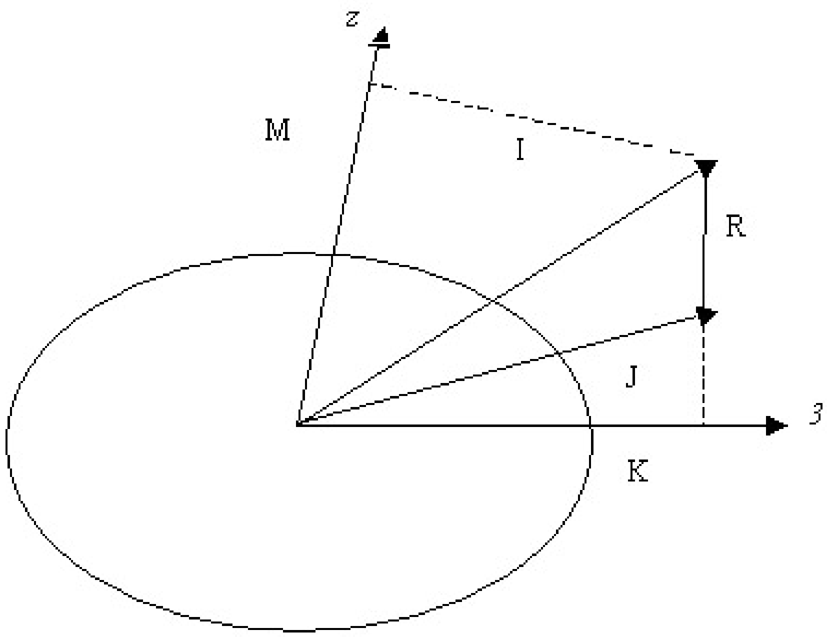

Fig. 7: Projections of the total angular momentum I on the space-fixed z-axis and the body- fixed 3-axis.

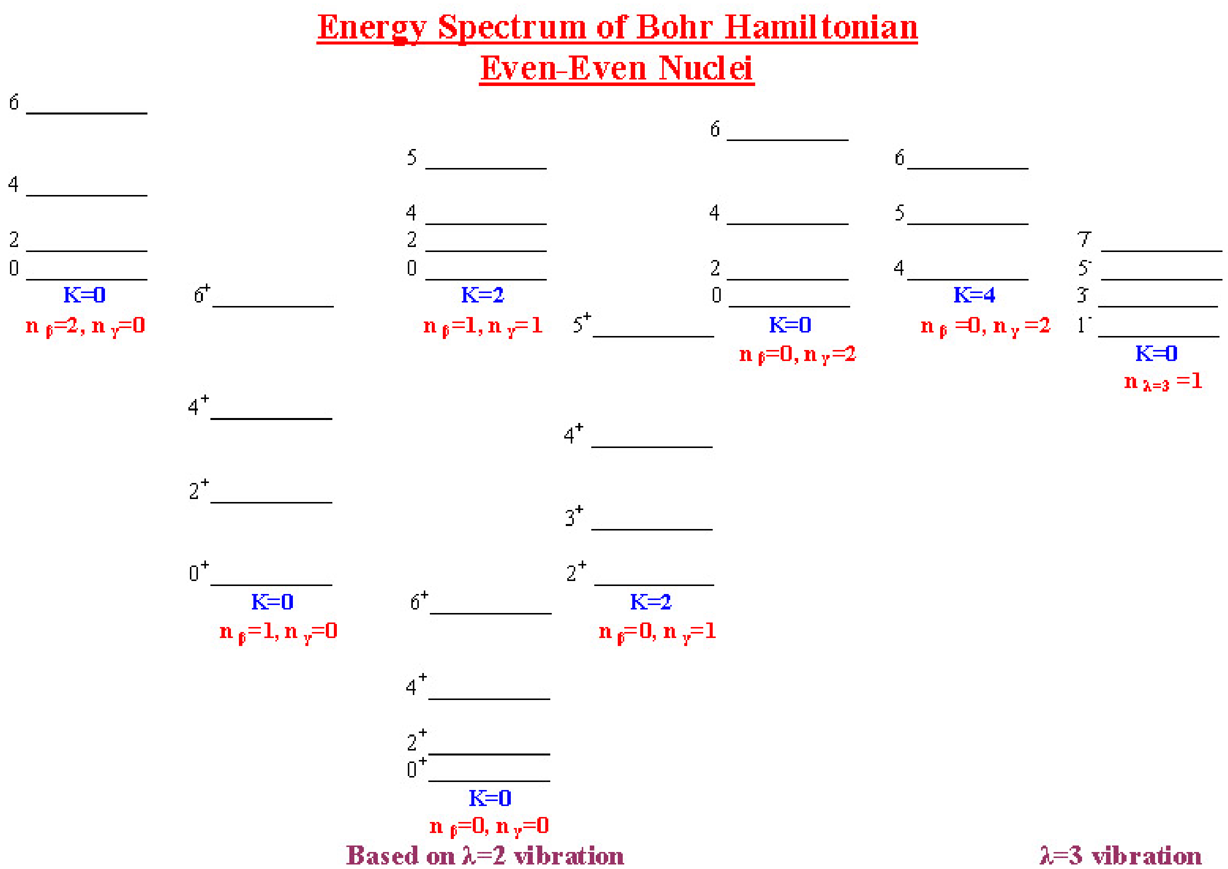

Fig. 8: Band structure of an even-even nucleus resulting from the quantization of a Bohr Hamiltonian for quadrupole shapes; one octupole band is also shown on the extreme right.

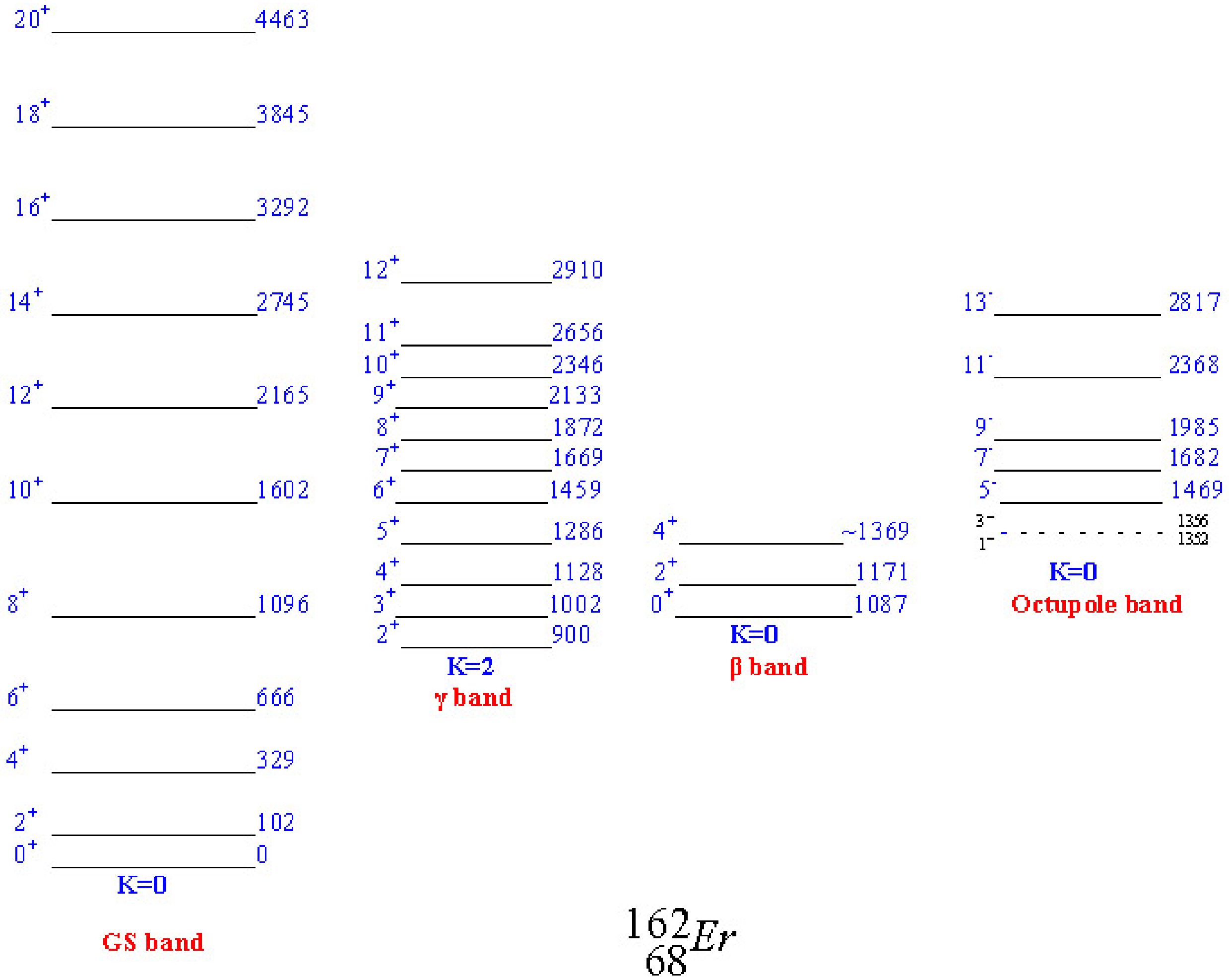

Fig. 9: Observed band structure in an even-even nucleus (^{162}Er) classified according to Fig. 8.

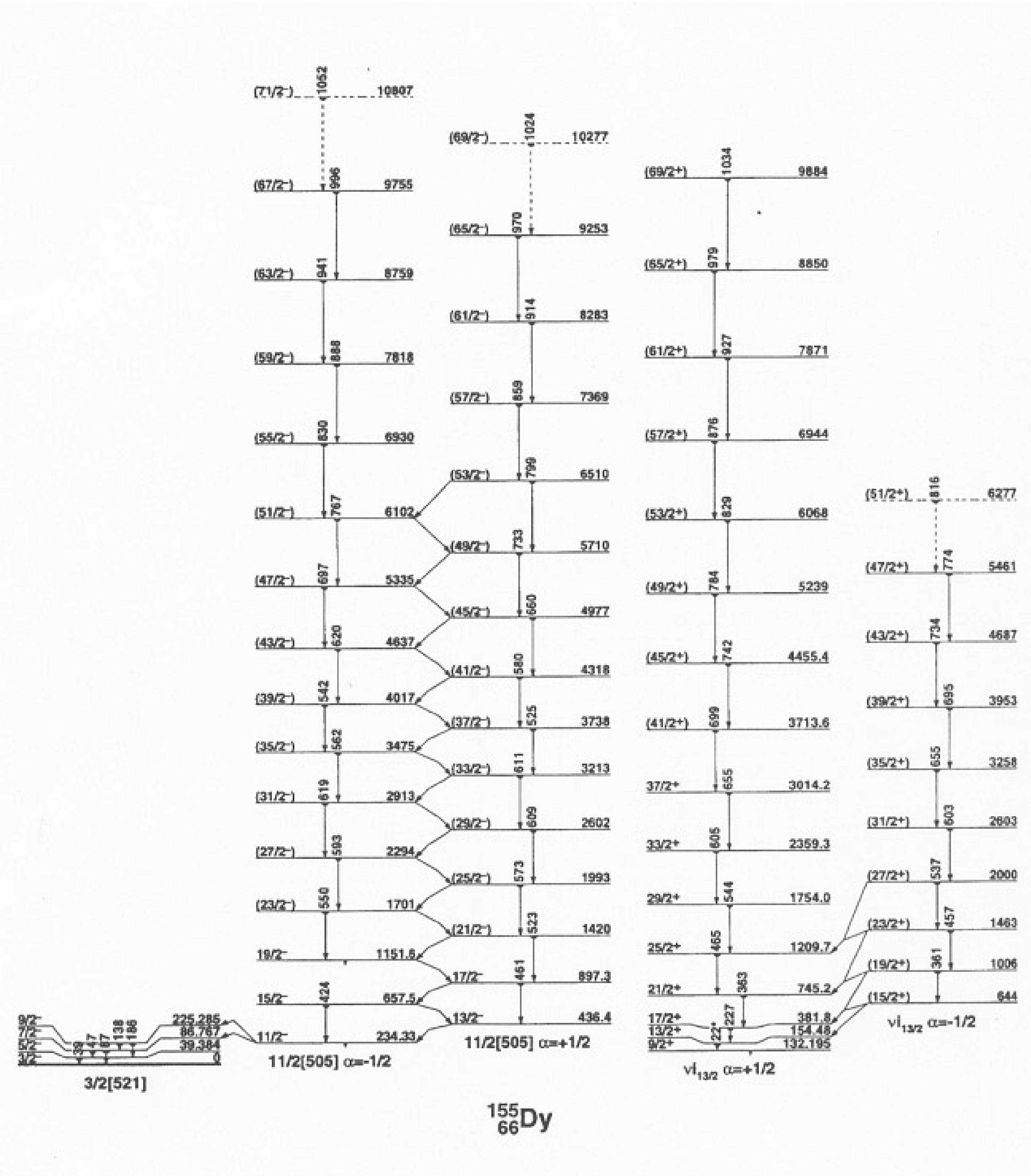

Fig. 10: Observed band structure in an odd-A nucleus (^{155}Dy) taken from the Table of Isotopes (bands are labeled by the signature quantum numbers).

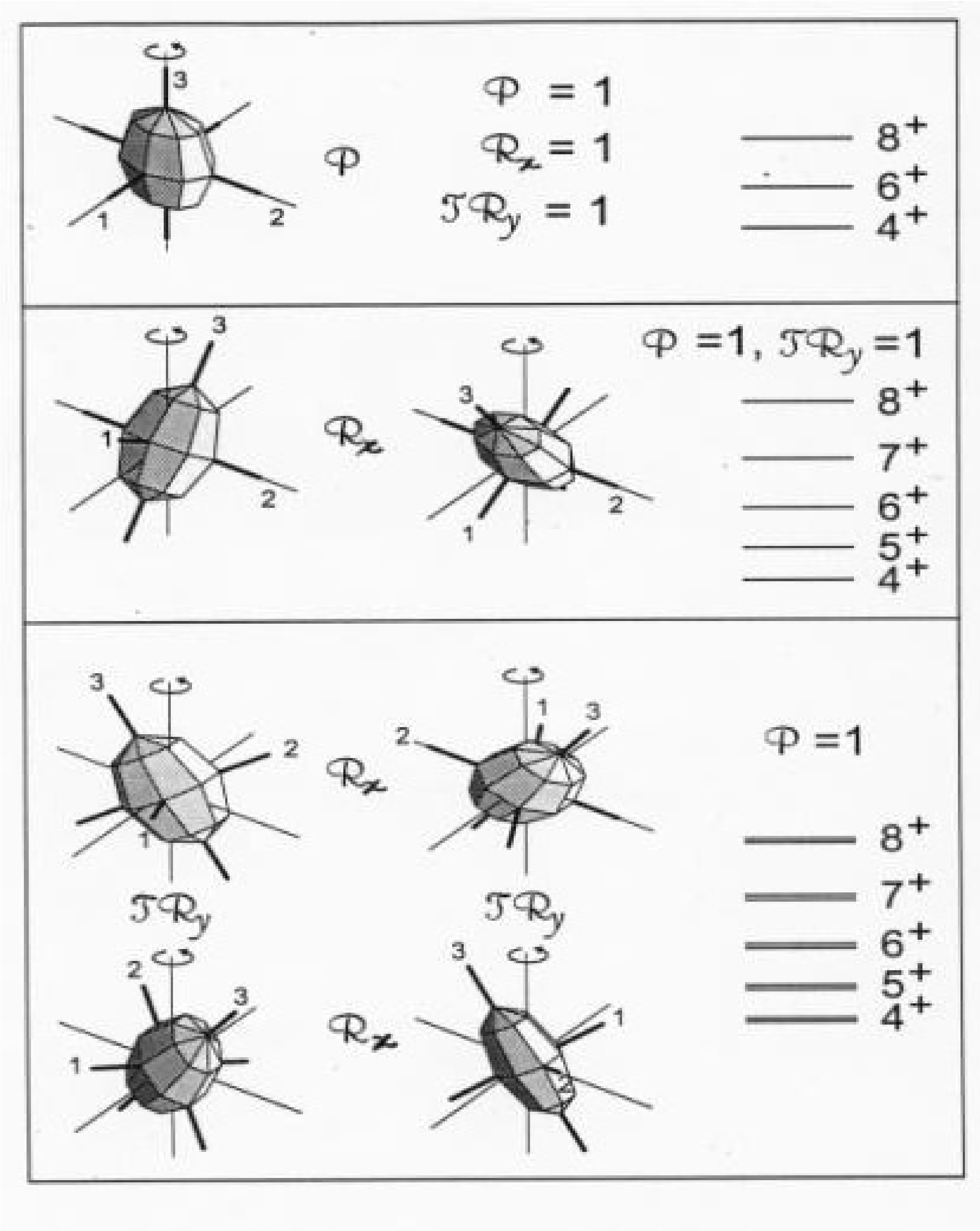

Fig. 11: Effect of planar (top and middle panel) and aplanar (bottom panel) axis of rotation on the rotational band of a tri-axial shape (Frauendorf, 2000).

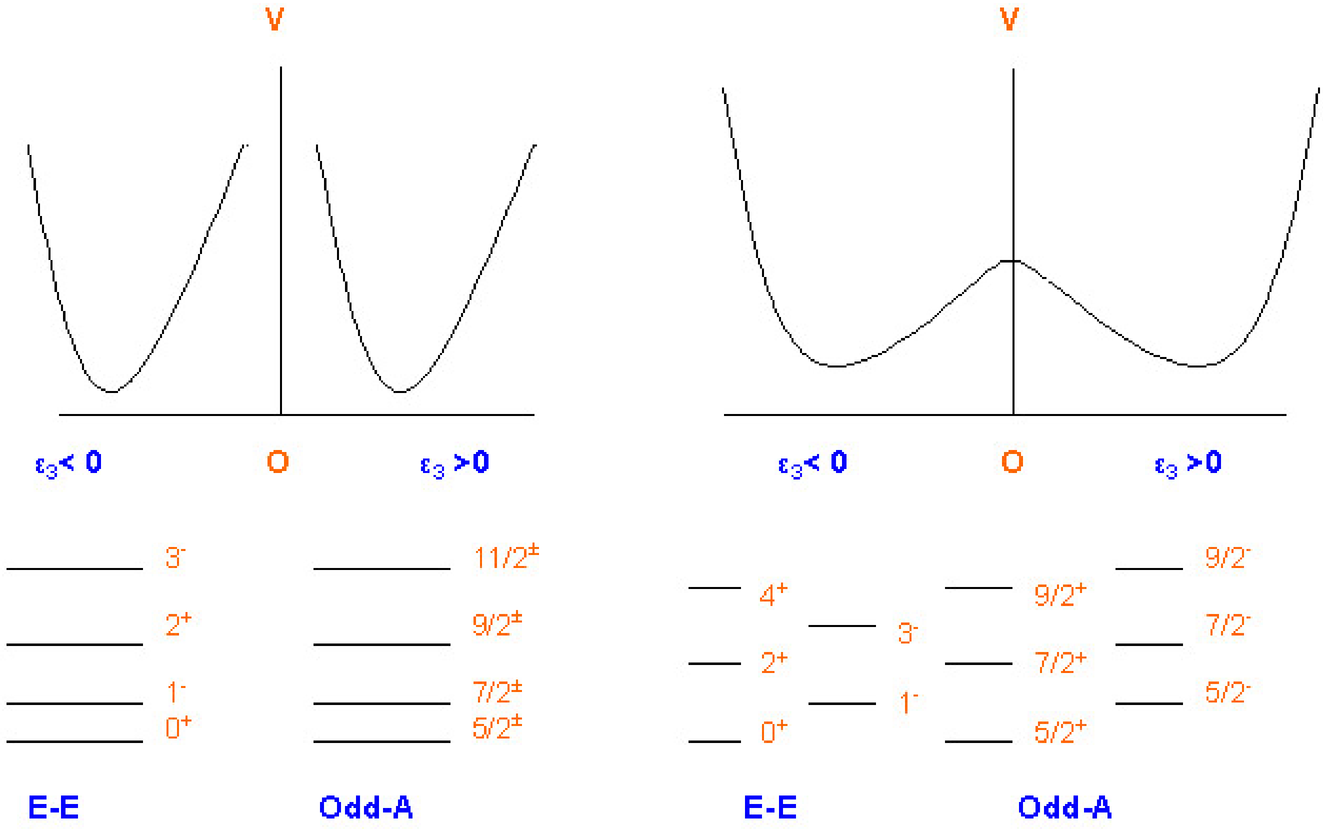

Fig. 12: Presence of an axially symmetric octupole shape leads to the breaking of parity: if the barrier in octupole degree of freedom is too high, the states do not mix and a band structure is obtained (as on the left); while mixing leads to a splitting of parity doublets for a finite barrier height.

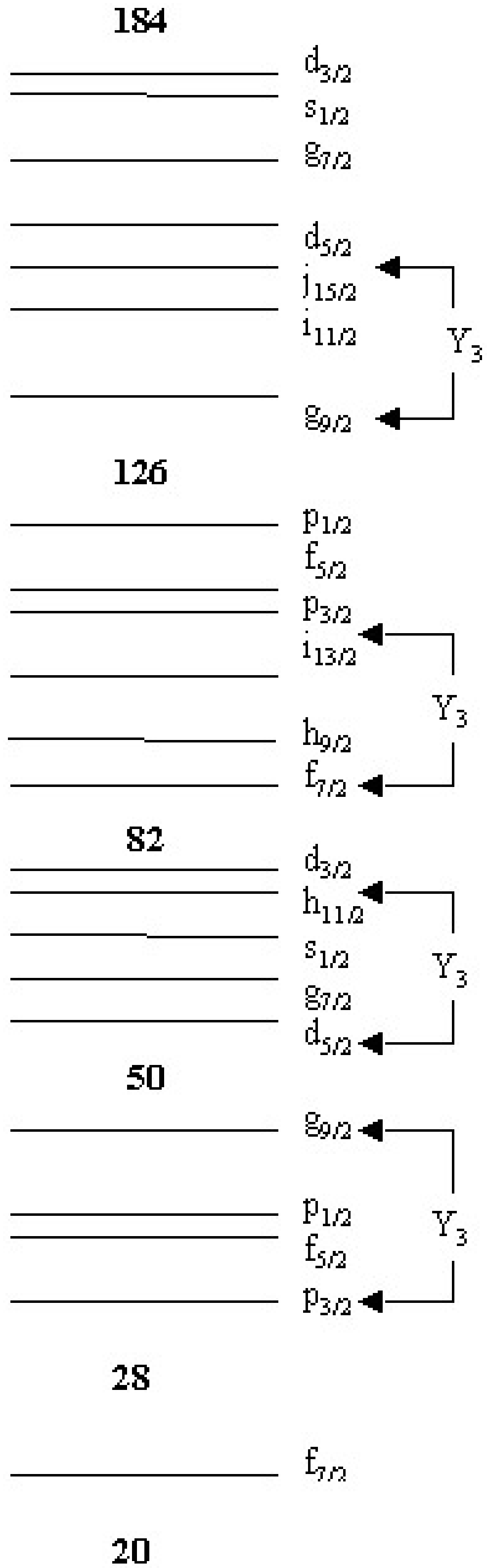

Fig. 13: Spherical single-particle states that show the proximity of levels differing in angular momentum by 3 units.

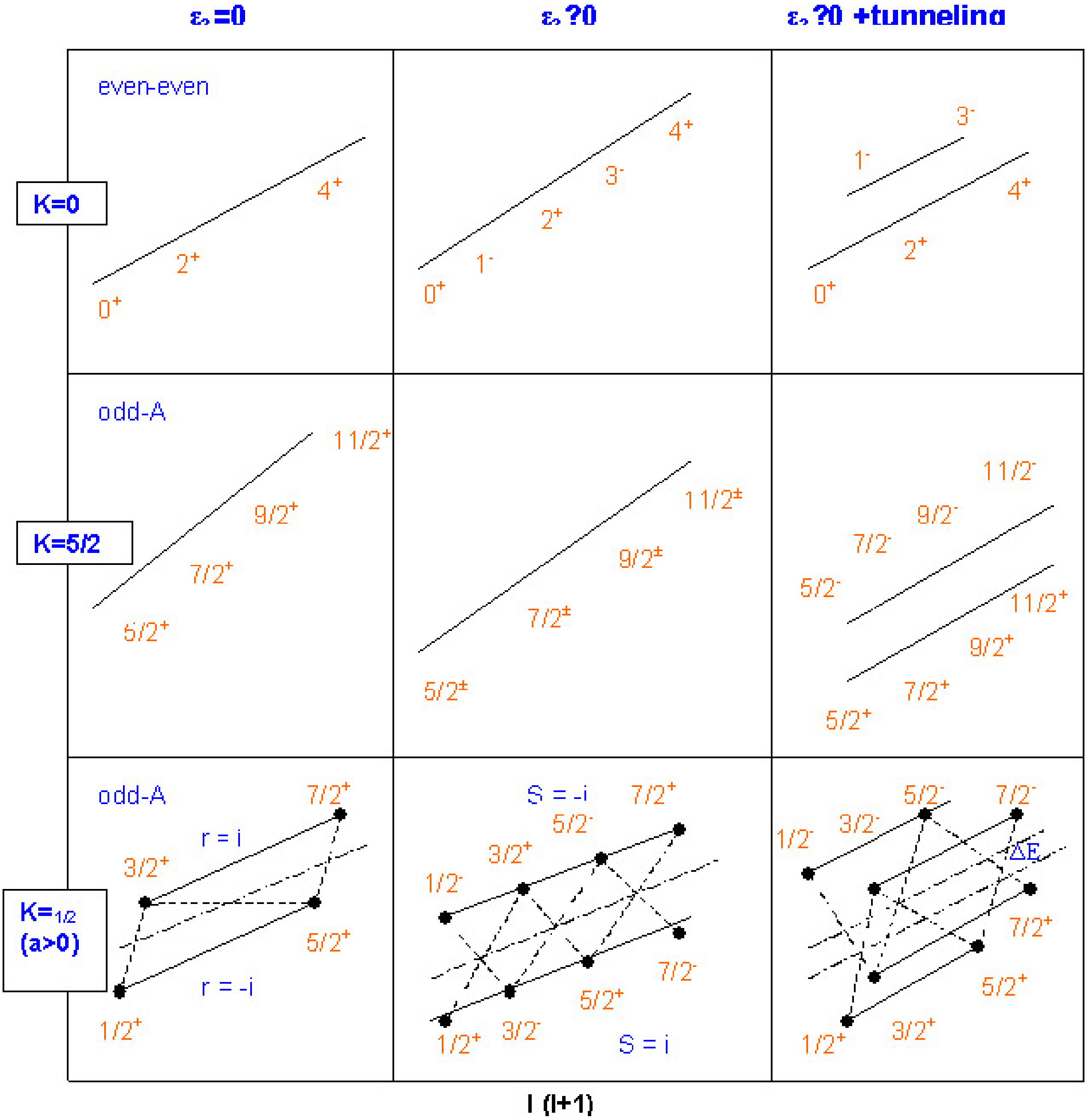

Fig. 14: Energy (on the vertical axis) vs. I(I+1) for various even-even (top), odd-A (middle), and K = 1/2 odd-A (bottom) bands in the absence and presence of octupole shape.

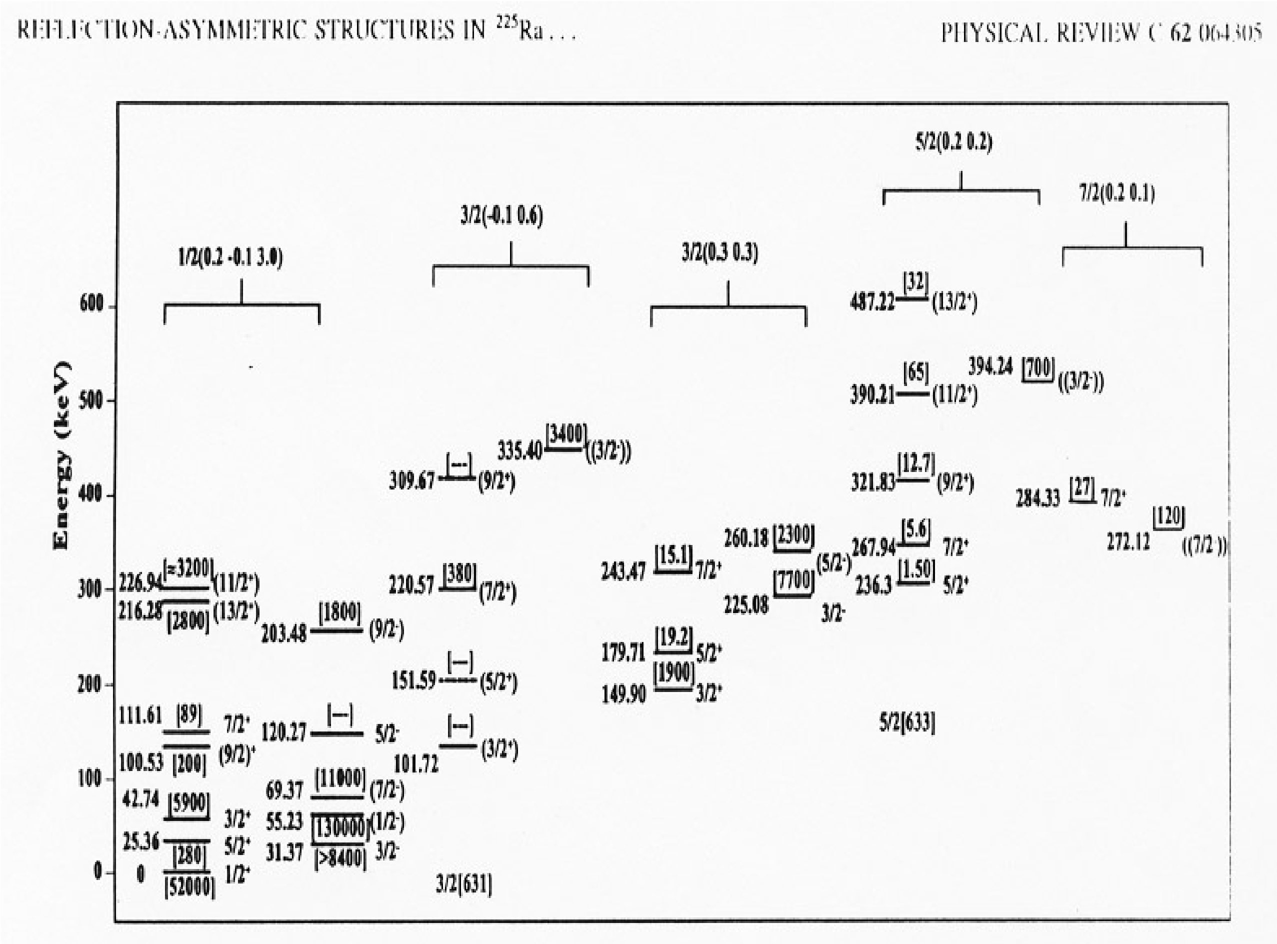

Fig. 15: Experimental data for ^{225}Ra, showing the classification of bands into parity doublets (Gasparo et al., 2000).

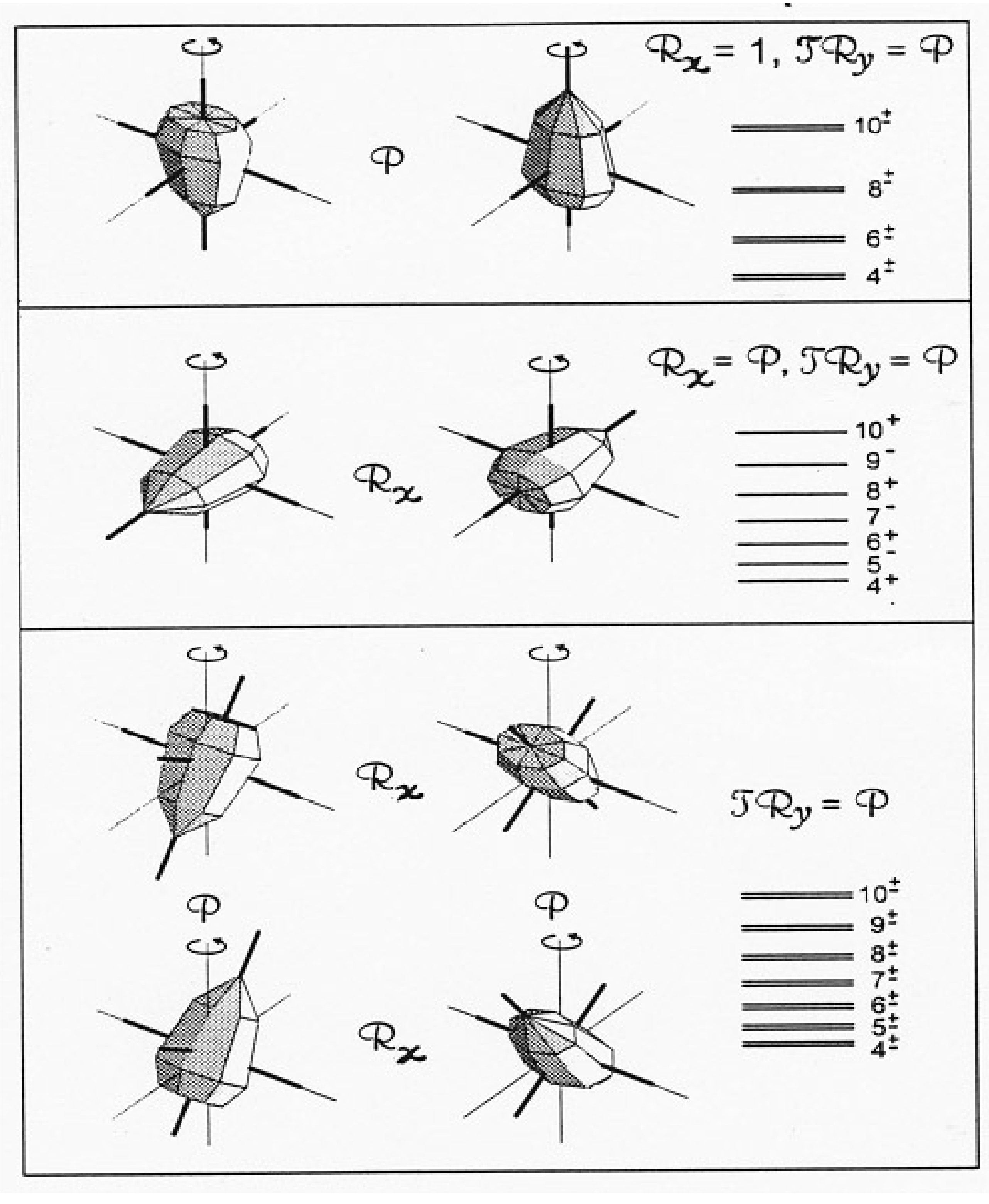

Fig. 16: Effect of planar (top and middle panel) and aplanar (bottom panel) axis of rotation on the rotational band of an axial octupole shape, in which the density distribution has two planes of symmetry (Frauendorf, 2000).

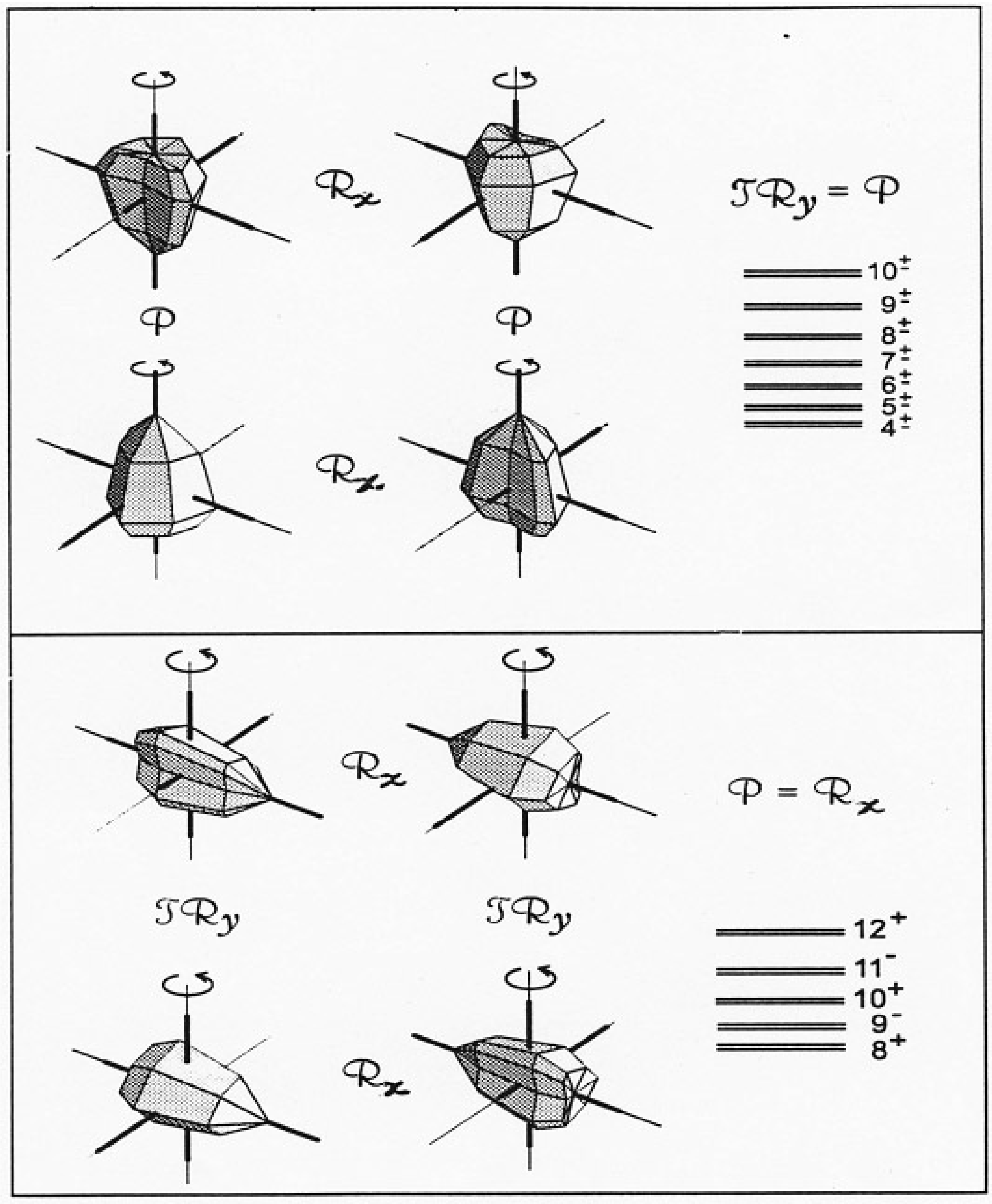

Fig. 17: Effect of planar axis of rotation on the rotational band of a shape that has only one plane of symmetry (Frauendorf, 2000).

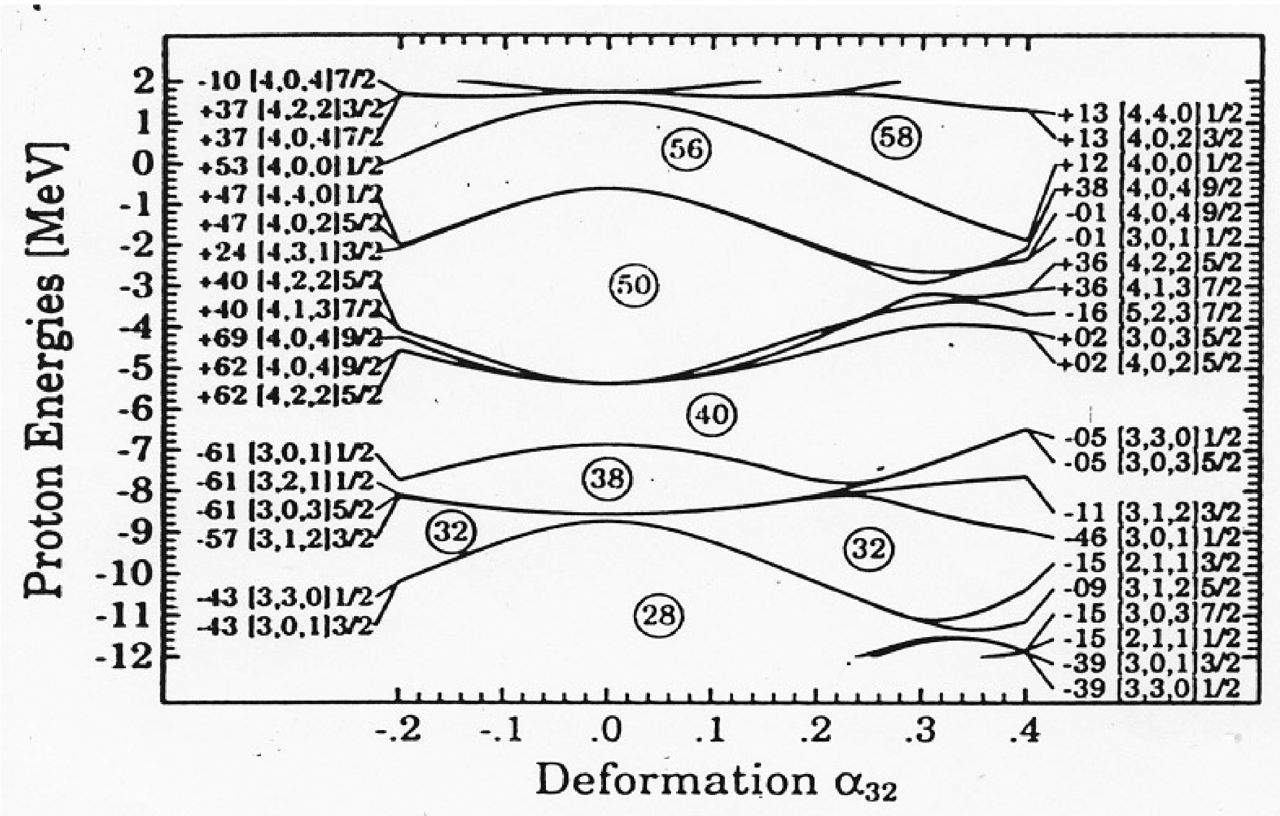

Fig. 18: Theoretical spectrum of single particle states as a function of the parameter $a_{32,}$ which is the coefficient of Y_{32} term; large gaps signify the magic numbers for this shape.

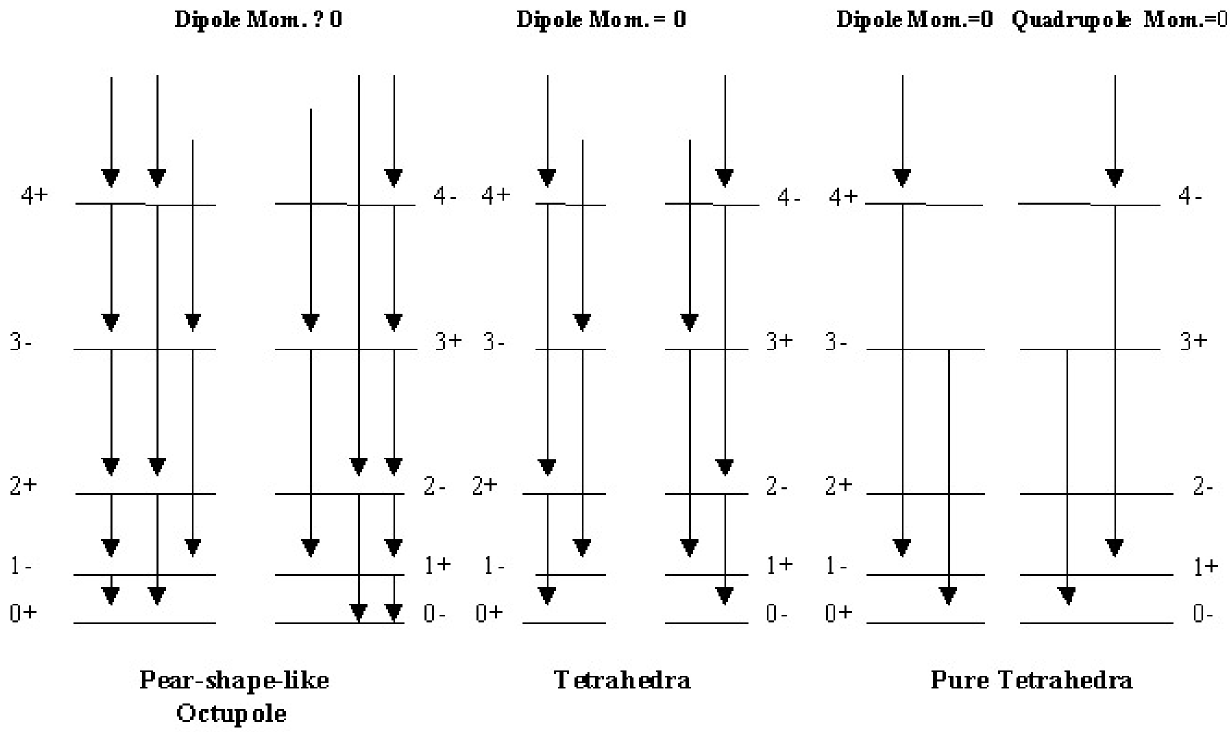

Fig. 19: Rotational spectrum of an axial octupole nucleus (left), quadrupole plus tetrahedral rotor (middle), and a pure tetrahedral rotor (right).

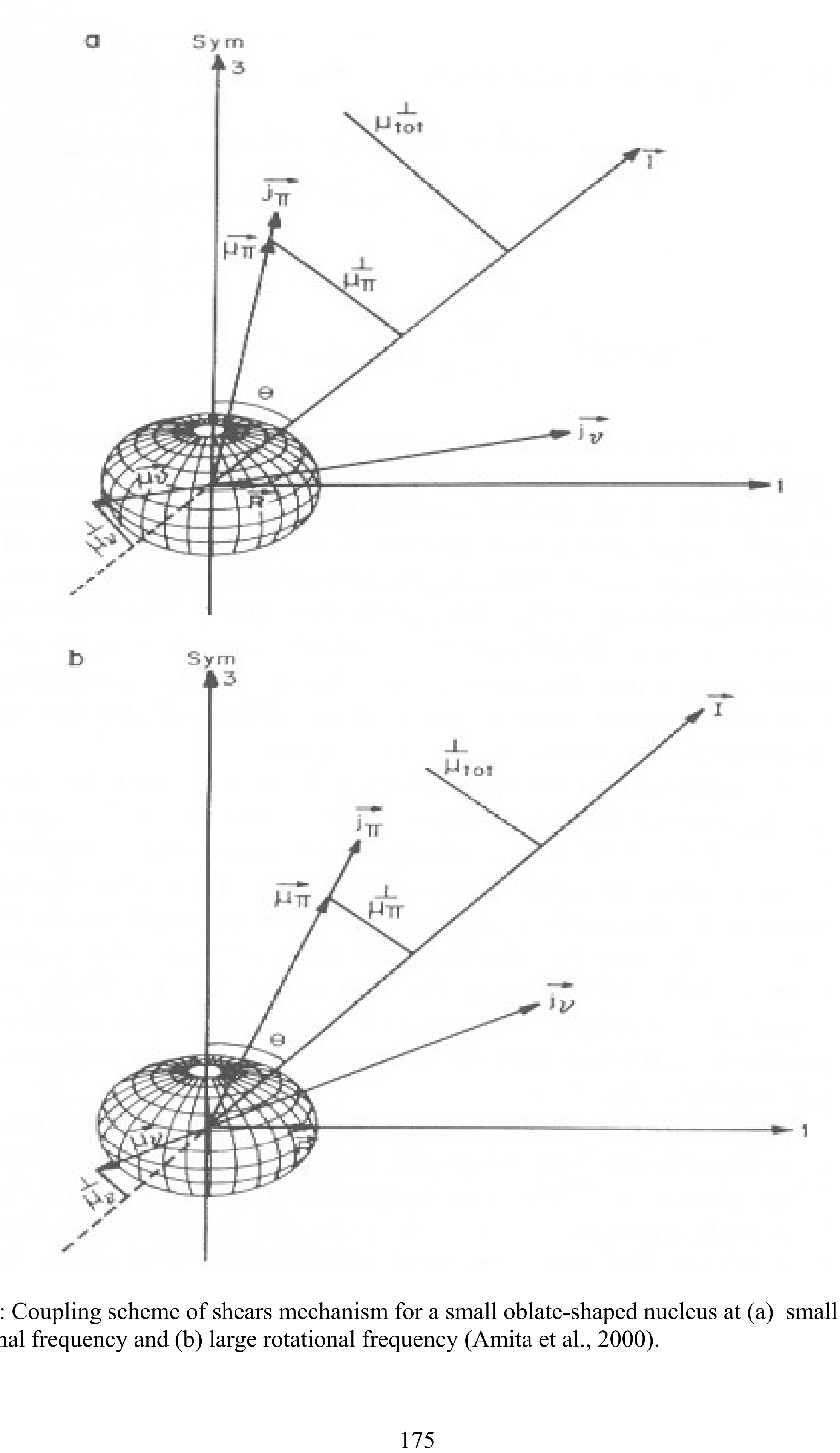

Fig. 20: Coupling scheme of shears mechanism for a small oblate-shaped nucleus at (a) small rotational frequency and (b) large rotational frequency (Amita et al., 2000).

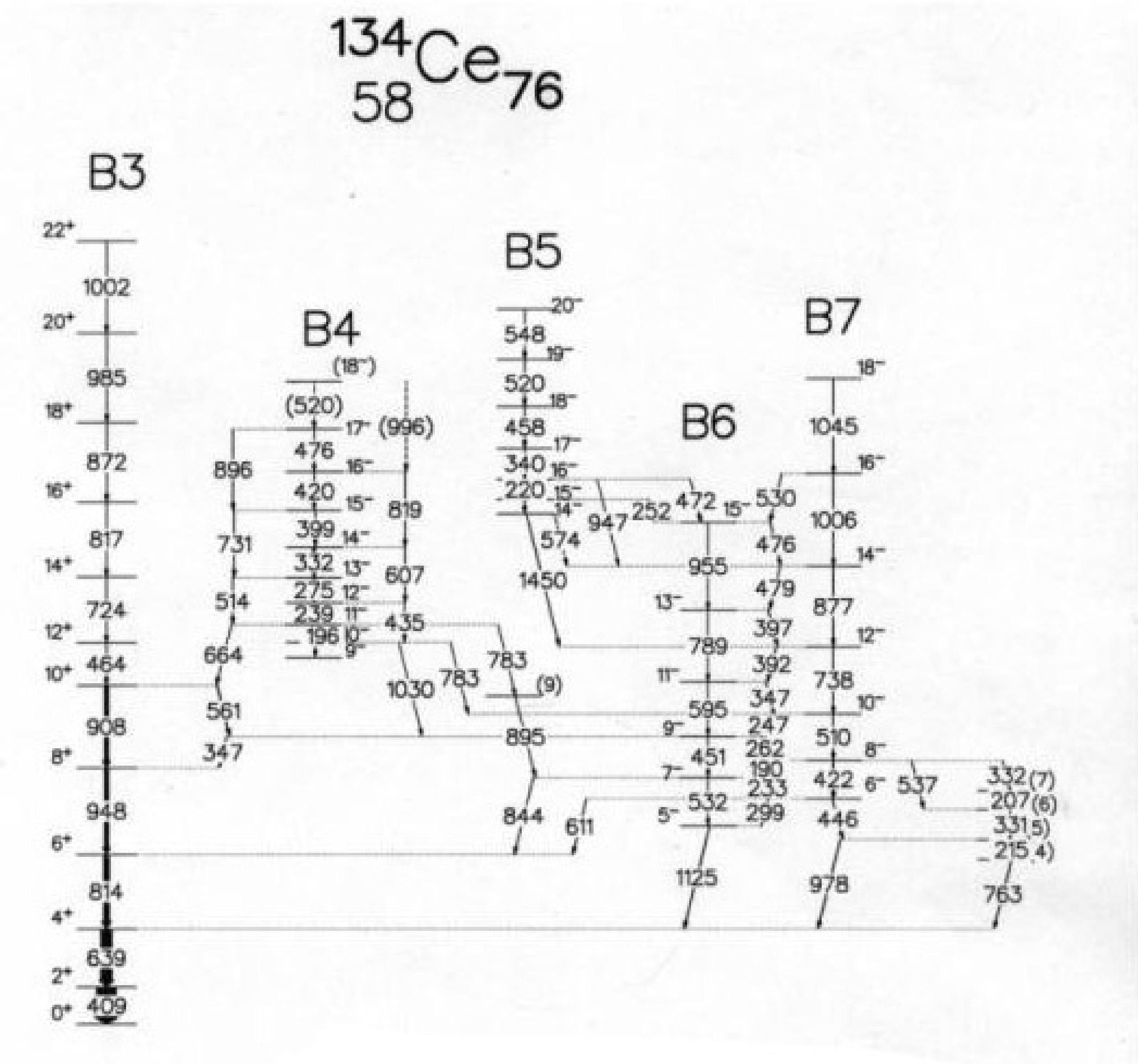

Fig. 21: Partial level scheme of ^{134}Ce that indicates the magnetic rotation band B5 (Lakshmi et al., 2004).

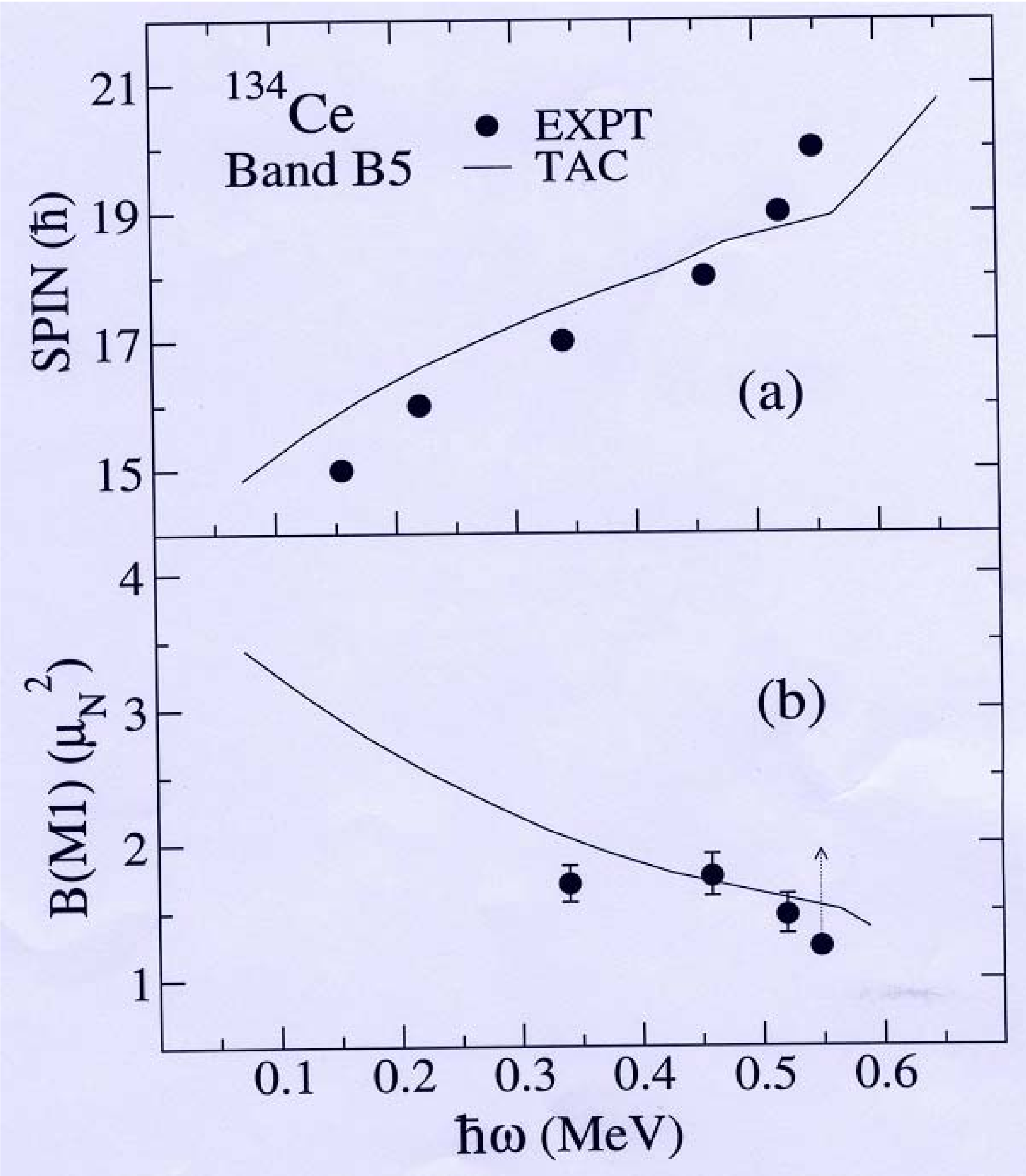

Fig. 22: Experimental plots of angular momentum vs. rotational frequency (top) and B(M1) vs. rotational frequency (bottom) as compared with the TAC calculations (Lakshmi et al., 2004).

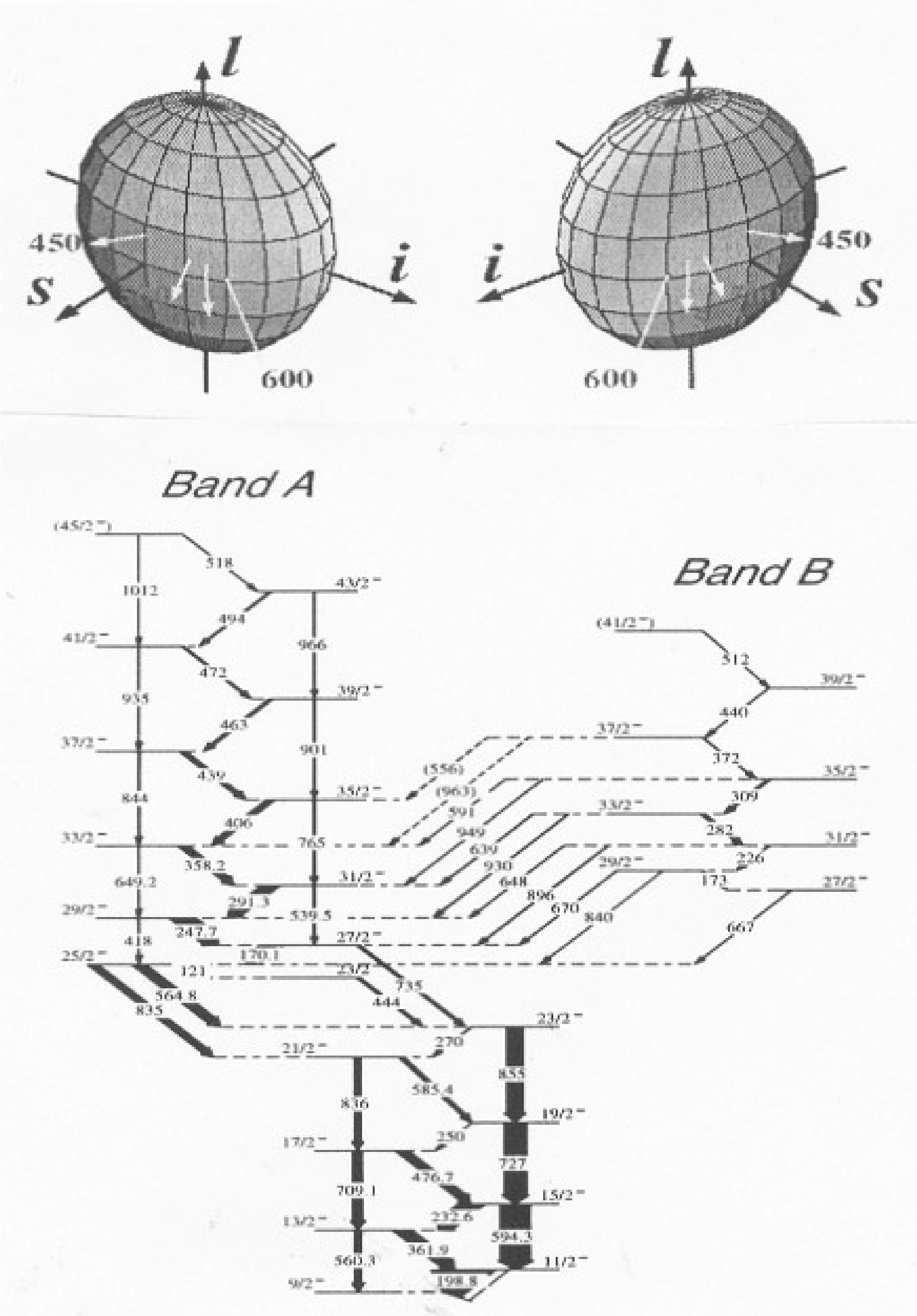

Fig. 23: Chiral pattern of bands observed in ^{135}Nd (Zhu et al., 2003).

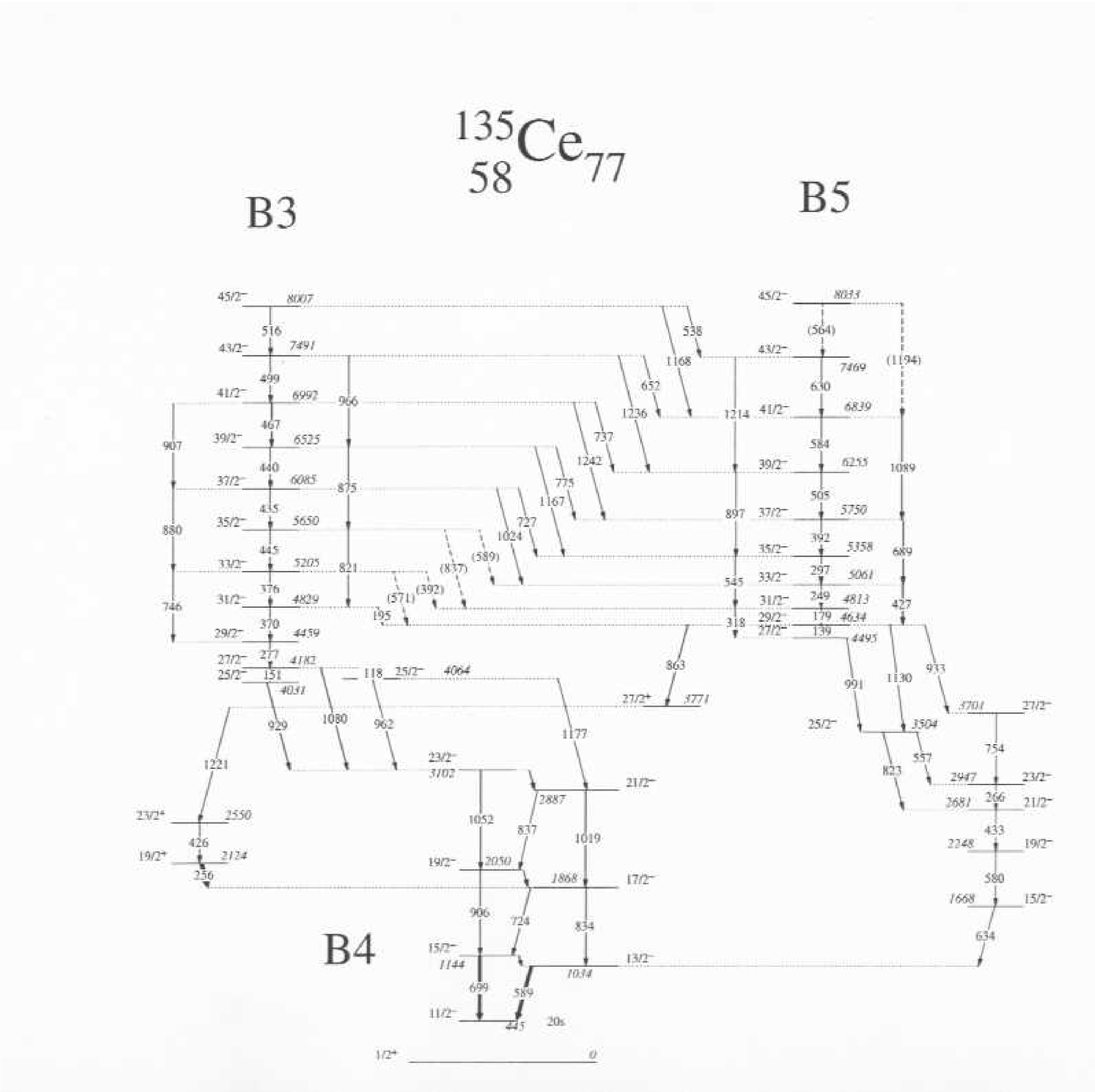

Fig. 24: Possible example of chiral pair of bands in ^{135}Ce (Lakshmi et al., private communication.)

Experimental nuclear spectroscopy:

Introduction

P. von Brentano

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Recommended reading: Experimental nuclear spectroscopy is a broad subject.

Excellent books:

R.F. Casten: Nuclear Structure from a Simple Perspective
Oxford Studies in Nuclear Physics, 23
Second edition, Oxford University Press (OUP)
ISBN: 0198507240

A. Bohr and B. R. Mottelson: Nuclear Structure
Publisher: World Scientific Pub Co.
1st edition (January 15, 1998)
ISBN: 9810231970

H. Ejiri and M. J. A. de Voigt: Gamma-ray and Electron Spectroscopy in Nuclear Physics
Oxford Studies in Nuclear Physics, 11
Clarendon Press, Oxford (1989)
ISBN: 0198517238

H. Morinaga and T. Yamazaki: In-beam Gamma Spectroscopy
ISBN: 0720402972

D. N. Poenaru and W. Greiner: Experimental Techniques in Nuclear Physics
Publisher: Walter De Gruyter Inc
Published Date: 6 January 1997
ISBN: 3110144670

R. Bock: Heavy Ion Collisions, Vols. 1-3
Elsevier Science & Technology Books
ISBN:0720407389

Experimental nuclear spectroscopy:

Introduction

States, energies, widths, electromagnetic transitions

Observables, quantum numbers

Example levels in ^{124}Xe vs IBA

Nuclear shapes rigid or soft?

Much new knowledge has been obtained in recent times; "conventional" shape parameters β and γ that apply to nuclei with a rigid shape have been generalized to parameters called Q-invariants and K-invariants, and are also applicable to nuclei with a soft shape.

States : energies, widths, lifetimes and electromagnetic transitions

Quasi-stationary state $\Psi_0(t)$ – modelling an excited nuclear state – has a complex energy:

$$\varepsilon_0 = E_0 - (i/2)\,\Gamma_0$$

where E_0 is the energy of the state, and Γ_0 is the width of the state.
Width is related to the lifetime of the state by the relationship:

$$\tau_0 = (h/2\pi)$$

Energy of the state can be measured most directly from the mass of the state (e.g., in an ion trap). Generally, measure energy differences in reactions, and not energies. Width Γ_0 of the state can be measured from the lifetime.

Lifetime τ_0 can be obtained from the exponential decay of the state

$$|\,\psi_0(t)\,|^2 = \mathrm{A} * exp(-t/\tau)$$

Given the lifetime τ_0 or the partial lifetimes τ_{0k}, one can obtain the electromagnetic transition probabilities $B(E, M, \lambda)$ – crucial observables

Experimental nuclear spectroscopy:

Observables, Quantum numbers:

Beside the Hamiltonian and energy E_0, there are a number of other important observables and quantum numbers, e.g., ,

$H,\ I^2,\ I_z,\ \sigma^2,\ T_z$

$P,\ T^2,\ K = I_3,\quad F^2$

where the observables and the corresponding quantum numbers in the second row are less well defind than those in the first row

An interesting question is whether a given state ψ_0 with an energy E_0 also has the other good quantum number numbers, e.g., parity π. Yes, if the following is true:

$[H, P] = 0$, and ψ_0 is not degenerate

Then, $H\psi_0 = E_0 * \psi_0$ and $HP\psi_0 = E_0 * P\psi_0$

Thus, $P\psi_0$ and ψ_0 are degenerate states with the same energy E_0, and therefore are identical states, i.e., $P\psi_0 = \lambda\ \psi_0$. A somewhat delicate point if one remembers that the various magnetic sub-states are degenerate in energy for $B = 0$.

Thus, in nuclear structure physics, most of the given observables have good or at least approximately good quantum numbers.

Crucial aim of nuclear structure physics: measure the additional quantum numbers for many nuclear states as well as the energies and partial lifetimes.

Undertake a critical evaluation, and compile and make this information easily accessible.

Experimental nuclear spectroscopy:

Example: levels in ^{124}Xe vs IBA

This level scheme is from the Cologne group: experiments provide a rather “complete” low-spin level scheme, with many spin multiplets, e.g., four 4^+ states.

Such data allow a very stringent test of theoretical models (IBA-1 proposed by Arima and Iacchello).

Provides the Hamiltonian that can be checked. Also “extra” levels with unknown spins and parities, and theoretical levels not used in the comparison. This “incomplete” information is very useful and should always be given.

Often theoretical papers show only the levels – authors do not appear to realize how much of the “testing” value of their data is lost in such “comparisons”.

Experimental nuclear spectroscopy:

Nuclear shapes: rigid or soft?

Crucial and fundamental parameters of the nucleus are the radius R_0 and the Bohr parameters β and γ, which descibe the quadrupole shape of the nuclear surface. These parameters are to some extent model dependent.

The most used simple model is the rigid axial rotor model of Bohr and Mottelson, and the generalization of the model to a triaxial shape by Davidov and Fillipov (see later).

The shape parameters β and γ are widely used. However, there is a problem: even in the "body-fixed" reference system, many nuclei have no fixed values of $\boldsymbol{\gamma}$ and β.

Thus, the values of β and γ found in the literature are effectively the parameters β_{eff} and γ_{eff}, although rarely admitted by the authors. Both β_{eff} and γ_{eff} shape parameters are model dependent. Kumar and Cline have suggested a rather clean way of introducing these effective parameters by using the concept of Q-invariants. Relative Q-invariants called K-invariants were introduced by the Cologne-Dubna group. Unfortunately, these invariants are defined by sum rules, and we have to undertake some extapolation – can be safely done by suitable nuclear models (e.g., Interacting Boson model 1 introduced by Arima and Iacchello, or the proton-neutron version IBA-2 as introduced by Iacchello, Arima, Otsuka and Talmi).

Shape parameters for the nucleus:

a) β and γ shape parameters for nuclei that have a rigid shape in the intrinsic system

b) β_{eff} and γ_{eff} shape parameters for nuclei that have a soft (vibrating) rigid shape in the intrinsic system

Values of the Q-invariant and K-invariant parameters for the dynamic symmetries of the interacting Boson model.

Data comparisons

Experimental progress has been made by improving the accuracy of measurements of the lifetimes of nuclear states. Problem of unknown side feeding in fusion reactions has been solved by suitable data and novel analysis methods (particularly the work of the Dewald group in Cologne). Thus, reliable lifetimes are now available from fusion reactions, allowing the determination of the shapes of collective excitations in nuclei.

Experimental nuclear spectroscopy:

Lifetimes from Döppler-shifted spectra of RDDS (recoil distance Döppler-shifted data).

Qualitative arguments:

Method, and example of ^{158}Er

Results for *Xe* isotopes

Three setups for low-spin spectroscopy at FN-Tandem, Cologne and in Lexington.

Comparison of spectra

Inelastic neutron scattering

Lifetimes from (n, n´t**γ)** data of Lexington

Lifetimes of highly-excited states from NRF at S-Dalinac, Darmstadt, and Dynamitron, Stuttgart

Nuclear Resonance Fluorescence (NRF)

resonant inelastic photon scattering

A(γ, γ´)A∗

Resonance reaction:

$$A + \gamma \rightarrow A**(E, I) \rightarrow \gamma + A*$$

Experimental nuclear spectroscopy:

Nuclear Shapes

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Cologne, Germany

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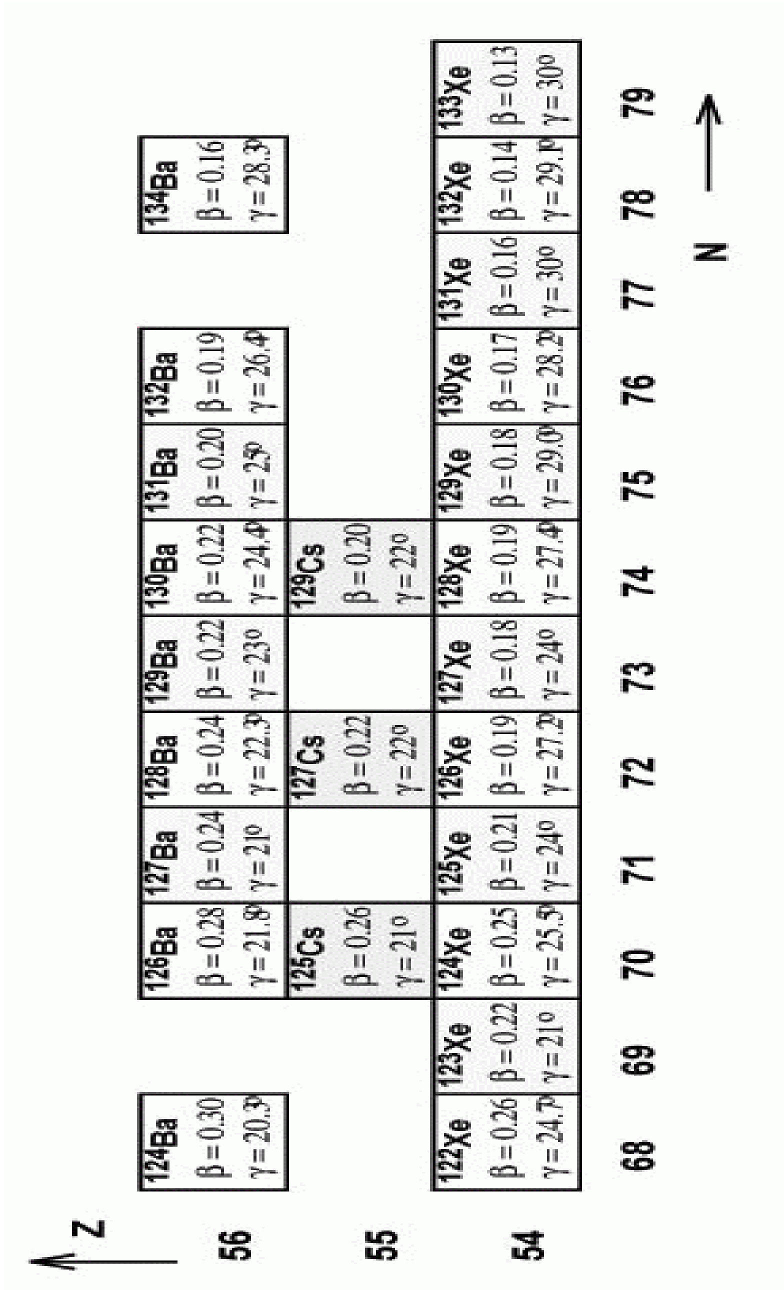
Shape parameters for the nucleus:

a) β and γ shape parameters for nuclei that have a rigid shape in the intrinsic system

b) Shape parameters β_{eff} and γ_{eff} for nuclei that have a soft (vibrating) shape in the intrinsic system



Z
N
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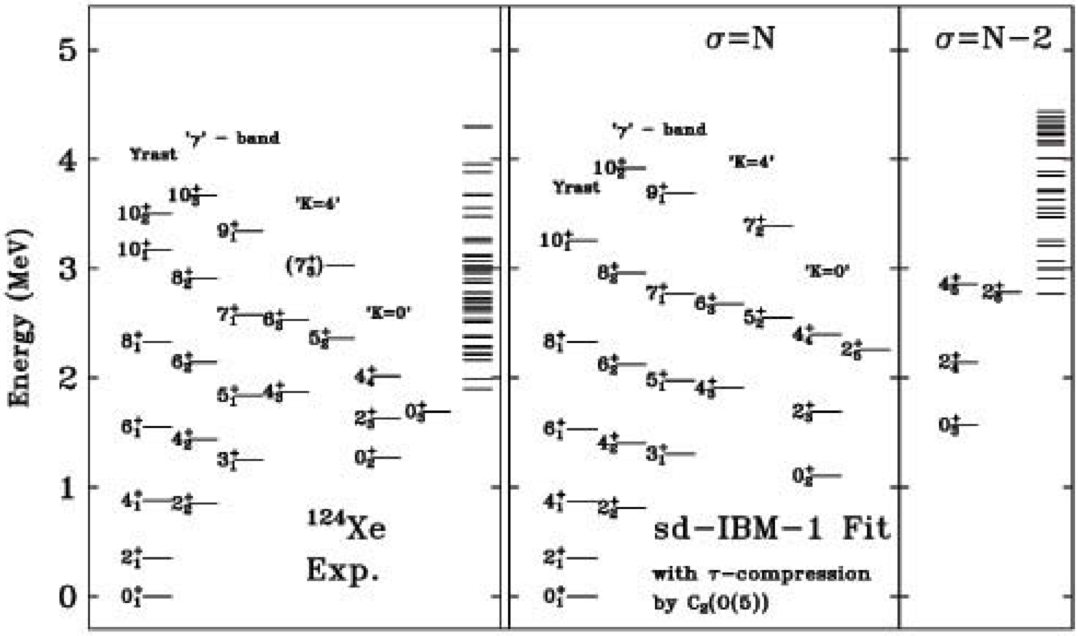
124Ba β=0.30 γ=20.3°
126Ba β=0.28 γ=21.8°
127Ba β=0.24 γ=21°
128Ba β=0.24 γ=22.3°
129Ba β=0.22 γ=23°
130Ba β=0.22 γ=24.4°
131Ba β=0.20 γ=25°
132Ba β=0.19 γ=26.4°
134Ba β=0.16 γ=28.3°
125Cs β=0.26 γ=21°
127Cs β=0.22 γ=22°
129Cs β=0.20 γ=22°
122Xe β=0.26 γ=24.7°
123Xe β=0.22 γ=21°
124Xe β=0.25 γ=25.5°
125Xe β=0.21 γ=24°
126Xe β=0.19 γ=27.2°
127Xe β=0.18 γ=24°
128Xe β=0.19 γ=27.4°
129Xe β=0.18 γ=29.0°
130Xe β=0.17 γ=28.2°
131Xe β=0.16 γ=30°
132Xe β=0.14 γ=29.1°
133Xe β=0.13 γ=30°

^{124}Xe

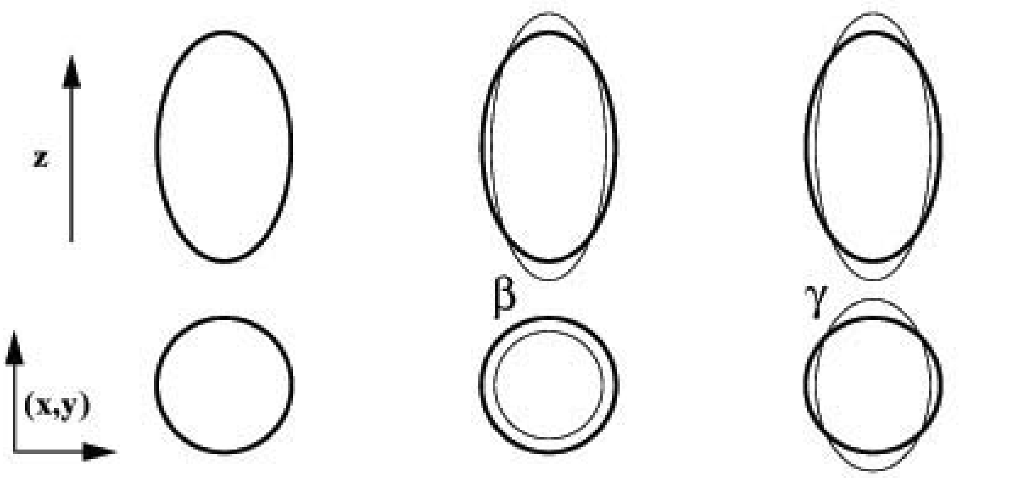


$$
\begin{aligned}
\mathbf{H}_{\tau-\mathbf{ECQF}} &= \epsilon \mathbf{n_d} + \lambda \mathbf{LL} + \kappa \mathbf{Q}^\chi \mathbf{Q}^\chi + \beta \mathbf{C_2}(\mathbf{O(5)}) \\
&= \kappa \left(\frac{\epsilon}{\kappa} \mathbf{n_d} + \frac{\tilde{\lambda}}{\kappa} \mathbf{LL} + \mathbf{Q}^\chi \mathbf{Q}^\chi + \mathbf{4} \frac{\beta}{\kappa} \mathbf{T}^{(\mathbf{3})} \mathbf{T}^{(\mathbf{3})} \right)
\end{aligned}
$$

$$
\epsilon/\kappa = -20.9 \ , \ \chi = -0.257 \ , \ \beta/\kappa = 0.563 \ , \ \lambda/\kappa = -0.284
$$
$$
\kappa = -34.91 keV \ , \ e_b = 0.14224 e^2 b^2
$$

V.Werner et al., Nucl. Phys. **A693** (2001) 451

Investigation of nuclear deformation



geometrical model ⟶ rigid β and γ

cannot describe γ - soft nuclei

⟶ adopt to quantities that can describe non-rigid deformations

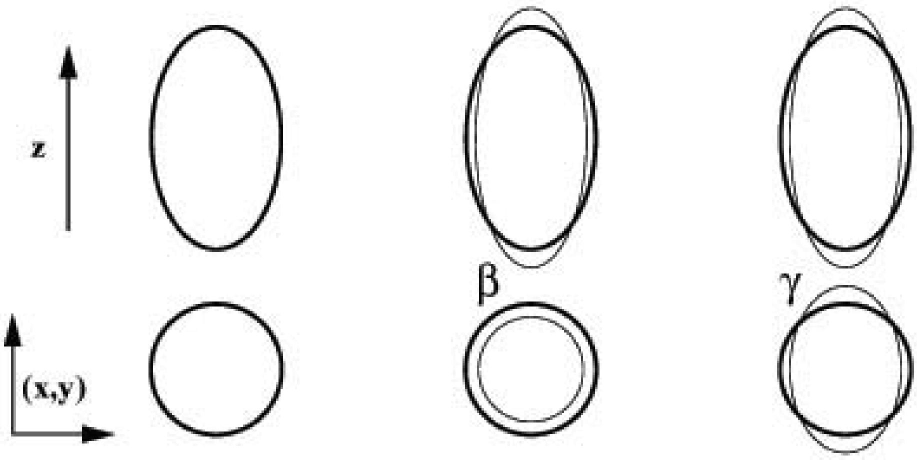
⟶ make them model-independent

One approach is:

Quadrupole-Shape-Invariants

K. Kumar, Phys. Rev. Lett **28** (1972) 249
D. Cline, Ann. Rev. Nucl. Part. Sci. **36** (1968) 683

Investigation of nuclear deformation



$$\mathbf{R}_\lambda = R\left(1+\beta\sqrt{\frac{5}{4\pi}}cos\left(\gamma-\frac{2\pi}{3}\lambda\right)\right) \qquad \lambda=1,2,3$$

$$\mathbf{Q_0} = \frac{3ZR^2\beta}{\sqrt{5\pi}}$$

$\mathbf{D^J_{MK}}$ = generalized spherical functions defining the unitary transformation from a coordinate system fixed in space to a coordinate system fixed to the nucleus

$$\hat{\mathbf{Q}}_{2\mu} = eQ_0\left(D^2_{\mu 0}cos\gamma+\frac{D^2_{\mu 2}+D^2_{\mu,-2}}{\sqrt{2}}sin\gamma\right)$$

Davydov and Filippov, Nucl. Phys. **8** (1958) 237

Simple E2-relations in the Q-phonon scheme

V. Werner, P. von Brentano, R. V. Jolos

Quadrupole shape invariants

- What are shape invariants?
- Relation to nuclear deformation

Method of obtaining relationships between E2 matrix elements

- Use various couplings of E2 operators
- Use Q−phonon scheme
- Check validity in IBM−1
- Check with data

Q–Invariants Definitions

$$\mathbf{q_2} = \langle 0_1^+ | (\mathbf{Q} \cdot \mathbf{Q}) | 0_1^+ \rangle = \sum_{\mathbf{j}} \mathbf{B}(\mathbf{E2}; 0_1^+ \cdot \mathbf{2j}^+)$$

$$\mathbf{q_3} = \sqrt{\frac{35}{2}} \; | \langle 0_1^+ | [\mathbf{QQQ}]^{(0)} | 0_1^+ \rangle |$$

$$\mathbf{q_4} = \langle 0_1^+ | (\mathbf{Q} \cdot \mathbf{Q}) \; (\mathbf{Q} \cdot \mathbf{Q}) | 0_1^+ \rangle$$

$$\mathbf{q_5} = \sqrt{\frac{35}{2}} \; | \langle 0_1^+ | (\mathbf{Q} \cdot \mathbf{Q}) \; [\mathbf{QQQ}]^{(0)} | 0_1^+ \rangle |$$

$$\mathbf{q_6} = \frac{35}{2} \; \langle 0_1^+ | [\mathbf{QQQ}]^{(0)} \; [\mathbf{QQQ}]^{(0)} | 0_1^+ \rangle$$

$$\mathbf{K_n} = \frac{\mathbf{q_n}}{\mathbf{q_2^{n/2}}} \qquad \text{for} \;\; n \in \{3, 4, 5, 6\}$$

Geometrical Interpretation

$$\mathbf{q_2} = \left(\frac{\mathbf{3ZeR^2}}{\mathbf{4\pi}}\right)^{\mathbf{2}} \langle\beta^{\mathbf{2}}\rangle \equiv \left(\frac{\mathbf{3ZeR^2}}{\mathbf{4\pi}}\right)^{\mathbf{2}} {\beta_{\text{eff}}}^{\mathbf{2}}$$

$$\mathbf{K_3} = \frac{\langle\beta^{\mathbf{3}}\cos\mathbf{3}\gamma\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{3/2}}} \equiv \cos\mathbf{3}\gamma_{\text{eff}}$$

$$\mathbf{K_4} = \frac{\langle\beta^{\mathbf{4}}\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{2}}}$$

$$\mathbf{K_5} = \frac{\langle\beta^{\mathbf{5}}\cos\mathbf{3}\gamma\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{5/2}}}$$

$$\mathbf{K_6} = \frac{\langle\beta^{\mathbf{6}}\cos^{\mathbf{2}}\mathbf{3}\gamma\rangle}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{3}}}$$

Fluctuations:

$$\sigma_\beta = \frac{\langle\beta^{\mathbf{4}}\rangle - \langle\beta^{\mathbf{2}}\rangle^{\mathbf{2}}}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{2}}} = \mathbf{K_4 - 1}$$

$$\sigma_\gamma = \frac{\langle\beta^{\mathbf{6}}\cos^{\mathbf{2}}\mathbf{3}\gamma\rangle - \langle\beta^{\mathbf{3}}\cos\mathbf{3}\gamma\rangle^{\mathbf{2}}}{\langle\beta^{\mathbf{2}}\rangle^{\mathbf{3}}} = \mathbf{K_6 - {K_3}^2}$$

Various Couplings of the 4th order moment

decouple via Wigner-Eckart and insert 1s (ones)

$$q_4^{(0)} = \langle 0_1^+ | (Q \overbrace{\cdot}^{\overset{1}{\sum_i |2_i^+\rangle\langle 2_i^+|}} Q) \underbrace{\;}_{\sum_j |0_j^+\rangle\langle 0_j^+|} (Q \overbrace{\cdot}^{\overset{1}{\sum_k |2_k^+\rangle\langle 2_k^+|}} Q) |0_1^+\rangle$$

$$q_4^{(2)} = \langle 0_1^+ | \Big[[Q \overbrace{\;}^{\sum_i |2_i^+\rangle\langle 2_i^+|} Q]^{(2)} \underbrace{\;}_{\sum_j |2_j^+\rangle\langle 2_j^+|} [Q \overbrace{\;}^{\sum_k |2_k^+\rangle\langle 2_k^+|} Q]^{(2)} \Big]^{(0)} |0_1^+\rangle$$

$$q_4^{(4)} = \langle 0_1^+ | \Big[[Q \overbrace{\;}^{\sum_i |2_i^+\rangle\langle 2_i^+|} Q]^{(4)} \underbrace{\;}_{\sum_j |4_j^+\rangle\langle 4_j^+|} [Q \overbrace{\;}^{\sum_k |2_k^+\rangle\langle 2_k^+|} Q]^{(4)} \Big]^{(0)} |0_1^+\rangle$$

Aim: $q_4^{(0)} \propto q_4^{(2)} \propto q_4^{(4)}$

Selection rules of the Q-phonon scheme

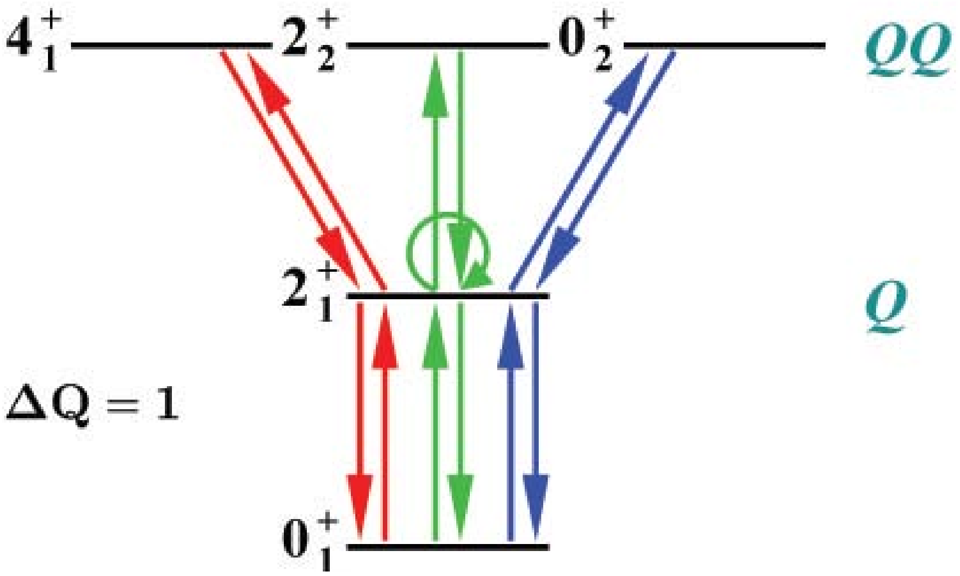
$$q_4^{(0)} = \sum_{i,j,k} \langle 0_1^+ \| Q \| 2_i^+ \rangle \langle 2_i^+ \| Q \| 0_j^+ \rangle \langle 0_j^+ \| Q \| 2_k^+ \rangle \langle 2_k^+ \| Q \| 0_1^+ \rangle$$

$$q_4^{(2)} = \frac{1}{5\sqrt{5}} \sum_{i,j,k} \langle 0_1^+ \| Q \| 2_i^+ \rangle \langle 2_i^+ \| Q \| 2_j^+ \rangle \langle 2_j^+ \| Q \| 2_k^+ \rangle \langle 2_k^+ \| Q \| 0_1^+ \rangle$$

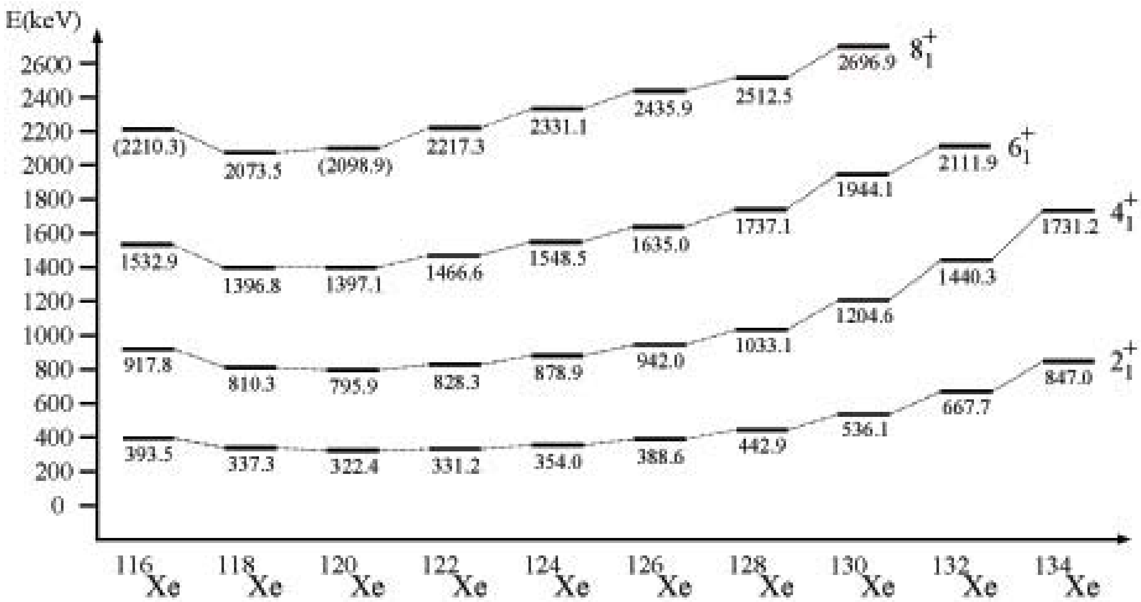
$$q_4^{(4)} = \frac{1}{15} \sum_{i,j,k} \langle 0_1^+ \| Q \| 2_i^+ \rangle \langle 2_i^+ \| Q \| 4_j^+ \rangle \langle 4_j^+ \| Q \| 2_k^+ \rangle \langle 2_k^+ \| Q \| 0_1^+ \rangle$$

$$|2_1^+ \propto Q \; |0_1^+\rangle$$

$$|J_1^+\rangle \propto (QQ)^{(J)} \; |0_1^+\rangle \propto (Q \; |2_1^+\rangle)^{(J)} \qquad \text{(J=0,2,4)}$$



G. Siems et al., Phys. Lett. **B320** (1994) 1
T. Otsuka, K.–H. Kim, Phys. Rev. **C50** (1994) 1768


E(keV)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(2210.3)
2073.5
(2098.9)
2217.3
2331.1
2435.9
2512.5
2696.9
8_1^+
1532.9
1396.8
1397.1
1466.6
1548.5
1635.0
1737.1
1944.1
2111.9
6_1^+
917.8
810.3
795.9
828.3
878.9
942.0
1033.1
1204.6
1440.3
1731.2
4_1^+
393.5
337.3
322.4
331.2
354.0
388.6
442.9
536.1
667.7
847.0
2_1^+
^{116}Xe
^{118}Xe
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^{122}Xe
^{124}Xe
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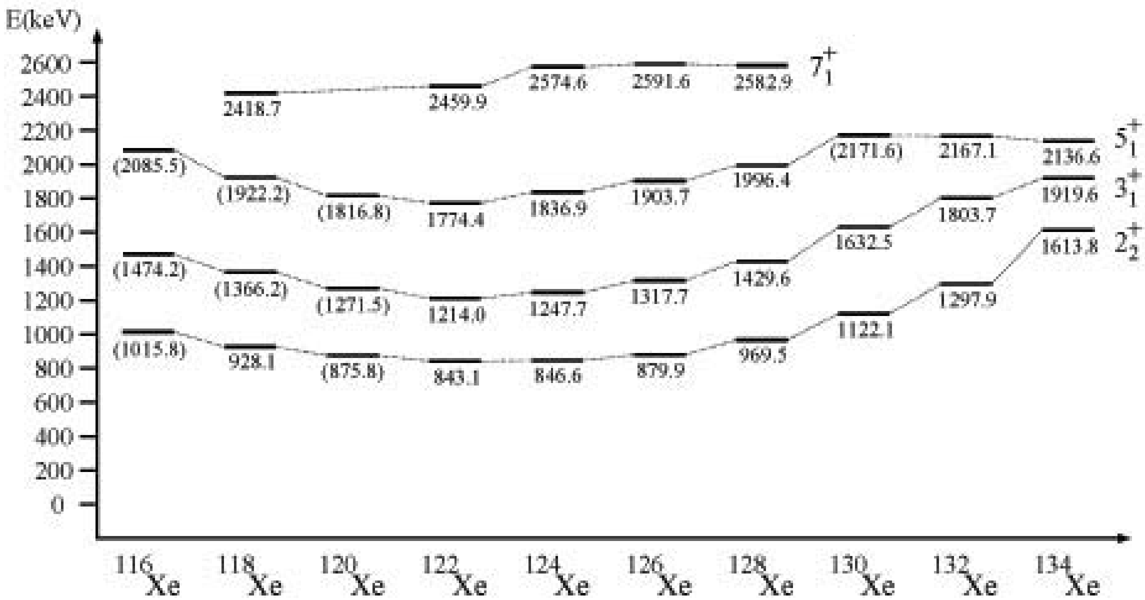
^{130}Xe
^{132}Xe
^{134}Xe


E(keV)
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2418.7
2459.9
2574.6
2591.6
2582.9
7_1^+
(2085.5)
(1922.2)
(1816.8)
1774.4
1836.9
1903.7
1996.4
(2171.6)
2167.1
2136.6
5_1^+
(1474.2)
(1366.2)
(1271.5)
1214.0
1247.7
1317.7
1429.6
1632.5
1803.7
1919.6
3_1^+
(1015.8)
928.1
(875.8)
843.1
846.6
879.9
969.5
1122.1
1297.9
1613.8
2_2^+
^{116}Xe
^{118}Xe
^{120}Xe
^{122}Xe
^{124}Xe
^{126}Xe
^{128}Xe
^{130}Xe
^{132}Xe
^{134}Xe

Values of Q-invariants and K-parameters for the dynamical symmetries of the Interacting Boson model

Comparison with data

Shape Invariants in the IBA limits

$$K_3 = \cos 3\gamma_{eff} \qquad \beta^2_{2,eff} = \left(\frac{4\pi}{3eZR_0^2}\right)^2 \cdot q_2$$

	SU(3)	O(6)	U(5)
$\gamma_{eff} = \frac{1}{3}\arccos K_3$	0°	30°	30°
$K_3 = \frac{q_3}{q_2^{3/2}}$	1	0	0
$K_4 = \frac{q_4}{q_2^2}$	1	1	1.4
$K_5 = \frac{q_5}{q_2^{5/2}}$	1	0	0
$K_6 = \frac{q_6}{q_2^3}$	1	0.32	0.68
$\sigma_4 = \frac{q_4 - q_2^2}{q_2^2} = K_4 - 1$	0	0	0.4
$\sigma_5 = \frac{q_5 - q_2 \cdot q_3}{q_2^{5/2}} = K_5 - K_3$	1	0	0
$\sigma_6 = \frac{q_6 - q_3^2}{q_2^3} = K_6 - K_3^2$	0	0.32	0.68

sd – IBA - 1 parameters

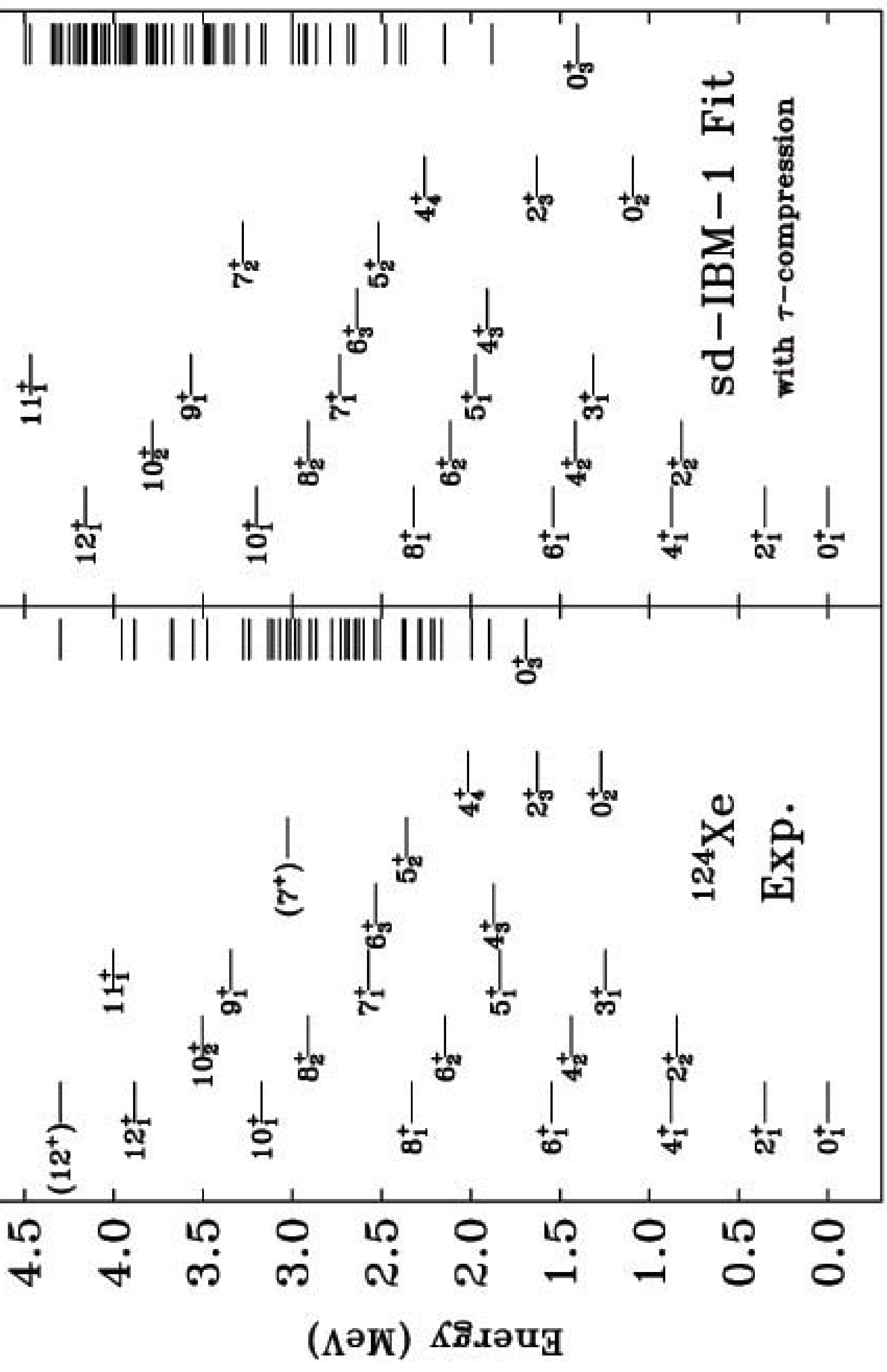
$$H_{CQF} = \kappa Q^{\chi} \cdot Q^{\chi}$$

$\Longrightarrow$ one structure parameter χ

$$\begin{aligned} H_{ECQF} &= \varepsilon n_d + \kappa Q^{\chi} \cdot Q^{\chi} \\ &= \kappa \left(\frac{\varepsilon}{\kappa} n_d + Q^{\chi} \cdot Q^{\chi} \right) \end{aligned}$$

$\Longrightarrow$ two structure parameter $(\varepsilon/\kappa, \chi)$

	SU(3)	O(6)	U(5)
ε/κ	0	0	$-\infty$
χ	$-\sqrt{7}/2$	0	0


Energy (MeV)
124Xe
Exp.
sd-IBM-1 Fit
with τ-compression

Calculated B(E2) - ratios

^{124}Xe

$Q_i \rightarrow$	Q_f	$I_i \rightarrow I_f$	exp.	τ-ECQF	ECQF	CQF	[1]
QQ $\rightarrow$	Q	$2_2^+ \rightarrow 2_1^+$	100	100	100	100	100
QQ $\not\rightarrow$		$2_2^+ \rightarrow 0_1^+$	2.4(4)	2.4	2.4	2.4	2.2
QQQ $\rightarrow$	QQ	$3_1^+ \rightarrow 2_2^+$	100*	100	100	100	100
QQQ $\rightarrow$	QQ	$3_1^+ \rightarrow 4_1^+$	32(6)*	32	33	36	30
QQQ $\not\rightarrow$	Q	$3_1^+ \rightarrow 2_1^+$	3.0(4)*	2.9	3.4	3.3	3.2
QQQ $\rightarrow$	QQ	$4_2^+ \rightarrow 2_2^+$	100	100	100	100	100
QQQ $\rightarrow$	QQ	$4_2^+ \rightarrow 4_1^+$	49(7)	69	69	75	64
QQQ $\not\rightarrow$	Q	$4_2^+ \rightarrow 2_1^+$	0.10(5)	0.53	0.08	0.03	0.18
QQQQ $\rightarrow$	QQQ	$5_1^+ \rightarrow 3_1^+$	100	100	100	100	100
QQQQ $\rightarrow$	QQQ	$5_1^+ \rightarrow 6_1^+$	71(36)*	37	37	41	33
QQQQ $\rightarrow$	QQQ	$5_1^+ \rightarrow 4_2^+$	95(17)	46	45	45	44
QQQQ $\not\rightarrow$	QQ	$5_1^+ \rightarrow 4_1^+$	1.9(3)	1.6	1.5	1.3	1.6
QQQ $\rightarrow$	QQ	$0_2^+ \rightarrow 2_2^+$	100	100	100	100	100
QQQ $\not\rightarrow$	Q	$0_2^+ \rightarrow 2_1^+$	21(9)	21	21	1.5	81
QQQQ $\rightarrow$	QQQ	$2_3^+ \rightarrow 0_2^+$	100	100	100	100	100
QQQQ $\not\rightarrow$	QQ	$2_3^+ \rightarrow 2_2^+$	2.7(17)*	4.2	6.8	0.05	20.6
QQQQ $\not\rightarrow$	QQ	$2_3^+ \rightarrow 4_1^+$	4.9(29)	10.8	14.7	0.75	31.4
QQQQ $\not\rightarrow$	Q	$2_3^+ \rightarrow 2_1^+$	0.4(2)*	0.001	0.06	0.0001	0.007
QQQQ $\not\rightarrow$		$2_3^+ \rightarrow 0_1^+$	0.26(15)	0.007	0.8	0.12	0.64
QQQQ $\rightarrow$	QQQ	$2_3^+ \rightarrow 3_1^+$	–	68	42	120	44
QQQQ $\rightarrow$	QQQ	$4_3^+ \rightarrow 4_2^+$	100*	100	100	100	100
QQQQ $\rightarrow$	QQQ	$4_3^+ \rightarrow 3_1^+$	23.9(7)	112	116	112	140
QQQQ $\rightarrow$	QQQ	$4_3^+ \rightarrow 6_1^+$	–	2.2	2.3	2.1	5.7
QQQQ $\not\rightarrow$	QQ	$4_3^+ \rightarrow 4_1^+$	0.08(18)	0.48	0.87	0.82	0.98
QQQQ $\not\rightarrow$	QQ	$4_3^+ \rightarrow 2_2^+$	4.3(13)	1.85	1.07	0.73	1.57

[1] calculated with fit parameters from
W.-T. Chou, N.V. Zamfir, R.F. Casten, Phys. Rev. **C56** (1997) 829

Calculated shape invariants

^{124}Xe

$$F_2 = \frac{B(E2; 0_1^+ \to 2_1^+)}{q_2} \qquad q_2 = \sum_j B(E2; 0 \to 2_j^+)$$

	τ–ECQF	ECQF	CQF	[1]
q_2	1.542	1.546(5)	1.543	1.541
F_2	0.98	0.97	0.98	0.98
K_3	0.26	0.32(4)	0.22	0.39
K_4	1.031	1.043(13)	1.000	1.107
K_5	0.29	0.36(5)	0.22	0.51
K_6	0.35	0.39(3)	0.30	0.53
β_{eff}	0.269	0.269(1)	0.269	0.269
γ_{eff}	25.0°	23.9(9)°	25.7°	22.3°
σ_4	0.031	0.043(13)	0.0	0.107
σ_5	0.03	0.04(6)	0.0	0.12
σ_6	0.28	0.29(4)	0.25	0.37

[1] calculated with fit parameters from
W.-T. Chou, N.V. Zamfir, R.F. Casten, Phys. Rev. **C56** (1997) 829

Calculated shape invariants in the O(6) - region

$$\mathbf{R_2^{SU(3)}} = \frac{\mathbf{q_2^{fit}}}{\mathbf{q_2(SU(3))}} \quad \mathbf{R_2^{O(6)}} = \frac{\mathbf{q_2^{fit}}}{\mathbf{q_2(O(6))}} \quad \mathbf{R_2^{U(5)}} = \frac{\mathbf{q_2^{fit}}}{\mathbf{q_2(U(5))}}$$

	^{124}Xe	^{126}Xe	^{132}Ce	O(6)
N_B	8	7	8	∞
e_B	0.130	0.120	0.150	
q_2	1.542	1.082	2.020	
F_2	0.98	0.98	0.94	1
$R_2^{SU(3)}$	0.60	0.63	0.60	
$R_2^{O(6)}$	0.95	0.98	0.96	
$R_2^{U(5)}$	2.21	2.10	2.23	
K_3	0.258	0.200	0.282	0
K_4	1.031	1.016	1.029	1
K_5	0.285	0.211	0.283	0
K_6	0.345	0.300	0.334	0.32
β_{eff}	0.269	0.223	0.275	
γ_{eff}	25.0°	27.7°	24.5°	30°
σ_4	0.031	0.016	0.029	0
σ_5	0.027	0.091	0.001	0
σ_6	0.278	0.286	0.254	0.32

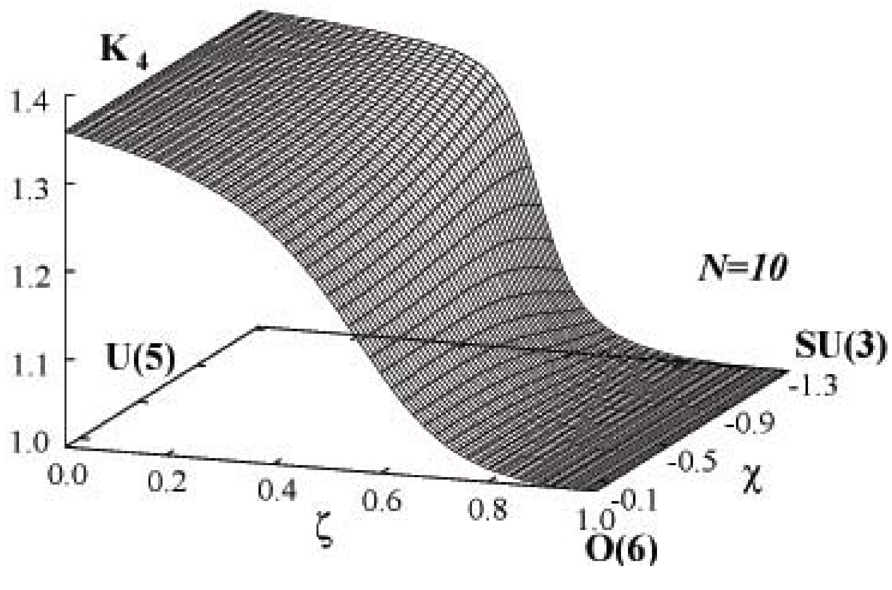
Approximations for K_4

$$K_4 = \frac{\langle 0_1^+|(Q\cdot Q)\ (Q\cdot Q)|0_1^+\rangle}{\langle 0_1^+|(Q\cdot Q)|0_1^+\rangle} \propto \frac{\langle 0_1^+|(QQ)^{(4)}\ (QQ)^{(4)}|0_1^+\rangle}{\langle 0_1^+|(Q\cdot Q)|0_1^+\rangle^2}$$

$$\longrightarrow \quad K_4^{\mathrm{appr}} = \frac{7}{10}\,\frac{B(E2;4_1^+\to 2_1^+)}{B(E2;2_1^+\to 0_1^+)}$$

$$K_4 = \frac{\langle 0_1^+|(Q\cdot Q)\ (Q\cdot Q)|0_1^+\rangle}{\langle 0_1^+|(Q\cdot Q)|0_1^+\rangle} \propto \frac{\langle 0_1^+|(QQ)^{(2)}\ (QQ)^{(2)}|0_1^+\rangle}{\langle 0_1^+|(Q\cdot Q)|0_1^+\rangle^2}$$

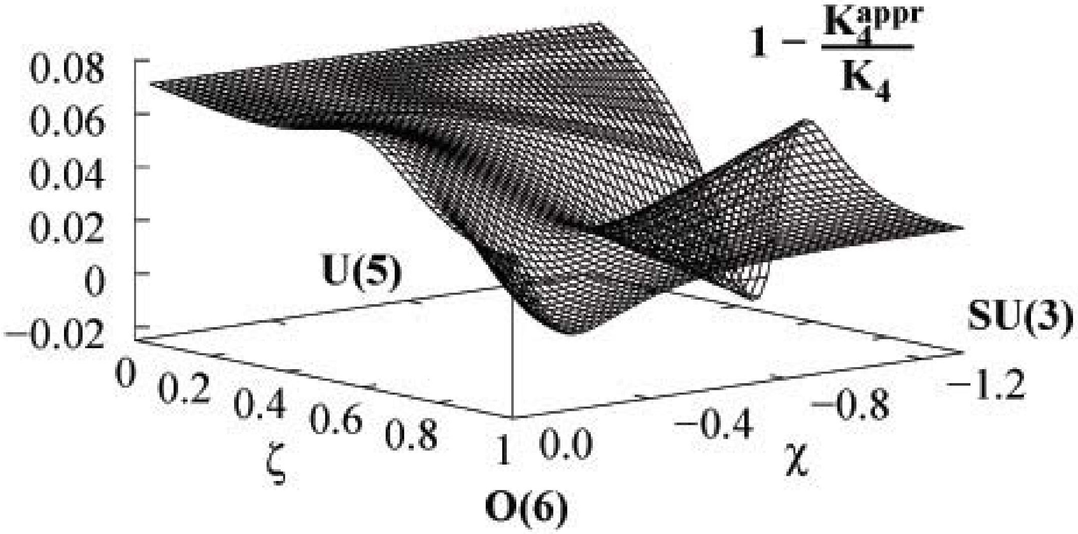
$$\longrightarrow \quad K_4 \approx \frac{7}{10}\left[\frac{\frac{35}{32\pi}Q_{2_1^+}^2 + B(E2;2_2^+\to 2_1^+)}{B(E2;2_1^+\to 0_1^+)}\right]$$



Quality of the K_4 relation

$$K_4 = \frac{\langle 0_1^+|(Q\cdot Q)\ (Q\cdot Q)|0_1^+\rangle}{\langle 0_1^+|(Q\cdot Q)|0_1^+\rangle}$$

$$K_4^{\mathrm{appr}} = \frac{7}{10}\ \frac{B(E2;4_1^+\to 2_1^+)}{B(E2;2_1^+\to 0_1^+)}$$



Summary

- Shape invariants give model-independent access to nuclear deformation

- Able to derive relations between matrix elements of low−lying states

- Validity of approximations was checked in IBM−1

- Important knowledge about basic observables: lifetimes of

$$\mathbf{2_1^+,\ 4_1^+,\ 2_\gamma^+}$$

V. Werner et al., Phys. Lett. **B521** (2001) 146

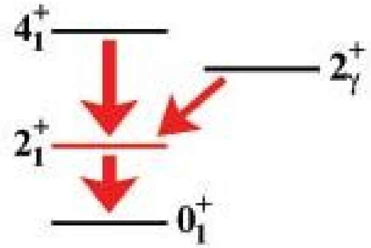
Relationship between quadrupole moment and two B(E2) values

Q-phonon model

Relative, energy-reduced γ intensities I_γ/E_γ^5 [arbitrary units] for $^{124\text{-}126}$Xe in comparison to the sd-IBM-1 prediction in the consistent Q-formalism. The first four columns specify the transitions: The dominant Q-phonon configurations [7, 8, 12, 19] and spins of the involved levels are given.

Transition			^{124}Xe		^{126}Xe	
'Ψ_i' $\to$	'Ψ_f'	$I_i \to I_f$	Expt.	IBM-1	IBM-1	Expt.
QQ $\to$	Q	$2_2^+ \to 2_1^+$	100	100	100	100
QQ $\not\to$		$2_2^+ \to 0_1^+$	2.4(4)	2.4	1.6	1.5(4)
QQQ $\to$	QQ	$3_1^+ \to 2_2^+$	100*	100	100	100
QQQ $\to$	QQ	$3_1^+ \to 4_1^+$	32(6)*	32	35	34(2)
QQQ $\not\to$	Q	$3_1^+ \to 2_1^+$	3.0(4)*	2.9	2.0	2.0(15)
QQQ $\to$	QQ	$4_2^+ \to 2_2^+$	100	100	100	100
QQQ $\to$	QQ	$4_2^+ \to 4_1^+$	49(7)	69	75	76(22)
QQQ $\not\to$	Q	$4_2^+ \to 2_1^+$	0.10(5)	0.53	0.5	0.4(1)
QQQQ $\to$	QQQ	$5_1^+ \to 3_1^+$	100	100		
QQQQ $\to$	QQQ	$5_1^+ \to 6_1^+$	71(36)*	37		
QQQQ $\to$	QQQ	$5_1^+ \to 4_2^+$	95(17)	46		
QQQQ $\not\to$	QQ	$5_1^+ \to 4_1^+$	1.9(3)	1.6		
QQQ $\to$	QQ	$0_2^+ \to 2_2^+$	100	100	100	100
QQQ $\not\to$	Q	$0_2^+ \to 2_1^+$	21(9)	21	7.9	7.7(22)
QQQQ $\to$	QQQ	$2_3^+ \to 0_2^+$	100	100	100	100
QQQQ $\not\to$	QQ	$2_3^+ \to 2_2^+$	2.7(17)*	4.2	1.0	2.2(10)*
QQQQ $\not\to$	QQ	$2_3^+ \to 4_1^+$	4.9(29)	10.8	4.5	2.0(8)
QQQQ $\not\to$	Q	$2_3^+ \to 2_1^+$	0.4(2)*	0.001	0.01	0.14(6)*
QQQQ $\not\to$		$2_3^+ \to 0_1^+$	0.26(15)	0.007	0.007	0.13(4)
QQQQ $\to$	QQQ	$2_3^+ \to 3_1^+$	–	68	94	67(25)*
QQQQ $\to$	QQQ	$4_3^+ \to 4_2^+$	100*	100	100	100*
QQQQ $\to$	QQQ	$4_3^+ \to 3_1^+$	23.9(7)	112	111	43.0(13)*
QQQQ $\not\to$	QQ	$4_3^+ \to 4_1^+$	0.08(18)	0.48	0.3	4.5(14)*
QQQQ $\not\to$	QQ	$4_3^+ \to 2_2^+$	4.3(13)	1.85	1.3	2.8(9)

Test with data - 1st relationship



$(Q^2_{2_1^+})$ $(\gamma - \text{band})$ $(\text{yrast} - \text{band})$

$$B(E2; 2_1^+ \rightarrow 2_1^+) + B(E2; 2_2^+ \rightarrow 2_1^+) = B(E2; 4_1^+ \rightarrow 2_1^+)$$

	$B(E2; 2_1^+ \rightarrow 2_1^+)$ $[e^2b^2]$	$B(E2; 2_2^+ \rightarrow 2_1^+)$ $[e^2b^2]$	$(1)+(2)$ $[e^2b^2]$	$B(E2; 4_1^+ \rightarrow 2_1^+)$ $[e^2b^2]$
^{156}Gd	1.296(54)	0.017(1)	1.314(54)	1.312(25)
^{160}Gd	1.51(6)	0.030(2)	1.54(6)	1.47(2)
^{164}Dy	1.43(28)	0.043(4)	1.48(28)	1.45(7)
^{186}Os	0.61^{+9}_{-15}	0.16^{+2}_{-1}	0.77^{+9}_{-15}	0.85^{+4}_{-4}
^{196}Pt	0.08(6)	0.32(2)	0.40(6)	0.41(6)
^{106}Pd	0.10(2)	0.12(1)	0.22(2)	0.21(2)
^{114}Cd	0.05(2)	0.093(6)	0.14(2)	0.20(2)

Test with data - 2nd relationship

$$\frac{10}{7}\left(B(E2;2_1^+\rightarrow 0_1^+)+B(E2;2_1^+\rightarrow 0_{QQ}^+)\right)=B(E2;4_1^+\rightarrow 2_1^+)$$

	$B(E2;2_1^+\rightarrow 0_1^+)$ [e^2b^2]	$B(E2;2_1^+\rightarrow 0_{QQ}^+)$ [e^2b^2]	$10/7\cdot[(1)+(2)]$ [e^2b^2]	$B(E2;4_1^+\rightarrow 2_1^+)$ [e^2b^2]
^{156}Gd	0.933(25)	n.o.	1.332(36)	1.312(25)
^{160}Gd	1.05(1)	n.o.	1.50(1)	1.47(2)
^{164}Dy	1.114(16)	n.o.	1.591(23)	1.45(7)
^{186}Os	0.56(1)	0.008(4)	0.81(1)	0.85(4)
^{196}Pt	0.264(11)	0.004(2)	0.38(1)	0.41(6)
^{106}Pd	0.13(2)	0.027(4)	0.23(2)	0.21(2)
^{114}Cd	0.102(6)	0.090(5)	0.27(1)	0.20(2)

Predictive power for various nuclei

$$Q^2_{2_1^+} = \frac{32\pi}{35}\left(B(E2; 4_1^+ \to 2_1^+) - B(E2; 2_2^+ \to 2_1^+)\right)$$

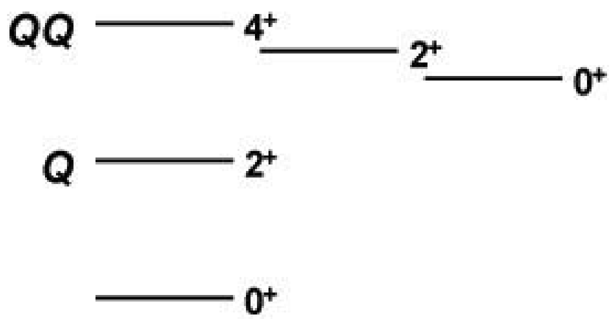
$$B(E2; 0^+_{QQ} \to 2_1^+) = \frac{7}{2}\, B(E2; 4_1^+ \to 2_1^+) - 5\ B(E2; 2_1^+ \to 0_1^+)$$

	$Q^2_{2_1^+}$(exp.) [e^2b^2]	$Q^2_{2_1^+}$(rel.) [e^2b^2]	$B(E2; 0^+_{QQ} \to 2_1^+)$(exp.) [$e^2b^2$]	$B(E2; 0^+_{QQ} \to 2_1^+)$(rel.) [$e^2b^2$]
^{156}Gd	3.72(15)	3.72(7)	n.o.	< 0.08
^{160}Gd	4.33(17)	4.14(6)	n.o.	(< -0.02)
^{164}Dy	4.12(81)	4.04(20)	n.o.	(< -0.2)
^{186}Os	1.76^{+26}_{-44}	1.98(13)	0.040(20)	0.18(15)
^{196}Pt	0.24(18)	0.26(18)	0.02(1)	0.12(21)
^{106}Pd	0.30(6)	0.26(6)	0.14(2)	0.09(12)
^{114}Cd	0.13(6)	0.31(6)	0.090(5)	0.19(8)

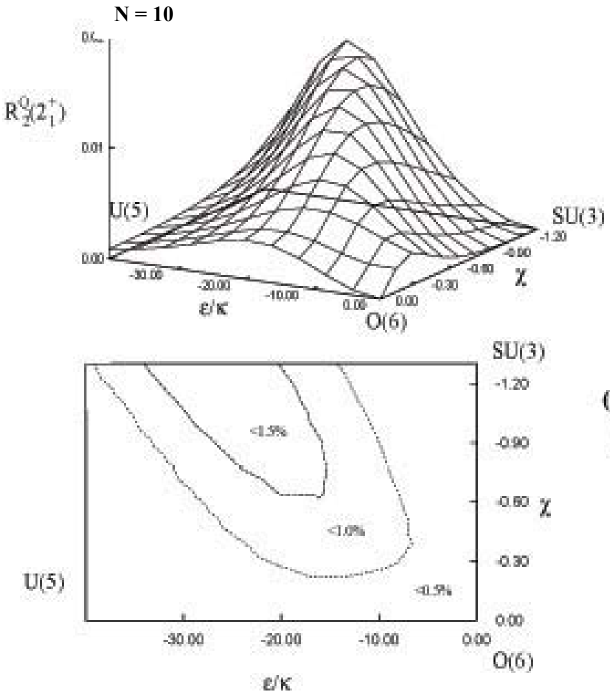
Q-phonon scheme

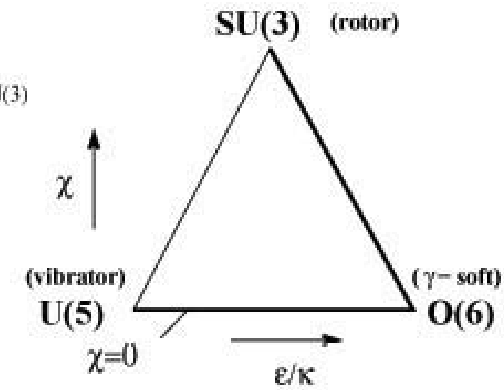
$$|2_1^+\rangle \propto \mathbf{Q}\ |0_1^+\rangle$$

$$|J^+\rangle \propto (\mathbf{QQ})^{(J)}\ |0_1^+\rangle \propto (\mathbf{Q}\ |2_1^+\rangle)^{(J)}$$



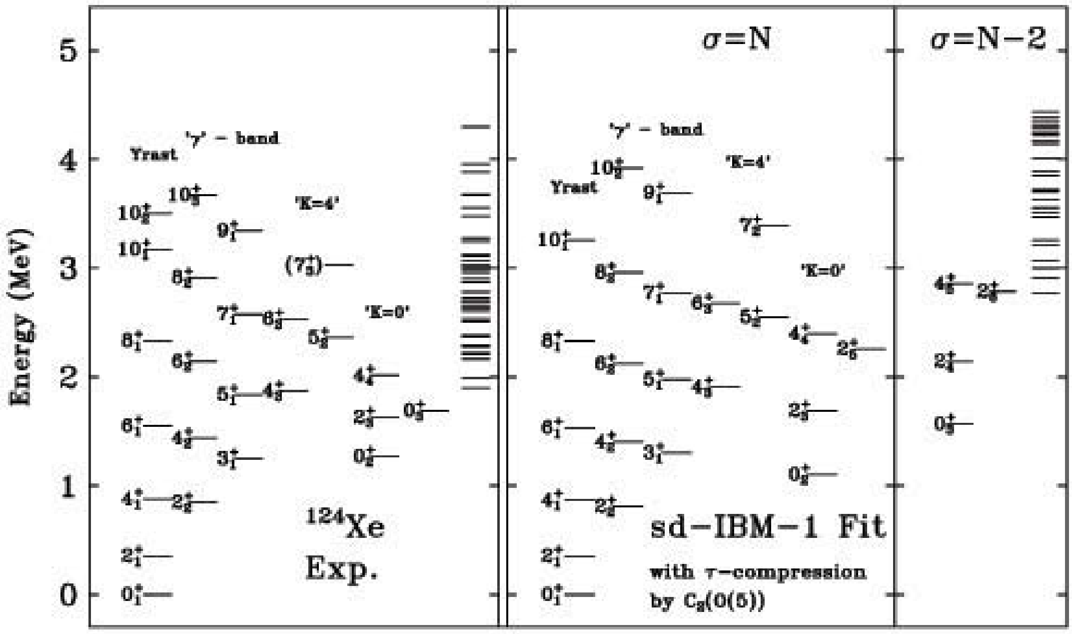
E2 transitions: $\Delta Q = 1$





N. Pietralla et al., Phys. Rev. **C57** (1998) 150

^{124}Xe



$$
\begin{aligned}
\mathbf{H}_{\tau-\mathbf{ECQF}} &= \epsilon \mathbf{n_d} + \lambda \mathbf{LL} + \kappa \mathbf{Q}^\chi \mathbf{Q}^\chi + \beta \mathbf{C_2}(\mathbf{O(5)}) \\
&= \kappa \left(\frac{\epsilon}{\kappa} \mathbf{n_d} + \frac{\tilde{\lambda}}{\kappa} \mathbf{LL} + \mathbf{Q}^\chi \mathbf{Q}^\chi + \mathbf{4} \frac{\beta}{\kappa} \mathbf{T}^{(3)} \mathbf{T}^{(3)} \right)
\end{aligned}
$$

$$
\epsilon/\kappa = -20.9\ ,\ \chi = -0.257\ ,\ \beta/\kappa = 0.563\ ,\ \lambda/\kappa = -0.284
$$
$$
\kappa = -34.91 keV\ ,\ e_b = 0.14224 e^2 b^2
$$

V. Werner et al., Nucl. Phys. **A693** (2001) 451

^{124}Xe

ΔQ	$I_i \to I_f$	^{124}Xe exp.	^{124}Xe IBM	^{134}Ce exp.	^{134}Ce IBM	^{190}Os exp.	^{190}Os IBM
1	$2_2^+ \to 2_1^+$	100	100	100	100	100	100
2	$2_2^+ \to 0_1^+$	2.4(4)	2.4	5.4	5.4	17.9(6)	18.1
1	$3_1^+ \to 2_2^+$	100*	100	54.5	100	100	100
1	$3_1^+ \to 4_1^+$	32(6)*	32	100	30.4	45(7)	16
2	$3_1^+ \to 2_1^+$	3.0(4)*	2.9	4	6	7.1(6)	10.2
1	$4_2^+ \to 2_2^+$	100	100	100	100	100	100
1	$4_2^+ \to 4_1^+$	49(7)	69	55	63	57(6)	41
2	$4_2^+ \to 2_1^+$	0.10(5)	0.53	0.6	2.0	1.29(5)	3.0
1	$5_1^+ \to 3_1^+$	100	100	100 (5_2^+)	100	100	100
1	$5_1^+ \to 6_1^+$	71(36)*	35	–	35	–	21
1	$5_1^+ \to 4_2^+$	95(17)	46	–	48	–	58
2	$5_1^+ \to 4_1^+$	1.9(3)	2.2	≤ 7.5	4.3	5(2)	8
1	$0_2^+ \to 2_2^+$	100	100	100	100	100	100
2	$0_2^+ \to 2_1^+$	21(9)	21	≤ 2.7	2.7	9.9(18)	9.7
	$2_3^+ \to 0_2^+$	100	100	100	100	100	100
	$2_3^+ \to 3_1^+$	–	117	–	117	27(5)	101
	$2_3^+ \to 2_2^+$	2.7(17)*	2.9	≤ 32	0.3	–	0.06
	$2_3^+ \to 4_1^+$	4.9(29)	12.5	–	2.0	–	5.8
	$2_3^+ \to 2_1^+$	0.4(2)*	0.001	0.7	0.0003	0.6(2)	0.04
	$2_3^+ \to 0_1^+$	0.26(15)	0.19	0.5	0.04	0.19(2)	0.34
	$4_3^+ \to 4_2^+$	100*	100	100	100	52(18)*	105
	$4_3^+ \to 3_1^+$	23.9(7)	114	120(70)	104	100	100
	$4_3^+ \to 6_1^+$	–	2.2	–	1.8	–	1.8
	$4_3^+ \to 4_1^+$	0.08(18)	0.69	13(8)	0.52	0.31(3)*	0.52
	$4_3^+ \to 2_2^+$	4.3(13)	2.45	4(2)	7	27.8(13)	26.3
	$4_3^+ \to 2_1^+$	–	0.01	0.05(3)	0.01	0.004(1)*	0.08

Experimental nuclear spectroscopy:

Measurement of lifetimes

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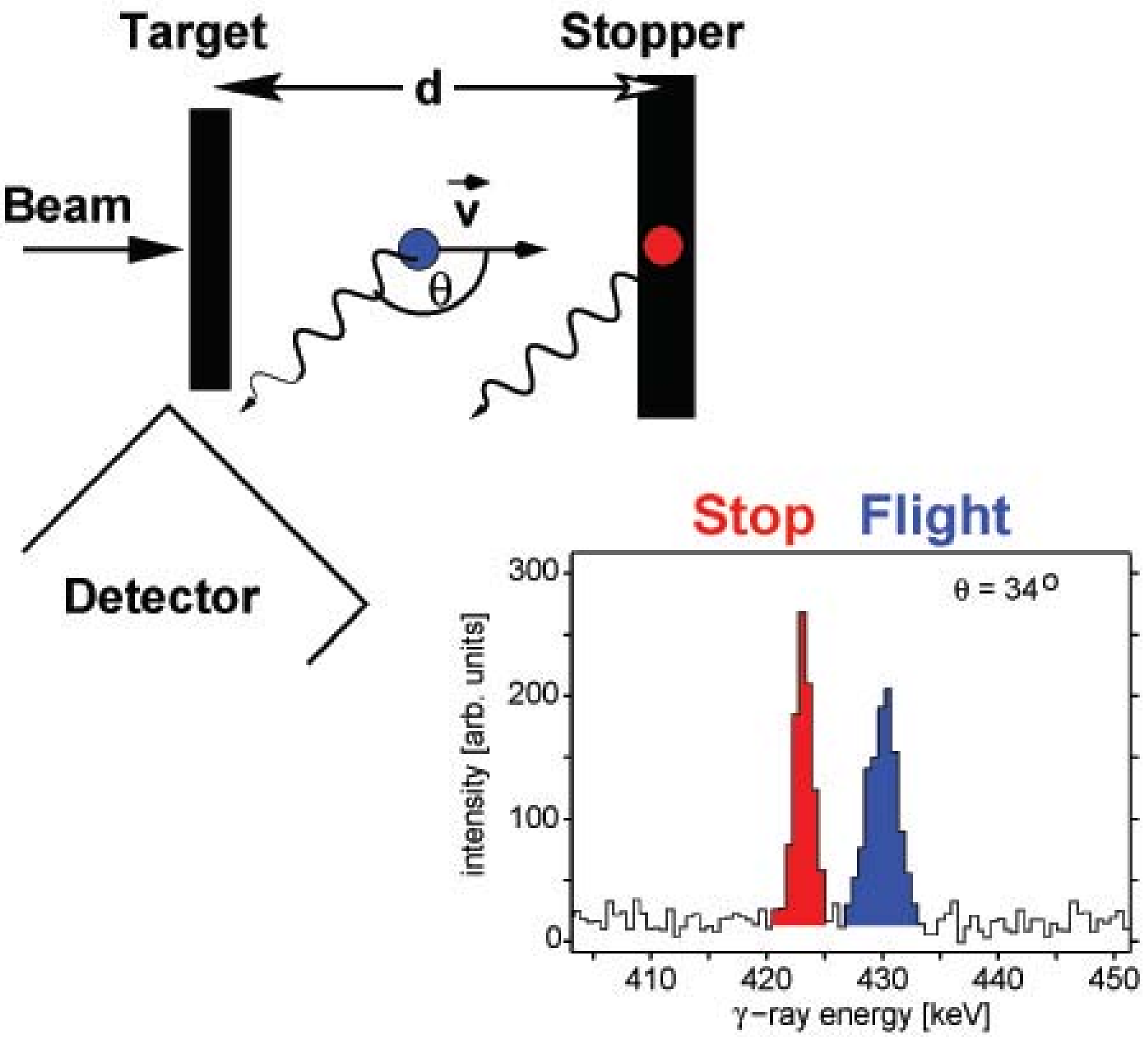
IKP University
Cologne, Germany

E-mail: brentano@ikp.uni-koeln.de

RDDS Method

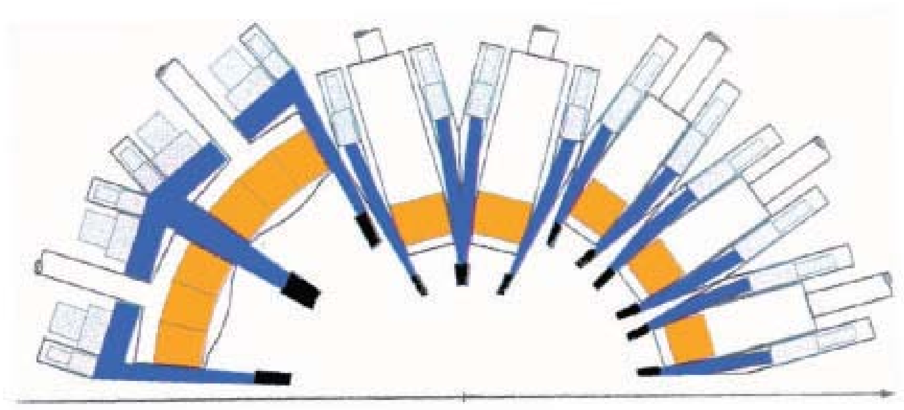
Recoil **D**istance **D**öppler-**S**hift
→ lifetimes in ps range

$$E_{Flight} \approx E_{Stop}\left(1+\frac{v}{c}\cos\theta\right)$$



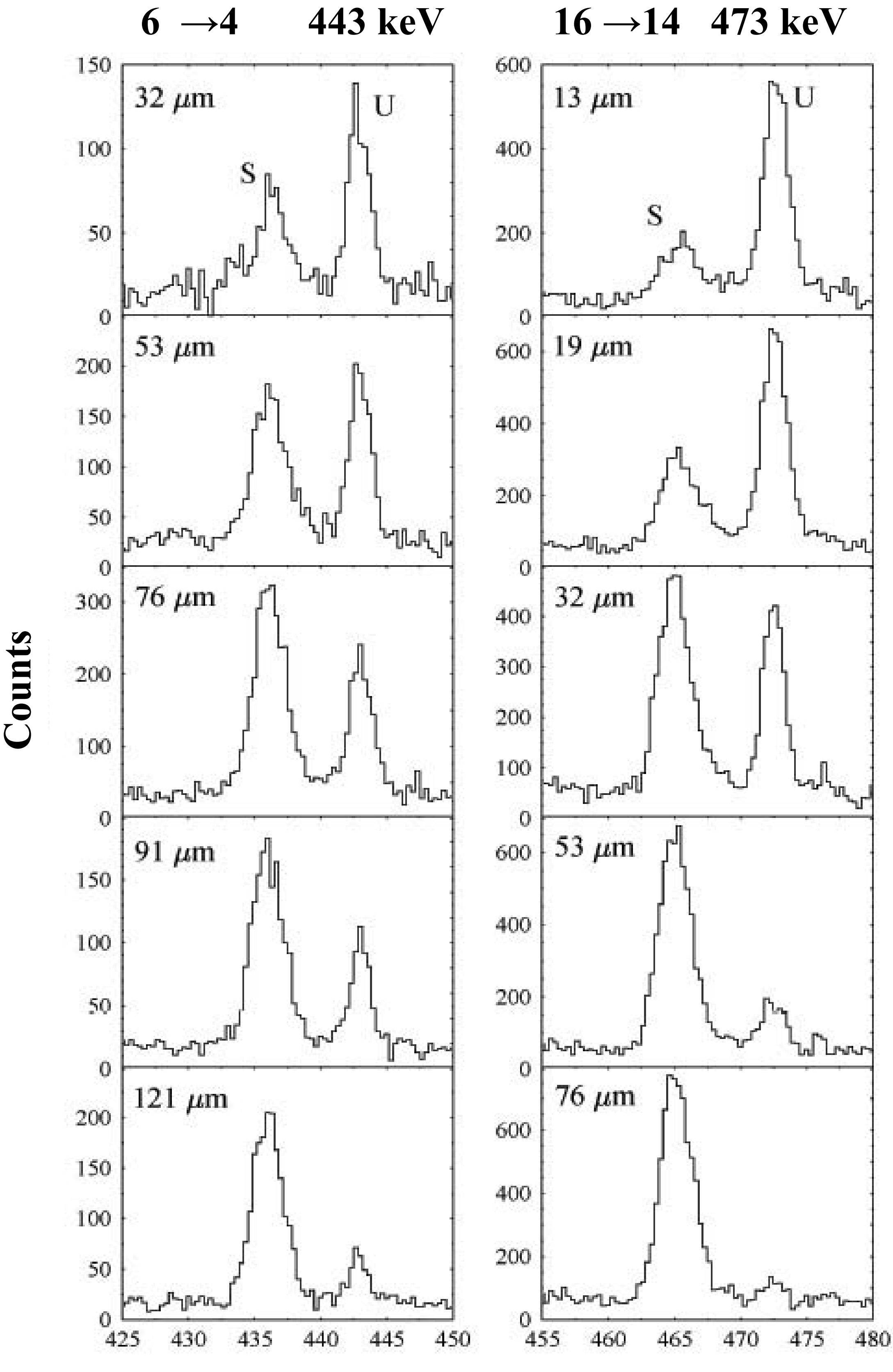
^{46}V: EUROBALL Experiment

RDDS-lifetime measurement with Köln Plunger
at Euroball IV, Strasbourg



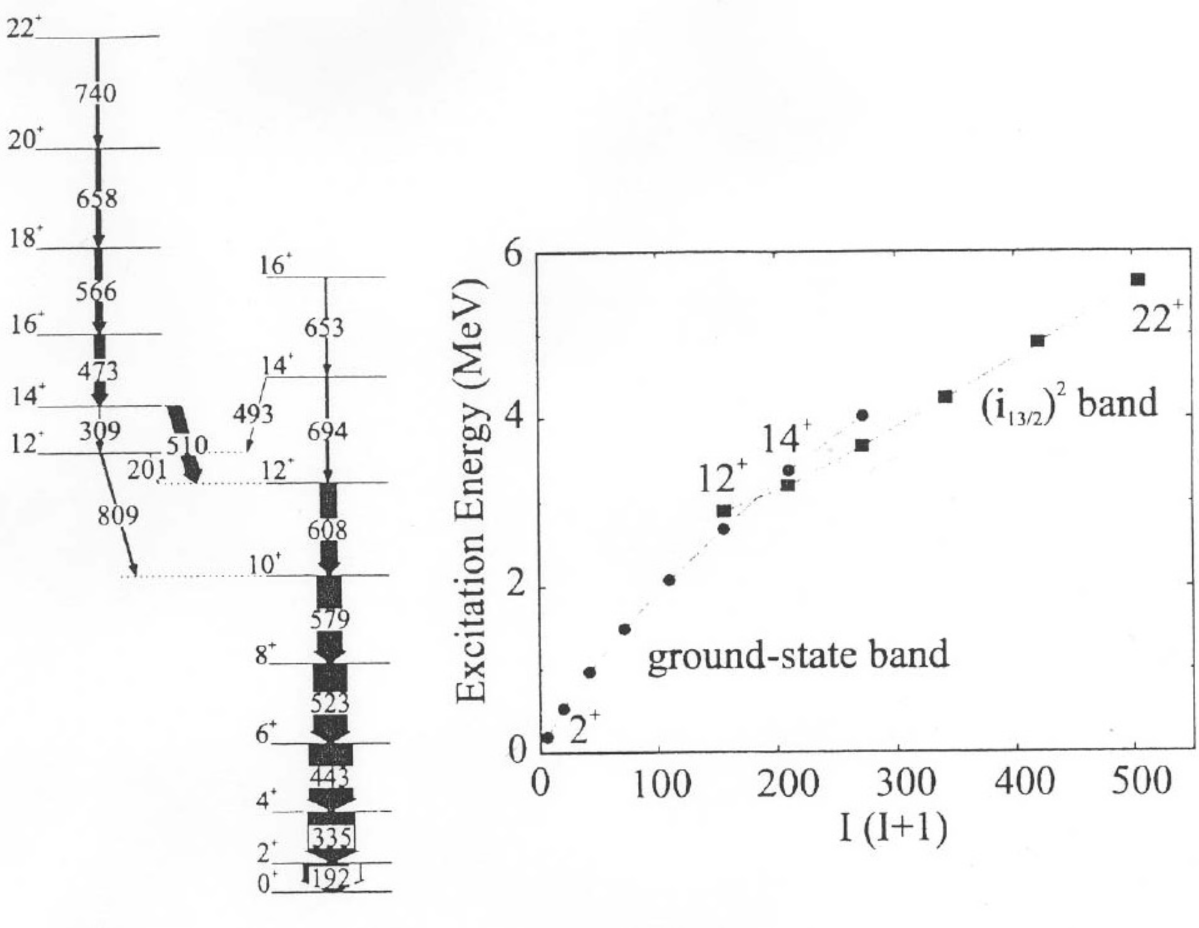
- $^{24}Mg(^{28}Si, \alpha pn)^{46}V$ at 110 MeV
  ⇒ $v/c = 4.5\%$
- 17 target-to-stopper distances between 1 and 7750 µm
- 3 x 10^9 γγ-events

Analysis of γγ-coincidence data using the
Differential Decay Curve Method



6 →4 443 keV
16 →14 473 keV
Counts
32 μm
53 μm
76 μm
91 μm
121 μm
13 μm
19 μm
32 μm
53 μm
76 μm
S
U
S
U

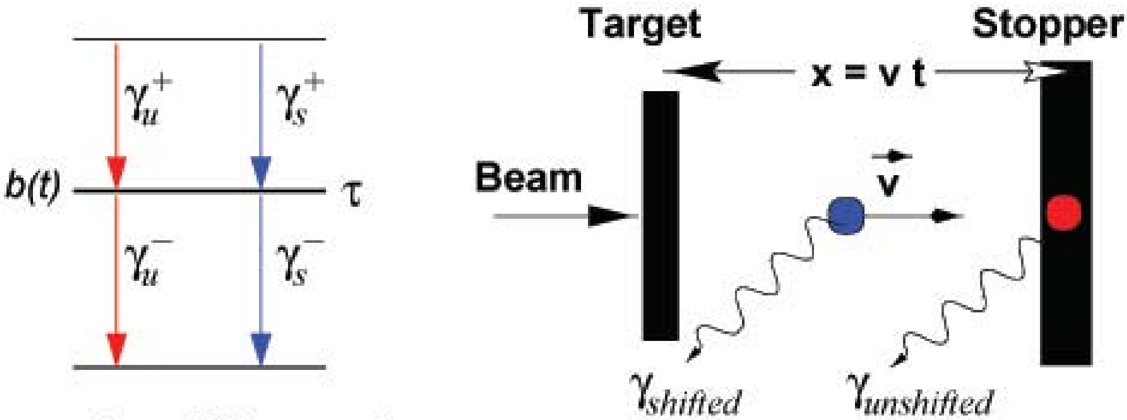
Gamma-ray energy [keV]



Lifetimes from Döppler-shifted Spectra using RDDS data

Quantitative analysis of ^{158}Er

Recoil Distance Döppler Shift Data



$$\#\gamma_u^+(t)\Big|_t^\infty = B_u^+(t),$$

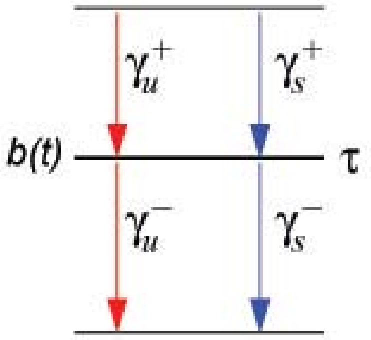
$$\#\gamma_u^-(t)\Big|_t^\infty = B_u^-(t)$$

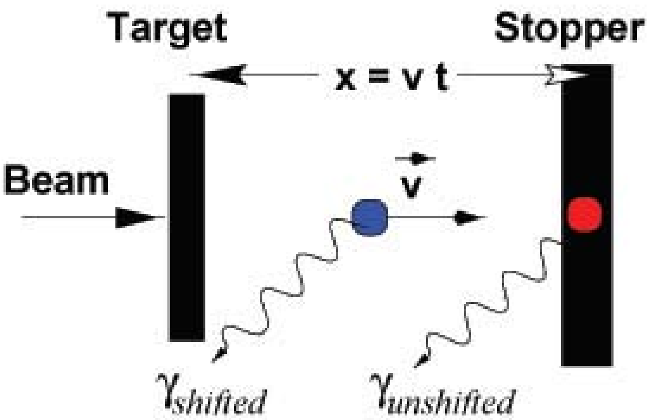
$$B_u^+(t) + b(t) = B_u^-(t)$$

$$B_u^-(t) = \int_t^\infty \frac{1}{\tau}\, b(t)dt \quad \Rightarrow \quad \dot{B}_u^-(t) = -\frac{1}{\tau}\, b(t)$$

$$\Rightarrow \quad \boxed{\dot{B}_u^- = -\tfrac{1}{\tau}\left(B_u^- - B_u^+\right)}$$

Lifetimes from γγ-coincidences





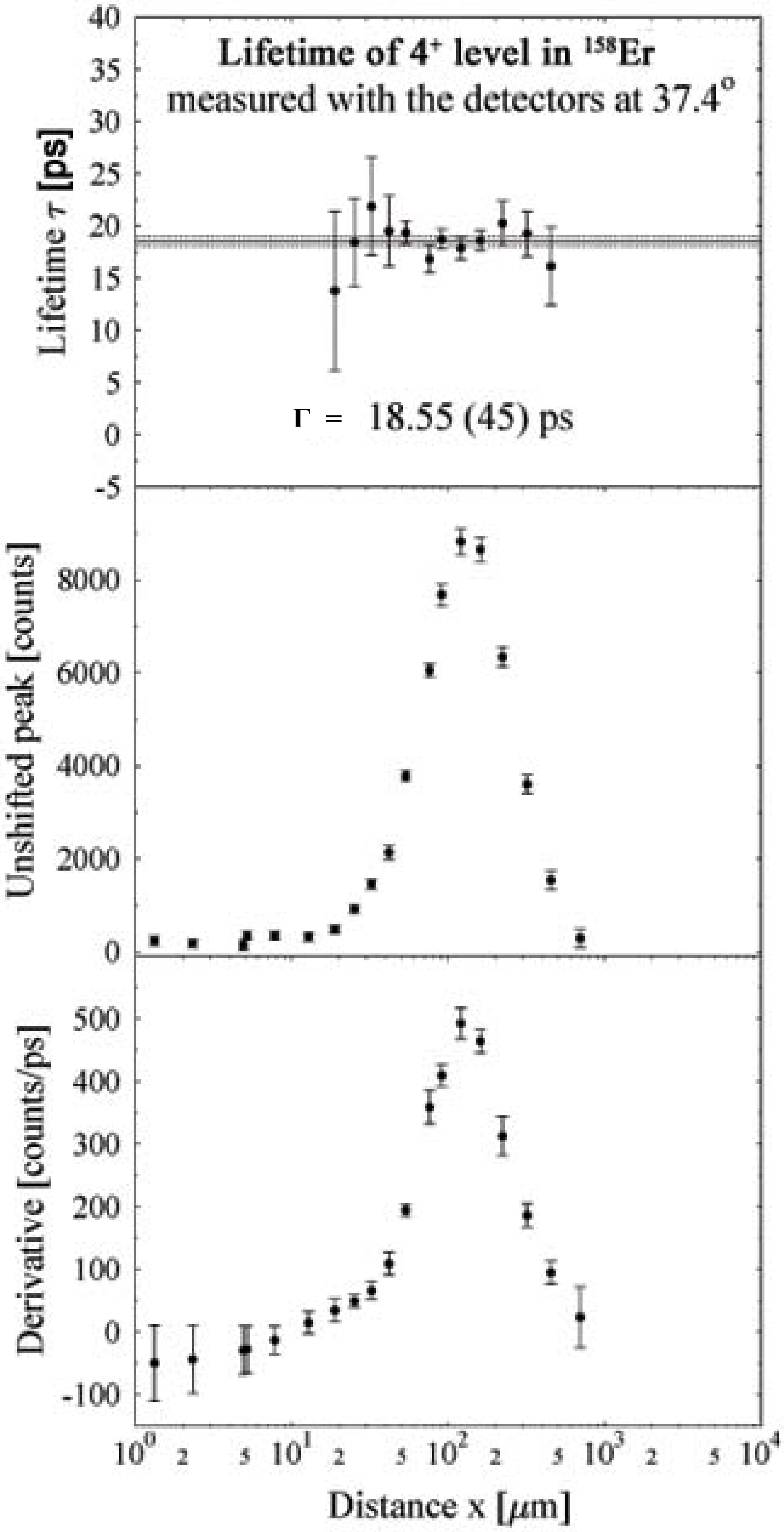
$$\{\gamma_1, \gamma_2\} := \#\gamma_2 \text{ in coincidence with } \gamma_1$$

$$B_u^+ = \{\gamma_u^+, \gamma_{u+s}^-\} = \{\gamma_u^+, \gamma_u^-\} + \underbrace{\{\gamma_u^+, \gamma_s^-\}}_{=0}$$

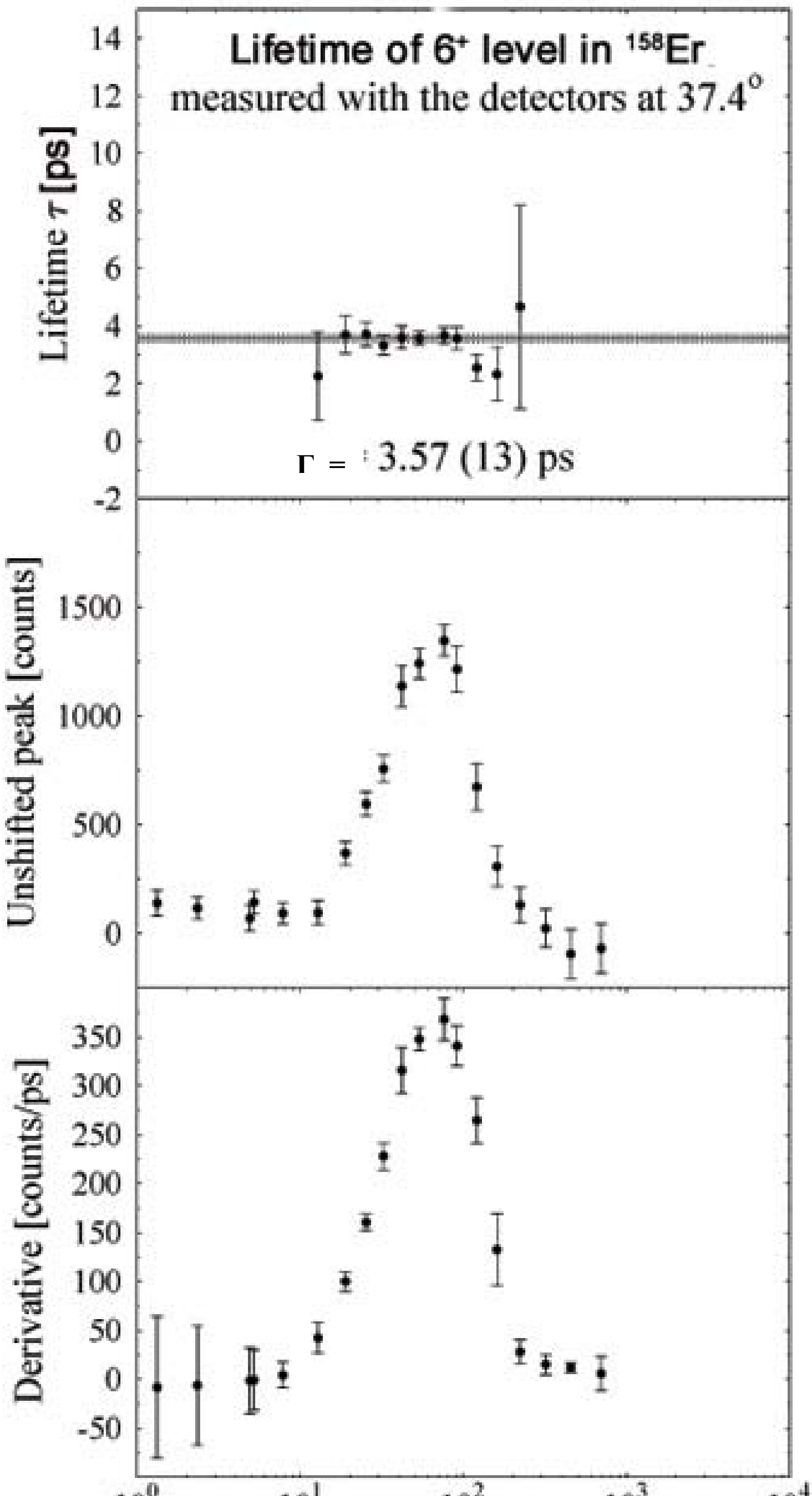
$$B_u^- = \{\gamma_{u+s}^+, \gamma_u^-\} = \{\gamma_u^+, \gamma_u^-\} + \{\gamma_s^+, \gamma_u^-\}$$

$$\{\gamma_{u+s}^+, \gamma_{u-s}^+\}^\bullet = 0 \qquad \Rightarrow \qquad \dot{B}_u^- = -\{\gamma_s^+, \gamma_s^-\}^\bullet$$

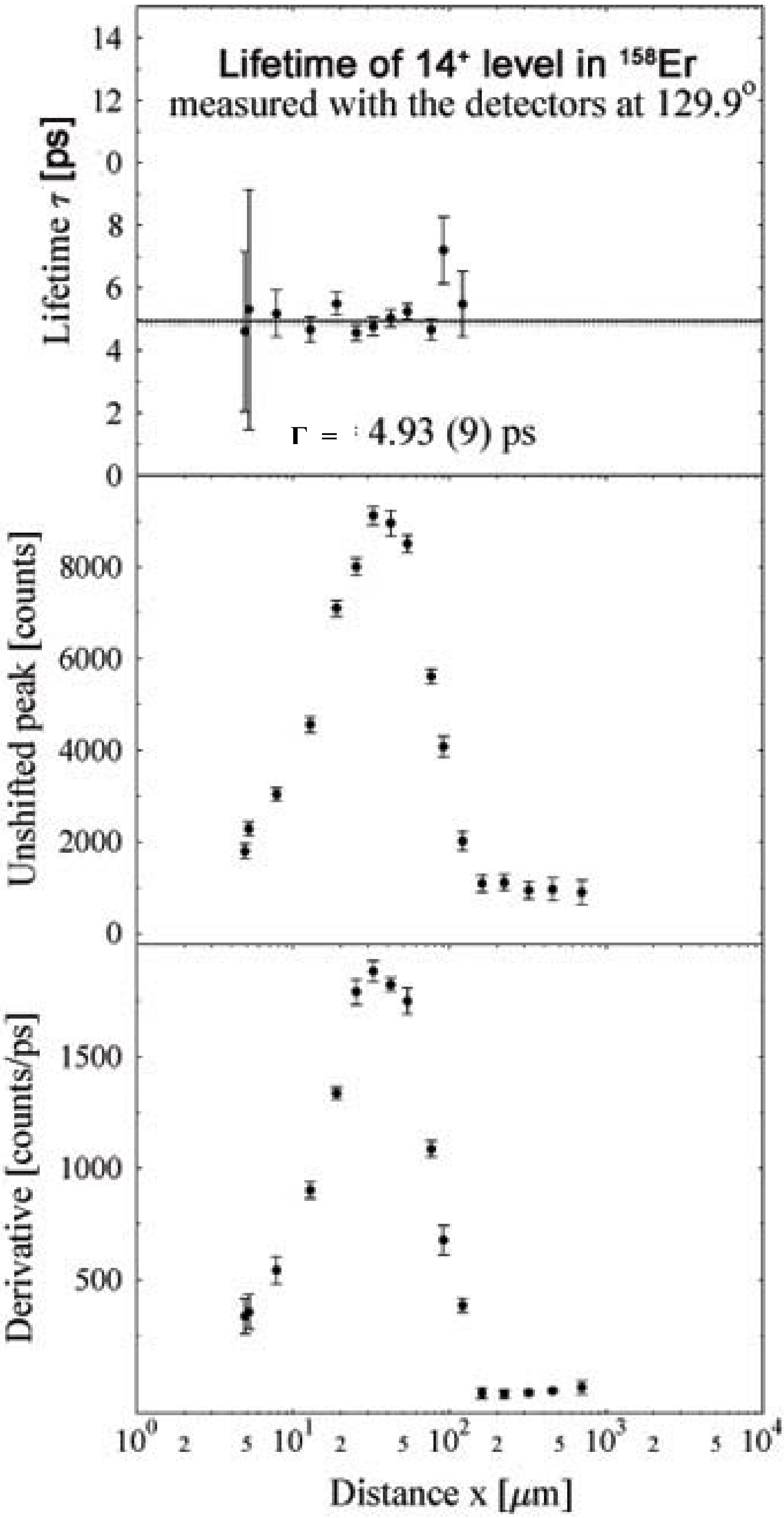
$$\dot{B}_u^- = -\tfrac{1}{\tau}\left(B_u^- - B_u^+\right) \quad \Rightarrow \quad \boxed{\{\gamma_s^+, \gamma_s^-\}^\bullet = \tfrac{1}{\tau}\{\gamma_s^+, \gamma_u^-\}}$$



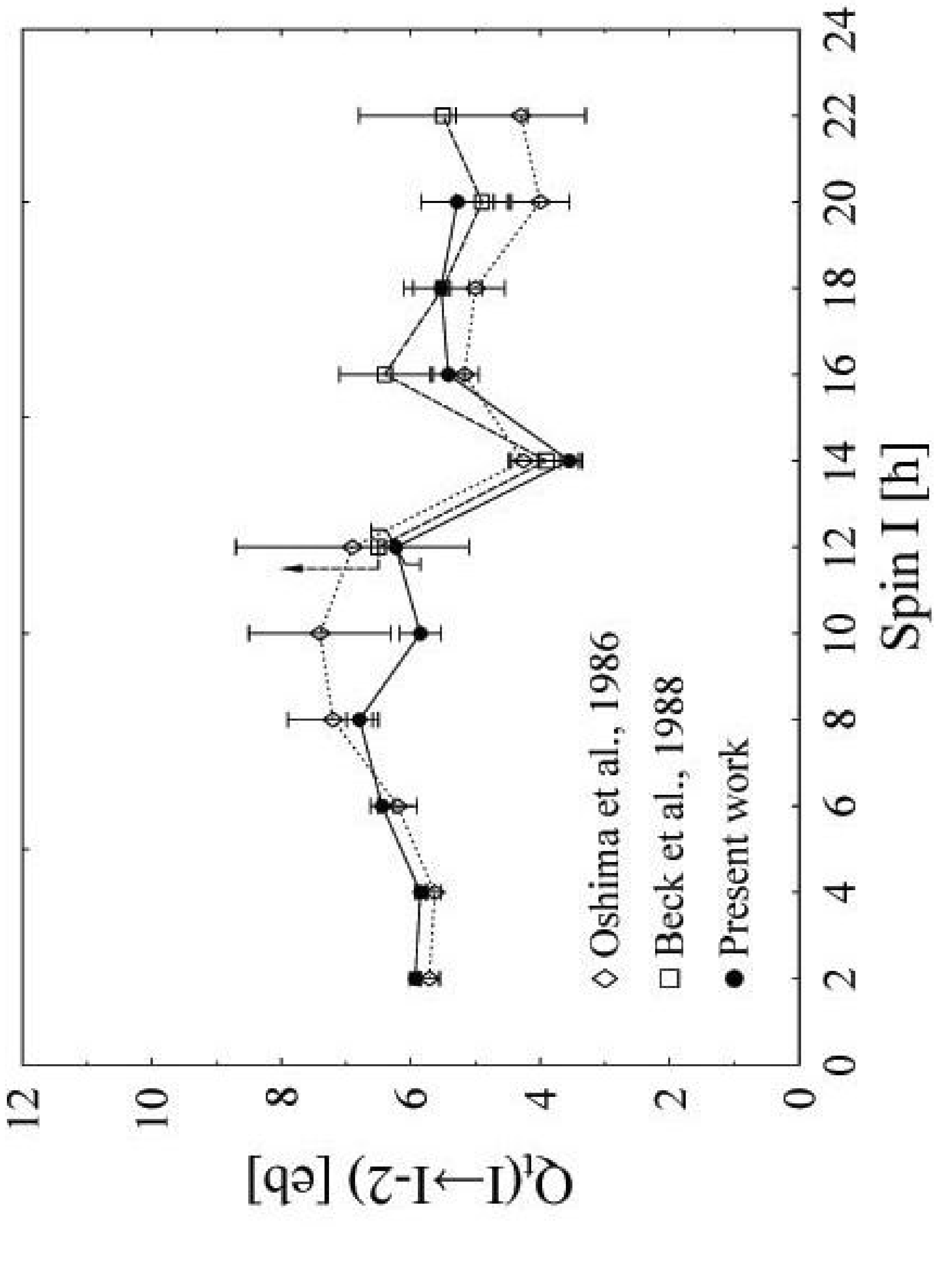
Lifetime of 4+ level in 158Er
measured with the detectors at 37.4°
Lifetime τ [ps]
Γ = 18.55 (45) ps
Unshifted peak [counts]
Derivative [counts/ps]
Distance x [μm]



Lifetime of 6+ level in 158Er
measured with the detectors at 37.4°
Lifetime τ [ps]
Γ = 3.57 (13) ps
Unshifted peak [counts]
Derivative [counts/ps]
Distance x [μm]



Lifetime of 14+ level in 158Er
measured with the detectors at 129.9°
Lifetime τ [ps]
τ = 4.93 (9) ps
Unshifted peak [counts]
Derivative [counts/ps]
Distance x [μm]

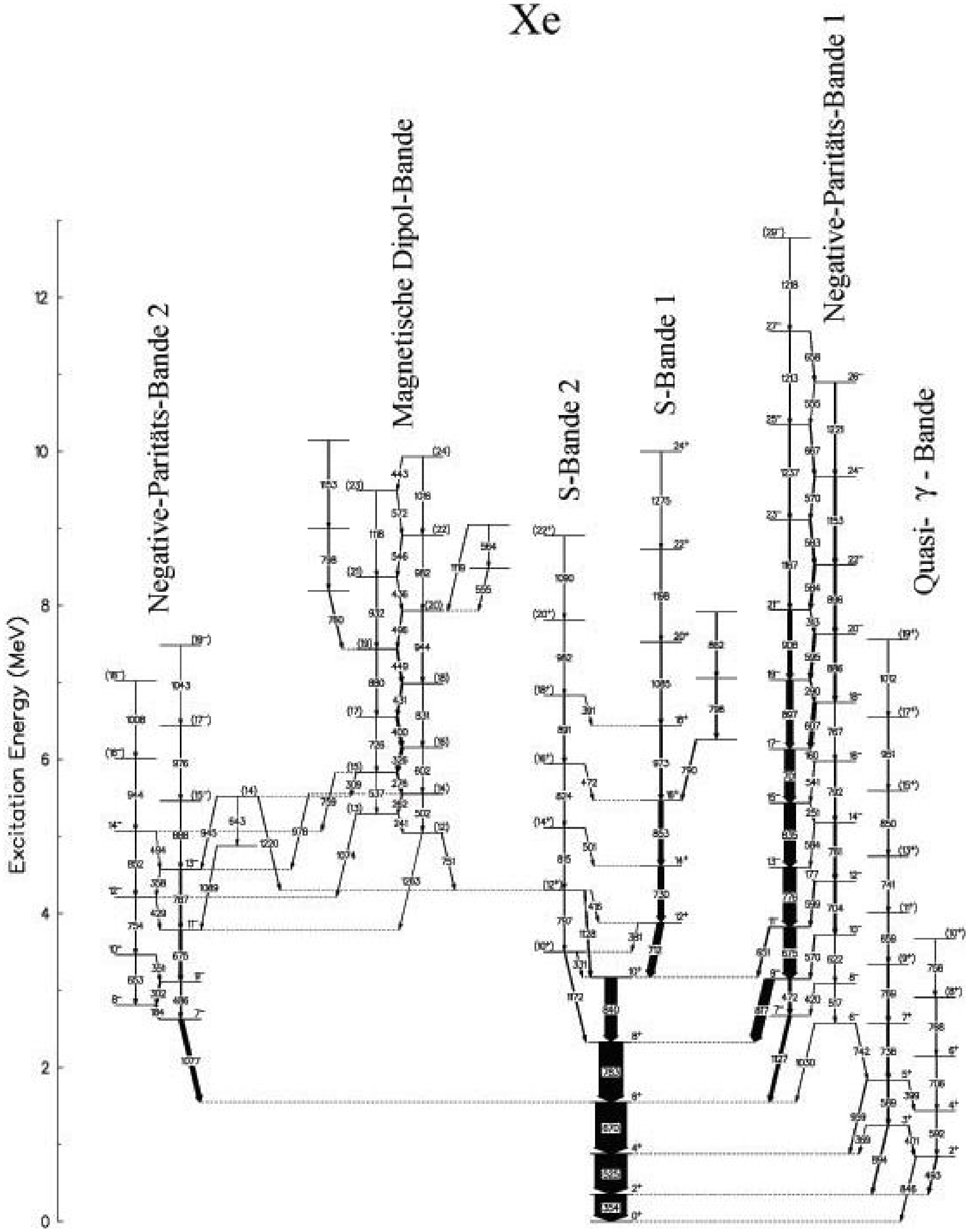


Oshima et al., 1986
Beck et al., 1988
Present work
Spin I [h]
Q_t(I→I-2) [eb]

Lifetimes from Döppler-shifted Spectra using RDDS data

Quantitative analysis of *Xe* isotopes

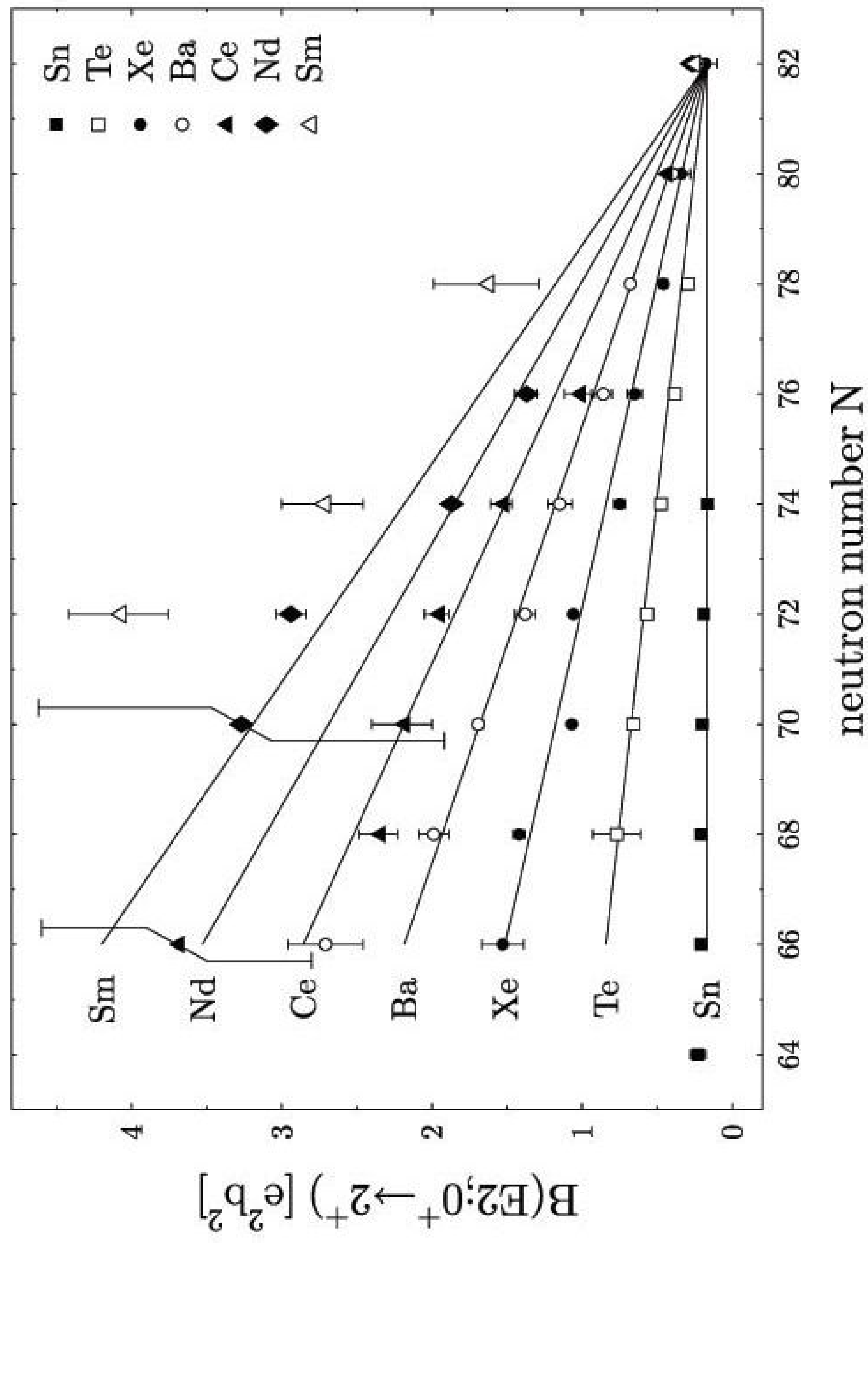
^{124}Xe

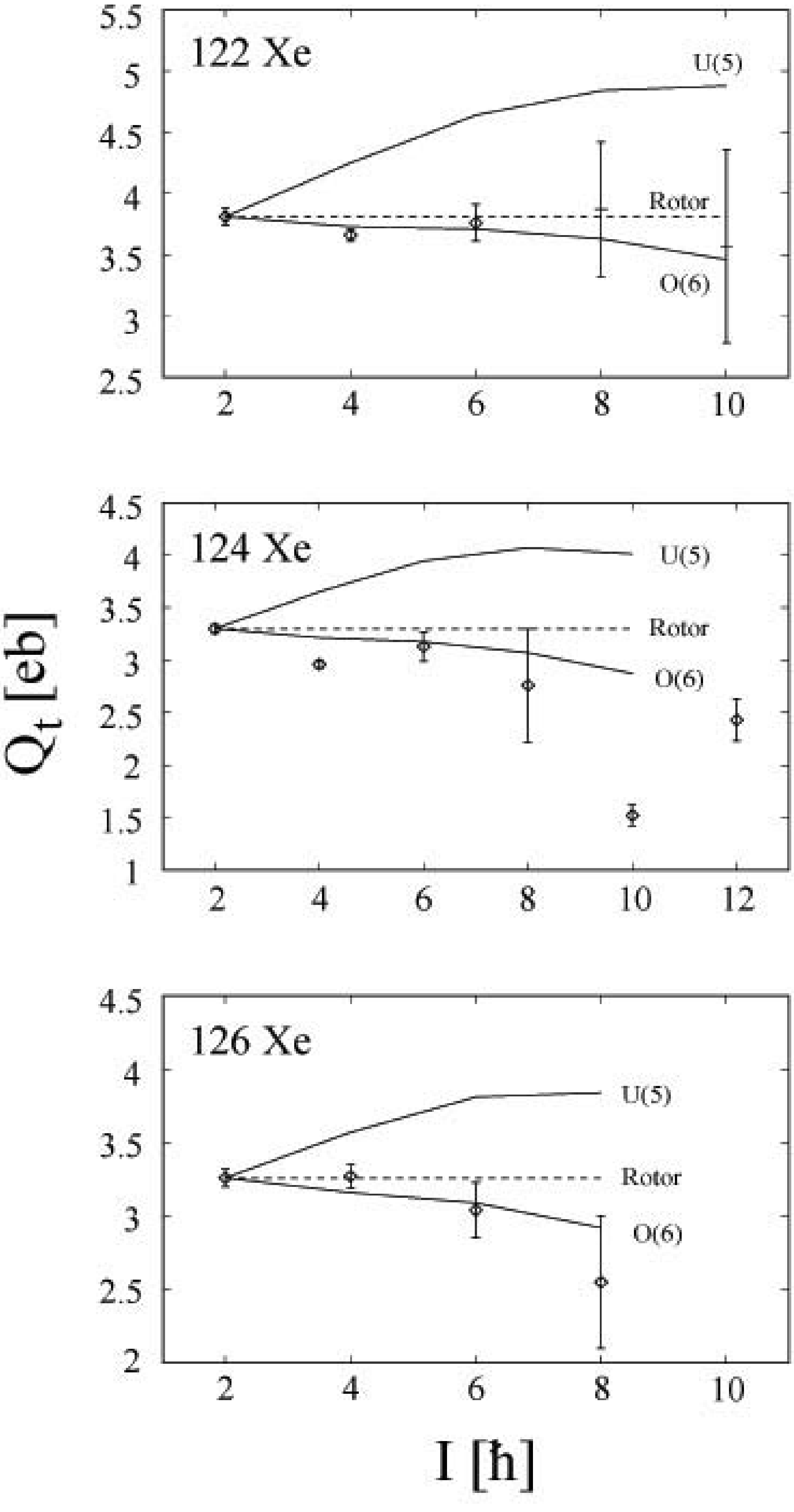


Excitation Energy (MeV)
Negative-Paritäts-Bande 2
Magnetische Dipol-Bande
S-Bande 2
S-Bande 1
Negative-Paritäts-Bande 1
Quasi- γ - Bande

^{124}Xe Lifetimes (τ)

E_{lev} $[keV]$	I^{π} $[\hbar]$	$\overline{\tau}(\Delta\overline{\tau})$ $[ps]$	$\overline{\tau}_c(\Delta\overline{\tau}_c)$ $[ps]$
354	2^+	67.5(17)	67.5(17)
879	4^+	8.19(23)	8.19(23)
1549	6^+	1.82(17)	1.86(16)
2331	8^+	1.03(39)	1.15(35)
3172	10^+	2.49(33)	2.51(32)
3883	12^+	2.13(37)	2.16(36)
4299	12^+	> 2.5	> 2.5
5552.7	(15)	0.89(8)	1.02(8)
5828.3	(16)	1.84(13)	1.88(12)
6154.8	(17)	1.75(8)	1.80(8)
6554.6	(18)	0.40(8)	0.56(9)


B(E2;0+→2+) [e2b2]
neutron number N
0
1
2
3
4
64
66
68
70
72
74
76
78
80
82
Sn
Te
Xe
Ba
Ce
Nd
Sm
Sn
Te
Xe
Ba
Ce
Nd
Sm


122 Xe
U(5)
Rotor
O(6)
124 Xe
U(5)
Rotor
O(6)
126 Xe
U(5)
Rotor
O(6)
Q_t [eb]
I [ħ]

Lifetimes of highly excited states from NRF: S-Dalinac, Darmstadt and Dynamitron, Stuttgart

NRF = Nuclear resonance fluorescence

NRF = Resonant inelastic photon scattering

NRF = $A(\gamma,\gamma)A*$

Resonance reaction:

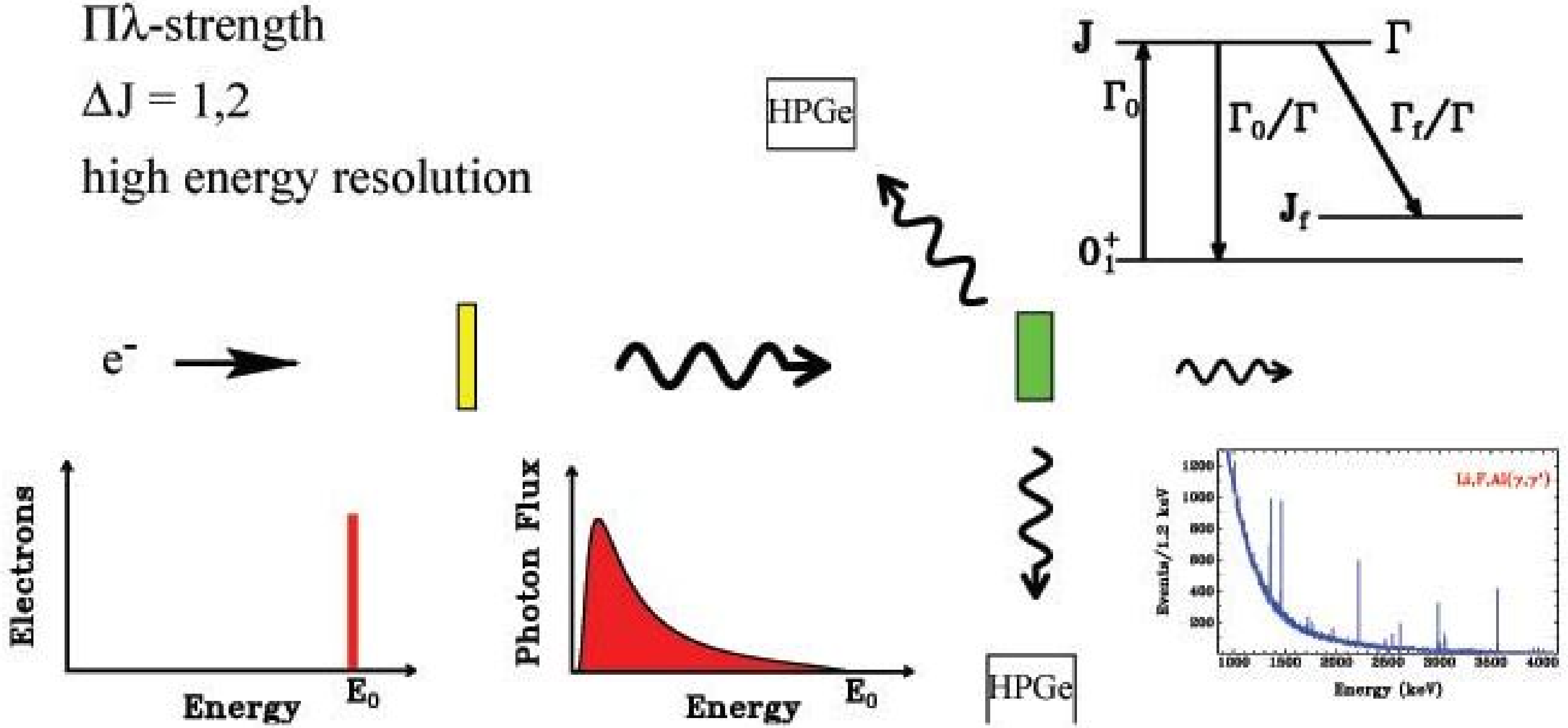
$A + \gamma \rightarrow A_{**}(E,I) \rightarrow \gamma + A_*$

Photon Scattering Technique
(Nuclear Resonance Fluorescence)

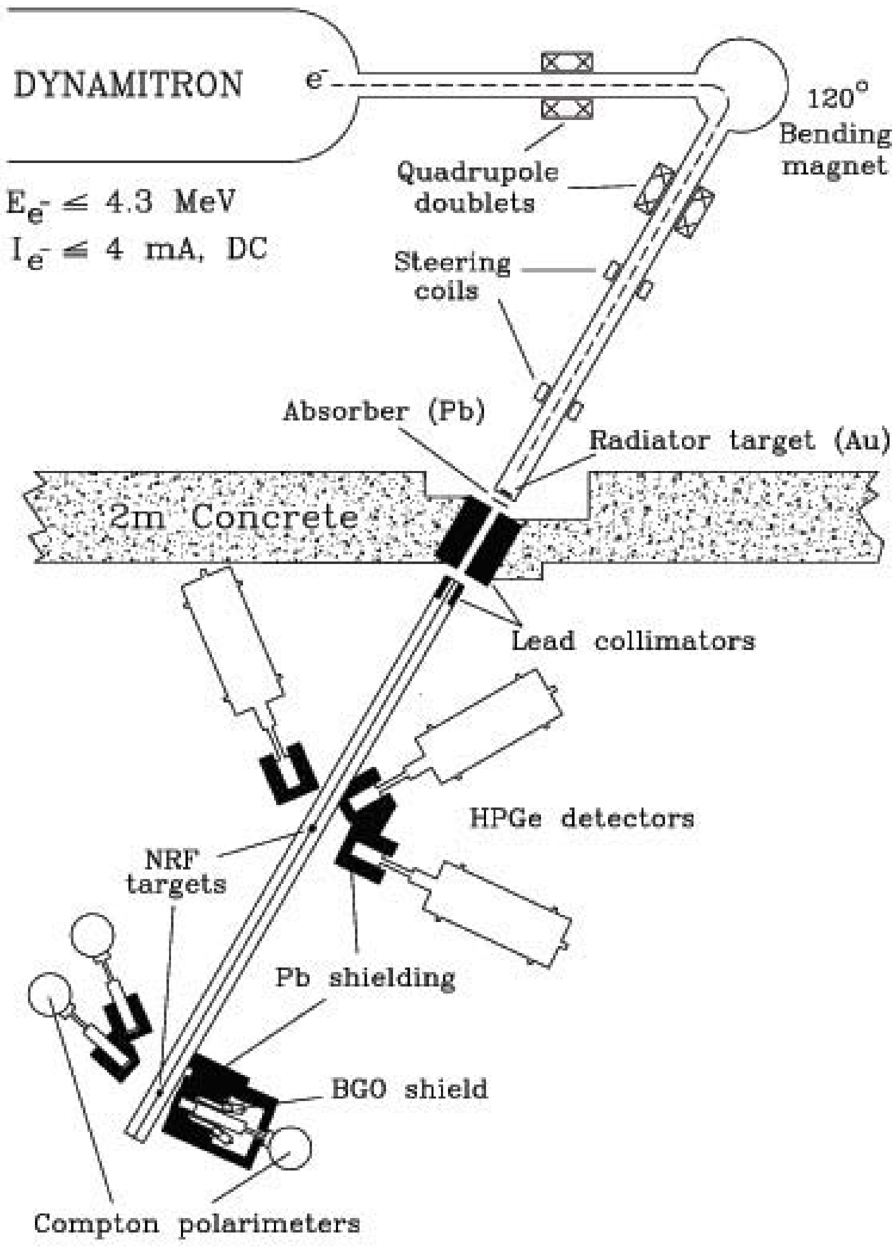
Πλ-strength

ΔJ = 1,2

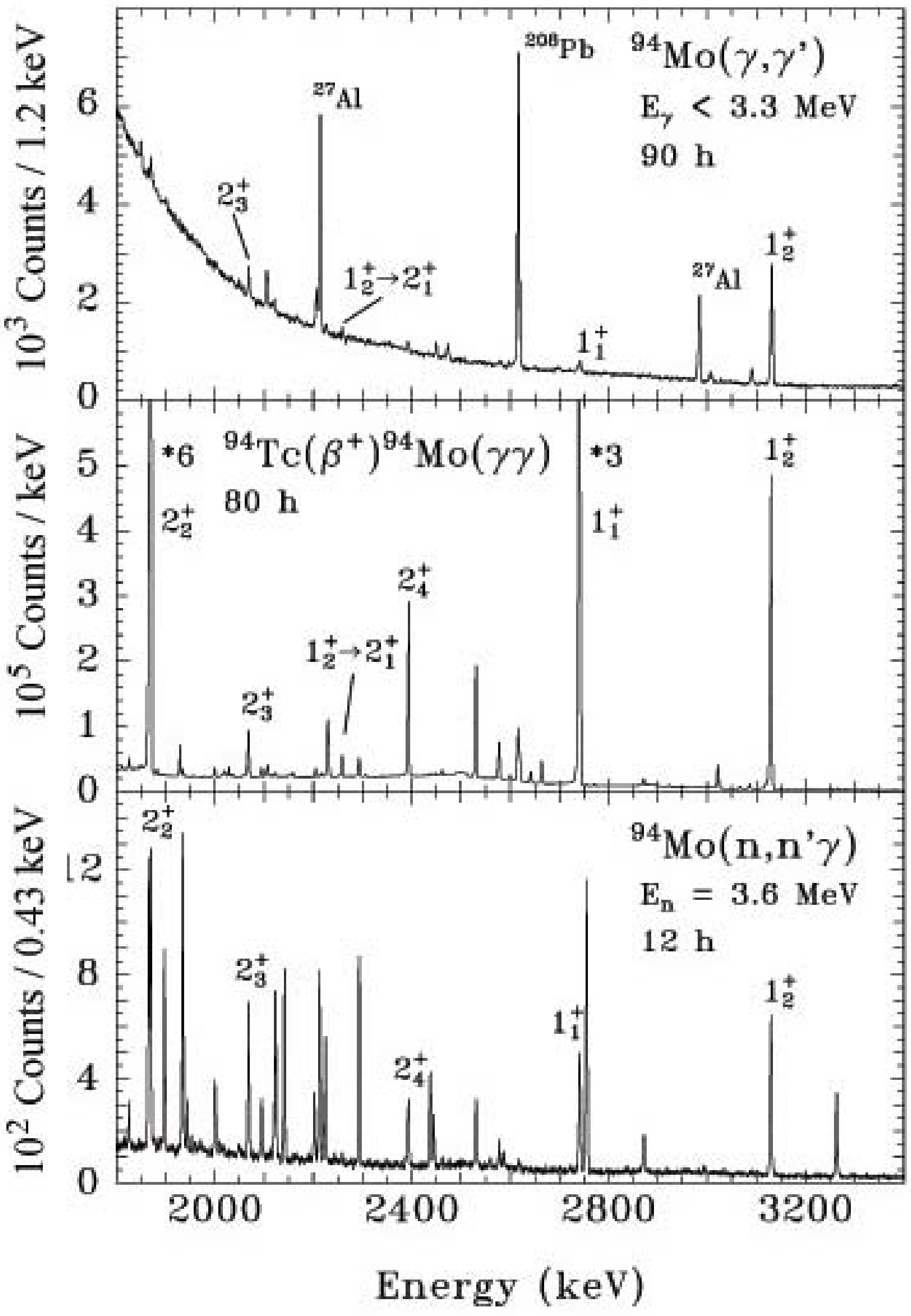
high energy resolution



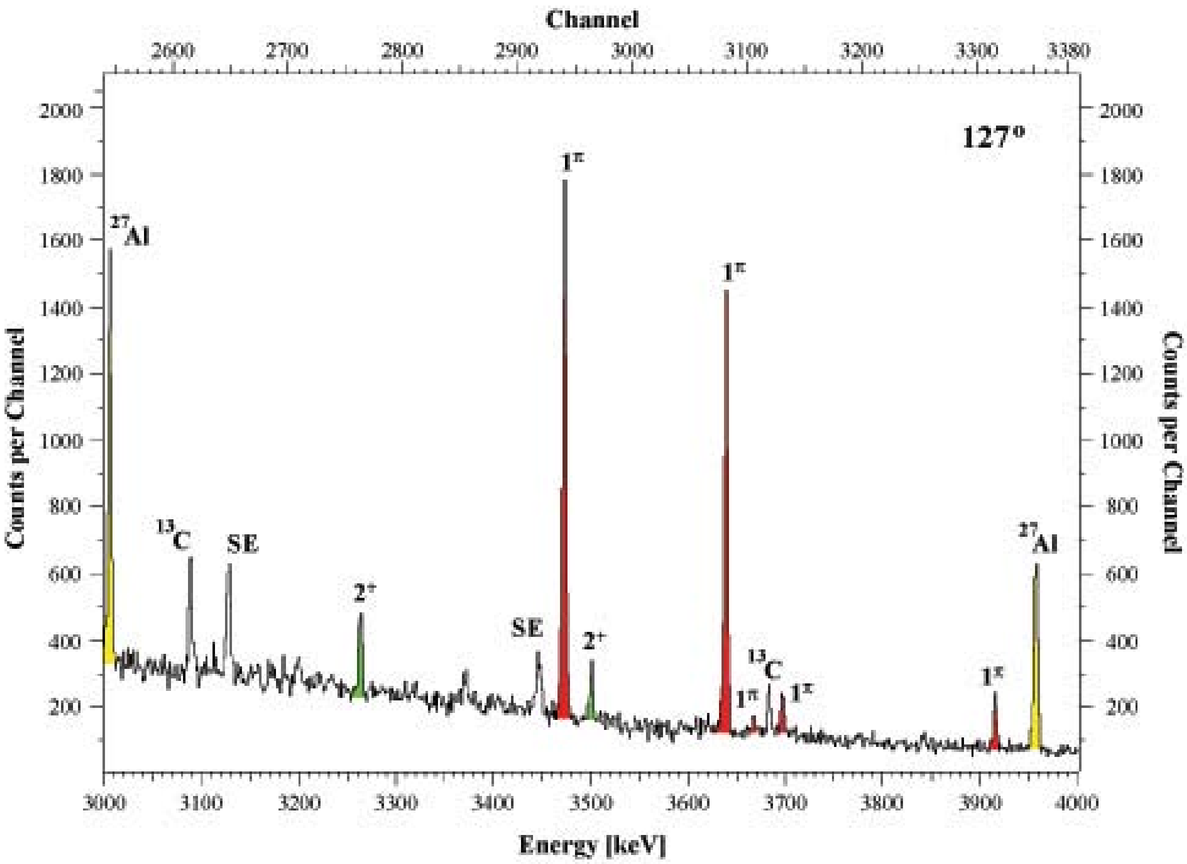
NRF – setup at the Stuttgart Dynamitron



γ–ray spectra of ^{94}Mo From different experiments



$^{92}Zr\ (\gamma, \gamma')$



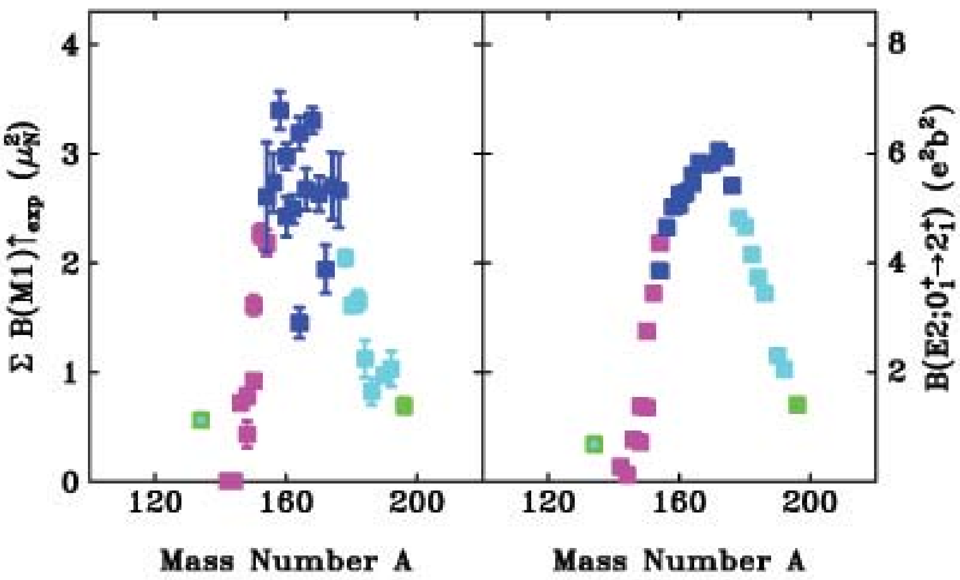
^{92}Zr (γ, γ′)

E_{Level} [keV]	J_i^π	J_f^π	$I_{s,0}$ [eV·b]	Γ_0 [meV]	Γ_f/Γ_0	δ	$B(\Pi\lambda)$	τ [fs]
				^{92}Zr				
1847.6(5)	2_2^+	0_1^+	2.4(3)	1.6(4)	1.0	E2	E2 3.7(8)[c]	118^{+33}_{-21}
		2_1^+			2.6(6)	$+0.032^{+22}_{-21}$	M1 0.46(15)[a]	
							E2 0.3(1)[c]	
3263.2(5)	2^+	0_1^+	3.1(2)	7.4(7)	1.0	E2	E2 1.0(1)[c]	20.6^{+22}_{-18}
		2_1^+			3.3(3)	-0.27^{+9}_{-5}	M1 0.16(2)[a]	
							E2 1.2(2)[c]	
3370(1)	$1^{(-)a}$	0_1^+	1.5(2)	1.45(17)	1.0	Π1	M1 0.0033(4)[a]	455^{+61}_{-48}
							E1 0.037(4)[b]	
3472.3(5)	1^{+a}	0_1^+	27.6(10)	45.2(18)	1.0	Π1	M1 0.094(4)[a]	9.3^{+4}_{-4}
							E1 1.04(4)[b]	
		2_1^+			0.37(2) (Π1)			
		0_2^+			0.19(2)	Π1	M1 0.08(1)[a]	
							E1 0.9(1)[b]	
3500.4(5)	2^+	0_1^+	2.7(2)	1.75(15)	1.0	E2	E2 0.17(1)[c]	376^{+35}_{-29}
3638.4(5)	1	0_1^+	37.0(13)	51.5(22)	1.0	Π1	M1 0.093(4)[a]	10.5^{+5}_{-4}
							E1 1.03(4)[b]	
		0_2^+			0.21(3)	Π1	M1 0.08(1)[a]	
							E1 0.9(1)[b]	
3667(1)	1	0_1^+	1.8(3)	2.1(3)	1.0	Π1	M1 0.0037(6)[a]	314^{+58}_{-43}
							E1 0.040(7)[b]	
3697.3(5)	1	0_1^+	4.2(4)	9.6(11)	1.0	Π1	M1 0.016(2)[a]	35.7^{+48}_{-38}
							E1 0.18(2)[b]	
		2_1^+			0.93(14) (Π1)			
3915.4(5)	1	0_1^+	11.8(14)	15.6(19)	1.0	Π1	M1 0.022(3)[a]	42.1^{+59}_{-46}
							E1 0.25(3)[b]	
				^{94}Zr				
2846.4(5)	1^-	0_1^+	113(7)	88(25)	1.0	E1	E1 3.7(11)[b]	6.7^{+26}_{-14}
		2_1^+			0.11(3)	E1	E1 1.3(5)[b]	

M1 [μ_N^2] E2 [W.u.] E1 [$10^{-3} e^2 fm^2$]

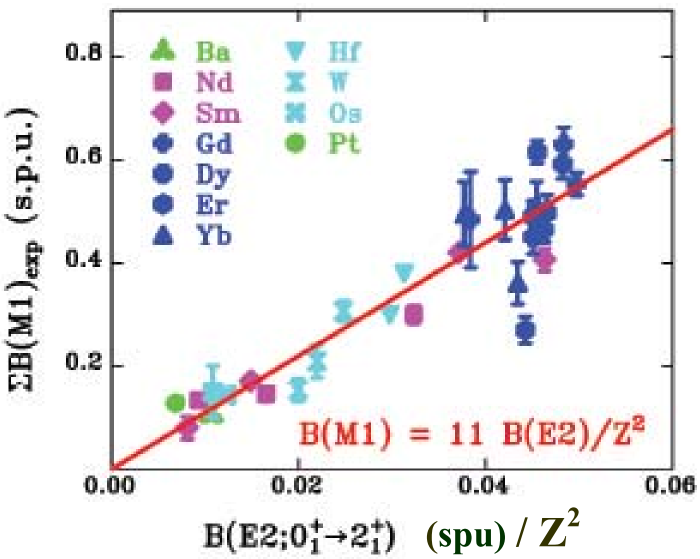
V. Werner et al., Phys. Lett. **B550** (2002) 140

M1 - systematics 1^+_{sc}



strong
at
mid-shell

strongly
correlated to
E2-strength



N. Pietralla et al., Phys.Rev. **C58** (1998) 184

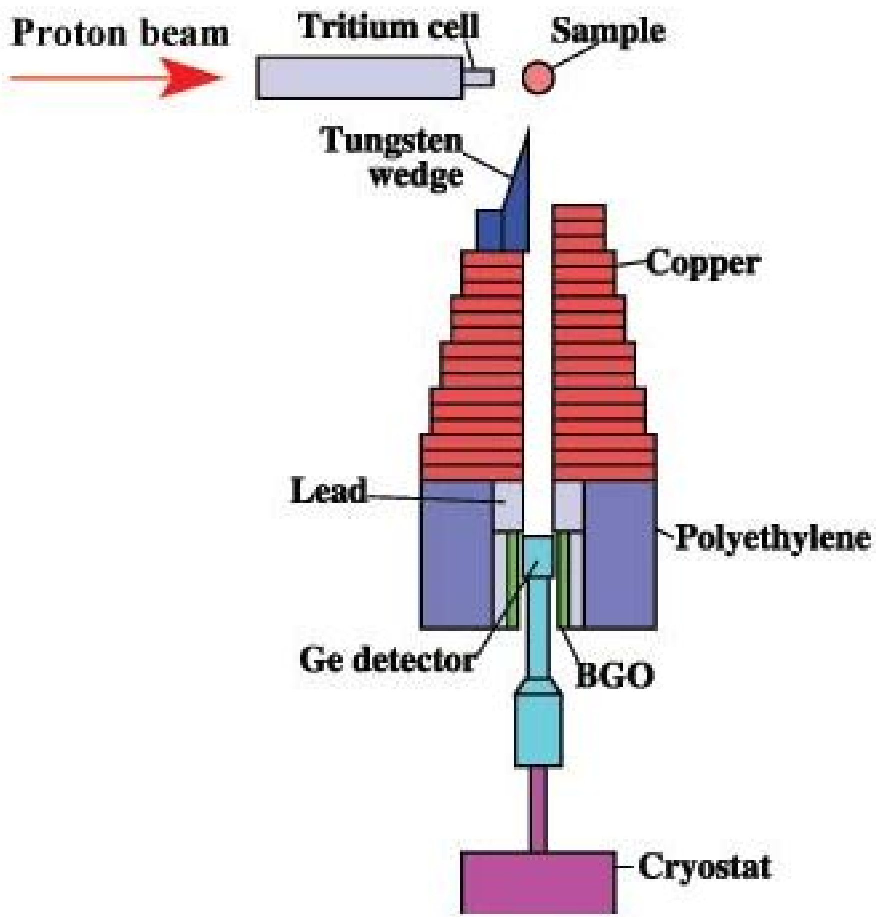
Three setups for low-spin spectroscopy at FN-Tandem, Cologne and in Lexington

Comparison of spectra

Inelastic neutron scattering

Lifetimes from (n, n´γ) data measured at Lexington

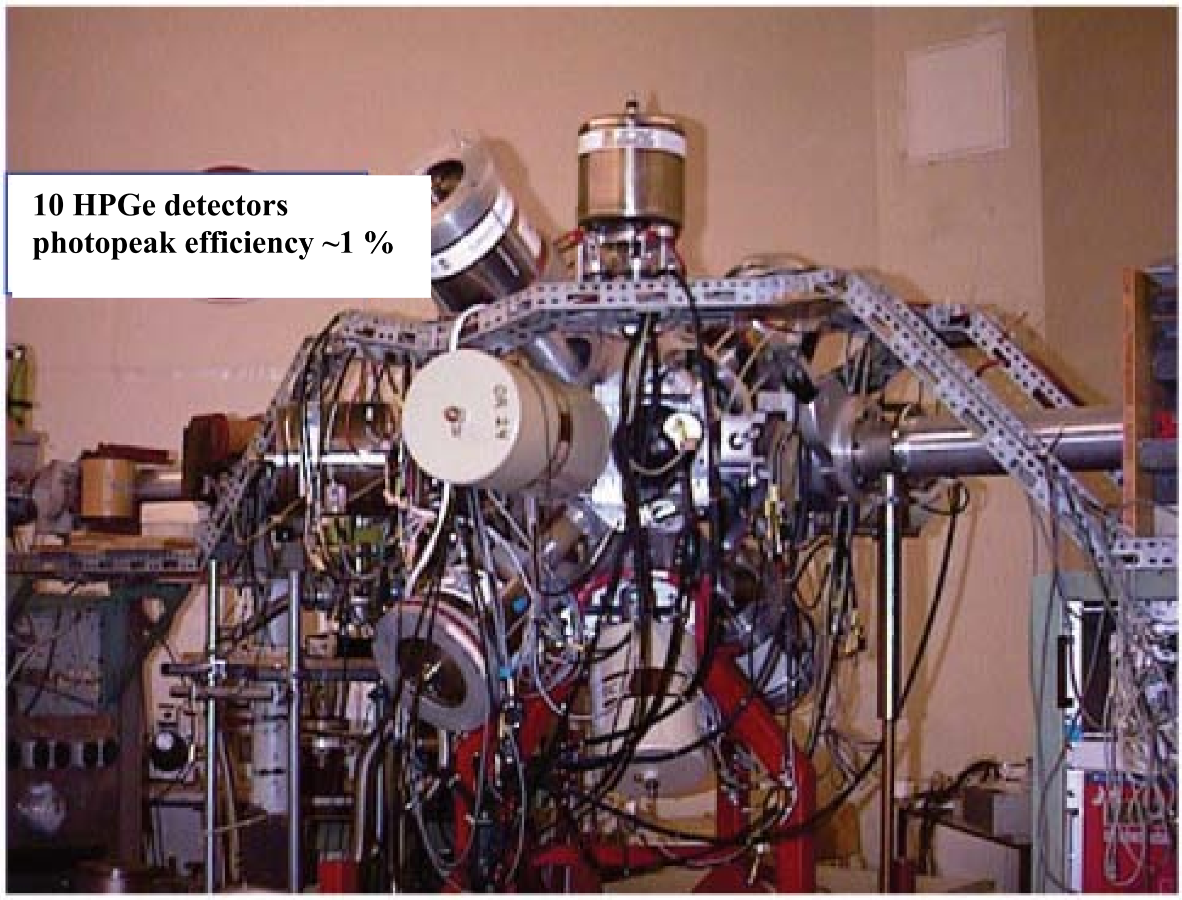
Experimental setup at the Van de Graaff accelerator of the University of Kentucky



Angular distributions: J , δ, τ

Excitation function: level scheme, J

γγ-coincidence experiments at the Osiris spectrometer, Cologne



Observables

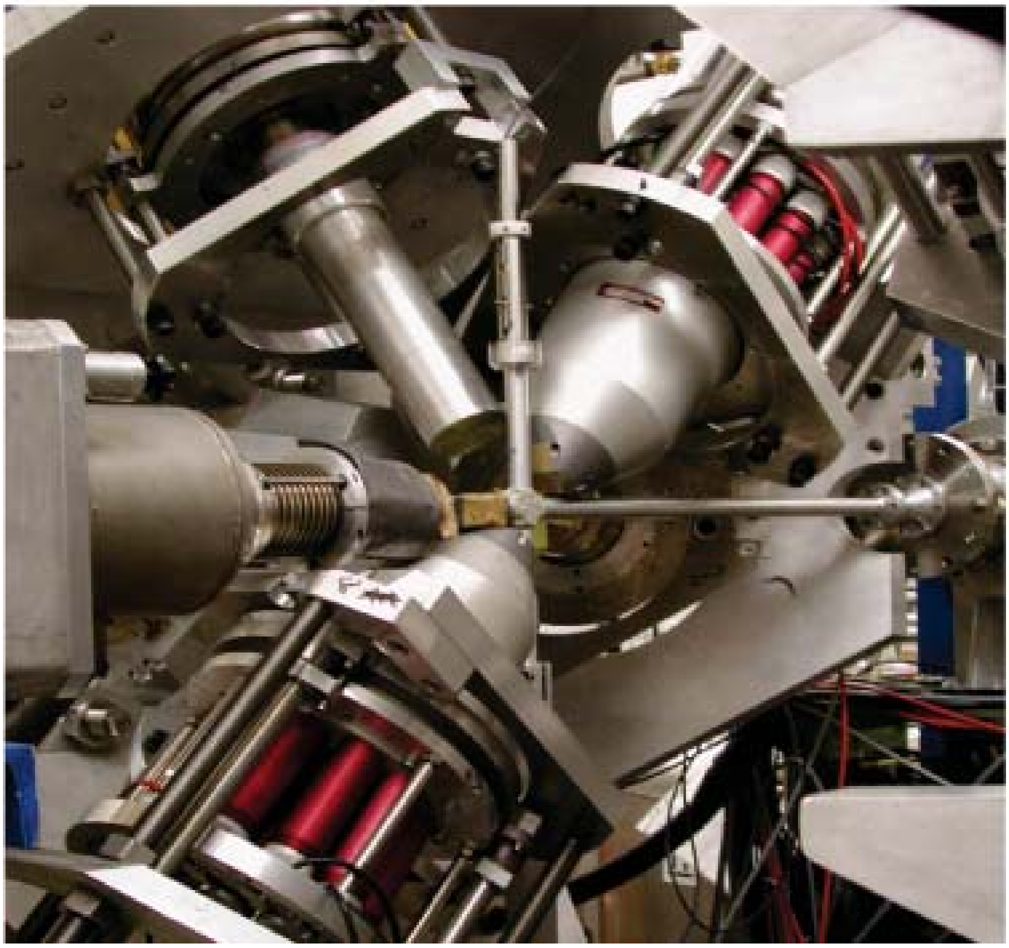
γ energies

branching ratios

multiple mixing ratios

effective lifetimes (Döppler shifts from in-beam experiments)

New HORUS spectrometer, Cologne

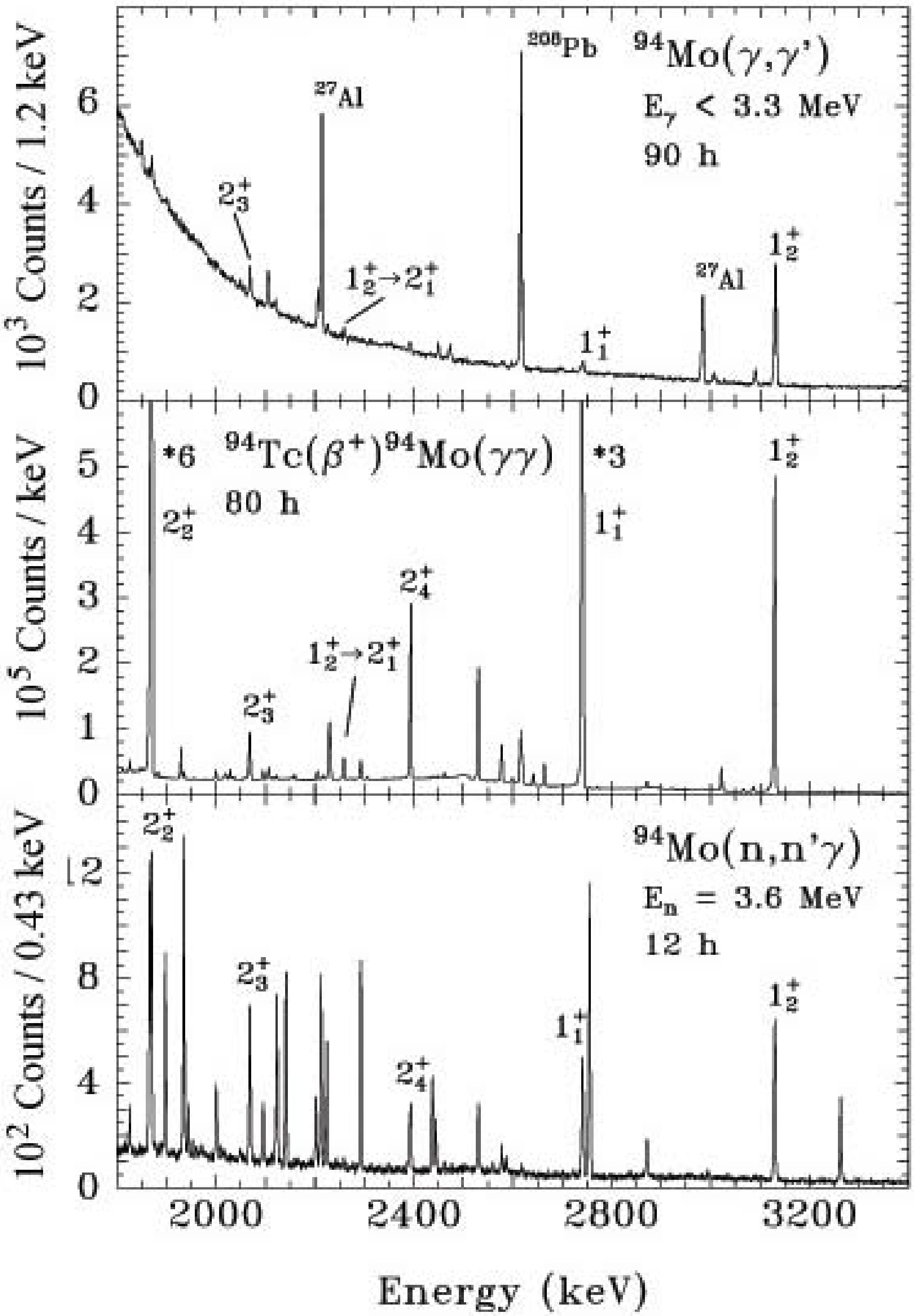


HORUS γγ coincidence

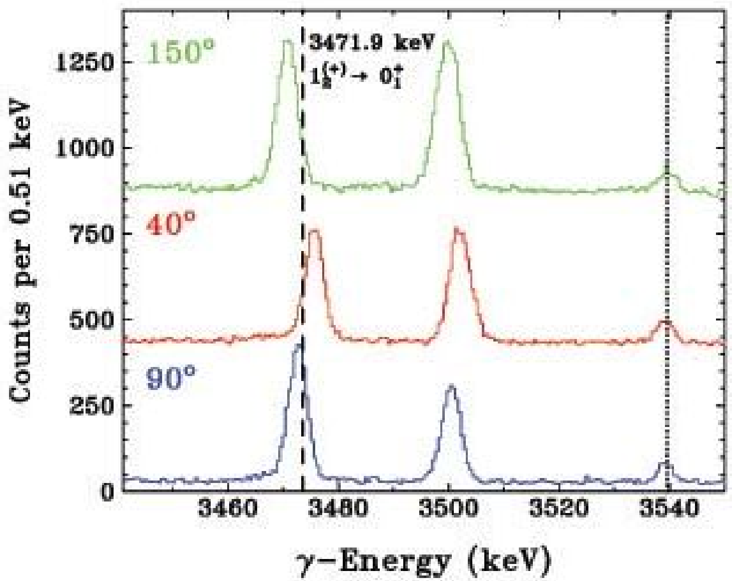
first experiments with the new HORUS spectrometer

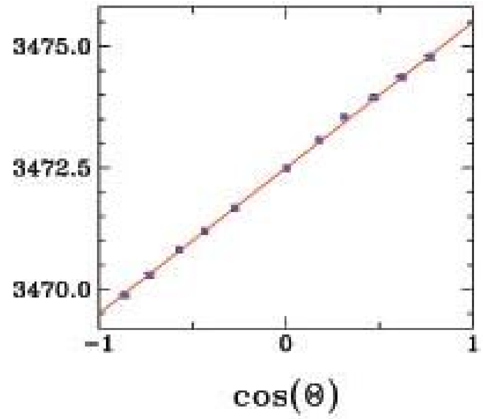
- 9 HPGe detectors, 4 with anti-Compton shields
- 1 EUROBALL cluster detector
- Photopeak efficiency: about 2 %
- Up to 14 HPGe detectors can be mounted

γ-ray spectra of ^{94}Mo from different experiments



Lifetime determination from Döppler shifts





F(τ) = 0.884(6)
τ = 7.6(9) fs

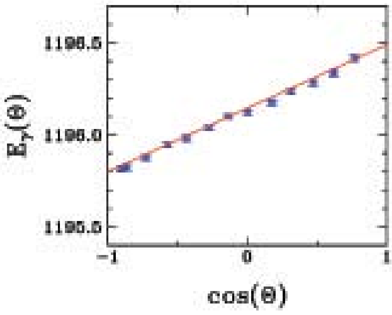
$$E_\gamma(\theta) = E_0\left(1 + F(\tau)\frac{v_{\rm cm}}{c}\right)\cos\theta$$

$F(\tau)$ Doppler shift attenuation factor
θ emission angle relative to the incident beam

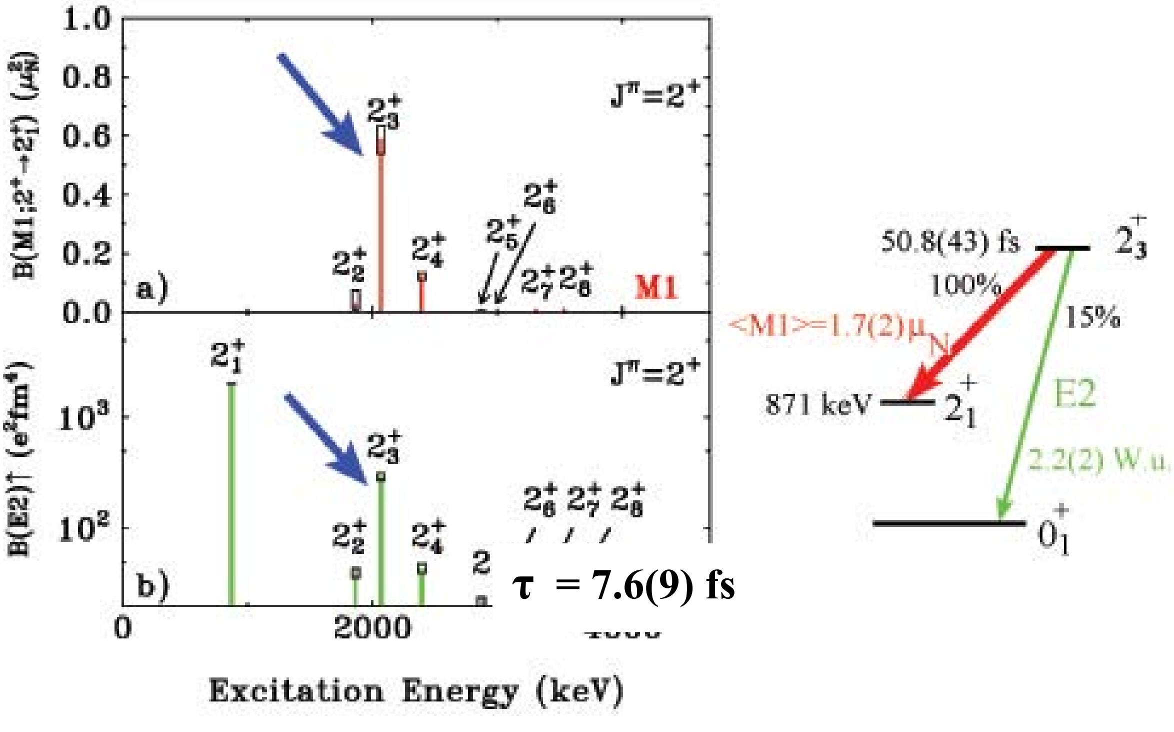
One-phonon 2_1^+ metastable state

^{94}Mo(n, n′γ)

2_3^+



→ τ = 50.8(43) fs



→ 2_3^+ identified as one-phonon metastable state

Statistical Analyses

Evaluation of Discrepant Data I

D. MacMahon

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Evaluation of Discrepant Data, I

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National Physical Laboratory
Teddington, United Kingdom

Evaluation of Discrepant Data

- What is the half-life of ^{137}Cs?

- Look at the published data from experimental measurements

- For greater detail: T. D. MacMahon, A. Pearce, P. Harris, Convergence of Techniques for the Evaluation of Discrepant Data, Appl. Radiat. Isot. **60** (2004) 275-281

Measured Half-lives of Cs-137

Authors	Measured half-lives in days $t_{1/2}$	σ
Wiles & Tomlinson (1955a)	9715	146
Brown et al. (1955)	10957	146
Farrar et al. (1961)	11103	146
Fleishman et al. (1962)	10994	256
Gorbics et al. (1963)	10840	18
Rider et al. (1963)	10665	110
Lewis et al. (1965)	11220	47
Flynn et al. (1965)	10921	183
Flynn et al. (1965)	11286	256
Harbottle (1970)	11191	157
Emery et al. (1972)	11023	37
Dietz & Pachucki (1973)	11020.8	4.1
Corbett (1973)	11034	29
Gries & Steyn (1978)	10906	33
Houtermans et al. (1980)	11009	11
Martin & Taylor (1980)	10967.8	4.5
Gostely (1992)	10940.8	6.9
Unterweger (2002)	11018.3	9.5
Schrader (2004)	10970	20

Evaluation of Discrepant Data

- The measured data range from 9715 to 11286 days.
- What value are we going to use for practical applications?
- Simplest procedure is to take the unweighted mean.
- If x_i (for i = 1 to N) are the individual values of the half-life, the unweighted mean (x_u), and associated standard deviation (σ_u) are given by:

Unweighted Mean

$$x_u = \frac{\sum x_i}{N}$$

$$\sigma_u = \sqrt{\frac{\sum (x_i - x_u)^2}{N\,(N-1)}}$$

Unweighted Mean

- Gives the result: 10936 ± 75 days
- However, the unweighted mean is influenced by outliers in the data, in particular the first low value of 9715 days
- Secondly, the unweighted mean takes no account of different authors making measurements of different precision, so we effectively lose some of the information content of the listed data

Weighted Mean

◆ We can take into account the authors' quoted uncertainties σ_i, i = 1 to N, by weighting each value, using weights w_i to give the weighted mean, (x_w):

$$w_i = \frac{1}{\sigma_i^2}$$

$$x_w = \frac{\sum x_i w_i}{\sum w_i}$$

Weighted Mean

◆ Standard deviation of the weighted mean (σ_w) is given by:

$$\sigma_w = \sqrt{\frac{1}{\sum w_i}}$$

◆ And for the half-life of Cs-137, a value of 10988 ± 3 days results

Weighted Mean

- This result has a small uncertainty, but how reliable is the value?
- How do we know that all the data are consistent?
- We can look at the deviations of the individual data from the mean, compared to their individual uncertainties
- We can define a quantity 'chi-squared'

$$\chi_i^2 = \frac{(x_i - x_w)^2}{\sigma_i^2}$$

Weighted Mean

- We can also define a 'total chi-squared':

$$\chi^2 = \sum_i \chi_i^2$$

- 'Total chi-squared' should be equal to the number of degrees of freedom (i.e., to the number of data points minus one) in an ideal consistent data set

Weighted Mean

- So, we can define a ‘reduced chi-squared’:

$$\chi_R^2 = \frac{\chi^2}{N-1}$$

- which should be close to unity for a consistent data set.

Weighted Mean

- For the Cs-137 data under consideration, ‘reduced chi-squared’ is 18.6, indicating significant inconsistencies in the data

- We need to look at the data again

- Can we identify the most discrepant data?

Measured Half-lives of Cs-137

Authors		Measured half-lives in days	
		$t_{1/2}$	σ
Wiles & Tomlinson (1955a)		**9715**	**146**
Brown et al. (1955)		10957	146
Farrar et al. (1961)		11103	146
Fleishman et al. (1962)		10994	256
Gorbics et al. (1963)		10840	18
Rider et al. (1963)		10665	110
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Houtermans et al. (1980)		11009	11
Martin & Taylor (1980)		10967.8	4.5
Gostely (1992)		10940.8	6.9
Unterweger (2002)		11018.3	9.5
Schrader (2004)		10970	20

Weighted Mean

- Highlighted values are the more discrepant
- Their values are far from the mean and their uncertainties are small
- In cases such as the Cs-137 half-life, the uncertainty (σ_w) ascribed to the weighted mean is far too small
- One way of taking into account the inconsistencies is to multiply the uncertainty of the weighted mean by the Birge ratio:

Weighted Mean

◆ Birge Ratio:

$$\sqrt{\frac{\chi^2}{N-1}} = \sqrt{\chi_R^2}$$

◆ This approach would increase the uncertainty of the weighted mean from 3 days to 13 for Cs-137, which would be more realistic.

Limitation of Relative Statistical Weights (LRSW)

◆ This procedure has been adopted by the IAEA in the Coordinated Research Programme on X-ray and gamma-ray standards

◆ A Relative Statistical Weight is defined as $\frac{w_i}{\sum w_i}$

◆ If the most precise value in a data set (value with the smallest uncertainty) has a relative weight greater than 0.5, the uncertainty is increased until the relative weight of this particular value has dropped to 0.5.

Limitation of Relative Statistical Weights (LRSW)

- Avoids any single value having too much influence in determining the weighted mean, although for Cs-137 there is no such value
- LRSW procedure compares the unweighted mean with the new weighted mean; if they overlap, i.e.,

$$\left| x_u - x_w \right| \leq \sigma_u + \sigma_w$$

the weighted mean is the adopted value

Limitation of Relative Statistical Weights (LRSW)

- If the weighted mean and the unweighted mean do not overlap, the data are inconsistent, and the unweighted mean is adopted
- Whichever mean is adopted, the associated uncertainty is increased if necessary, to cover the most precise value in the data set

Limitation of Relative Statistical Weights (LRSW)

- Cs-137 half-life:
- Unweighted Mean is 10936 ± 75 days
- Weighted Mean is 10988 ± 3 days
- These two means do overlap, so the weighted mean is adopted
- Most precise value in the data set is that of Dietz and Pachucki (1973) of 11020.8 ± 4.1 days
- Therefore, the uncertainty in the weighted mean is increased to 33 days to give 10988 ± 33 days

Median

- Individual values in a data set are listed in order of magnitude
- If there is an odd number of values, the middle value is the median
- If there is an even number of values, the median is the average of the two middle values
- Median has the advantage that this approach is very insensitive to outliers
- See also: J. W. Müller, Possible Advantages of a Robust Evaluation of Comparisons, J. Res. Nat. Inst. Stand. Technol. **105** (2000) 551-555; Erratum, *ibid.*, **105** (2000) 781.

Median

- We now need some way of attributing an uncertainty to the median
- First we have to determine the quantity ‘median of the absolute deviations’ or ‘MAD’

$$MAD \quad = \quad med\ \{\left| x_i - \tilde{m} \right|\} \quad for\ i = 1, 2, 3 \ldots\ldots N$$

where $\tilde{m}$ *is the median value*

Median

- Uncertainty in the median can be expressed as:

$$\frac{1.9 \times MAD}{\sqrt{(N-1)}}$$

Median

- Median is 10970 ± 23 days for the Cs-137 half-life data presented
- As for the unweighted mean, the median does not use the uncertainties assigned by the authors, so again some information is lost
- However, the median is much less influenced by outliers than is the unweighted mean

Evaluation of Discrepant Data

- In summary, we have:

◆ Unweighted Mean:	10936 ± 75 days
◆ Weighted Mean:	10988 ± 3 days
◆ LRSW:	10988 ± 33 days
◆ Median:	10970 ± 23 days

Statistical Analyses:

Evaluation of Discrepant Data, II

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Evaluation of Discrepant Data, II

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National Physical Laboratory
Teddington, United Kingdom

Evaluation of Discrepant Data

Cs-137 half-life:

- Unweighted Mean: 10936 ± 75 days
- Unweighted mean can be influenced by outliers and has a large uncertainty
- Weighted Mean: 10988 ± 3 days
- Weighted mean has an unrealistically low uncertainty due to the high quoted precision of one or two measurements; value of ‘chi-squared’ is very high, indicating inconsistencies in the data

Evaluation of Discrepant Data

Cs-137 half-life:

- ◆ LRSW: 10988 ± 33 days
- ◆ Limitation of Relative Statistical Weights has not increased the uncertainty of any value in the case of Cs-137, but has increased the overall uncertainty to include the most precise value
- ◆ Median: 10970 ± 23 days
- ◆ Median is not influenced by outliers, nor by particularly precise values; however, this approach ignores all the uncertainty information supplied with the measurements

Evaluation of Discrepant Data

- ◆ There are two other statistical procedures which attempt to:

  (i) identify the more discrepant data, and

  (ii) decrease the influence of these data by increasing their uncertainties
- ◆ These procedures are known as the Normalised Residuals technique and the Rajeval technique
- ▪ See also: M.U. Rajput, T. D. MacMahon, Techniques for Evaluating Discrepant Data, Nucl. Instrum. Meth. Phys. Res., **A312** (1992) 289-295.

Evaluation of Discrepant Data

- Normalised Residuals technique:

  A normalised residual for each value in a data set is defined as follows:

$$R_i = \sqrt{\frac{w_i\, W}{(W - w_i)}} \times (x_i - x_w)$$

$$\text{where} \quad x_w = \frac{\sum x_i\, w_i}{W}; \quad w_i = \frac{1}{\sigma_i^2}; \quad W = \sum w_i$$

Evaluation of Discrepant Data

- A limiting value (R_0) of the normalised residual for a set of N values is defined as:

$$R_0 = \sqrt{1.8 \ln N + 2.6} \quad \text{for} \quad 2 \le N \le 100$$

- If any value in the data set has $|R_i| > R_0$, the weight of the value with the largest R_i is reduced until the normalised residual is reduced to R_0
- This procedure is repeated until no normalised residual is greater than R_0

Evaluation of Discrepant Data

- Weighted mean is then re-calculated with the adjusted weight
- Result of applying this method to the Cs-137 data is shown in the next table, which shows only those values whose uncertainties have been adjusted

Author	Half-life (days)	Original Uncertainty	R_i **R_0 = 2.8**	Adjusted Uncertainty
Wiles 1955	9715	146	- 8.7	453
Gorbics 1963	10840	18	- 8.3	52
Rider 1963	10665	110	- 2.9	114
Lewis 1965	11220	47	4.9	88
Dietz 1973	11020.8	4.1	10.1	18.4
Martin 1980	10967.8	4.5	- 5.4	8.7
Gostely 1992	10940.8	6.9	- 7.4	16.4
Unterweger 2002	11018.3	9.5	3.3	15.5
New Weighted Mean	**10985**	**10**		

Rajeval Technique

- This technique is similar to the normalised residuals technique: only inflate the uncertainties of the more discrepant data, although a different statistical recipe is used
- Also has a preliminary population test which allows the rejection of highly discrepant data
- Normally makes more adjustments than the normalised residuals method, but the outcomes are usually very similar

Rajeval Technique

Initial Population Test:

outliers in the data set are detected by calculating the quantity y_i:

$$y_i = \frac{x_i - x_{ui}}{\sqrt{\sigma_i^2 + \sigma_{ui}^2}}$$

where x_{ui} is the unweighted mean of the whole data set excluding x_i, and σ_{ui} is the standard deviation associated with x_{ui}

Rajeval Technique

- Critical value of $|y_i|$ at 5% significance is 1.96
- At this stage, only values with $|y_i| > 3 \times 1.96 = 5.88$ are rejected

- Cs-137 half-life data: only the first value of 9715 ± 146 days is rejected, with a value of $|y_i| = 8.61$

Rajeval Technique

Standardised deviates Z_i are calculated in the next stage of the procedure

$$Z_i = \frac{x_i - x_w}{\sqrt{\sigma_i^2 - \sigma_w^2}} \quad where \quad \sigma_w = \sqrt{\frac{1}{W}}$$

Rajeval Technique

Probability integral for each Z_i

$$P(Z) = \int_{-\infty}^{Z} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-t^2}{2}\right) dt$$

is determined.

Rajeval Technique

- Absolute difference between P(Z) and 0.5 is a measure of the 'central deviation' (CD)
- Critical value of the central deviation (cv) can be determined by the expression:

$$cv = \left[(0.5)^{\frac{N}{N-1}}\right] \quad for\ N > 1$$

Rajeval Technique

If the central deviation (CD) of any value is greater than the critical value (cv), that value is regarded as discrepant, and the uncertainties of the discrepant values are adjusted to

$$\sigma_i' = \sqrt{\sigma_i^2 + \sigma_w^2}$$

Rajeval Technique

- An iteration procedure is adopted in which σ_w is recalculated each time and added in quadrature to the uncertainties of those values with CD > cv
- Iteration process is terminated when all CD < cv
- Cs-137 half-life data: one value is rejected by the initial population test, and 8 of the remaining 18 values have their uncertainties adjusted as shown in the next table

Author	Half-life (days)	Original Uncertainty	CD **cv = 0.480**	Adjusted Uncertainty
Gorbics 1963	10840	18	0.500	74
Rider 1963	10665	110	0.498	159
Lewis 1965	11220	47	0.500	125
Dietz 1973	11020.8	4.1	0.500	28
Corbett 1973	11034	29	0.443	34
Houtermans 1980	11009	11	0.473	22
Gostely 1992	10940.8	6.9	0.500	15
Unterweger 2002	11018.3	9.5	0.499	27
New Weighted Mean	**10970**	**4**		

Rajeval Technique

Compare Rajeval technique table with that for the Normalised Residuals technique; differences are seen to be:

1. Rajeval technique has rejected the Wiles and Tomlinson value

2. Normally the Rajeval technique makes larger adjustments to the uncertainties of discrepant data than does the Normalised Residuals technique, and has a lower final uncertainty

Evaluation of Discrepant Data

- We now have 6 methods of extracting a half-life from the measured data:

Evaluation Method	Half-life (days)	Uncertainty
Unweighted Mean	10936	75
Weighted Mean	10988	3
LRSW	10988	33
Median	10970	23
Normalised Residuals	10985	10
Rajeval	10970	4

Evaluation of Discrepant Data

- Already pointed out that the unweighted mean can be influenced by outliers, and therefore is to be avoided if possible.

- Weighted mean can be heavily influenced by discrepant data that have small quoted uncertainties, and would only be acceptable if the reduced chi-squared is small, i.e., close to unity. This criterion is certainly not the case for Cs-137 half-life, with a reduced chi-squared of 18.6

Evaluation of Discrepant Data

- Limitation of Relative Statistical Weights (LRSW) for Cs-137 half-life data still chooses the weighted mean, but inflates the associated uncertainty to cover the most precise value
- Therefore, both the LRSW value and associated uncertainty are heavily influenced by the most precise value of Dietz and Pachucki, which is identified as the most discrepant value in the data set by the Normalised Residuals and Rajeval techniques

Evaluation of Discrepant Data

- Median is a more reliable estimator - very insensitive to outliers and to discrepant data
- However, by not using the experimental uncertainties, the median approach is not making use of all the information available
- Normalised Residuals and Rajeval techniques have been developed to address the problems of other techniques and to maximise the use of all the experimental information available

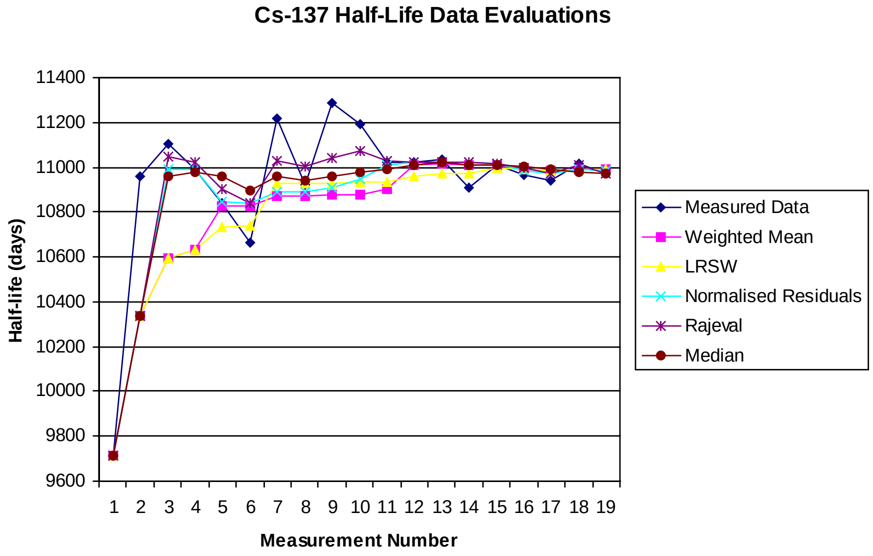
Evaluation of Discrepant Data

- Normalised Residuals and Rajeval techniques use different statistical methods to reach the same objective: to identify discrepant data and to increase the uncertainties of such data to reduce their influence on the final weighted mean
- Author's opinion: best value for the half-life of Cs-137 would be that obtained by taking the mean of the Normalised Residuals and Rajeval values, together with the larger of the two uncertainties

Evaluation of Discrepant Data

Adopted half-life of Cs-137 would be

10977 ± 10 days

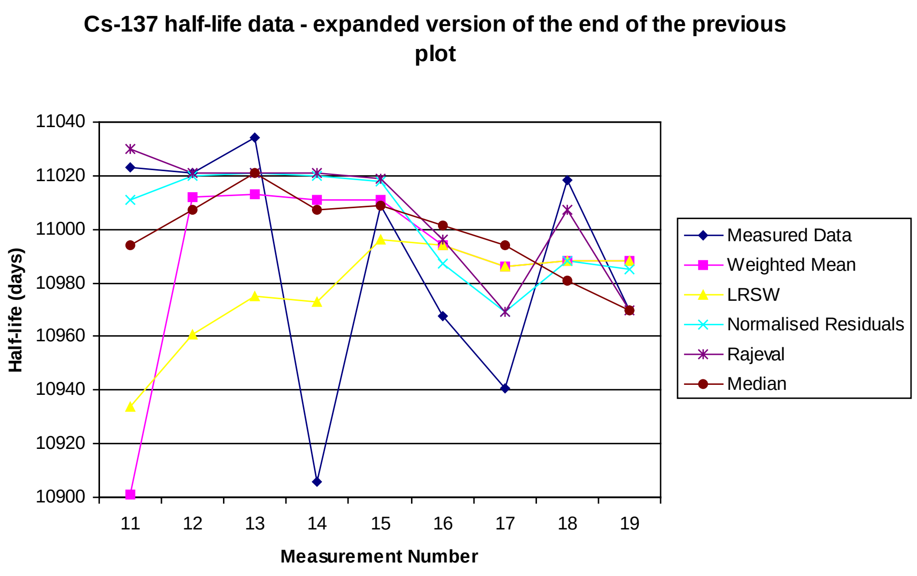


Evaluation of Discrepant Data

- ◆ The previous figure shows how the evaluation techniques behave as each new data point is added to the data set
- ◆ Left-hand portion of the plot shows that the weighted mean and LRSW values take much longer to recover from the first low and discrepant value than do the other techniques

Evaluation of Discrepant Data

- ◆ Next figure shows an expanded version of the second half of the previous figure, revealing in more detail how the different techniques behave as the number of data points reaches 19
- ◆ Taking into account the 19th point, the overall spread in the evaluation techniques is only 18 days or 0.16%



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DRAFT

Evaluation of Decay Data: Relevant IAEA Co-ordinated Research Projects

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Summary

Specific IAEA Co-ordinated Research Projects (CRPs) have been directed towards the generation of recommended high-quality decay data for a number of important applications. Decay-scheme data for specific radionuclides have required study and evaluation through an agreed set of procedures. The role of the IAEA Nuclear Data Section in creating these dedicated data files is described, and both the objectives and resulting decay data from these most relevant CRPs are also reviewed.

1. Introduction

Two primary aims of the IAEA Nuclear Data Section (NDS) are to develop and disseminate atomic and nuclear data in forms appropriate for a wide range of applications [1], as requested by IAEA Member States. Hence, NDS staff prepare and maintain a significant number of databases, including atomic and molecular data for fusion energy and plasma research that are accessible through a separate server [2]. NDS staff are also involved in technology transfer activities to assist scientists of developing countries in their use of these atomic and nuclear databases.

Data development within the NDS is conducted mainly through Co-ordinated Research Projects (CRPs). Usually these projects result in the production of a new (or significant upgrades of an existing) database; typically 5-12 scientific groups from different countries work together under IAEA contracts or agreements over a period of 3-4 years, maintaining contact throughout the course of the CRP. Examples of recent CRPs sponsored and organised by the NDS are listed in Table 1.

Following a brief description of the IAEA-NDS and how to gain access to their facilities and databases, the contents of this paper focus on those CRPs devoted over the previous 30 years to improving the recommended decay data used in both energy- and non-energy-based applications. Specific decay-data requirements were identified by users and consultants, and a suitable evaluation procedure was adopted to achieve the desired objectives. The reader should be warned that the decay data recommended by the CRP on X-ray and Gamma-ray Standards for Detector Calibration (1986-90) in 1991 will soon be

Table 1. Recent IAEA-NDS Co-ordinated Research Projects (CRPs).

Short Title	Duration	No. of Participants
Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications	1998-2002	11
RIPL-II: Input Parameter Testing	1998-2002	8
Prompt Gamma Activation Analysis	1999-2003	10
Standard Cross Sections	2002-06	9
RIPL-III: Parameters for Nuclear Reaction Applications – Non-energy Applications	2002-06	11
Nuclear Data for Th-U Fuel Cycle	2003-07	9
Cross Sections for Production of Therapeutic Radionuclides	2003-07	8
Updated Decay Data Library for Actinides	2005-09	approved
Reference Database for Ion Beam Analysis	2005-09	approved
Reference Database for Neutron Activation Analysis	2005-07 (?)	approved
Minor Actinide Neutron Reaction Data	2007-11 (?)	

replaced with a completely new set of recommended decay data at the conclusion of a recent CRP dedicated to the improvement and extension of this important database (see Section 4).

1.1 Nuclear data

Nuclear data are commonly categorized in terms of two main groups:

- **Nuclear reaction data:** Encompasses cross sections, angular and energy distributions of secondary particles, resonance parameters and related quantities. These libraries are complete for neutron-induced reactions up to 20 MeV; however, coverage at higher energies is less comprehensive. Although few evaluations exist for photonuclear and charged-particle induced reactions, some selected experimental data have been compiled in EXFOR.
- **Nuclear structure and decay data:** Atomic masses, half-lives, decay schemes, nuclear level properties, and energies and intensities of emitted particles and γ rays are included in these data. The major database is ENSDF, while related bibliographic data are contained in NSR. There are many other nuclear structure and decay data libraries, mostly derived from or related to ENSDF and including the *Table of Isotopes* [3], *Isotope Explorer* [4] and NUBASE [5].

The type of information given for both groupings can also be classified on the basis of bibliographic detail, experimental data and evaluated data.

- **Bibliographic data:** References with some description of the contents, but no numerical data. Examples are CINDA (Computer Index of Neutron Data) and NSR (Nuclear Science References).
- **Experimental data:** Results of individual measurements as reported by the authors. The most important example of a compiled library of experimental nuclear reaction data is EXFOR/CSISRS.
- **Evaluated data:** Recommended values are based on all available data from experiments and/or theory, derived from a critical analysis of the experimental data and their uncertainties, inter- and extrapolation, and/or nuclear model calculations. The resulting libraries are assembled in strictly defined formats such as ENDF-6

(international format for evaluated nuclear reaction data) or ENSDF (format of the Evaluated Nuclear Structure Data File). The main cross-section libraries in ENDF format also contain the relevant decay data needed in their main application(s).

1.2 Nuclear data centre networks

Both the collection and distribution of nuclear data are organised worldwide. Two international networks are coordinated by the IAEA to collect and distribute nuclear data (Table 2):

- Network of Nuclear Reaction Data Centres [6],
- Nuclear Structure and Decay Data Evaluators' Network [7].

The data centres participating in these nuclear data networks are involved in the various stages of data preparation between measurement and application (i.e., compilation, review, evaluation, processing and distribution).

Specialized data centres cooperate with the major centres in the various functions (particularly data compilation and evaluation). This sharing of the work on a worldwide basis is normally defined by their geographical location and data expertise, and is coordinated by the IAEA Nuclear Data Section.

Table 2. Nuclear Data Networks.

Nuclear Reaction Data Centres Network	Nuclear Structure and Decay Data Evaluators' Network
IAEA Nuclear Data Section, Vienna, Austria	**IAEA Nuclear Data Section,** Vienna, Austria
OECD, NEA Data Bank, Paris, France	**US National Nuclear Data Center,** Brookhaven, USA (maintains Master database)
US National Nuclear Data Center, Brookhaven, USA	**13 data evaluation centres:** Belgium, Canada, PRChina, France, Japan, Kuwait, the Netherlands, Russian Federation, UK and USA
Russian Federation Nuclear Data Centre, Obninsk, Russian Federation	**Data dissemination centres:** France, Sweden, USA, IAEA and OECD-NEA
9 co-operating specialised centres: PRChina, Hungary, Japan, Republic of Korea, Russian Federation and Ukraine	

1.3 Access to IAEA-NDS data libraries

The IAEA Nuclear Data Section holds a total of about 100 nuclear data libraries, representing enormous economic and scientific value. All libraries and the related documentation are available free of charge to scientists in IAEA Member States. An overview is given in the document *Index of Nuclear Data Libraries available from the* IAEA *Nuclear Data Section* [8], and brief descriptions of the contents and/or format of most libraries are published in the IAEA-NDS-report series [9].

The main method of distributing numerical nuclear data in the early 21st century is via the Internet, and therefore the IAEA Nuclear Data Section offers a variety of such electronic services. At the same time, conventional mail services have been maintained for the convenience of users with their varying needs and technical infrastructures (ie., sending customized retrievals or complete libraries as hardcopy, magnetic tape, CD-ROM and diskettes, as well as by e-mail). Users are also kept up to date about new data libraries and other developments through the *IAEA Nuclear Data Newsletter* [10].

- **Worldwide Web (WWW)**: The web page of IAEA Nuclear Data Services can be found at the web addresses (URL) *http://www-nds.iaea.org* (IAEA Vienna, Austria), *hhtp://www-nds.indcentre.org.in* (BARC, India), and *http://www-nds.ipen.br* (IPEN, Brazil). This page contains interactive access to the major databases as well as an overview of all nuclear data libraries and databases available from the IAEA *(IAEA Nuclear Data Guide)*, access to various reports, documents and manuals, nuclear data utility programs, and the *IAEA Nuclear Data Newsletter*.

- **Secure FTP:** IAEA Nuclear Data Section keeps several accounts for file transfers requiring no password (all accessible by the IP address *ndsalpha.iaea.org* using a secure client, such as sftp, scp, pscp or WinSCP3): ANONYMOUS contains several complete libraries, utility codes and documents for public use; FENDL2 and RIPL permit access to the respective data libraries; NDSOPEN is used for bilateral file exchange.

Hardcopy documents published by NDS include handbooks, research and meeting reports (INDC report series), data library documents (IAEA-NDS report series), and the *IAEA Nuclear Data Newsletter*. Most new reports are available electronically on the WWW in PDF format. NDS staff can be contacted by e-mail to request hardcopy documents, and other mail services and nuclear data related information [11].

1.4 Technology transfer

Technology transfer to developing countries is carried out in several ways by the NDS:

- Technical co-operation projects to provides online nuclear data services to countries with insufficient Internet connections to the NDS through the installation of mirror servers in Brazil and India.

- Nuclear data workshops are organized on a regular basis, and are usually held at the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. Regular topics have included “Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety” (held every even year) and “Nuclear Data for Science and Technology” (held every odd year, with extensive changes in their content (varying from medical physics to materials analysis)). More appropriately, over the previous 3 years, a combination of IAEA and IAEA-ICTP workshops have been dedicated to Nuclear Structure and Decay Data: Theory and Evaluation.

2. Co-ordinated Research Project: Decay Data for the Transactinium Nuclides (IAEA Technical Reports Series No. 261, 1986)

Transactinium nuclides are important in the nuclear fuel cycles of both thermal and fast reactors, and have found increasing application in other fields. The IAEA convened an Advisory Group Meeting on Transactinium Isotope Nuclear Data (TND) at the Kernforschungszentrum Karlsruhe in 1975 [12]. Users and measurers were brought together to review the status and requirements of the nuclear data for transactinium nuclides relevant to fission reactor research and technology. One of the areas specifically addressed at this meeting was the status of the decay data for these nuclides; participants recommended that the IAEA implement a Co-ordinated Research Project to review, measure and evaluate the required transactinium decay data. Five groups experienced in decay data measurements agreed to participate in the work of this CRP, and met for the first time at IAEA, Vienna in 1978 [13]. Subsequent CRP meetings were held annually up to 1984 [14-19], in conjunction with two further IAEA Advisory Group Meetings in 1979 and 1984 [20, 21].

2.1 Actinide and transactinium nuclides

The accuracies requested for many of the data were quite high, especially the γ-ray emission probabilities that presented challenging experimental problems. Nevertheless, during the seven years of the CRP, some of these problems were solved, and a considerable amount of data was produced with the required accuracy (at least for the prominent transitions of most interest to the user). The work of the CRP not only helped improve the existing capabilities of the participating laboratories, but also encouraged the development of such capabilities at other laboratories. Together with the systematic production of highly accurately measured decay data, this interaction between laboratories represented one of the more significant long-term effects of the work.

CRP participants established the following guidelines for the assignment of uncertainties:

- total uncertainty to be based on 1σ random error plus one-third the linear sum of the systematic errors based on a statistical confidence-level of 68.3%;
- an uncertainty assigned to a mean value should not be smaller than the smallest uncertainty of the values used to calculate the mean;
- for those nuclides that are sufficiently long lived that their half-lives cannot simply be determined by following their decay, the half-lives are generally determined through the measurement of two quantities: number of atoms in the sample and sample activity; since the CRP participants believe that both these quantities cannot be determined reliably with accuracies better than 0.1%, they assigned a minimum uncertainty of 0.1% to these resulting half-lives.

2.2 Recommended transactinium decay data, 1985/86

The CRP highlighted a significant number of data requirements and succeeded in satisfying many of them. Examples of the recommended decay data and their literature sources are given in Appendix A. Improvements have subsequently been made in the quality of specific decay data for the transactinium nuclides, although several of the identified decay data needs remained unsatisfied.

The CRP accomplished a number of goals:

(a) Evaluated the accuracy requirements for decay data requested by users at the Advisory Group Meetings, and grouped them into three general categories:
   (i) those satisfied by available data;
   (ii) those which lie beyond the capabilities of measurement techniques (of 1985/6);
   (iii) those not satisfied, but are achievable with existing experimental capabilities.
(b) Assessed the status of the existing data in the light of these requirements, and maintained an awareness of new measurements.
(c) Identified and co-ordinated the measurement expertise in order to acquire the required data.
(d) Prepared a report that presented a critical evaluation of the data and summarized their status (IAEA Technical Reports Series No. 261, IAEA Vienna, Austria, 1986).

Table 3. Transactinium Isotope Decay Data: Requirements, Status and CRP Activities.

AEEW – UKAEA Atomic Energy Establishment, Winfrith, UK;
AERE – UKAEA Atomic Energy Research Establishment, Harwell, UK;
CBNM – CEC Central Bureau for Nuclear Measurements, Geel, Belgium;
INEL – Idaho National Engineering Laboratory, Idaho Falls, USA;
JAERI – Japan Atomic Energy Research Institute, Tokai-Mura, Japan;
LMRI – CEA Laboratoire de Métrologie des Rayonnements Ionisants, Saclay, France.

The label "+" refers to measurements or evaluations performed by laboratories that have contributed indirectly to the IAEA Co-ordinated Research Project.

Nuclide	Data type	Accuracy (%) (a) Required	Achieved	Needs	CRP activities Measurements	Evaluations	Comments
Th-228	$T_{1/2}$	1	0.1	Decay chain calculations (includes daughters)	–	CBNM	
	P_γ	2 (b)	2–5		CBNM, INEL	CBNM, LMRI	
Th-229	$T_{1/2}$	1	2	Mass determination in U-233 chain	–	–	CRP participants believe that the achieved accuracy of the half-life is adequate
	P_γ	2 (b)	1–3		INEL, +	INEL	
Th-230	$T_{1/2}$	1	0.4	Marine dating	+	+	
Th-232	$T_{1/2}$	not requested	0.4	Includes daughters	–	+	
	P_γ	not requested			–		
Th-233	$T_{1/2}$	1	0.5	Thorium cycle-decay heat	–	–	P_β and P_γ requirements are not satisfied. AERE measurement of P_γ planned
	P_β	2	unknown		–	–	
	P_γ	2	unknown		AERE	–	
Pa-231	$T_{1/2}$	1	0.3	Non-destructive assay	–	–	
	P_α	2	2–7		–	AEEW	
	P_γ	2	2–5		AERE	AEEW	
Pa-233	$T_{1/2}$	1	0.4	Decay heat and mass determination	–	–	
	P_β	2	unknown		–	–	Requirement for P_β is not satisfied
	P_γ	2	1		AERE, CBNM, INEL	INEL	
U-232	$T_{1/2}$	1	0.7	Shielding calculations (includes daughters)	AERE, +	+	$T_{1/2}$ requires confirmation. AERE measurement is planned
	P_α	2	1		–	–	
	P_γ	2	1–2		AERE, CBNM, INEL, +	CBNM	

Table 3 (cont.)

Nuclide	Data type	Accuracy (%) (a) Required	Achieved	Needs	CRP activities Measurements	Evaluations	Comments
U-233	$T_{1/2}$	0.5	0.1		+	+	
	$T_{1/2}$ (SF)	not requested		Thorium fuel cycle	+	–	
	P_α	2	1–2	and environmental	+	INEL	
	P_γ	2	1–2	studies	AERE, INEL	INEL	AERE measurement planned
	P_X (d)	5	unknown		–	–	P_X requirement not satisfied
U-234	$T_{1/2}$	0.3	0.1		+	AEEW	
	$T_{1/2}$ (SF)	not requested		Mass determination	+	–	
	P_α	1	0.03–1	and non-destructive	CBNM, JAERI, +	AEEW	
	P_γ	2	1–2	assay	CBNM	AEEW	
U-235	$T_{1/2}$	0.5	0.1		–	+	
	$T_{1/2}$ (SF)	not requested		Mass determination	+	–	The required accuracy of 3% for P_α is unlikely to be achieved
	P_α	3	5–12	and non-destructive	–	–	
	P_γ	1	1	assay	AERE, CBNM, INEL, +	CBNM	
U-236	$T_{1/2}$	1	0.1		–	+	
	$T_{1/2}$ (SF)	not requested	3	Mass determination	+	–	
	P_α	3	5–15	and non-destructive	–	–	P_α and P_γ requirements are not satisfied
	P_γ	3	10	assay	–	–	
U-237	P_γ	1	2–3	Non-destructive assay of Pu	AERE, INEL	LMRI	AERE measurement of P_γ in progress
U-238	$T_{1/2}$	1	0.1	Mass determination	–	+	Required accuracies for P_α, P_γ and P_X are unlikely to be achieved. AERE measurement of P_γ planned
	$T_{1/2}$ (SF)	2	1.2	and non-destructive	+	+	
	P_α	3	5–20	assay; $T_{1/2}$ (SF) for	–	–	
	P_γ	3	13	geochronology;	AERE, +	–	
	P_X (d)	3	unknown	P_X for environmental studies	–	–	
U-239	$T_{1/2}$	1	0.2		–	AEEW	
	P_β	2	2–20	Decay heat	+	AEEW	P_β requirement is not satisfied
	P_γ	2	2		+	AEEW	
Np-236	$T_{1/2}$	5	10		+	–	$T_{1/2}$ and P_β requirements not satisfied
	Branching ratio	5	2	U-232 production	–	–	
	P_β	2	unknown		–	–	
	P_γ	2	2		–	–	
Np-236m	$T_{1/2}$	5	2		–	–	
	Branching ratio	5	2	U-232 production	–	–	
Np-237	$T_{1/2}$	0.5	0.5		AERE/CBNM	–	Confirmatory measurement of $T_{1/2}$ is definitely required. New $T_{1/2}$ results are expected from AERE and CBNM in 1985. P_α and P_X requirements are not satisfied. Measurement of P_α is planned by CBNM
	P_α	1	20	Environmental studies	CBNM	–	
	P_γ	1	1–2	and mass	AERE, CBNM, +	INEL	
	P_X (d)	2	unknown	determination			

Table 3 (cont.)

Nuclide	Data type	Accuracy (%) (a) Required	Achieved	Needs	CRP activities Measurements	Evaluations	Comments
Np-238	$T_{1/2}$ P_γ	2 2	0.1 5	Activation analysis of Np-237 and Am-242m determination	– –	– –	P_γ requirement is not satisfied
Np-239	$T_{1/2}$ P_β P_γ	1 2 1	0.2 (c) 1–2	Decay heat and detector calibration standard	– – CBNM, +	– – CBNM	
Pu-236	$T_{1/2}$ P_α P_γ	1 2 3	3.0 1–3 30	U-232 production	– – –	+ – –	$T_{1/2}$, P_α and P_γ requirements are not satisfied
Pu-237	$T_{1/2}$ P_X (d)	not requested 2	0.1 unknown	Environmental studies	+ –	CBNM –	P_X requirement is not satisfied
Pu-238	$T_{1/2}$ $T_{1/2}$ (SF) P_α P_γ P_X (d)	0.5 2 1 1 2	0.3 4 <1 1–2 2–3	Mass determination and non-destructive assay; P_X for detector calibration	+ – CBNM, + CBNM, INEL, LMRI –	+ + LMRI LMRI –	$T_{1/2}$ (SF) requirement is not satisfied. LMRI measurement of P_γ planned
Pu-239	$T_{1/2}$ P_α P_γ P_X(d)	0.5 1 1 3	0.1 1–2 <1 3	Mass determination, non-destructive assay and environmental studies	AERE, CBNM, + + INEL, LMRI, + –	CBNM JAERI JAERI –	
Pu-240	$T_{1/2}$ $T_{1/2}$ (SF) P_α P_γ P_X (d)	0.5 2 1 1 3	0.1 3 1–2 1–2 3	Mass determination, non-destructive assay and environmental studies; $T_{1/2}$ (SF) for waste management	+ CBNM + INEL, LMRI –	CBNM/LMRI + LMRI LMRI –	$T_{1/2}$(SF) requirement is not satisfied. P_γ measurement planned by LMRI
Pu-241	$T_{1/2}$ $T_{1/2}$ (α) P_γ	0.5 1 1	0.7 0.8 1–2	Mass determination and non-destructive assay	AERE, CBNM, + CBNM INEL, +	CBNM – LMRI	$T_{1/2}$ requirement is not satisfied (measurements in progress)
Pu-242	$T_{1/2}$ $T_{1/2}$ (SF) P_α P_γ P_X (d)	1 5 5 5 3	0.3 1.5 <1 2–5 unknown	Mass determination, non-destructive assay and environmental studies	+ – – CBNM –	+ + – – –	P_X requirement is not satisfied
Am-241	$T_{1/2}$ P_α P_γ P_X (d)	0.2 not requested 0.5–1 2	0.1 1–2 1–10 3	Non-destructive assay and low energy gamma emission standard. 0.5% accuracy requested for 59.5 keV gamma emission probability	– + CBNM, LMRI –	CBNM CBNM CBNM –	CBNM measurement of P_γ in progress. P_X requirement not satisfied

Table 3 (cont.)

Nuclide	Data type	Accuracy (%) (a) Required	Achieved	Needs	CRP activities Measurements	Evaluations	Comments
Am-242	$T_{1/2}$	1	0.1	Cm-244 production and	–	y	
	Branching ratio	1	1	Am mass determination	–	–	
Am-242m	$T_{1/2}$	1	1.4	Cm-244 production	+	AEEW	$T_{1/2}$ requires confirmatory
	Branching ratio	1	0.03	and Am mass determination	–	AEEW	measurement. P_X requirements not satisfied
	P_X (d)	3	unknown		–	–	
Am-243	$T_{1/2}$	1	0.2	Mass determination,	+	CBNM	
	P_α	1	unknown	long term storage and	–	CBNM	P_α, P_γ and P_X
	P_γ	1	2	environmental studies	CBNM, +	CBNM	requirements are not
	P_X(d)	2	unknown		–	–	satisfied
Cm-242	$T_{1/2}$	0.2	0.04		AERE, JAERI, +	JAERI	
	$T_{1/2}$ (SF)	5	2	Non-destructive	JAERI, +	JAERI	
	P_γ	5	4–20	assay	–	–	
Cm-243	$T_{1/2}$	1	0.3		–	+	
	P_α	5	1–3	Non-destructive	–	–	
	P_γ	5	2–10	assay and environ-	–	–	
	P_X(d)	5	unknown	mental studies	–	–	P_X requirement is not satisfied
Cm-244	$T_{1/2}$	1	0.3		–	+	
	$T_{1/2}$ (SF)	3	0.4		–	+	
	P_α	3	<1	Non-destructive assay	+	LMRI	
	P_γ	3	2–10	and environmental	–	LMRI	P_γ requirement is not
	P_X (d)	3	3	studies	–	–	satisfied
Cm-245	$T_{1/2}$	1	1	Long term storage and	+	+	
	P_α	5	0.5–2	environmental studies	–	–	
	P_γ	5	10		–	–	P_γ and P_X requirements
	P_X (d)	5	unknown		–	–	are not satisfied
Cm-246	$T_{1/2}$	1	2	Long term storage and	–	+	$T_{1/2}$, P_α, P_γ and P_X
	P_α	3	1–5	environmental studies	–	–	requirements are not
	P_γ	3	unknown		–	–	satisfied
	P_X (d)	3	unknown		–	–	
Cm-248	$T_{1/2}$	2	1	Long term storage and	–	+	
	P_α	3	<1	environmental studies	–	–	P_γ and P_X requirements
	P_γ	3	unknown		–	–	are not satisfied
	P_X (d)	3	unknown		–	–	
Cf-250	$T_{1/2}$	0.2	0.7	Impurity in Cf-252	–	–	$T_{1/2}$ and $T_{1/2}$ (SF)
	$T_{1/2}$ (SF)	2	4	neutron standard	–	–	requirements are not satisfied
Cf-252	$T_{1/2}$	0.2	0.3	Neutron standard	LMRI	INEL	$T_{1/2}$ requirement is not
	$T_{1/2}$ (SF)	1	0.3		–	+	satisfied; discrepancies exist among measured half-lives

(a) Uncertainties for α, γ and X-ray emission probabilities: required and achieved accuracies apply to the major transitions only.
(b) Listed requirements represent those for the more prominent transitions from all members of the decay chain of these nuclides.
(c) β emission probabilities are inferred from the γ-ray emission probabilities.
(d) P_x refers to L-X-ray emission probabilities.

The CRP participants concluded that, despite the large body of accurate decay data produced by the laboratories up to 1985/86, much remained to be done. A number of the accuracy requirements were not met. The outstanding transactinium decay data requirements have indeed encouraged others to become involved in producing highly accurate data, and plans are currently being made by IAEA-NDS staff to establish a new CRP to re-evaluate these data and update the recommended database (see Section 2.3).

2.3 Future plans – Co-ordinated Research Project: Updated Decay Data Library for Actinides

The previous CRP on actinide decay data addressed the preparation of a database directly, and provided the catalyst for a series of new measurements that continued well into the 1990s. All of this new work and earlier data need to be re-compiled and evaluated to produce an updated set of recommended decay data to replace the current IAEA database (of 1985/86). Thus, the International Nuclear Data Committee (INDC) in their advice to the Nuclear Data Section on nuclear data issues for 2002 and 2004 had noted the need for further improvements to the actinide decay data files for a wide range of applications. Thus, an appropriate CRP will begin in late 2005, with the following aims:

- promotion of actinide decay data research and development;
- evaluation of actinide decay data - proposed actinides and associated decay chains include: ^{226}Ra and daughters (?), ^{232}Th and daughters (?), ^{231}Th, ^{231}Pa, ^{233}Pa, $^{232-237}$U, ^{239}U, ^{237}Np, ^{239}Np, $^{238-242}$Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm, ^{244}Cm and ^{252}Cf;
- assembly of recommended decay data files for the agreed set of actinides, and all recommended data to be added to the NDS home page.

3. Co-ordinated Research Project: X-ray and Gamma-ray Standards for Detector Calibration (IAEA-TECDOC-619, 1991)

The question of γ-ray detector efficiency calibration arose during the CRP on Transactinium Decay Data (Section 2) when the importance of reputable reference standards became apparent. Although a provisional compilation of calibration data was agreed upon for that work [22], a strong recommendation was made to prepare an internationally-accepted file of X- and γ-ray decay data of nuclides used to calibrate detector efficiencies [21]. Furthermore, the International Nuclear Data Committee (INDC) proposed a preparative meeting with experts associated with the International Committee for Radionuclide Metrology (ICRM) to pursue this aim. An IAEA Consultants' Meeting was held at the Centre d' Etudes Nucléaires de Grenoble in May 1985 to discuss the quality of all relevant data and define a suitable programme to resolve the various issues [23]. As a consequence of these discussions, a CRP on X-ray and Gamma-ray Standards for Detector Calibration was established in 1986 by the IAEA Nuclear Data Section. Participants in the programme were specialists in γ-ray spectroscopy, and the related areas of standards and data evaluation. Their objective was to produce a recommended set of decay parameters for selected radionuclides judged as the most important for the efficiency calibration of equipment used to detect and quantify X- and γ-ray emissions. CRP meetings were held in Rome (1987 [24]) and Braunschweig (1989 [25]) to monitor progress, promote the necessary measurements, determine an evaluation methodology, and agree upon the final recommended half-lives and X- and γ-ray emission probabilities.

Various factors, such as source preparation and source-detector geometry, may affect the quality of measurements made with intrinsic germanium and other γ-ray spectrometers. However, the accuracy of such measurements depends invariably upon the accuracy of the efficiency versus energy calibration curve, and hence upon the accuracy of the decay data for the radionuclides from which calibration standard sources are prepared. Both half-lives and X- and γ-ray emission probabilities need to be known to good accuracy. Participants were given the task of establishing a data file that would be internationally accepted. Valuable contributions were also provided by multinational intercomparison projects organised by the International Committee for Radionuclide Metrology (ICRM) and the Bureau International des Poids et Mesures (BIPM).

3.1 Calibrant Radionuclides

The objectives of the CRP were identified with the following steps:

a) selection of appropriate calibration nuclides,
b) assessment of the status of the existing data,
c) identification of data discrepancies and limitations,
d) stimulation of measurements to meet the data needs, and
e) evaluation and recommendation of improved calibration data.

Other considerations for the selection of radionuclides included: commonly used and readily available nuclides; nuclides used and offered as standards by national laboratories; multi-line nuclides for rapid calibrations; definition of a set of single-line nuclides to avoid the need for coincidence summing corrections; and choice of nuclides with accurately known emission probabilities.

Emission probability data for selected photons were evaluated and expressed as absolute probabilities of the emission per decay. A recommended list of 36 nuclides evolved from the CRP meetings (Table 4). After assessing the status of the existing data, the participants agreed to measure and/or evaluate data which were either discrepant or of inadequate accuracy. The laboratories contributing to this effort are listed in the columns marked "CRP activities" of Table 4.

An evaluation procedure was developed for the half-life data, which was also used, when appropriate, for the γ-ray emission probabilities. This methodology is described in detail in Ref. [26]. The recommended value consisted of the weighted average of the published values in which the weights were taken to be the inverse of the squares of the overall uncertainties. A set of data was self-consistent if the reduced-χ^2 value was approximately 1.0 or less. When the data in a set were inconsistent and there were three or more values, the method of limitation of the relative weight proposed by Zijp [27] was recommended. The sum of the individual weights was computed; if any one weight contributed over 50% of the total, the corresponding uncertainty was increased so that the contribution of the value to the sum of the weights would be less than 50%. The weighted average was then recalculated and used if the reduced-χ^2 value for this average was < 2. If the reduced-χ^2 was > 2, the weighted or unweighted mean was chosen according to whether or not the 1σ uncertainty on each mean value included the other term. The basis for the latter choice is that it may be unreasonable to use the weighted average if the data do not comprise a consistent set.

Table 4. Calibration Standards: Decay Parameters and CRP Activities.

AEA – UK Atomic Energy Authority, Winfrith Technology Centre, UK;
CBNM – CEC-JRC Central Bureau of Nuclear Measurements, Geel, Belgium;
Hiroshima University, Hiroshima, Japan;
INEL – Idaho National Engineering Laboratory, Idaho Falls, USA;
LMRI – CEA Laboratoire de Métrologie des Rayonnements Ionisants, Saclay, France;
NIST – US National Institute of Standards and Technology, Washington DC, USA;
NPL – National Physical Laboratory, Teddington, UK;
OMH – National Office of Measures, Budapest, Hungary;
PTB – Physikalisch-Technische Bundesanstalt, Braunschweig, German.

$T_{½}$ - half-life
P_X – X-ray emission probability
P_γ - γ-ray emission probability
α_t – total internal conversion coefficient

Radio-nuclide	Data Type	Uncertainty Achieved(%)+	CRP activities: Measurements	CRP activities: Evaluations	Comments
^{22}Na	$T_{1/2}$	0.1	NIST	NPL/PTB	
	P_γ	0.015	-	NIST	
^{24}Na	$T_{1/2}$	0.03	-	NPL/PTB	
	P_γ	0.0015-0.005	-	NIST	
^{46}Sc	$T_{1/2}$	0.05	-	NPL/PTB	
	P_γ	0.0016	-	Hiroshima Univ.	
^{51}Cr	$T_{1/2}$	0.03	-	NPL/PTB	
	P_X	1.3	-	CBNM	
	P_γ	0.5	OMH	AEA	
^{54}Mn	$T_{1/2}$	0.13	NIST/NPL	NPL/PTB	
	P_X	3.1	-	CBNM	
	P_γ	0.0024	-	Hiroshima Univ.	
^{55}Fe	$T_{1/2}$	0.8	PTB	NPL/PTB	
	P_X	3.5	-	CBNM	

Table 4 (cont.)

Radio-nuclide	Data Type	Uncertainty Achieved(%)+	CRP activities: Measurements	CRP activities: Evaluations	Comments
^{56}Co	$T_{1/2}$	0.3	PTB/NPL	NPL/PTB	
	P_γ	0.007-0.4	-	Hiroshima Univ.	
^{57}Co	$T_{1/2}$	0.03	NIST/NPL	NPL/PTB	P_γ for 14.4 keV transition parti-
	P_x	0.7	-	CBNM	cularly uncertain
	P_γ	0.2-1.5	PTB	OMH	
^{58}Co	$T_{1/2}$	0.1	NPL	NPL/PTB	
	P_x	3.8	-	CBNM	
	P_γ	0.01	-	OMH	
	α_t	3	-	LMRI	
^{60}Co	$T_{1/2}$	0.03	NIST/NPL	NPL/PTB	
	P_γ	0.006-0.02	-	NIST	
^{65}Zn	$T_{1/2}$	0.11	NPL	NPL/PTB	Few direct measurements of
	P_x	2.3	-	CBNM	P_γ for 1115 keV transition
	P_γ	0.5	NPL/PTB	AEA	
^{75}Se	$T_{1/2}$	0.2	NIST/NPL	NPL/PTB	Significant uncertainty in
	P_x	7.1	-	CBNM	P_γ arises from quantifying direct
	P_γ *	0.3-1.2	LMRI/NIST/OMH/PTB	AEA	population of ^{75}As ground state
	α_t	1-7	-	LMRI	
^{85}Sr	$T_{1/2}$	0.006	-	NPL/PTB	P_γ for 514 keV transition depends
	P_x	1.4	-	CBNM	on a theoretical estimate of the
	P_γ	0.4	-	Hiroshima Univ.	branch to the ground state
	α_t	12	-	Hiroshima Univ.	
^{88}Y	$T_{1/2}$	0.02	-	NPL/PTB	
	P_x	1.3	-	CBNM	
	P_γ	0.03-0.3	PTB	LMRI	
	α_t	1	-	LMRI	
^{93m}Nb	$T_{1/2}$	0.85	-	PTB/NPL	
	P_x	3.2	-	CBNM	
^{94}Nb	$T_{1/2}$	12	-	PTB/NPL	
	P_γ	0.05	-	INEL	
	α_t	1	-	LMRI	

Table 4 (cont.)

Radio-nuclide	Data Type	Uncertainty Achieved(%)+	CRP activities Measurements	CRP activities Evaluations	Comments
^{95}Nb	$T_{1/2}$	0.02	-	PTB/NPL	
	P_γ	0.03	-	INEL	
	α_t	1-3	-	LMRI	
^{109}Cd	$T_{1/2}$	0.15	NIST	PTB/NPL	
	P_x	2.0	-	CBNM	
	P_γ #	0.6	PTB	LMRI	
	α_t	2	-	LMRI	
^{111}In	$T_{1/2}$	0.02	-	PTB/NPL	
	P_x	2.4	-	CBNM	
	P_γ #	0.1	-	Hiroshima Univ.	
	α_t	1.2	-	Hiroshima Univ.	
^{113}Sn	$T_{1/2}$	0.03	-	PTB/NPL	
	P_x	0.6	-	CBNM	
	P_γ #	0.2	-	INEL	
^{125}Sb	$T_{1/2}$	0.06	-	PTB/NPL	
	P_γ	1	INEL	LMRI	
^{125}I	$T_{1/2}$	0.02	NIST/NPL/PTB/CBNM	PTB/NPL	
	P_x	2.2	-	CBNM	
	P_γ #	1.2	PTB	LMRI	
	α_t	1.5	-	LMRI	
^{134}Cs	$T_{1/2}$	0.03	-	PTB/NPL	
	P_γ	0.06-1.3	-	Hiroshima Univ.	
^{137}Cs	$T_{1/2}$	0.4	NIST	PTB/NPL	
	P_x	2.9	-	CBNM	
	P_γ	0.24	-	LMRI	
	α_t	0.7	-	LMRI	
^{133}Ba	$T_{1/2}$	0.4	-	PTB/NPL	Resolution of 79 and 81 keV gamma transitions poses problems
	P_x	1.3	-	CBNM	
	P_γ *	0.3-0.8	OMH/PTB	OMH	
	α_t	5.5-7	-	LMRI	
^{139}Ce	$T_{1/2}$	0.02	-	PTB/NPL	
	P_x	2.8	-	CBNM	
	P_γ	0.08	-	LMRI	
	α_t	0.4	-	LMRI	

Table 4 (cont.)

Radio-nuclide	Data Type	Uncertainty Achieved(%)[+]	CRP activities		Comments
			Measurements	Evaluations	
^{152}Eu	$T_{1/2}$	0.2	NIST/NPL	PTB/NPL	
	P_x	1.6	-	CBNM	
	P_γ *	0.5	-	INEL	
^{154}Eu	$T_{1/2}$	0.09	-	PTB/NPL	
	P_x	2.3	-	CBNM	
	P_γ	1.1-1.7	INEL/NIST/NPL	Hiroshima Univ.	
^{155}Eu	$T_{1/2}$	2.8	PTB	PTB/NPL	
^{198}Au	$T_{1/2}$	0.03	-	PTB/NPL	
	P_x	7.1	-	CBNM	
	P_γ	0.5	-	AEA	
^{203}Hg	$T_{1/2}$	0.03	-	PTB/NPL	
	P_x	3.1	-	CBNM	
	P_γ	0.1	-	INEL	
^{207}Bi	$T_{1/2}$	6	-	PTB/NPL	Additional P_γ measurements are underway to resolve discrepant data
	P_x	5.2	-	CBNM	
	P_γ	0.03-0.6	INEL/NIST/PTB	Hiroshima Univ.	
	α_t	1.4	-	Hiroshima Univ.	
^{228}Th (and daughters)	$T_{1/2}$	0.9	-	NPL/PTB	
	P_γ	0.2-3.3	-	LMRI	
^{239}Np	$T_{1/2}$	0.17	-	PTB/NPL	
	P_γ	1.5	-	LMRI	
^{241}Am	$T_{1/2}$	0.15	-	PTB/NPL	
	P_x	2.0	-	CBNM	
	P_γ	1-4	PTB	CBNM	
^{243}Am	$T_{1/2}$	0.3	-	NPL/PTB	
	P_γ	1.5-1.9	-	AEA/LMRI	
	α_t	2	-	LMRI	

\+ Uncertainties for X-and γ-ray emission probabilities and internal conversion coefficients apply to the major transitions only, corresponding to 1σ confidence level.

* Measurement programme co-ordinated by ICRM.

\# Measurement programme co-ordinated as BIPM intercomparison.

It was not considered necessary to carry out evaluations of the X- and γ-ray energies, because the photon energies are only required to the nearest 1 or 0.1 keV. However, for completeness it was decided to include the best available energy values, many of which had been precisely measured and evaluated [28]. Most of the energy values were taken from Ref. [28]; original references were cited when such data were not available from this source. Internal conversion coefficients are often used in the evaluation of γ-ray emission probabilities, either directly in the determination of a particular emission probability or in testing the consistency of the decay scheme. Theoretical internal conversion coefficients were normally taken from Rösel et al. [29]; when necessary these data were obtained by interpolation using a computer program written at LMRI [30].

3.2 High-energy gamma rays

The radioactive sources discussed above permit the precise determination of the efficiency of a germanium detector up to about 2.7 MeV with either a ^{24}Na or ^{228}Th source, or to 3.6 MeV with a ^{56}Co source. Some sources of radiation can be used to extend the efficiency calibration to above 10 MeV, and were also considered. Except for one radioactive nuclide (^{66}Ga), these sources of radiation are based on nuclear reactions. While other reactions could be used, only thermal neutron capture and (p, γ) reactions were considered.

The high-energy γ-ray data were generally taken from a single reference, and were not subjected to the detailed evaluation of the other data. Furthermore, the data were of somewhat uneven quality. Some of the measurements had been undertaken with metrological goals in mind; other measurements were less well defined.

3.2.1 ^{66}Ga

^{66}Ga is the only radionuclide that has been used in the energy region above 3600 keV. This nuclide has a half-life of 9.5 hours, and can be produced by ^{63}Cu(α, n), ^{66}Zn(p, n) and ^{64}Zn(α, 2n) reactions. The γ rays with emission probabilities > 0.01 are listed in Table 5, including six lines from 3.2 to 4.8 MeV. However, two limitations are immediately apparent: half-life of 9.5 hours means that this radionuclide can only be used by spectroscopists with access to an appropriate production facility, and the uncertainties in the emission probabilities above 3 MeV range from 7% to 27% which does not result in a precise calibration.

Since a source of unknown activity would be used, the relative efficiencies would be measured and normalised to efficiencies determined previously at lower energies, for example at 1039 or 2752 keV. Despite a high decay energy of 5.2 MeV, the multiplicity of the γ-ray cascades is not high. Considering that the decay scheme consists only of the γ rays listed in Table 5, 6% of the decays produce three γ rays in cascade, 32% produce only two cascade γ rays, 10% produce only one γ ray, and 50% do not produce any γ rays at all. This means that any coincidence summing corrections will be similar to those of simple sources (e.g., ^{60}Co) with cascades of two γ rays (assuming X-rays from the electron-capture process do not reach the detector).

However, considerable improvements have been made with respect to ^{66}Ga γ-ray analysis since this CRP was completed (as noted in Section 4), and spectroscopists are urged to use the more recently recommended data on release.

Table 5. Gamma-ray Emission Probabilities from the Decay of ^{66}Ga (9.5 hours) for those Gamma Rays with Probabilities greater than 0.01 (Refs [31] and [32]).

E_γ (keV)	P_γ [a]
833.6	0.0603(12)
1039.4	0.379
1333.2	0.01232(25)
1918.8	0.0214(4)
2189.9	0.0571(11)
2422.9	0.0196(4)
2752.3	0.232(8)
3229.2	0.0148(11)
3381.4	0.0140(11)
3791.6	0.0102(11)
4086.5	0.0114(19)
4295.7	0.035(7)
4807.0	0.015(4)

a The uncertainties are those for the probabilities relative to that for the 1039-keV gamma-ray. A normalization uncertainty of 3.2% should be added (in quadrature) to obtain the overall uncertainty in the emission probabilities.

3.2.2 Thermal neutron capture reactions

Efficiency calibrations can be derived using γ rays from the thermal neutron capture reaction on selected target materials. Of the many thermal neutron capture reactions that could have been assessed, only a few were considered by the CRP.

^{14}N(n, γ)^{15}N reaction was judged to be of particular interest [33]: as shown in Table 6, there are twelve γ-ray emission probabilities (per neutron capture) ranging from 3 to 11 MeV that have uncertainties of ~ 1%. This accuracy was achieved in part because the level scheme is quite simple (for capture γ-ray decay), and the authors could use intensity balances at each level to constrain the deduced emission probabilities.

^{35}Cl(n, γ)^{36}Cl reaction was also assessed, with seventeen strong γ rays (> 0.020 photons per thermal neutron capture) ranging from 0.516 to 8.58 MeV of which eight are above 5 MeV [34]. The accuracy of the reported emission probabilities were not as good as the ^{14}N(n, γ)^{15}N data for several reasons, including a more complex scheme which precludes the confident use of intensity balances to constrain the values.

Some ratios of γ-ray emission probabilities are given in Table 7 (taken from Ref. [35]). The adoption of these reactions depends on the availability of a neutron source, and the usefulness of any particular reaction depends on the reaction cross section, a suitable sample, and the lack of any interference from background radiation (including the production of the same reaction outside the target).

Table 6. Gamma-ray Emission Probabilities per Neutron Capture (P_γ) for Prompt Gamma Rays from the $^{14}N(n, \gamma)^{15}N$ Reaction from Kennett et al. [33]).

E_γ(keV)	P_γ
1678.174(55)	0.0723(18)
1884.879(21)	0.1866(25)
2520.418(15)	0.0579(7)
3532.013(13)	0.0924(9)
3677.772(17)	0.1489(15)
4508.783(14)	0.1654(17)
5269.169(12)	0.3003(20)
5297.817(15)	0.2131(18)
5533.379(13)	0.1975(21)
5562.062(17)	0.1065(12)
6322.337(14)	0.1867(14)
7298.914(33)	0.0973(9)
8310.143(29)	0.0422(5)
9149.222(47)	0.0162(2)
10829.087(46)	0.1365(21)

Footnote: A.H. Wapstra [Nucl. Instrum. Meth. Phys. Res. A292, 671 (1990)] has given an alternate set of gamma-ray energies based on the average of three sets of measurements and a revised value of the neutron binding energy.

Table 7. Thermal Neutron Capture Reactions with Subsequent Emission of Gamma Rays in Cascade at Energies E_1 and E_2 and with Emission Probabilities P_1 and P_2.

Reaction	E_1	E_2	P_1/P_2
$^{35}Cl(n,\gamma)^{36}Cl$	5.716	2.864	0.86(7) [a]
	6.111	1.951	1.05(9) [a]
	6.111	0.517	0.87(7) [a]
	6.620	1.959	0.67(6) [a]
	6.978	1.601	0.65(6) [a]
	7.791	0.788	0.57(5) [a]
$^{48}Ti(n,\gamma)^{49}Ti$	4.882	1.499	0.92(3)
	6.419	0.342	1.23(2)
	6.761	1.382	0.54(2)
$^{52}Cr(n,\gamma)^{53}Cr$	5.618	2.231	1.00
$^{53}Cr(n,\gamma)^{54}Cr$	6.645	2.239	0.95
	7.100	1.785	1.07
	8.884	0.835	0.60

[a] Uncertainty includes statistical uncertainties, and 8% for the systematic uncertainty.

3.2.3 Proton capture reactions

Proton capture reactions can be used to provide γ rays to calibrate germanium detectors. Although there are some experimental difficulties, these reactions have the advantage that simple γ-ray spectra are often produced when the proton energy is chosen to coincide with a resonance. Some useful proton resonances and the related γ-ray emission probability ratios are listed in Table 8. Many other potentially useful resonances may also be identified from the review articles of Endt and van der Leun [36] and Ajzenberg-Selove [37].

Table 8. Proton Capture Reactions with Subsequent Emission of Gamma Rays in Cascade at Energies E_1 and E_2 and with Emission Probabilities P_1 and P_2; Proton Resonance Energy is E_p.

Reaction	E_p (MeV)	$E_{\gamma 1}$ (MeV)	$E_{\gamma 2}$ (MeV)	P_1/P_2
$^{11}B(p,\gamma)^{12}C$	0.675	12.14	4.44	1.000
	1.388	12.79	4.44	1.000
	2.626	13.92	4.44	1.000
$^{14}N(p,\gamma)^{15}O$	0.278	5.183	2.374	1.00
		6.176	1.381	1.00
		6.793	0.764	1.00
$^{23}Na(p,\gamma)^{24}Mg$	1.318	11.588	1.368	0.963(3)
	1.416	8.929	2.754	0.985(3)
$^{24}Al(p,\gamma)^{28}Si$	0.767	7.706	2.837	0.981(2)
	0.992	10.76	1.780	0.806(10)
	1.317	6.58	4.50	1.017(7)

3.3 Recommended X-ray and Gamma-ray Standards, 1990/91

A set of recommended half-life and emission probability data was prepared by participants of the IAEA Co-ordinated Research Project on X-ray and Gamma-ray Standards for Detector Calibration. The results from this work represented a significant improvement in the quality of specific decay parameters required for the efficiency calibration of X- and γ-ray detectors. Data inadequacies were highlighted, several of the identified inconsistencies remain unresolved, and further efforts are required to address these uncertainties. Accomplishments of this CRP included:

- assessment of the existing relevant data during 1986/87,
- co-ordination of measurements within the existing project and extensive cooperation among the participating research groups,
- performance of a large number of measurements stimulated by the CRP, and
- preparation of an IAEA-TECDOC report which consolidated most of the data needed for γ-ray detector efficiency calibration (IAEA-TECDOC-619, IAEA Vienna, Austria, 1991).

The resulting data were internationally accepted as a significant contribution to the improved quality of X- and γ-ray spectrometry. However, the recommended database that evolved from this CRP will soon be superseded by the results of a new CRP initiative that began in 1998 to update calibrant decay data (see Section 4).

4. Co-ordinated Research Project: Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications (both the technical document and database are still in preparation, 2005)

A strong recommendation was formulated at the 1997 biennial meeting of the International Nuclear Data Committee for the IAEA-NDS to re-visit and place further emphasis on the development of improved decay data for standards applications. This recommendation arose as a consequence of the publication of relevant measured data beyond 1990 that were not included in the original CRP (see Section 3, above). Many such studies had been catalysed by the demands of this earlier CRP, and new efforts were required to incorporate the new data and extend the existing database to encompass the related needs of a number of important applications such as environmental monitoring and nuclear medicine. High-quality decay data are essential in the efficiency calibration of X- and γ-ray detectors that are used to quantify radionuclidic content by determining the intensities of any resulting X- and γ rays. A Consultants' Meeting was held at IAEA Headquarters in 1997 to assess the current needs, and identify the most suitable radionuclides [38]. The expert participants at this meeting advised the establishment of a new Co-ordinated Research Project: Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications.

Members of the new CRP reviewed and modified the list of radionuclides most suited for detector calibration, and were able to include some of the specific needs of such nuclear applications as safeguards, material analysis, environmental monitoring, nuclear medicine, waste management, dosimetry and basic spectroscopy. CRP meetings were held at IAEA, Vienna (1998 [39]), PTB, Braunschweig (2000 [40]), and IAEA Vienna (2002 [41]) to monitor progress, promote measurements, formulate and implement the evaluation procedures, and agree upon the final recommended half-lives and X- and γ-ray emission probabilities. All evaluations were based on the available experimental data, supplemented with the judicious use of well-established theory. As with the previous CRP, three types of data (half-lives, energies, and emission probabilities) were compiled and evaluated. Consideration was also given to the use of the γ-γ coincidence technique for efficiency calibrations, as well as adopting a number of prompt high-energy γ rays from specific nuclear reactions. Well-defined evaluation procedures were applied to determine the recommended half-lives and emission probabilities for all prominent X- and γ rays emitted by each selected radionuclide.

4.1 Main issues

4.1.1 Update of 1991 IAEA database

IAEA-TECDOC-619 contains recommended decay data for 36 radionuclides, extending up to γ-ray energy of 3.6 MeV. These data were revisited and revised where appropriate, as a consequence of the availability of new experimental data measured and published after 1990. New measurements of half-lives have also been published for at least 29 of the original 36 radionuclides. Most of the γ-ray energies were taken from Ref. [42], while original references were cited when such data were not available from this source. Only average X-ray energies and their emission probabilities were given in IAEA-TECDOC-619 - the new work eliminates this shortcoming through a systematic analysis of the emissions of the individual $K_{\alpha1}$, $K_{\alpha2}$, $K_{\beta1}$ and $K_{\beta2}$ components. However, X-ray energies were not evaluated, but taken from Schönfeld and Rodloff [43] and Browne and Firestone [31].

4.1.2 Additional radionuclides

A comprehensive list of 68 radionuclides was originally prepared at the Consultants' Meeting, and adopted as a suitable starting point by the participants of the CRP. Decay data were compiled, evaluated and recommended for the half-lives, and X-ray and γ-ray emission probabilities. These radionuclides have been re-evaluated in an international exercise led by laboratories involved in the Decay Data Evaluation Project (DDEP) [44] and affiliated to the International Committee for Radionuclide Metrology (ICRM), with the IAEA-CRP providing additional impetus and the necessary co-ordination to achieve the desired objectives.

4.1.3 Extension of the energy range

New nuclear techniques (for example, radiotherapy) suffer from a lack of high-energy calibration standards. Hence, there is an urgent need to provide such data for the calibration of γ-ray detectors up to 25 MeV. Appropriate radionuclides and nuclear reactions have been identified, and γ-ray emission probabilities were compiled and evaluated. Various options were explored in order to provide energy and intensity calibration γ-lines above 10 MeV.

4.1.4 Other features

Angular correlation coefficients were evaluated for a few appropriate radionuclides of relevance to the γ-γ coincidence method of calibration. Attention was also focused on the analysis of uncertainties, including an investigation of the feasibility and usefulness of including error correlations in the evaluation procedures. A limited number of nuclides were evaluated in this manner. One conclusion arising from this exercise was the need to establish rules for the documentation of experiments that would enable the evaluators to estimate input covariances from the published decay data.

4.2 Specified radionuclides and nuclear reactions

A recommended list of 62 nuclides evolved from the meetings of the IAEA CRP (Table 9), including specific parent-daughter combinations and two heavy-element decay chains. A primary standard is a nuclide for which γ-ray emission probabilities are calculated from various data that do not include significant γ-ray measurements (emission probabilities are usually close to 1.0, expressed per decay); these data may include internal conversion coefficients and the intensities of weak beta branches. Secondary standards are nuclides for which the recommended γ-ray intensities depend on prior measurements of the γ-ray intensities. When relative intensities had been measured, these parameters were evaluated as well as the normalisation factor; this combination of data was then used to generate absolute emission probabilities. Thus, both relative intensities and absolute emission probabilities were included in the evaluation exercise, and both can be extracted from the database.

The following nuclear reactions were also adopted as γ-ray calibration standards:

$^{14}N(n, \gamma)^{15}N^*$
$^{35}Cl(n, \gamma)^{36}Cl^*$
$^{48}Ti(n, \gamma)^{49}Ti^*$
$^{50, 52, 53}Cr(n, \gamma)^{51, 53, 54}Cr^*$
$^{11}B(p, \gamma)^{12}C^*$
$^{23}Na(p, \gamma)^{24}Mg^*$
$^{27}Al(p, \gamma)^{28}Si^*$

Their cross sections, and the energies and transition probabilities of the most prominent high-energy γ rays have been evaluated.

Emphasis has been placed on the X- and γ rays most suited as detector efficiency calibrants, and only these emissions have been included in the final CRP dataset (i.e., only a limited number of strong lines are recommended). Detailed comments and complete decay-data listings will not necessarily be included in the final technical document; however, the user will be referred to relevant parallel publications by laboratories involved in the DDEP [45-47], and web pages located through: http://www.nucleide.org/DDEP_WG/DDEPdata.htm

4.3 Recommended X-ray and Gamma-ray Decay Data Standards: Revisited, 2004/05

A new set of recommended half-life and emission probability data has been prepared by participants in the IAEA-CRP to Update X- and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications. The results from this work represent a further significant improvement in the quality of specific decay parameters required for the efficiency calibration of X- and γ-ray detectors. Examples of the data as presented to the reader of the technical report are given in Appendix B (these data are provisional, and subject to modification before release of the final database).

The accomplishments of the CRP include:

- re-evaluations of all existing relevant data from the 1986-90 programme;
- extension of the recommended database to satisfy the needs of a number of important applications;
- specific measurements were undertaken, particularly with respect to high-energy γ-ray emissions;
- preparation of an IAEA technical report which summarizes the recommended decay data for X- and γ-ray detector efficiency calibration and other applications.

As before, one important expectation is that the resulting set of data will be internationally accepted as a significant contribution to improving the quality of both X- and γ-ray spectrometry.

Table 9: Selected Radionuclides and Applications.

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{22}Na	P	-	x	-	-	-
^{24}Na	P	-	-	-	-	-
^{40}K	S	-	-	x	-	-
^{46}Sc	P	-	-	-	-	-
^{51}Cr	S	-	x	-	-	-
^{54}Mn	P	-	-	x	x	-
^{56}Mn	P	-	x	-	-	-
^{55}Fe	S	-	x	-	x	-
^{59}Fe	S	-	x	-	-	-
^{56}Co	S	-	-	-	-	-
^{57}Co	P (122 keV)	-	x	-	-	x
^{58}Co	P	-	-	x	-	-
^{60}Co	P	-	x	x	x	x
^{64}Cu	-	-	x	-	-	-
^{65}Zn	S	-	-	x	x	-
^{66}Ga	S	-	x	-	-	-
^{67}Ga	S	-	x	-	-	-
^{68}Ga	-	-	x	-	-	-
^{75}Se	S	-	x	-	-	-
^{85}Kr	-	-	-	x	-	-
^{85}Sr	P	-	x	x	-	-
^{88}Y	P (1836 keV) S (898 keV)	-	-	-	-	-
^{93m}Nb	-	x	-	-	-	-
^{94}Nb	P	-	-	-	-	-
^{95}Nb	P	-	-	x	-	-
^{99}Mo	P (140.5 keV)	-	x	-	-	-
^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{103}Ru	-	-	x	x	-	-
^{106}Ru-^{106}Rh	S	-	x	x	-	-
^{110m}Ag	S	-	-	x	x	-
^{109}Cd	S	-	-	x	-	-
^{111}In	P	-	x	-	-	-
^{113}Sn	P	-	-	-	-	-
^{125}Sb	-	-	-	x	-	-
^{123m}Te	-	-	-	-	-	-
^{123}I	P	-	x	-	-	-
^{125}I	S	x	x	-	-	-
^{129}I	S	-	-	x	x	-
^{131}I	S	x	x	x	-	-
^{134}Cs	S	-	-	x	-	-

Table 9: Selected Radionuclides and Applications (cont.).

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Application	Environmental Monitoring	Waste Management	Safeguards
^{137}Cs	P	-	-	x	x	-
^{133}Ba	S	-	x	-	-	-
^{139}Ce	P	-	-	x	-	-
^{141}Ce	S	-	-	x	-	-
^{144}Ce	S	-	x	x	-	-
^{153}Sm	-	-	x	-	-	-
^{152}Eu	S	-	-	x	x	x
^{154}Eu	S	-	-	x	x	x
^{155}Eu	S	-	-	x	x	-
^{166m}Ho-^{166}Ho	S	-	x	-	-	x
^{170}Tm	S	-	-	-	-	-
^{169}Yb	S	-	x	-	-	-
^{192}Ir	S	x	x	-	-	-
^{198}Au	P	-	-	-	-	-
^{203}Hg	P	-	-	-	-	-
^{201}Tl	-	-	x	-	-	-
^{207}Bi	P (569.7 keV)	-	x	-	-	-
^{226}Ra decay chain	S	x	-	x	x	-
^{228}Th decay chain	P	-	-	x	-	-
^{234m}Pa	-	-	-	x	x	-
^{241}Am	P	-	-	x	x	x
^{243}Am	-	-	-	-	x	-

P primary efficiency calibration standard.
S secondary efficiency calibration standard.

5. Concluding Remarks

Decay-data studies undertaken under the auspices of the International Atomic Energy Agency are strongly linked to the needs of Member States, and are therefore applications oriented. Specific inadequacies in our knowledge of important decay-data parameters have been identified through IAEA-sponsored Advisory Group Meetings and Consultants' Meetings.

At various periods of time over the previous 30 years, staff in the IAEA Nuclear Data Section have been encouraged by Member States to organise four Co-ordinated Research Projects (CRPs) to resolve difficulties and uncertainties identified with:

- decay data of transactinium nuclides (two CRPs, 1977-85 and 2005-09 (in planning stage));
- X-ray and γ-ray decay data standards for detector calibration and other applications (two CRPs, 1986-1990 and 1998-2002).

New measurements have been performed and in-depth evaluations undertaken in order to formulate recommended decay data for the relevant radionuclides, as specified at the various Consultants' Meetings.

A comprehensive form of in-depth evaluation methodology has been developed in conjunction with the Decay Data Evaluation Programme (DDEP). The various agreed evaluation procedures have been applied to all relevant decay data for each individual radionuclide, representing a high degree of analysis. Such detail is extremely labour intensive, and the limited amount of expertise worldwide prevents general application to the full range of mass chain evaluations.

Much has been achieved to resolve a wide range of specific difficulties and discrepancies, and a number of extremely useful applications-based decay-data files have been assembled by the IAEA Nuclear Data Section to ensure that the most up-to-date values are adopted by users in Member States. Further work is merited, including the need to update the IAEA database of actinide decay data (indeed plans are being formulated to initiate such a CRP in 2005). One further intention will be to maintain strong technical links between the relatively modest number of experts to be found working within the DDEP and involved in IAEA-CRPs dedicated to the evaluation and recommendation of decay data.

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A. Lorenz and H.D. Lemmel (X-ray and Gamma-ray Standards for Detector Calibration);
M. Herman (Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications).

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APPENDIX A

TRANSACTINIUM DECAY DATA, 1985/86

EXAMPLE DATA AND RECOMMENDATIONS

I. HALF-LIFE

Recommended value: $(7.037 \pm 0.007) \times 10^8$ a

This value was adopted from the 1984 review by Holden [1].

The quoted uncertainty, corresponding to the 2σ level, has been reduced to 0.1%, being the minimum value adopted by the CRP participants for half-lives of long lived nuclides.

II. EMISSION PROBABILITIES OF SELECTED GAMMA RAYS

Evaluated by R. Vaninbroukx (CBNM, Geel, Belgium).

A. Recommended values

E_γ (keV)	P_γ
41.96	0.0006 ± 0.0001
74.8	0.0006 ± 0.0001
109.16	0.0154 ± 0.0005
140.76	0.0022 ± 0.0002
143.76	0.1096 ± 0.0008
150.93	0.0008 ± 0.0001
163.33	0.0508 ± 0.0004
182.61	0.0034 ± 0.0002
185.72	0.572 ± 0.002
194.94	0.0063 ± 0.0001
198.90	0.0042 ± 0.0006
202.11	0.0108 ± 0.0002
205.31	0.0501 ± 0.0005
221.38	0.0012 ± 0.0001
233.50	0.00029 ± 0.00005
240.85	0.00075 ± 0.00006
246.84	0.00053 ± 0.00003

B. CRP measurements

E_γ (keV)	Vaninbroukx and Denecke (1982) [2]	Banham and Jones (1983) [3]	Helmer and Reich (1984) [4]
41.96		0.0006 *1*	
74.8		0.0051 *5*	
109.16		0.0153 *5*	
140.76		0.00214 *15*	
143.76	0.109 *2*	0.107 *2*	0.1101 *8*
150.93		0.00066 *10*	
163.33	0.050 *1*	0.0497 *10*	0.0512 *4*
182.61		0.00339 *17*	
185.72	0.575 *9*	0.573 *6*	0.572 *5*
194.94		0.00626 *13*	
198.90		0.00047 *6*	
202.11		0.0108 *2*	
205.31	0.050 *2*	0.0505 *5*	0.0496 *5*
221.38		0.00114 *6*	
233.50		0.00029 *5*	
240.85		0.00076 *6*	
246.84		0.00053 *3*	

C. Comparison with other measurements

E_γ (keV)	CRP measurements			Other measurements			Evaluated values[c]
	Vaninbroukx and Denecke (1982) [2]	Banham and Jones (1983) [3]	Helmer and Reich (1984) [4]	Teoh et al. (1974) [5][a]	Vano et al. (1975) [6][a]	Olson (1983) [7]	
41.96		0.0006 *1*		0.0007 *3*			0.0006 *1*
74.8		0.0051 *5*[b]		0.0005 *1*	0.0007 *1*		0.0006 *1*
109.16		0.0153 *5*		0.018 *2*	0.015 *2*		0.0154 *5*
140.76		0.00214 *15*		0.0026 *3*	0.0022 *3*		0.0022 *2*
143.76	0.109 *2*	0.107 *2*	0.1101 *8*	0.112 *11*	0.111 *11*	0.1093 *15*	0.1096 *8*
150.93		0.00066 *10*		0.0008 *1*	0.00081 *10*		0.0008 *1*
163.33	0.050 *1*	0.0497 *10*	0.0512 *4*	0.050 *5*	0.051 *5*	0.0507 *8*	0.0508 *4*
182.61		0.00339 *17*		0.0042 *14*	0.0044 *9*		0.0034 *2*
185.72	0.575 *9*	0.573 *6*	0.572 *5*			0.561 *8*	0.572 *5*
194.94		0.00626 *13*		0.0061 *9*	0.0062 *6*		0.0063 *1*
198.90		0.00047 *6*		0.00046 *6*	0.00033 *5*		0.0042 *6*
202.11		0.0108 *2*		0.0108 *11*	0.0107 *10*		0.0108 *2*
205.31	0.050 *2*	0.0505 *5*	0.0496 *5*	0.049 *4*	0.050 *5*	0.0503 *9*	0.0501 *5*
221.38		0.00114 *6*		0.0012 *3*	0.0012 *1*		0.0012 *1*
233.50		0.00029 *5*		0.0003 *1*	0.0003 *1*		0.00029 *5*
240.85		0.00076 *6*		0.0006 *2*	0.0008 *2*		0.00075 *6*
246.84		0.00053 *3*		0.0005 *2*	0.0008 *2*		0.00053 *3*

Notes to Table C

[a] The P_γ values have been calculated from the measured relative intensities using $P_\gamma = 0.572 \pm 0.005$ for the 185 keV reference line.

[b] The value, deviating by a factor of about 10 from the results of the other measurements, has not been considered in the calculation of the evaluated value.

[c] The evaluated values and uncertainties are based on weighted means calculated according to Topping [8].

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I. HALF-LIFE

Evaluated by A.L. Nichols (UKAEA, AEE Winfrith).

I.1. Total half-life

Recommended value: 141 ± 2 a

Weighted mean with 1σ standard deviation.

Value (years)	Reference[e]
152 *7* [a,b]	Barnes et al. (1959) [1]
141.9 *17* [a,c]	Zelenkov et al. (1979) [2]
139.7 *18* [a,d]	Zelenkov et al. (1979) [2]

Notes to Table

[a] Quoted uncertainty estimated to be 1σ standard deviation.
[b] Derived from unpublished data and measured alpha half-life: recalculated, but includes erroneous identification of decay modes.
[c] In-growth of ^{242}Cm via ^{242}Am.
[d] Measurement of emission ratios of $^{242}Am^m$ and ^{242}Am.
[e] Exclusive consideration of 1979 measurements (see note b) results in a weighted mean half-life of 141 *1* years.

I.2. Alpha half-life

Recommended value: (3.11 ± 0.05) × 10^4 a

Weighted mean with 1σ standard deviation.

Value (years)	Reference
2.9 *2* × 10^4 [a,b]	Barnes et al. (1959) [1]
3.12 *5* × 10^4 [a]	Zelenkov et al. (1979) [2]

Notes to Table

[a] Quoted uncertainty estimated to be 1σ standard deviation.
[b] Recalculated from activity measurements using latest estimates of half-life data.

I.3. Spontaneous fission half-life

Recommended value: $(8.8 \pm 3.2) \times 10^{11}$ a

Value (years)	Reference
8.8 *32* $\times 10^{11}$ [a]	Caldwell et al. (1967) [3]

Note to Table

[a] Reported value of 9.5 *35* $\times 10^{11}$ years has been recalculated using latest values for the half-life of $^{242}Am^m$ and the branching fraction to ^{242}Cm.

I.4. Branching fractions

Alpha branching fraction: 0.0045 ± 0.0003.
Isomeric transition branching fraction: 0.9955 ± 0.0003.
Spontaneous fission branching fraction: $(1.6 \pm 0.6) \times 10^{-10}$.

REFERENCES

[1] BARNES, R.F., HENDERSON, D.J., HARKNESS, A.L., DIAMOND, H., J. Inorg. Nucl. Chem. 9 (1959) 105.

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APPENDIX B

X-RAY AND GAMMA-RAY DECAY DATA STANDARDS, 1998-2002

EXAMPLE DATA AND RECOMMENDATIONS

Health Warning: all recommended data are subject to change (see Section 4.3)

^{51}Cr

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by E. Schönfeld (PTB, Germany) and R. G. Helmer (INEEL. USA), February 2000.

Recommended data:

Half-life

$T_{1/2}$ = 27.7009 (20) d

Selected gamma ray

E_γ (keV)	P_γ per decay
320.0835 (4) [a]	0.0987 (5) [b]

[a] from Ref. [1].
[b] from direct emission probability measurements.

Selected X-rays

Origin		E_X (keV)	P_X per decay
V	Kα	4.94 - 4.95	0.202 (3)
V	Kβ	5.43 - 5.46	0.0269 (7)

Input data:

Half-life

Half-life (d)	Reference
27.7010 (12) [a]	Unterweger *et al* [H1]
27.71 (3)	Walz *et al* [H2]
27.704 (3)	Rutledge *et al* [H3]
27.690 (5)	Houtermans *et al* [H4]
27.72 (3)	Lagoutine *et al* [H5]
27.703 (8)	Tse *et al* [H6]
27.75 (1) [b]	Visser *et al* [H7]
28.1 (17) [b]	Araminowicz and Dresler [H8]
27.76 (15) [b]	Emery *et al* [H9]
27.80 (51) [b]	Bormann *et al* [H10]
27.7009 (20)	

[a] uncertainty increased to (25) to ensure weighting factor not greater than 0.50.
[b] rejected as an outlier.

References - half-life

[H1] M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349
[H2] K. F. Walz, K. Debertin, H. Schrader, Int. J. Appl. Radiat. Isot. **34** (1983) 1191.
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[H8] J. Araminowicz, J. Dresler, INR-1464 (1973) 14.

[H9] J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason, Nucl. Sci. Eng. **48** (1972) 319.
[H10] M. Bormann, A. Behrend, I. Riehle, O. Vogel, Nucl. Phys. **A115** (1968) 309.

Gamma ray: measured and evaluated emission probability

Eγ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
320.0835	9.8 (6)	9 (1)	9.72 (15)	10.2 (6)	9.75 (20)	10.2 (10)

Eγ (keV) [1]	[8]	[9]	[10]	**Evaluated**
320.0835	9.85 (9)	10.30 (19)	9.86 (8)	9.87 (5)

Evaluated emission probabilities are the weighted averages calculated according to the Limitation of Relative Statistical Weights Method; no value has a relative weighting factor greater than 0.50.

References - radiations

[1] R. G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.
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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{203}Hg

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by A. L. Nichols (IAEA and AEA Technology, UK), January 2002.

Recommended data:

Half-life

$T_{1/2}$ = 46.594 (12) d

Selected gamma rays

E_γ (keV)	P_γ per decay
279.1952 (10) [a]	0.8148 (8)

[a] from Ref. [1].

Selected X-rays

Origin		E_X (keV)	P_X per decay
Tl	L	8.953 - 14.738	0.0543 (9)
Tl	$K\alpha_2$	70.8325 (8)	0.0375 (4)
Tl	$K\alpha_1$	72.8725 (8)	0.0633 (6)
Tl	$K\beta_1'$	82.118 - 83.115	0.0215 (4)
Tl	$K\beta_2'$	84.838 - 85.530	0.0064 (2)

Input data:

Half-life

Half-life (d)	Reference
46.619 (27)	Unterweger *et al* [H1]
46.612 (19)	Walz *et al* [H2]
46.60 (1)	Rutledge *et al* [H3]
46.582 (2) [a]	Houtermans *et al* [H4]
46.76 (8) [b]	Emery *et al* [H5]
47.00 (3) [b]	Lagoutine *et al* [H6]
46.594 (12)	

[a] uncertainty increased to (9) to ensure weighting factor not greater than 0.50.
[b] rejected as an outlier.

References - half-life

[H1] M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349.
[H2] K. F. Walz, K. Debertin, H. Schrader, Int. J. Appl. Radiat. Isot. **34** (1983) 1191.
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[H5] J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason, Nucl. Sci. Eng. **48** (1972) 319.
[H6] F. Lagoutine, Y. L. Gallic, J. Legrand, Int. J. Appl. Radiat. Isot. **19** (1968) 475.

Gamma ray: energy and emission probability

Comments:

γ-ray energy of 279.1952 keV have been adopted from Ref. [1].

279.1952-keV γ-ray is of mixed (25%M1 + 75%E2) multipolarity, and α_{tot} = 0.2271 (12) and α_K = 0.1640 (10) have been adopted from Ref. [2], in good agreement with specific measurements [3-6].

beta-particle emission probabilities were calculated from the limit of 0.0001 (1) set on the beta transition to the $½^+$ ground state of ^{203}Tl [7, 8], to give 0.9999 (1) for the transition to the first excited state of ^{203}Tl ($5/2^- \rightarrow 3/2^+$).

as defined above, transition probability of 0.9999 (1) for the 279.1952-keV γ ray was used in conjunction with α_{tot} to calculate an absolute emission probability of 0.8148 (8).

X-rays: energies and emissions

Calculated using the evaluated γ-ray data, and atomic data from Refs. [9-11].

References - radiations

[1] R. G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.
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[6] E. Schönfeld, H. Janβen, R. Klein, Appl. Radiat. Isot. **52** (2000) 955.
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Detailed tables and comments can be found on:
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{226}Ra with Daughters

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by R. G. Helmer (INEEL, USA), August 2002.

Recommended data:

Half-life (^{226}Ra)
$T_{1/2}$ = 5.862 (22) × 10^5 d

Selected gamma rays

Only γ rays with emission probabilities greater than 0.010 are included.

Parent	E_γ (keV)	P_γ per decay
^{214}Pb	53.2275 (21) [a]	0.01066 (14)
^{226}Ra	186.211 (13) [a]	0.03533 (28)
^{214}Pb	241.997 (3) [a]	0.0719 (6)
^{214}Pb	295.224 (2) [a]	0.1828 (14)
^{214}Pb	351.932 (2) [a]	0.3534 (27)
^{214}Bi	609.316 (3) [b]	0.4516 (33)
^{214}Bi	665.453 (22) [a]	0.01521 (11)
^{214}Bi	768.367 (11) [b]	0.04850 (38)
^{214}Bi	806.185 (11) [b]	0.01255 (11)
^{214}Bi	934.061 (12) [a]	0.03074 (25)
^{214}Bi	1120.287 (10) [a]	0.1478 (11)
^{214}Bi	1155.19 (2) [a]	0.01624 (14)
^{214}Bi	1238.110 (12) [a]	0.05785 (45)
^{214}Bi	1280.96 (2) [a]	0.01425 (12)
^{214}Bi	1377.669 (12) [a]	0.03954 (33)
^{214}Bi	1401.516 (14) [c]	0.01324 (11)
^{214}Bi	1407.993 (7) [b]	0.02369 (19)
^{214}Bi	1509.217 (8) [b]	0.02108 (21)
^{214}Bi	1661.316 (13) [b]	0.01037 (10)
^{214}Bi	1729.640 (12) [b]	0.02817 (23)
^{214}Bi	1764.539 (15) [b]	0.1517 (12)
^{214}Bi	1847.420 (25) [a]	0.02000 (18)
^{214}Bi	2118.536 (8) [b]	0.01148 (11)
^{214}Bi	2204.071 (21) [b]	0.0489 (10)
^{214}Bi	2447.673 (10) [b]	0.01536 (15)

[a] from Ref. [1].
[b] from Ref. [2].
[c] from Ref. [3].

Input data:

Half-life

Half-life (d)	Reference
584035 (853) [a]	Ramthun [H1]
585131 (3204)	Martin and Tuck [H2]
590609 (4135)	Sebaoun [H3]
592436 (4749)	Kohman *et al* [H4]
5.862 (22) × 10^5	

[a] uncertainty increased to (2250) to ensure weighting factor not greater than 0.50.

References - half-life

[H1] H. Ramthun, Nukleonik **8** (1966) 244.
[H2] G. R. Martin, D. G. Tuck, Int. J. Appl. Radiat. Isot. **5** (1959) 141.
[H3] W. Sebaoun, Ann. Phys., Paris **1** (1956) 680.
[H4] T. P. Kohman, D. P. Ames, J. Sedlet, Nat. Nucl. Energy Series **14** (1949) 1675.

Gamma rays: measured and evaluated relative emission probabilities

Eγ (keV)	[4]	[5]	[6] [a]	[7]	[8]	[3]	**Evaluated**
53.2	-	-	-	-	2.329 (23)	2.384 (20)	2.360 (27)
186.21	8.7 (11)	9.2 (10)	8.58 (5)	7.6 (8)	7.812 (31)	7.85 (5)	7.824 (26)
241.99	17.5 (17)	16.1 (24)	16.23 (10)	16.1 (10)	15.90 (5)	15.98 (6)	15.93 (4)
295.22	40 (4)	42 (5)	41.85 (26)	40.8 (12)	40.36 (12)	40.61 (13)	40.48 (9)
351.93	86 (9)	82 (11)	81.5 (5)	78.5 (24)	78.16 (23)	78.34 (23)	78.25 (16)
609.32	≡100	100	100	100	100	100	100
665.45	3.6 (4)	3.36 (37)	3.51 (20)	3.33 (10)	3.359 (17)	3.386 (21)	3.369 (13)
768.37	11.4 (12)	11.9 (17)	10.91 (8)	10.39 (31)	10.66 (5)	10.768 (29)	10.740 (29)
806.18	3.0 (4)	2.92 (43)	2.90 (22)	2.76 (11)	2.788 (22)	2.777 (14)	2.780 (12)
934.06	7.3 (7)	7.0 (9)	6.88 (5)	6.70 (20)	6.783 (34)	6.834 (36)	6.806 (25)
1120.29	34 (3)	-	33.13 (22)	32.3 (10)	32.71 (10)	32.77 (12)	32.73 (8)
1155.19	4.0 (5)	-	3.5 (4)	4.3 (7)	3.594 (36)	3.595 (17)	3.595 (15)
1238.11	14.9 (15)	-	12.87 (9)	12.7 (4)	12.83 (6)	12.80 (4)	12.810 (33)
1280.96	3.6 (5)	-	3.17 (17)	3.15 (11)	3.147 (28)	3.159 (16)	3.156 (14)
1377.67	9.9 (11)	-	8.82 (25)	8.52 (25)	8.69 (4)	8.794 (30)	8.755 (35)
1401.52	3.5 (4)	-	2.91 (16)	3.0 (4)	2.924 (20)	2.934 (13)	2.932 (11)
1407.99	6.2 (7)	-	5.37 (6)	5.5 (5)	5.233 (26)	5.250 (19)	5.245 (15)
1509.22	5.5 (5)	-	4.76 (5)	4.63 (15)	4.61 (6)	4.682 (31)	4.668 (31)
1661.32	2.72 (25)	-	2.33 (12)	2.37 (22)	2.271 (34)	2.299 (14)	2.296 (14)
1729.64	7.5 (7)	-	6.60 (4)	6.33 (15)	6.226 (31)	6.245 (32)	6.238 (25)
1764.54	40 (4)	-	34.48 (25)	33.3 (10)	33.54 (10)	33.63 (9)	33.59 (7)
1847.42	5.3 (5)	-	4.57 (6)	4.35 (13)	4.448 (36)	4.419 (28)	4.429 (25)
2118.54	3.03 (29)	-	2.56 (3)	2.65 (25)	2.536 (20)	2.548 (21)	2.543 (15)
2204.07	12.38 (27)	-	11.02 (9)	11.1 (3)	10.74 (5)	10.75 (9)	10.83 (20)
2447.67	4.0 (4)	-	3.42 (3)	3.30 (10)	3.402 (24)	3.409 (36)	3.402 (21)

[a] data rejected as outliers.

Evaluated emission probabilities are the weighted averages calculated according to the Limitation of Relative Statistical Weights Method, and using the data from Refs. [3-5, 7, 8]; no value has a relative weighting factor greater than 0.50.

Absolute emission probabilities for specific γ rays have been measured by several authors [9-13]. Generally, the uncertainties in the relative emission probabilities from these authors have larger uncertainties than those for the relative values in the above table. Therefore, the above relative emission probabilities have been normalized simply by use of P_γ(609 keV) = 0.4516 (33) from the average of the values from Refs. [9-13].

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ON NUCLEAR STRUCTURE AND DECAY DATA:

THEORY AND EVALUATION

MANUAL – PART 2

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Distr. SD/EL

WORKSHOP
ON NUCLEAR STRUCTURE AND DECAY DATA:
THEORY AND EVALUATION
Manual – Part 2

ICTP Trieste, Italy

17 – 28 November 2003

Prepared by

A.L. Nichols and P.K. McLaughlin

IAEA Nuclear Data Section

Vienna, Austria

Abstract

A two-week Workshop on Nuclear Structure and Decay Data was organized and administrated by the IAEA Nuclear Data Section, and hosted at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy from 17 to 28 November 2003. The aims and contents of this workshop are summarized in Part 1 of this manual, along with the agenda, list of participants, comments and recommendations. Workshop materials are also included that are freely available on CD-ROM (all relevant PowerPoint presentations and manuals along with appropriate computer codes):

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P.O. Box 100
Wagramer Strasse 5
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Austria

January 2004

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Evaluated Nuclear Structure Data Base

J. K. Tuli

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E-mail: tuli@bnl.gov

Evaluated Nuclear Structure Data Base

J. K. Tuli
National Nuclear Data Center
Brookhaven National Laboratory
Upton, NY 11973 USA

BROOKHAVEN NATIONAL LABORATORY

ENSDF

- Source for
  Table of Isotopes
  Nuclear Data Sheets
  Nuclear Wallet Cards
  NUDAT
- Update – continuous
- Distributed – six monthly

BROOKHAVEN NATIONAL LABORATORY

Content of ENSDF

- Collection of Data Sets by A and Z

  Abstract (Comments)

  Adopted Levels, Gammas

  Experimental Data Sets

  - Radioactive Decay

  - Nuclear Reactions

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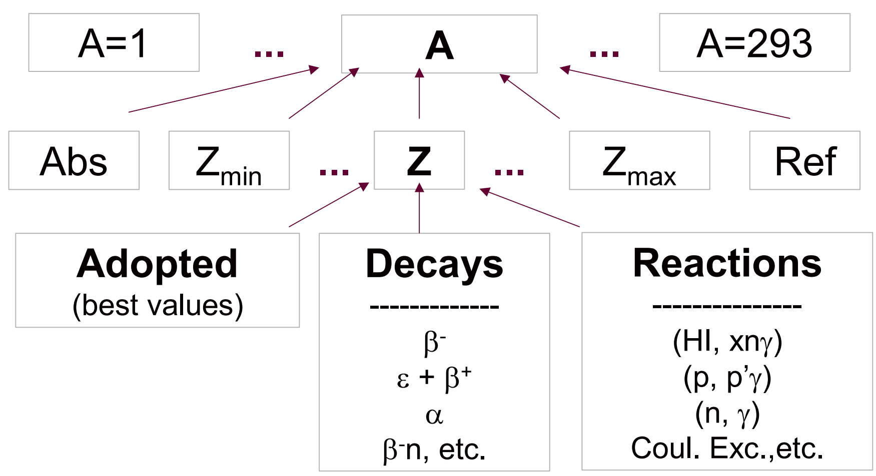
ENSDF Schematic



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Record Types

ID	LEVEL
History	BETA
XREF	EC
Comments	ALPHA
Q-value	PARTICLE
Parent	GAMMA
Normalization	END

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Identification Record

Required for all data sets-must precede all other records

Field (Col.)	Name
1-5	NUCID
10-39	DSID
40-65	DSREF
66-74	PUB
75-80	DATE (year/month)

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History Record

Field (Col.)	Name
1-5	NUCID
6	Blank
7	Blank
8	H
9	Blank
10-80	History

Q-value Record

Field (Col.)	Name		
1-5	NUCID		
8	Q	Letter ‘Q’ is required	
10-19	Q^-	20-21	DQ^-
22-29	SN	30-31	DSN
32-39	SP	40-41	DSP
42-49	QA	50-55	DQA
56-80	QREF		

Cross-Reference Record

Field (Col.)	**Name**	
1-5	NUCID	
8	X	Letter ‘X’ is required
9	DSSYM	Any ASCII character
10-39	DSID	*Must* exactly match one of IDs

Comment Record

Field (Col.)	Name	
1-5	NUCID	
7	Letter ‘C’, ‘D’, or ‘T’ is required	
8	RTYPE	Blank or record type
9	PSYM	Blank, or symbol
10-80	CTEXT	Text of the comment

Parent Record

Field	Name	
1-5	NUCID	
8	P (required)	
9	Blank or integer	
10-19	E Energy	20-21 DE
22-39	JPI	
40-49	T	50-55 DT
65-74	QP	75-76 DQP
77-80	Ionization State	

Normalization Record

Field	Name	
8	N (required)	
10-19	NR	20-21 DNR
22-29	NT	30-31 DNT
32-39	BR	40-41 DBR
42-49	NB	50-55 DNB
56-62	NP	63-64 DNP

Production Normalization Record

Field	Name	
8	N (required)	
10-19	NR*BR	20-21 DNR
22-29	NT*BR	30-31 DNT
42-49	NB*BR	50-55 DNB
56-62	NP	63-64 DNP
77	Blank or C	78 Opt (1-7)

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Level Record

Field	**Name**		
1-5	NUCID		
8	L (required)		
10-19	E Energy	20-21 DE	
22-39	JPI		
40-49	T	50-55 DT	
56-64	L (angular momentum transfer)		
65-74	S (spect at)	75-76 DS	
77	Flag	78-79 MS	80 Q

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Beta Record

Field	Name	
1-5	NUCID	
8	B (required)	
10-19	E Energy	20-21 DE
22-29	IB Intensity	30-31 DIB
42-49	Logft	50-55 DFT
77	Flag	
78-79	Forbiddenness 80 Q	

EC Record

Field	Name		
1-5	NUCID		
8	E (required)		
10-19	E Energy	20-21 DE	
22-29	IB Intensity	30-31 DIB	
32-39	IE Intensity	40-41 DIE	
42-49	Logft	50-55 DFT	
65-74	TI	75-76 DTI	77 Flag
78-79	Forbiddenness 80 Q		

Alpha Record

Field	Name	
1-5	NUCID	
8	A (required)	
10-19	E Energy	20-21 DE
22-29	IA Intensity	30-31 DIA
32-39	HF	40-41 DHF
77	Flag	
80	Q	

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Gamma Record

Field	Name		
8	G (required)		
10-19	E Energy	20-21 DE	
22-29	RI rel Intensity	30-31 DRI	
32-41	M multipolarity		
42-49	MR mix ratio	50-55 DMR	
56-62	CC total CC	63-64 DCC	
65-74	TI	75-76 DTI	
77	Flag	78 COIN	80 Q

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(Delayed-)Particle Record

Field	Name		
8	D (for delayed)	9	particle (N, P,..)
10-19	E Energy	20-21 DE	
22-29	IP % Intensity	30-31 DIP	
32-39	EI lev en int nuc		
40-49	T Width	50-55 DT	
56-64	L angular momentum transfer		
77	Flag	78 COIN	80 Q

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ENSDF – Evaluations: Methodology and Worked Examples

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DECAY DATA EVALUATIONS

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Decay Data

1. Statistical treatment of data
2. Properties of the parent nucleus
3. Gamma rays
4. Decay scheme normalization
5. Beta particles
6. Electron capture
7. Alpha particles
8. Level structure and decay scheme

1. Statistical treatment of data

- Weighted and unweighted averages
- Limits
- Discrepant data
- Limitation of relative statistical weight method

2. Properties of the parent nucleus

- Energy
- Spin/parity
- Half-life
- Q-value

3. Gamma rays

- Energy (E_γ)
- Relative intensity (I_γ (rel))
- Multipolarity and mixing ratio (δ)
- Internal conversion coefficients (α_i)
- Total transition intensity [I_γ (1 + α)]
- Absolute intensity (%I_γ)

4. Beta particles

- Relative intensity (I_β)
- Absolute intensity (%I_β)
- Average energy (I_{avg})
- Log *ft*
- Energy (E_β)

5. Electron capture

- Relative probability (I_ε)
- Absolute probability ($\%I_\varepsilon$)
- Relative sub-shell probabilities(P_K, P_L, P_M, P_N)
- Log *ft*

6. Alpha particles

- Energy (E_α)
- Relative intensity (I_α)
- Absolute intensity ($\%I_\alpha$)
- Hindrance factor (HF)

7. Level structure and decay scheme

- Level energy (E)
- Level spin/parity ($J\pi$), particle configuration (CONF)
- Level half-life ($T_{1/2}$)
- Decay scheme normalization

1. Statistical treatment of data

- Average, Weighted Average (weight = $1/\sigma_i^2$)
- Limits (given by authors: < 10; changed by evaluator: 5 ± 5)
- Confidence level for limits deduced by evaluators from transition intensity balances
- Discrepant data – Limitation of Relative Statistical Weight (LWEIGHT)

Averages

Unweighted

$x(avg) = 1 / n \sum x_i$

$\sigma_{x(avg)} = [1 / n\,(n - 1) \; \sum (x(avg) - x_i)^2]^{1/2}$ Std. dev.

Weighted

$x(avg) = W \sum x_i / \sigma_{xi}^2$; $W = 1 / \sum \sigma_{xi}^{-2}$

$\chi^2 = \sum (x(avg) - x_i)^2 / \sigma_{xi}^2$ Chi sqr.

$\chi_\nu^2 = 1 / (n - 1) \; \sum (x(avg) - x_i)^2 / \sigma_{xi}^2$ Red. Chi sqr

$\sigma_{x(avg)}$ = larger of $W^{1/2}$ and $W^{1/2} \chi_\nu$. Std. dev.

Limits

B_m = measured value

σ = Standard deviation

B_0 = True value

Example: -2 $\pm$ 3

For a Gaussian distribution, the formula to convert measured values to limits are:

$B_0 < B_m + 1.28\,\sigma$ (90% confidence limit); example: < 1.84

$B_0 < B_m + 1.64\,\sigma$ (95% confidence limit); example: < 2.92

$B_0 < B_m + 2.33\,\sigma$ (99% confidence limit); example; < 4.99

Discrepant Data

Simple definition: a set of data for which $\chi_\nu^2 > 1$.

But, χ_ν^2 has a Gaussian distribution, i.e., varies with the degrees of freedom (*n – 1*).

Better definition: a set of data is discrepant if χ_ν^2 is greater than χ_ν^2 (critical), where χ_ν^2 (critical) is such that there is a 99% probability that the set of data is discrepant.

Limitation of Relative Statistical Weight Method

For discrepant data ($\chi^2_n > \chi^2_n$(critical)) with at least three sets of input values, apply the *Limitation of Relative Statistical Weight* method. The program identifies any measurement that has a relative weight > 50% and increases its uncertainty to reduce the weight to 50%. Then it recalculates χ^2_n and produces a new average and a best value as follows.

If $\chi^2_n \leq \chi^2_n$(critical), the program chooses the weighted average and associated uncertainty (larger of the internal and external values).

If $\chi^2_n > \chi^2_n$(critical), the program chooses either the weighted or the unweighted average, depending on whether the uncertainties in the average values make them overlap with each other. If that is so, the program chooses the weighted average and (internal or external) uncertainty. Otherwise, the program chooses the unweighted average. In either case, the uncertainty may be expanded to cover the most precise input value

2. Properties of the parent nucleus

- Level energy (keV): 0.0, 328.0 *25*, 942 *4*, 0.0 + X
- Spin/parity: 1/2+, (3/2+), 5-, 6(+), (5/2-,7/2-)
- Half-life: 3.8 d *2*, 432.2 y *7*, 2 m, 35 ms *10*, ~3 s, 1.2×10^{15} y
- Units: (sidereal) y (= 365.25636 d), d, h, m, s, ms, ms, ns, ps, fs, …
- Q-value (keV): 1995Au04 (G. Audi and A.H. Wapstra, Nucl. Phys. **A595**, 409 (1995))
- Theoretical values: 1997Mo25 (P. Möller et al., At. Data Nucl. Data Tables **66**, 131 (1997))

3. Gamma rays

1. Energy (keV)

- Weighted average from radioactive decay
- Very precise measurements (e.g., bent crystal)
- Recommended standards for energy calibration:
  Helmer and van der Leun (Nucl. Instrum. Meth. Phys. Res. **A450**, 35 (2000)
- Not observed, but expected (from level energy difference)
- Deduced from conversion electron energies (give atomic electron binding energy)
- Multiplets:
  broader peak in spectrum
  known levels involved

2000He14

ELSEVIER Nuclear Instruments and Methods in Physics Research A 450 (2000) 35–70

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

Recommended standards for γ-ray energy calibration (1999)

R.G. Helmer[a,*], C. van der Leun[b,*]

[a]Idaho Accelerator Center, Idaho State University, Pocatello, Idaho, USA

[b]R.J. Van de Graaff Laboratorium, Utrecht University, P.O. Box 80,000, 3508 TA Utrecht, The Netherlands

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1. Uncertainties: statistical

Give (in comments) estimate of systematic errors.

When uncertainties are known to include systematic errors, no result from weighted average should have an uncertainty smaller than the smallest on the input uncertainty.

No uncertainty should be smaller than the uncertainty in the calibration standard.

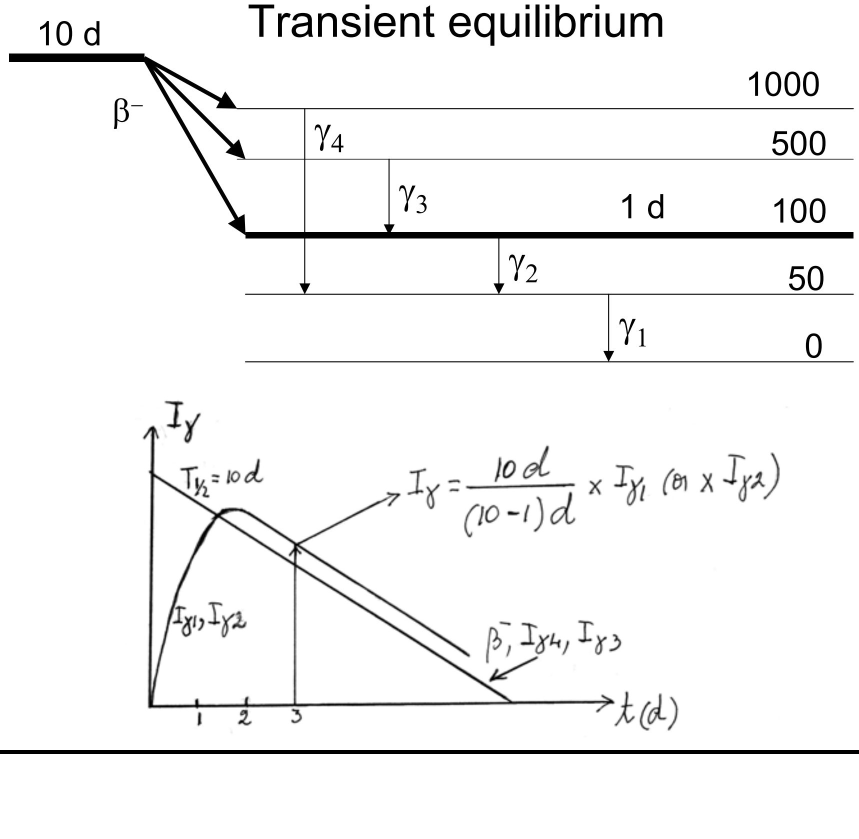
Uncertainties larger than *25* should be rounded.

Author	ENSDF
351.53 ± 0.25	351.53 25
351.53 ± 0.30	351.5 3
8346 ± 29	83.5E2 3

2. <u>Relative intensity</u>

- Weighted average from radioactive decay
- Use 100 for the most intense gamma ray.
- Use a limit for an expected (but unobserved) γ ray.
- Use total transition intensity (TI) if this is the only quantity measured, or deduced from transition intensity balance. If α_T is known, deduce and give I_γ.
- Limits are acceptable (e.g., I_γ < A), but I_g= ½ A ± ½ A is preferable (for calculating transition intensity balances).
- Intensity from an isomer in the daughter nucleus <u>should not</u> be given if such intensity is time dependent. Include comments that give the percent feeding to the isomer, and explain the reason for not giving I_γ.

Transient equilibrium



3. Multipolarity and mixing ratio (δ)

- From conversion electron data. If I_K and I_γ were used to determine α_K, explain normalization between electron and photon intensity scales. Conversion electron sub-shell ratios.
- From γ-ray angular correlations ($\gamma(\theta)$). Notice that $\gamma(\theta)$ determines *only* the L component of the γ-ray character, thus mult.= D, D + Q, etc. $T_{1/2}$(exp.) may be used to rule out choices, usually Q = M2 and D + Q = E1 + M2.

Multipolarity and mixing ratio (δ) from conversion electron data

Using experimental conversion coefficients

δ^2 = E2 γ-ray intensity / M1 γ-ray intensity = $I_\gamma(E2)/I_\gamma(M1)$ …. (1)

$I_\gamma(M1) + I_\gamma(E2) = I_\gamma$ …. (2)

From equations (1) and (2) we obtain:

$I_\gamma(M1) = I_\gamma / 1 + \delta^2$, and $I_\gamma(E2) = I_\gamma\ \delta^2 / 1 + \delta^2$

Conversion electron intensity: $I_e = I_e(M1) + I_e(E2)$

Experimental conversion coefficient

$\alpha(\text{exp}) = I_e / I_\gamma = 1/ I_\gamma\ [I_\gamma(M1) \times \alpha(M1)^{th} + I_\gamma(E2) \times \alpha(E2)^{th}]$

or, $\alpha(\text{exp}) = 1/ I_\gamma\ [I_\gamma / 1 + \delta^2 \times \alpha(M1)^{th} + I_\gamma\ \delta^2 / 1 + \delta^2 \times \alpha(E2)^{th}]$

$$\delta^2 = (\alpha(M1)^{th} - \alpha(\text{exp})) / (\alpha(\text{exp}) - \alpha(E2)^{th})$$

%M1 = $100/1 + \delta^2$, %E2 = $100\ \delta^2 / 1 + \delta^2$

Using experimental electron sub-shell ratios

$$R(exp) = I_e(L1)/ I_e(L3)$$

Then

$$\delta^2 / 1 + \delta^2 = A / [\alpha(E2,L1)^{th} - \alpha(M1,L1)^{th} + R(exp) (\alpha(M1,L3)^{th} - \alpha(E2,L3)^{th})]$$

where

$$A = R(exp)\ \alpha(M1,L3)^{th} - \alpha(M1,L1)^{th}$$

Consistency of entries for α and δ:

For a single multipolarity the δ field should be blank.

For δ < V:

Give *only* dominant multipolarity and corresponding α. Give δ < V in a comment, or

give both multipolarities and δ < V in the δ field. Calculate α from δ = ½ V $\pm$ ½ V.

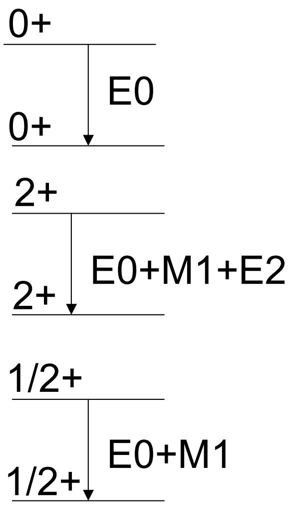
Examples: E2 + M3 with δ < 0.5 should preferably be entered as E2, whereas M1 + E2 with δ < 0.5, as M1 + E2 (δ = 0.25 $\pm$ 0.25).

M1, E2 is not the same as M1 + E2.

Assumed multipolarity

[M1], [E2], [M1 + E2], [M4], etc.

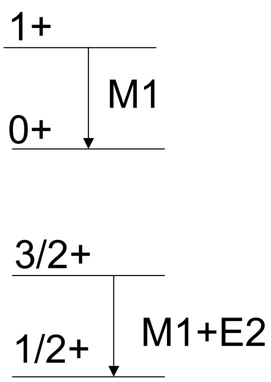
More about multipolarities



$0 \le \mathbf{l} \le 0$; $\mathbf{l} = 0$

$0 \le \mathbf{l} \le 2$; $\mathbf{l} = 0, 1, 2$

$0 \le \mathbf{l} \le 1$; $\mathbf{l} = 0, 1$



$1 \le \mathbf{l} \le 1$; $\mathbf{l} = 1$

$1 \le \mathbf{l} \le 2$; $\mathbf{l} = 1, 2$

4. Internal conversion coefficients

Theoretical values:

From Hager and Seltzer (1968Ha53) for K, L_i, M_i shells, and $Z \geq 30$

From Dragoun et al. (1971Dr11) for N, O ….. shells.

From Dragoun et al. (1971Dr09) for N_i shells.

From Band et al. (1976Ba63) for $E_\gamma \leq 6000$ keV, Z=3, 6, 10, and $14 \leq Z \leq 30$.

From Trusov (1972Tr09) for $E_\gamma > 2600$ keV.

From Hager and Seltzer (1969Ha61), K/L_1, L_1/L_2 for E0 transitions.

Experimental values:

For very precise values (≤ 3% uncertainty)

E_γ = 661 keV – ^{137}Cs ($\alpha_K = 0.0902 \pm 0.0008$, M4)

Nuclear penetration effects

^{233}Pa β^- decay to ^{233}U

E_γ = 312 keV almost pure M1 from electron sub-shell ratios

However $\alpha_K(exp) = 0.64 \pm 0.02$

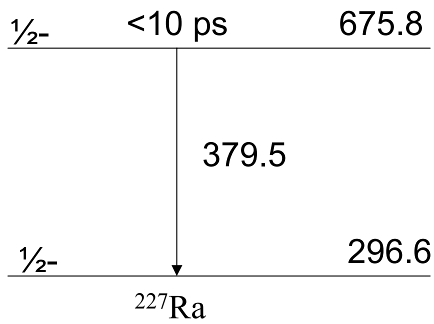
($\alpha_K{}^{th}(M1) = 0.78$, $\alpha_K{}^{th}(E2) = 0.07$)

For mixed E0 transitions (e.g., M1+E0)

$^{227}Fr\ (\beta)^{-227}Ra$

E_{γ} = 379.1 keV (M1+E0); α(exp) = 2.4 $\pm$ 0.8

α^{th}(M1) = 0.40; α^{th}(E2) = 0.08



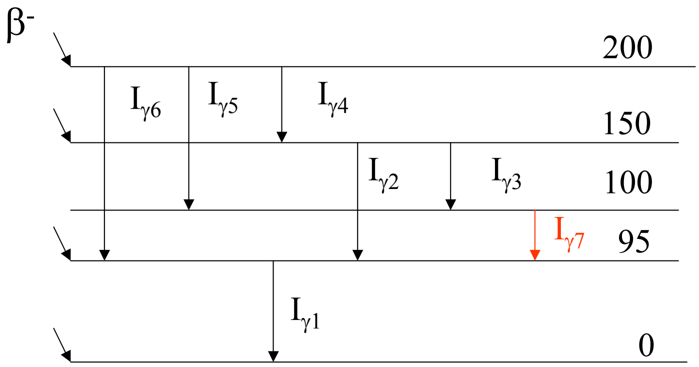
Total transition intensity (TI)

TI field should be used *only* if TI (rather than I_{γ}) is the measured or deduced quantity. Usual cases are:

TI deduced from transition intensity balance

TI = $\Sigma\ I_i$(ce), if I_{γ} is known to be negligible. If I_{γ} is not negligible and the total conversion coefficient is known, deduce and give I_{γ}

Total intensity from transition-intensity balance



$TI(\gamma_7) = TI(\gamma_5) + TI(\gamma_3)$

If $\alpha(\gamma_7)$ is known,

$I\gamma_7 = TI(\gamma_7) / [1 + \alpha(\gamma_7)]$

5. Absolute intensities

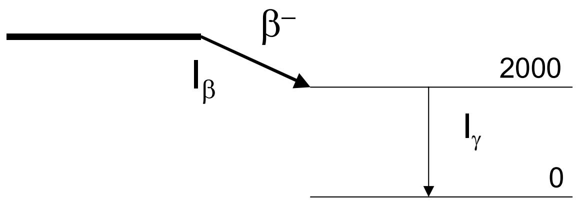
   Intensities per 100 disintegrations of the parent nucleus

- Measured (Photons from β^-, $\varepsilon + \beta^+$, and α decay)

  Simultaneous singles measurements

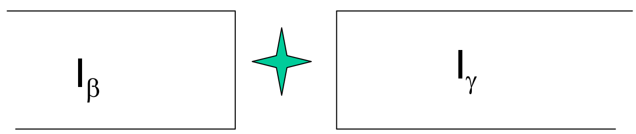
  Coincidence measurements

Absolute γ-ray intensity



$$\gamma(\%) = I_\gamma / I_\beta = 100\%$$

Simultaneous singles measurement



I_β: β^- intensity corrected for detector efficiency

I_γ: γ-ray intensity corrected for detector efficiency

I_γ / I_β = absolute γ-ray intensity

Units: photons per β^- (or per 100 β^-) disintegrations

4. Decay scheme normalization

Rel. int.	Norm. factor	Abs. Int.
I_γ	NR × BR	$\%I_\gamma$
I_T	NT × BR	$\%I_T$
I_β	NB × BR	$\%I_\beta$
I_ε	NB × BR	$\%I_\varepsilon$
I_α	NB × BR	$\%I_\alpha$

BR: factor for converting intensity per 100 *decays through this decay branch*, to intensity per 100 *decays of the parent nucleus*

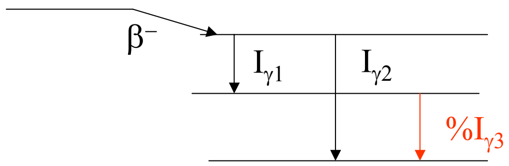
NR: factor for converting relative I_γ to I_γ per 100 decays through this decay branch.

NT: factor for converting relative TI to TI per 100 decays through this decay branch.

NB: factor for converting relative β^- and ε intensities to intensities per *100 decays of this decay branch*.

Normalization Procedures

1. Absolute intensity of one gamma ray is known ($\%I_\gamma$)



Relative intensity $I_\gamma \pm \Delta I_\gamma$

Absolute intensity $\%I_\gamma \pm \Delta\%I_\gamma$

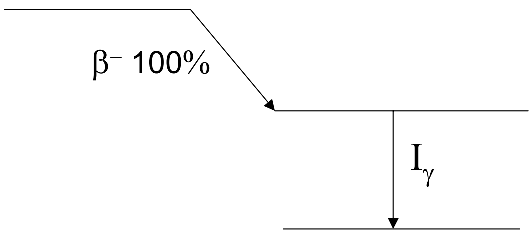
Normalization factor $N = \%I_\gamma / I_\gamma$

Uncertainty $\Delta N = [(\Delta\%I_\gamma / \%I_\gamma)^2 + (\Delta I_\gamma / I_\gamma)^2]^{1/2} \times N$

Then $\%I_{\gamma 1} = N \times I_{\gamma 1}$

$\Delta\%I_{\gamma 1} = [(\Delta N/N)^2 + (\Delta I_\gamma / I_\gamma)^2]^{1/2} \times I_{\gamma 1}$

2. From Decay Scheme



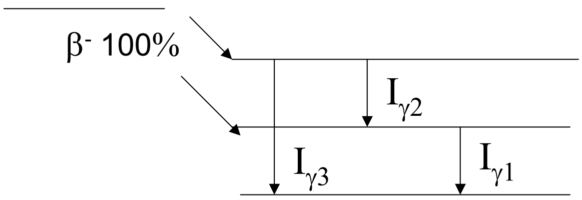
Iγ: Relative γ-ray intensity; α: total conversion coefficient

$$N \times I_\gamma \times (1 + \alpha) = 100\%$$

Normalization factor $N = 100/ I_\gamma \times (1 + \alpha)$

Absolute γ-ray intensity $\% I_\gamma = N \times I_\gamma = 100/ (1 + \alpha)$

Uncertainty $\Delta\% I_\gamma = 100 \times \Delta\alpha/(1 + \alpha)^2$



Normalization factor $N = 100 / I_{\gamma1}(1 + \alpha_1) + I_{\gamma3}(1 + \alpha_3)$

$\% I_{\gamma1} = N \times I_{\gamma1} = 100 \times I_{\gamma1} / I_{\gamma1}(1 + \alpha_1) + I_{\gamma3}(1 + \alpha_3)$

$\% I_{\gamma3} = N \times I_{\gamma3} = 100 \times I_{\gamma3} / I_{\gamma1}(1 + \alpha_1) + I_{\gamma3}(1 + \alpha_3)$

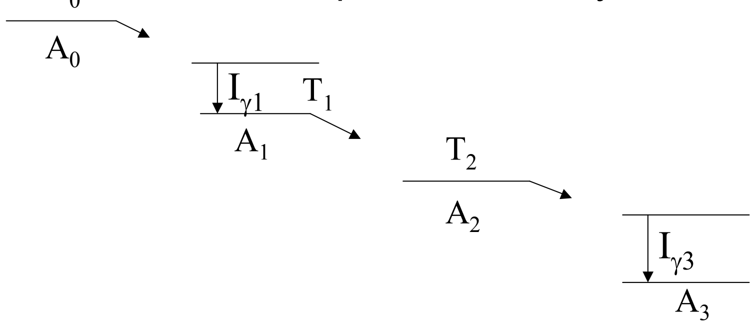
$\% I_{\gamma2} = N \times I_{\gamma2} = 100 \times I_{\gamma2} / I_{\gamma1}(1 + \alpha_1) + I_{\gamma3}(1 + \alpha_3)$

Calculate uncertainties in $I_{\gamma1}$, $I_{\gamma2}$, and $I_{\gamma3}$. Use 3% fractional uncertainty in α_1 and α_3.

See Nucl. Instrum. Meth. **A249**, 461 (1986)

Use computer program GABS to save time

3. Equilibrium Decay Chain



$T_0 > T_1$, T_2 are the radionuclide half-lives,

At $t = 0$, only radionuclide A_0 exists,

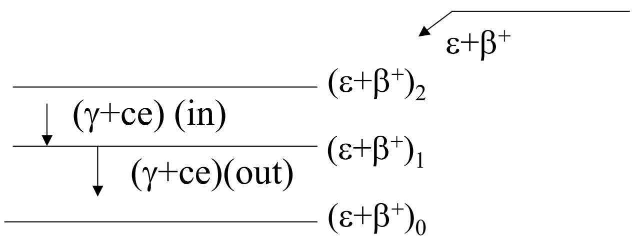
$\% I_{\gamma 3}$, $I_{\gamma 3}$, and $I_{\gamma 1}$ are known

Then, at equilibrium

$\% I_{\gamma 1} = (\% I_{\gamma 3}/I_{\gamma 3}) \times I_{\gamma 1} \times (T_0/(T_0 - T_1) \times (T_0/(T_0 - T_2)$

Normalization factor $N = \%I_{\gamma 1}/ I_{\gamma 1}$

4. Annihilation radiation intensity is known



$I(\gamma\pm)$ = Relative annihilation radiation intensity

X_i = Intensity imbalance at the i^{th} level = $(\gamma+ce)$ (out) – $(\gamma+ce)$ (in)

$r_i = \varepsilon_i / \beta^+_i$ theoretical ratio to i^{th} level

$X_i = \varepsilon_i + \beta^+_i = \beta^+_i\ (1 + r_i)$, therefore $\beta^+_i = X_i / 1 + r_i$

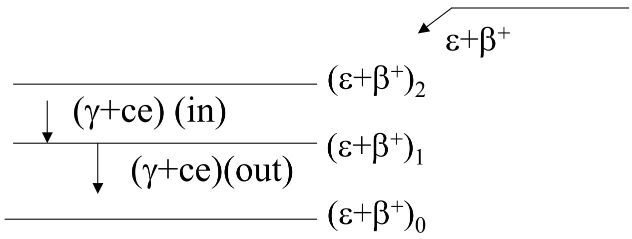
$$2\,[X_0 / (1 + r_0) + \Sigma\, X_i / (1 + r_i)] = I(\gamma\pm) \;\ldots\ldots\ldots\; (1)$$

$$[X_0 + \Sigma\, I_{\gamma i}\ (\gamma + ce) \text{ to gs }]\ N \;=\; 100 \;\ldots\ldots\ldots.\; (2)$$

Solve equation (1) for X_0 (rel. gs feeding)

Solve equation (2) for N (normalization factor)

5. X-ray intensity is known



I_K = Relative Kx-ray intensity

X_i = Intensity imbalance at the i[th] level = (γ+ce) (out) – (γ+ce) (in)

$r_i = \varepsilon_i / \beta^+_i$ theoretical ratio to i[th] level

$X_i = \varepsilon_i + \beta^+_i$, so $\varepsilon_i = X_i r_i / 1 + r_i$ (atomic vacancies); ω_K = K-fluorscence yield

P_{Ki} = Fraction of the electron-capture decay from the K shell

$I_K = \omega_K [\varepsilon_0 \times P_{K0} + \Sigma\, \varepsilon_i \times P_{Ki}]$

$$I_K = \omega_K [P_{K0} \times X_0 r_0 / (1 + r_0) + \Sigma\, P_{Ki} \times X_i r_i / 1 + r_i] \ldots (1)$$

$$[X_0 + \Sigma\, I_i(\gamma + ce) \text{ to gs}]\, N = 100 \;\ldots.\; (2)$$

Solve equation (1) for X_0; equation (2) for N

5. Beta particles

1. Energy (keV)

   Give E_β(max) *only* if experimental value is so accurate that the data could be used as input to mass adjustment.

   Do not give E_β(avg); program LOGFT calculates these values.

2. Absolute intensity (%I_β per 100 decays of the parent nucleus)

   Give experimental value, if used for normalizing the decay scheme.

   Give absolute value deduced from γ-ray transition intensity balance (Program GTOL).

3. Log*ft*

   Usually authors assign spins and parities. Nevertheless, verify that the relevant log*ft* values are consistent with their assignments.

6. Electron capture

- Give ($I_\varepsilon + I_{\beta+}$) feedings deduced from γ-ray transition intensity balance. Program LOGFT calculates ε and β^+ probabilities from theory.
- Program LOGFT calculates sub-shell (P_K, P_L, P_M …) probabilities from theory.
- Give (in comments) x-ray intensities. These data are useful for normalizing or testing the decay scheme.

7. Alpha particles

- Energy (keV)

Most measurements are relative to a line from a standard radionuclide. Include this information in a comment.

Use Rytz (At. Data Nucl. Data Tables **47**, 205 (1991)) evaluated E_α and I_α when no new values are available.

- Intensity

Give intensities preferably "per 100 α decays" (NB = 1), and a branching factor BR to convert them to "per 100 decays of the parent nucleus".

- Hindrance factor

HF= experimental $T_{1/2}(\alpha)$/theoretical $T_{1/2}(\alpha)$. The theoretical value is from 1947Pr17 (M.A. Preston). The assumption is that 0^+ to 0^+ α transitions from even-even nuclei are the fastest (HF = 1). These transitions are used to determine the radius parameter r_0 (see 1998Ak04, Y.A. Akovali). Use program ALPHAD.

Favored alpha-particle transition

- HF < 4
- Takes place between levels with the same spin and parity

Radius parameter r_0
(Y. Akovali, Oak Ridge)

Odd-N nucleus (Z, A)

$r_0(Z, N) = [r_0(Z, N-1) + r_0(Z, N+1)]/2$

Odd-Z nucleus (Z, A)

$r_0(Z, N) = [r_0(Z-1, N) + r_0(Z+1, N)]/2$

Odd-Odd nucleus (Z, A)

$r_0(Z, N) = [r_0(Z, N-1) + r_0(Z, N+1)]/2 =$

$[r_0(Z-1, N+1)+r_0(Z-1, N-1)+r_0(Z+1, N+1) +r_0(Z+1, N-1)]/4$

Example

$^{219?}Rn \rightarrow ^{215}Po$ (Odd-N)

$$r_0\ (Z = 84, N = 131) = [r_0(84, 130) + r_0(84, 132)]\ /2$$

From 1998Ak04:

$r_0(84,214) = 1.559\ \mathit{8}$

$r_0(84,216) = 1.5555\ \mathit{2}$, therefore

$$r_0\ (Z = 84, N = 131) = 1.557$$

Use Table 1 – "Calculated r_0 for even-even nuclei" (1998Ak04). Insert R0 = … in *comment* record:

CA HF R0 =…

Run program ALPHAD to calculate hindrance factors.

8. Level structure and decay scheme

Deduce best γ-ray energies and relative intensities

↓

Calculate conversion coefficients (HSICC)

↓

Normalize radiation intensities to absolute scale (GABS)

↓

Deduce level energies and decay branchings (GTOL)

↓

Calculate: logft values (LOGFT), alpha decay hindrance factors (ALPHAD)

ENSDF – Evaluations: Methodology and Worked Examples

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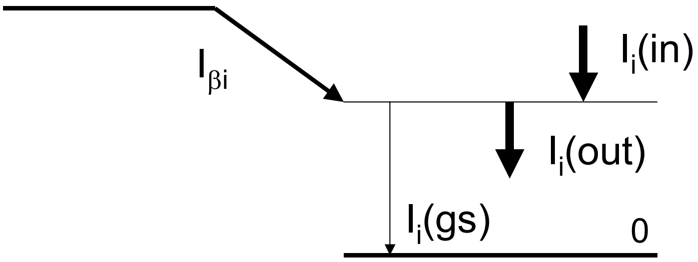
DECAY DATA EVALUATIONS: MODEL EXERCISES

Edgardo Browne

γ-ray transition intensity balance



The corresponding normalization factor is

$N = 100 / \Sigma[\, I_i(out) + I_i(gs) - I_i(in)] =$
$100 / \Sigma[\, I_i(out) - I_i(in)] + \Sigma\, I_i(gs),$
but $\Sigma[\, I_i(out) - I_i(in)] = 0,$
therefore $N = 100 / \Sigma\, I_i(gs)$

^{233}Pa β^- decay

I_γ(312) = 38.6 (5) % (experimental value, Gehrke et al.)
$\Sigma I(\gamma+ce)$ (gs) = 102 (2) %

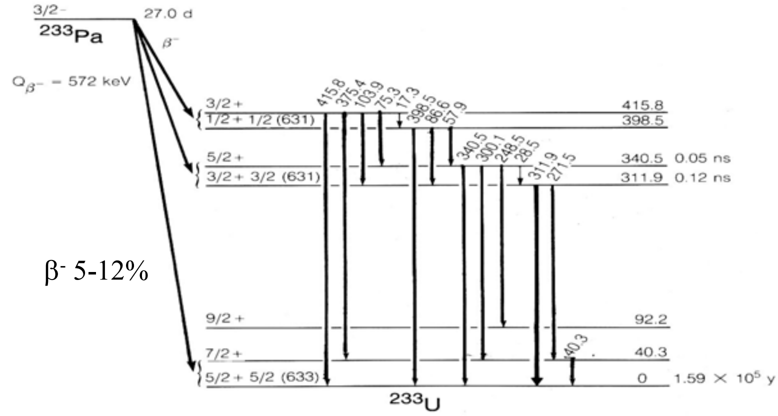


Fig. 1. Simplified ^{233}Pa decay scheme from ref. [1]).

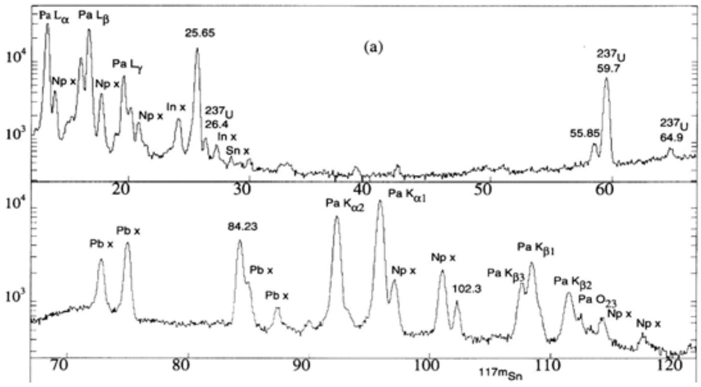
What went wrong?

E_γ(keV)	α_T(exp.)	α_T(theo. M1)
300	0.83 (2)	1.04
312	0.79 (2)	0.96
340	0.61 (2)	0.75

Answer: nuclear penetration effects

Using X rays to normalize decay schemes

^{231}U γ-ray spectrum



$I_\gamma(25)=100\ (6)$

$I_\gamma(84)=50\ (3)$

$I_{KX}=390\ (14)$

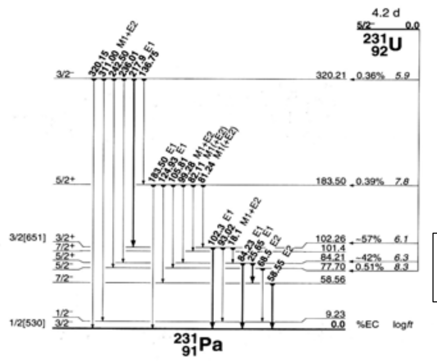


Fig. 4. ^{231}U electron-capture decay scheme. Gamma rays measured in this work are shown with thicker arrows; other data are from refs. [3,11]. Electron-capture branches per 100 decays of ^{231}U and log *ft* values are from gamma-ray transition probability balances (see Table 3).

EC(K)/EC(Total) = 0.59

$\omega_K = 0.972$

B_K=115.6 keV, thus most K-x rays originate from vacancies produced by the electron-capture process.

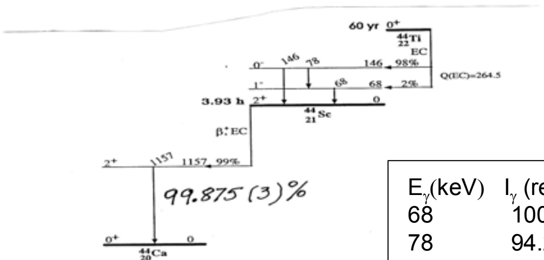
Total vacancies = I_{KX} EC(Total) / ω_K EC(K) = 680 (33)

Normalization factor N = 100 / 680 (33) = 0.147 (7)

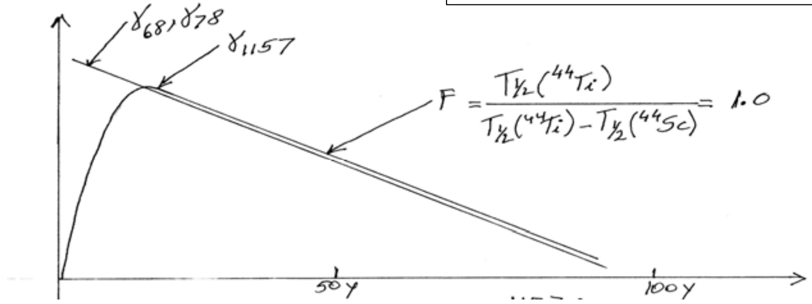
$I_\gamma(25)=100\ (6) \times 0.147\ (7) = 15\ (1)\%$

$I_\gamma(84)=50\ (3) \times 0.147\ (7) = 7.5\ (6)\%$

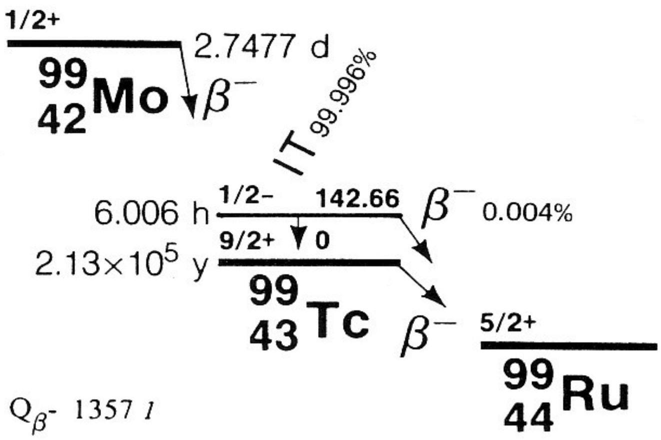
^{44}Ti electron capture decay

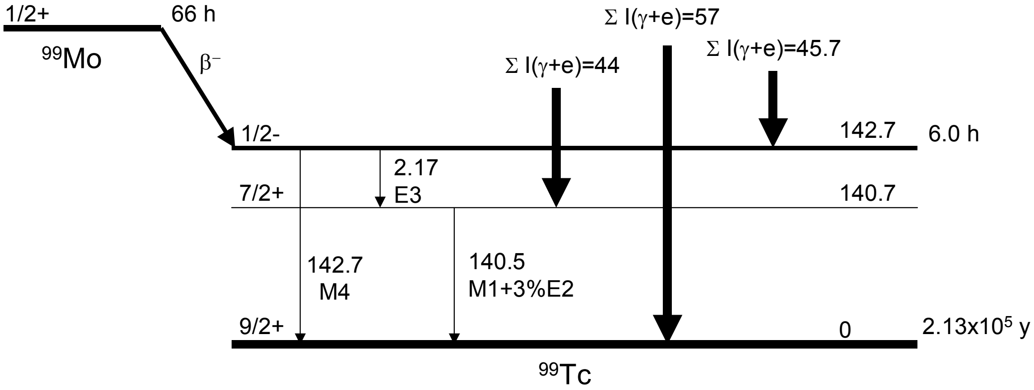


E_γ(keV)	I_γ (rel)	I_γ(%)
68	100 (1)	96.6 (10)
78	94.2 (8)	91.0 (8)
1157	103.4 (10)	99.875 (3)



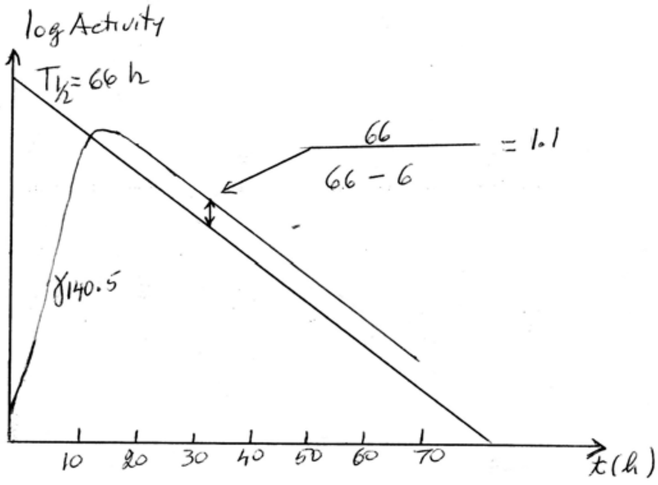
^{99}Mo(2.75 d) $\xrightarrow{\beta^-}$ ^{99m}Tc(6.0 h) $\xrightarrow{IT}$ ^{99}Tc(2.1x10^5 y)

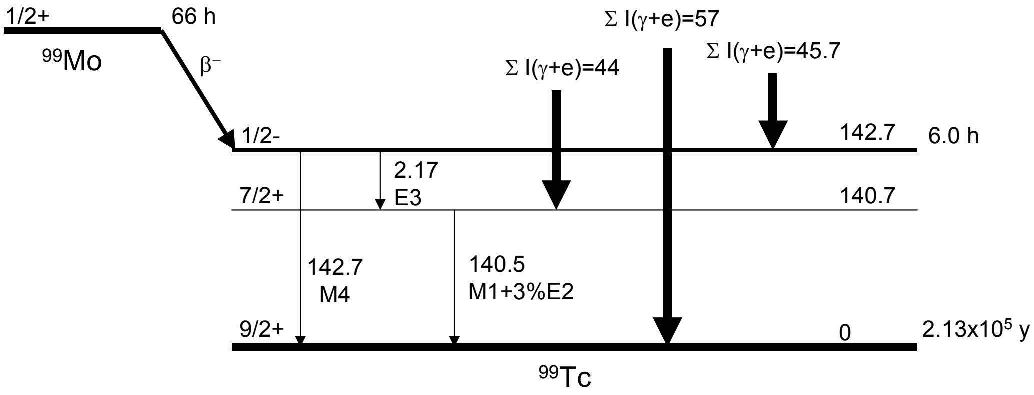




Equilibrium Intensities

E_γ(keV)	I_γ	α	$I_{\gamma+ce}$
140.5	742 (11)	0.114 (3)	827 (12)
142.7	0.17 (2)	40.9 (12)	7.3 (7)





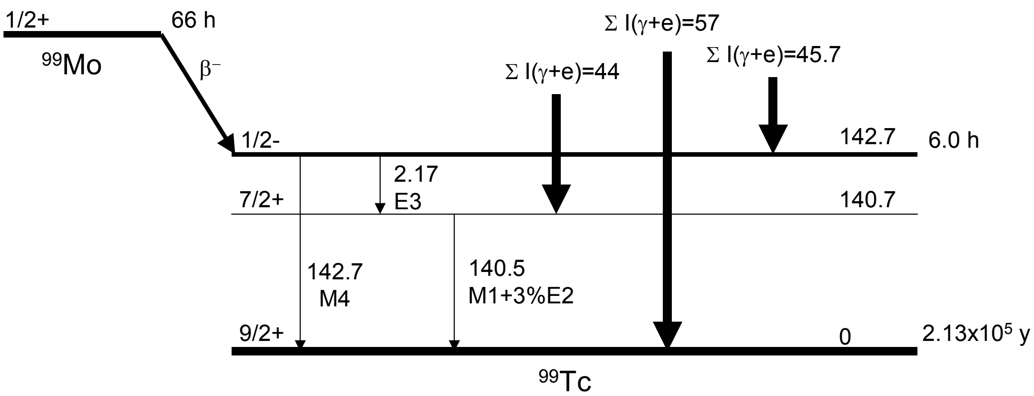
Decay Scheme Normalization

$$[I(\gamma+ce)(142.7)/1.1 + I(\gamma+ce)(140.5)/1.1 + \Sigma I(\gamma+ce)_{gs}] \times N = 100$$

$$[7.3\ (7)/1.1 + 827\ (12)/1.1 + 57.0\ (8)] \times N = 100$$

$$N = 100/816\ (11) = 0.1226\ (17)$$

So, $I_\gamma(\%)(140.5) = 742\ (11) \times 0.1226\ (7) = 91.0\ (\mathbf{3})\%$



β^- feeding to 142.7-keV level

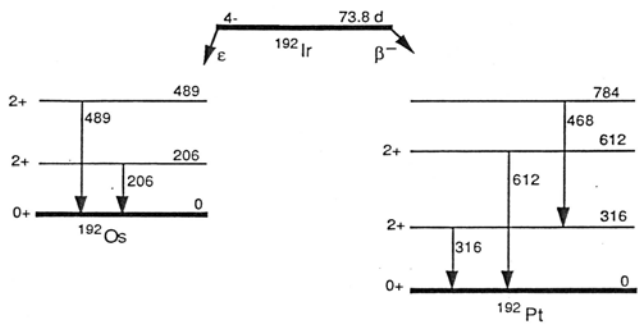
$$I_{\beta-} = I(\gamma+ce)(142.7)/1.1 + I(\gamma+ce)(2.17)/1.1 - \Sigma I(\gamma+ce)_{142.7}$$

$$I(\gamma+ce)(140.5)/1.1 - I(\gamma+ce)(2.17)/1.1 - \Sigma I(\gamma+ce)_{140.5} = 0$$

$$I_{\beta-} = 668$$

So, $I_{\beta-}(\%) = 668 \times 0.1226 = 82.0\%$

^{192}Ir β^- and electron capture decay



E_γ(keV)	I_γ	α	$I_\gamma\,(1+\alpha)$	
206	4.01 (6)	0.305 (9)	5.23 (8)	
489	0.527 (9)	0.0242 (7)	0.540 (9)	Σ= 5.77 (8)
316	100.0 (5)	0.085 (3)	108.5 (6)	
468	57.76 (20)	0.0294 (9)	58.43 (20)	
612	6.365 (25)	0.0155 (5)	6.464 (25)	Σ= 114.9 (6)

Normalization factor is:

$N = 100 / [I_\gamma(489)\,(1+\alpha_{489}) + I_\gamma(206)\,(1+\alpha_{206}) + I_\gamma(316)\,(1+\alpha_{316}) + I_\gamma(612)\,(1+\alpha_{612})]$

$= 100 / 120.7\,(7) = 0.828\,(5)$

N = 0.828 (5)

Electron capture (ε) and β^- decay branchings are:

$\varepsilon = 100\,[I_\gamma(489)\,(1+\alpha_{489}) + I_\gamma(206)\,(1+\alpha_{206})]\,/120.7\,(7) =$

$100 / [1 + (I_\gamma(316)\,(1+\alpha_{316}) + I_\gamma(612)\,(1+\alpha_{612})/(I_\gamma(489)\,(1+\alpha_{489}) + I_\gamma(206)\,(1+\alpha_{206})) =$

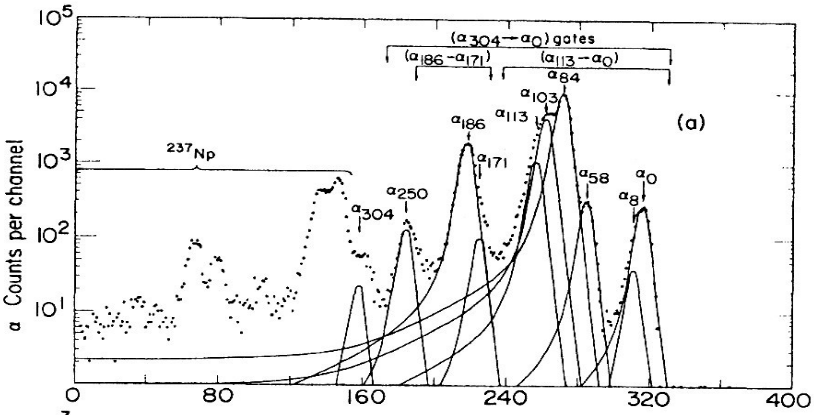
$100 / [1 + 114.9\,(6)/5.77\,(8)] = 100 / 20.9\,(3) = 4.78\,(7)\%$

$\beta^- = 100 - EC = 100 - 4.78\,(7) = 95.22\,(7)\%$

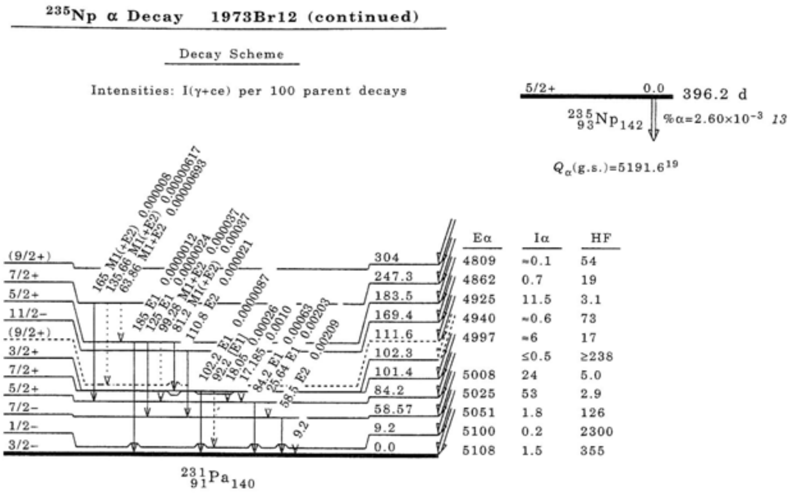
β^- = 95.22 (7)%

ε = 4.78 (7)%

^{235}Np alpha-particle spectrum



^{235}Np alpha decay scheme

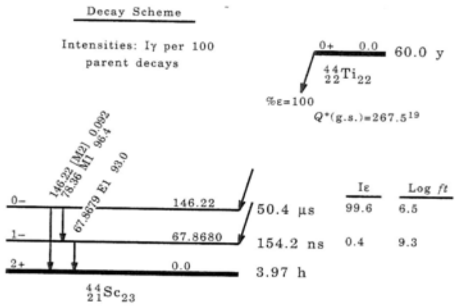


^{235}Np alpha-particle intensities

E_α(keV)	E_{lev}(keV)	I_α(spec.)	I_α(bal.)
4809	304	~0.1	
4862	247	0.7 (1)	0.8 (2)
4925	183	11.5 (5)	16 (3)
4940	169	~0.6	0.8 (3)
4997	112	~6	
5008	101	24 (8)	33 (10)
5025	84	53 (8)	51 (12)
5051	58	1.8 (3)	~2
5100	9	0.2	
5108	0	1.5 (2)	

Preparing ENSDF Data Sets

^{44}Sc ENSDF Data Set




```
44SC    44TI EC DECAY
44TI  P 0            0+              60.0 Y    11            267.5     19
44SC  N 0.964      13         1.0
44SC  L 0            2+              3.97 H    4
44SC  L 67          1-               154.2 NS  8
44SC  G 67.8679   14   96.5 16    E1                  0.0845
44SCS G KC=   0.0766  $LC=   0.00664
44SC  L 146         0-               50.4 US   7
44SC  G 78.36      3  100.0 11    M1                  0.0302
44SCS G KC=   0.0273  $LC=   0.00243
44SC  G 146.22     3  0.095 3    [M2]                 0.0460
44SCS G KC=   0.0414  $LC=   0.00385
```

^{44}Ti Half-life (LWEIGHT)

```
           44Ti Half-life Measurements

INP. VALUE  INP. UNC.     R. WGHT  chi**2/N-1 REFERENCE
.607000E+02 .120E+01      .141E+00  .826E-01   99Wi01
.590000E+02 .600E+00 MIN *.563E+00* .479E+00   98Ah03
.603000E+02 .130E+01      .120E+00  .163E-01   98Go05
.620000E+02 .200E+01      .507E-01  .214E+00   98No06
.666000E+02 .160E+01      .792E-01  .348E+01   90Al11
.542000E+02 .210E+01      .460E-01  .149E+01   83Fr27

No. of Input Values N= 6  CHI**2/N-1=  5.76  CHI**2/N-1(critical)=  3.00

UWM   :.604667E+02  .164796E+01
WM    :.599288E+02  .450317E+00(INT.)  .108057E+01(EXT.)

INP. VALUE  INP. UNC.     R. WGHT  chi**2/N-1 REFERENCE
.607000E+02 .120E+01      .161E+00  .563E-01   99Wi01
.590000E+02 .681E+00     *.500E+00* .487E+00   98Ah03
* Input uncertainty increased .114E+01 times *
.603000E+02 .130E+01      .137E+00  .663E-02   98Go05
.620000E+02 .200E+01      .580E-01  .188E+00   98No06
.666000E+02 .160E+01      .907E-01  .334E+01   90Al11
.542000E+02 .210E+01      .526E-01  .156E+01   83Fr27

No. of Input Values N= 6  CHI**2/N-1=  5.63  CHI**2/N-1(critical)=  3.00
UWM   :.604667E+02  .164796E+01
WM    :.600634E+02  .481846E+00(INT.)  .114378E+01(EXT.)
LWM   :.600634E+02  .114378E+01   Min. Inp. Unc.=.600000E+00
LWM has used weighted average   and external uncertainty
```

Recommended value: 60.0 (11) y

^{44}Sc ENSDF Data Set (GTOL)

```
                TI            TI              TI            NET FEEDING
LEVEL         (OUT)         (IN)           (NET)         (CALC)       (USE)

0.0           0.000         104.8 18       -104.8 18      -1.0 17      0.0
67.8679 14    104.7 18      103.0 12        1.6 21         1.6 21      0.6 11
146.224 22    103.1 12      0.000           103.1 12       99.4 11     99.4 1
```

```
44SC    44TI EC DECAY
44TI  P 0            0+               60.0 Y    11            267.5     19
44SC  N 0.964      13         1.0
44SC  L 0            2+               3.97 H    4
44SC  L 67.8679   141-                154.2 NS  8
44SC  E                           0.6     11
44SC  G 67.8679   14   96.5 16    E1                  0.0845
44SCS G KC=   0.0766  $LC=   0.00664
44SC  L 146.224   220-                50.4 US   7
44SC  E                           99.4    11
44SC  G 78.36      3  100.0 11    M1                  0.0302
44SCS G KC=   0.0273  $LC=   0.00243
44SC  G 146.22     3  0.095 3    [M2]                 0.0460
44SCS G KC=   0.0414  $LC=   0.00385
```

^{44}Sc ENSDF Data Set (LOGFT)

```
44SC    44TI EC DECAY
44TI  P 0            0+               60.0 Y    11            267.5     19
44SC  N 0.964     13          1.0
44SC  L 0            2+               3.97 H    4
44SC  L 67.8679   141-                 154.2 NS 8
44SC  E                           0.6  11   9.2   8
44SCS E  CK=0.8910 $CL=0.09309 $CM+=0.01592
44SC  G 67.8679   14   96.5 16    E1                  0.0845
44SCS G KC=   0.0766  $LC=   0.00664
44SC  L 146.224   220-                 50.4 US  7
44SC  E                          99.4  11  6.509 17
44SCS E  CK=0.8883 $CL=0.09533 $CM+=0.016352 18
44SC  G 78.36      3  100.0 11    M1                  0.0302
44SCS G KC=   0.0273  $LC=   0.00243
44SC  G 146.22     3  0.095 3    [M2]                 0.0460
44SCS G KC=   0.0414  $LC=   0.00385
```

ENSDF – Evaluations: Methodology and Worked Examples

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ENSDF – Reaction Data

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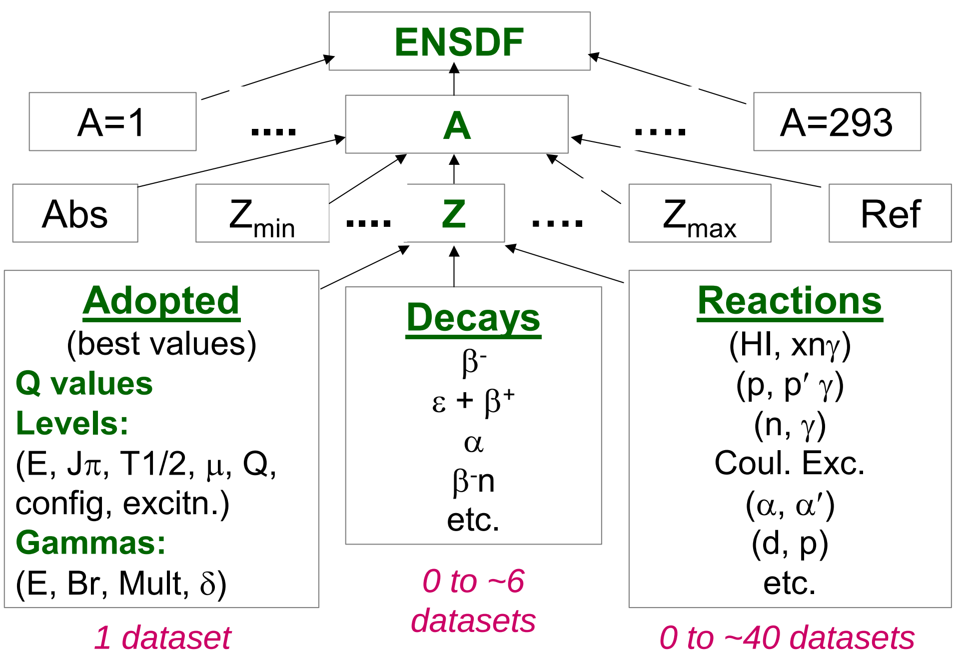
ENSDF Database Structure



Summary

Principal Categories of Reactions:

- Reactions in which gamma emissions are not detected:
  - Stripping and Pickup Reactions
  - Multi-particle Transfer Reactions
  - Charge-Exchange Reactions
  - Inelastic Scattering
  - Coulomb Excitation (particles detected)
  - Resonance Reactions …
- Reactions in which gamma emissions are detected:
  - Summary of information available from γ-ray measurements
  - Inelastic Scattering
  - Nuclear Resonance Fluorescence
  - (light ion, xnypγ)
  - (heavy ion, xnypγ)
  - Particle Capture
  - Coulomb Excitation (γs detected)

Gamma emissions not detected

Measured Quantities of Interest:

- E(level) from particle spectrum or excitation function.
- L – angular momentum transfer
- S, C^2S - spectroscopic factors
- β_2, β_4 - deformation parameters (if model independent)
- Γ, Γ_i – total or partial widths for level
- B(Eλ), B(M λ) – transition probabilities

Stripping and Pickup

Examples:

Stripping: (d, p), (α, ^{3}He), (pol d, p), (^{3}He, d), etc.

Pickup: (p, d), (^{3}He, α), etc.

Quantities to Record:

- **E(level)** from charged particle spectrum.
- **L** and **S** or **C²S** from DWBA analysis

$(d\sigma/d\omega(\theta))_{exp} = (d\sigma/d\omega(\theta))_{DWBA}.x\ C^2S' \text{ x } N$

where $S'=S$ (pickup) or

$S'=Sx(2J_f+1)/(2J_i+1)$ (stripping)

- **J** from L±1/2 for polarised beam if vector analysing power shows clear preference between L+1/2 and L-1/2.

($d\sigma/d\omega$ is not normally given, but may be useful in absence of angular distribution; give in S field with suitable label.)

Relevant Documentation:

Target Jπ (unless 0^+)

Spectrum resolution (FWHM, keV)

Normalisation factor for DWBA analysis

Range of angles measured, lab or c.m. (but say which).

Stripping and Pickup

Deformed Nuclides; α and lighter beams:

- Pattern of cross sections among rotational-band members characteristic of a particular Nilsson configuration (**fingerprint)** enables a set of levels to be assigned as specific J members of that band if:

  (i) fingerprint agrees well with that predicted by Nilsson-model wavefunctions, and

  (ii) fingerprint is distinct from those for other possible configurations.

- Authors may give ‘spectroscopic strength’ (S) which can be entered in spectroscopic factor field (with suitable label).

Multi-particle Transfer

Examples:

(p, t), (α, d), (t, p), (α, p), (^{6}Li, d) …

Quantities to Record:

E(level)

L – if angular distribution can be fitted by a unique value

Deduced Quantities:

Jπ- from J(target) + L (vector sum) and $\pi_i\pi_f = (-1)^{Jf}$, for strong groups only in two-neutron, two-proton or α–particle transfer

pairs of identical particles can be assumed to be transferred in relative s state for strong groups

Charge-Exchange Reactions

Examples:

(p, n), (^{3}He, t)

Quantities of interest:

E(level)

Isobaric analog state information

Inelastic Scattering

Examples:

(e, e′), (p, p ′), (d, d ′), (α, α ′) at projectile energies **above** the Coulomb barrier

Quantities to Record:

E(level)

L – if angular distribution is fitted by unique L value

β2, β4 … - deformation parameters (if model independent); specify whether 'charge' or 'nuclear', if relevant (typically from (α, α ′) or (e, e ′)).

B(Eλ), B(Mλ) – transition probabilities (typically from (e, e ′)).

Coulomb Excitation - particles detected

Examples:
(p, p′), (d, d′), (α, α′) with projectile energy **below** Coulomb barrier
Quantities to Record:

E(level)

Jπ:

- determined if the excitation probability agrees with that calculated by Alder (1960Al23).
- low energy Coulomb excitation is predominantly E2

B(Eλ) – for excitation

Resonance Reactions

Examples:

(p, p), (p, X), (γ, n) … (excitation function data, σ(E), dσ/dω(θ,E))

Quantities of interest:

E(level) – can be given as 'S(p) + 976.3', etc., where 976.3 is E(p) for resonance (c.m. or lab. energy, but must specify which).

Is this an isobaric analog state? If so, specify analog state

Partial widths

Is this a giant resonance?

Note:

ENSDF is primarily concerned with bound levels, but includes all isobaric analog states, giant resonances and unbound levels that overlap or give information on bound levels

Reactions with Gamma Emissions - Detected

Measured Quantities of Interest:

- E_γ - photon energy
- Iγ - relative intensity (or photon branching)
- α, α_K, … - electron conversion coefficients, usually from I(ce)/Iγ, sometimes from intensity balance (note: this gives α_{exp}).
- K/L, L1/ L3 … - ce subshell ratios
- A_2, A_4 … - Legendre polynomial coefficients characterizing angular distribution ($\gamma(\theta)$) or angular correlation ($\gamma\gamma(\theta)$).
- DCO ratio – directional correlation of gammas from oriented nuclei.
- Asymmetry ratio - e.g., I$\gamma(\theta_1)$/I$\gamma(\theta_2)$
- Linear polarization
- Level $T_{1/2}$ – from γ(t), DSAM, RDM, centroid-shift, delayed coincidence, etc., if measured in that reaction
- g-factor – include if measured in that reaction

Reactions with Gamma Emissions - Detected

Deduced Quantities of Interest:

• E(level) – from least-squares adjustment of Eγ (GTOL), avoiding Eγ for lines that have uncertain or multiple placements whenever possible. Note serious misfits.
• Band structure – indicate via band flags for levels (note: life will be easier if a given band has the same band-flag character in each dataset in the nuclide!)
• Jπ - default is adopted value; however, much more useful to indicate authors' values in reaction dataset and add parentheses in *Adopted Levels* if insufficient (or no!) supporting arguments are available
• M - transition multipolarity
• δ – mixing ratio (√((L+1)-pole/(L-pole)), Krane-Steffen sign convention

Gamma-ray Energies

• Give measured energy and uncertainty (i.e., do not correct for recoil energy loss)

• State source of data (unless obvious, e.g., if only one keynumber)

• Uncertainties: if authors give uncertainty as:

(i) "0.3 keV for strong lines, 1 keV for weak or poorly resolved lines"; assign 0.3 to those which could be reasonably considered 'strong' and 1 to all others, but give authors' statement in general comment on Eγ and define Iγ that you consider 'strong' (or assign 1 keV to all)

(ii) "do not exceed 0.5 keV"; 0.5 could be assigned for all lines

(iii) if no uncertainty is stated, point out in general comment (for the purpose of deducing E(level) using GTOL, default of 1 keV (adjustable by user via control record at head of dataset)will be used and this should be noted in comments on level energy)

• If measured Eγ not available but G record needed in order to give other information, deduce from level energy difference and remove recoil energy loss; give no ΔEγ and state origin of Eγ

Gamma-ray Intensities

• Give relative intensities, if available (do not renormalise so strongest is 100).

• Do not mix data from different reactions or data from same reaction at different energies when entering RI on G records (use different datasets instead, or include in comments or tabulation)

• If branching ratios are measured independently (e.g., from $\gamma\gamma$ coincidences), quote these data(e.g., in comments); one set of data may be more precise than the other

• Give uncertainties whenever authors state them; if authors give both statistical and systematic uncertainties, show statistical on G record but state systematic in comments (so uncertainty in $I\gamma$ ratios is not distorted)

• If both prompt and delayed $I\gamma$ are given, use separate datasets or give one set under comments.

• For multiply-placed lines, specify whether quoted $I\gamma$ has been suitably divided between placements (& or @ in column 77)

Conversion Coefficients

• Give measured α_K, α_L, etc., and subshell ratios (in comments or on continuation of G record); state how photon and ce intensity scales were normalised

• Quote experimental coefficients (usually α) obtained using intensity balance arguments (these are frequently buried in the text of the paper); specify as "from intensity balance at xxxx level" where relevant

• Include α(theory) on G record (from HSICC) when needed for calculation or argument

γ Linear Polarisation

γ linear polarisation data may be available from Compton polarimeter measurements of relative $I\gamma$ in planes perpendicular and parallel to reaction plane
Such data may distinguish between electric and magnetic radiations

Angular Distributions

$I\gamma$ as a function of angle θ with respect to beam direction:

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)+\ldots$$

- Inclusion of A_2, A_4 … is optional, but data are so useful to evaluators and readers alike, they really should be given whenever available!
- Remember that these are signed quantities
- A_2, A_4 … depend on ΔJ, mixing ratio and degree of alignment σ/J, where σ is half-width of Gaussian describing the magnetic substate population
- σ/J is usually determined from measurements of $W(\theta)$ for known ΔJ = 2 transitions. However, many authors assume σ/J = 0.3, for practical purposes.
- σ/J affects only the magnitudes of A_2, A_4
- $W(\theta)$ is largely independent of J for high-spin states
- Alignment is reduced if level lifetime is not small
- **$W(\theta)$ can determine ΔJ but not $\Delta\pi$**

Angular Distributions

Typical values of A_2, A_4 for θ relative to beam direction if σ/J=0.3
(B. Singh, McMaster University)

ΔJ	Multipolarity	Sign of A_2	Sign of A_4	Typical A_2	Typical A_4
2	Q	+	-	+0.3	-0.1
1	D			-0.2	0.0
1	Q	+	+	-0.1	+0.2
1	D+Q	+ or -	+	+0.5 to -0.8	0.0 to +0.2
0	D	+		+0.35	0.0
0	Q	-	-	-0.25	-0.25
0	D+Q	+ or -	-	+0.35 to - 0.25	0.0 to -0.25

DCO Ratios

Directional **C**orrelations of γ-rays from **O**riented states of Nuclei

• If γ_K (known multipolarity) and γ_U (unknown multipolarity) are measured in coincidence using detectors at angles θ_1 and θ_2 to the beam:

DCO = I(γ_U(at θ_1) gated by (γ_K(at θ_2)/I(γ_U(at θ_2) gated by γ_K(at θ_1))

• Sensitive to ΔJ, multipolarity and mixing ratio; **independent of Δπ**

• Gating transitions are frequently stretched Q, but stretched D may also be used, so specify

• Authors frequently state expected DCO values for stretched Q and stretched D transitions for the geometry used; helpful to specify

• Remember that identical values are expected for stretched Q and for D, ΔJ = 0 transitions (although latter are less common)

DCO Ratios

Typical DCO values for θ_1 = 37°, θ_2 = 79°, σ/J = 0.3 (B. Singh, McMaster U.)

$\Delta J_\gamma{}^{gate}$, Mult	ΔJ_γ	Mult	Typical DCO
2, Q	2	Q	1.0
2, Q	1	D	0.56
2, Q	1	D+Q	0.2 to 1.3
2, Q	0	D	1.0
2, Q	0	D+Q	0.6 to 1.0
1, D	2	Q	1/0.56
1, D	1	D	1.0
1, D	0	D	1/0.56

Multipolarity

• L and $\Delta\pi$ may be determined from measured subshell ratios or conversion coefficients

• L alone can be determined by angular distributions or DCO ratios or γ asymmetry ratios

• $\Delta\pi$ may be determined by γ linear polarisation measurements

• When transition strengths are calculable ($T_{1/2}$ and branching known), **R**ecommended **U**pper **L**imits (RUL) can be used to rule out some multipolarities (e.g., stretched Q transition for which $B(M2)_W$ exceeds 1 can be assigned as E2); similarly, for a D+Q transition with large mixing, RUL may enable the rejection of E1+M2

• Assign Multipolarity only when measured information indicates clear preference for that assignment; otherwise, let $\gamma(\theta)$ or DCO data speak for themselves (exception: if no measurement exists but multpolarity is needed use [M1 + E2], etc., type of entry)

• Multipolarity determined for a doublet will be not reliable; can be given in comments (with disclaimer), but not on G record

Mixing Ratios

• Include on G record whenever available

• Calculate from conversion electron data or $\gamma\gamma(\theta)$ using DELTA or from subshell ratios

• Rely on authors' deductions from $\gamma(\theta)$, DCO or nuclear orientation data

• In (HI, xnγ) studies: model-dependent values of δ are sometimes deduced from in-band cascade to crossover transition intensity ratios; these could be given in comments (stating relevant K) if considered really important, but should not be entered on G record

• Check that correct sign convention was used by authors – if not, convert to Krane-Steffen, and take special care if uncertainties are asymmetric (-2.3 +4-2 becomes +2.3 +2-4 upon sign reversal)

Inelastic Scattering

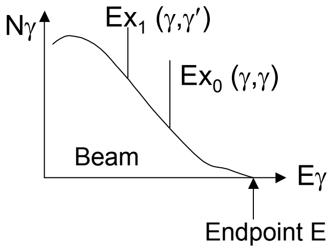
(p, p′γ), (n, n′γ), etc.; beam energies > Coulomb barrier

Separate these datasets from those for (p, p′), (n, n′) … and from that for Coulomb excitation

Information of interest: typically Eγ, Iγ, γ(θ); maybe γ linear polarisation

Nuclear Resonance Fluorescence

(γ, γ) and (γ, γ′) measurements with Bremsstrahlung spectrum; low momentum transfer so excite low-spin states (mainly E1 and M1, some E2 excitation)



- γ spectrum measured; areas of γ peaks at Ex_0 and Ex_1 combined with knowledge of $N\gamma(Ex_0)$ yields scattering cross section from which width and branching information may be obtained
- γ asymmetry differentiates D and Q excitation
- γ linear polarization differentiates M and E

Nuclear Resonance Fluorescence

(Integrated) scattering crossection I_s (eV b) is often given:

$$I_s = ((2J+1)/(2J_0+1))\ (\Gamma\gamma_0\Gamma\gamma_f / \Gamma\gamma)\ (\pi\hbar c/E\gamma)^2\ W(\theta)/4\pi$$

where J is g.s. spin, J_0 is spin of excited level, $\Gamma\gamma \cong \Gamma$ is total width and $\Gamma\gamma_0$, $\Gamma\gamma_f$ are decay widths for γ decay to the g.s. and the final state f (for elastic scattering, $\Gamma\gamma_0 = \Gamma\gamma_f$); W(θ) represents the normalised angular distribution. Data are often taken at 127° where W = 1 for D transitions

- Give $\Gamma\gamma_0^2/\Gamma$ values (extract if necessary) on L record (col. 65 (value), 75 (unc.)); relabel field
- If $\Gamma\gamma_f/\Gamma\gamma_0$ is measured, include relative branching on G records

Γ is calculable from:

$$(\Gamma\gamma_0^2/\Gamma) / (\Gamma\gamma_0/ \Gamma)^2$$

using known branching, or under assumption $\Gamma = \Gamma\gamma_0+\Gamma\gamma_f$ (which needs to be stated)

- Then: $T_{1/2}$ (fs)= 0.456 /Γ (meV); include on L record

Propagate uncertainties with care!

(Light Ion, xnypg)

(p, xnγ), (^{3}He, xnγ), (α, pγ), etc.

Separate from (HI, xnγ) studies

Separate from datasets in which gammas are not measured (e.g., do not combine (d, pγ) and (d, p)).

(Heavy Ion, xnypγ)

- Relative intensities differ for different reactions and also for a given reaction measured at different beam energies; in general, simplest to use separate datasets for each study that provides significant Iγ or branching data
- (HI, xnγ) reactions tend to populate yrast (lowest energy for given J) levels or near-yrast levels; populated states tend to have spins that increase as the excitation energy increases
- Use band flags to delineate deduced band structure; if authors give configuration for band, include in band description

(Heavy Ion, xnypγ)

- Note inconsistencies in γ order, postulated Jπ, configuration, etc., compared with other studies, and especially with that in *Adopted Levels, Gammas*
- Beware of multipolarity and Jπ assignments for which no supporting measurements exist - values are sometimes inserted in order to generate a RADWARE band drawing, and live on in the published table of data; these do not qualify as 'data'!
- Multipolarities determined as D, Q, D+Q, etc, by $\gamma(\theta)$ or DCO are best left this way in the reaction dataset unless definite arguments exist to establish $\Delta\pi$ (otherwise 'D' (strong Jπ argument) and '(D)' (weak Jπ argument) become indistinguishable when written as, say (M1))
- Report statements of coincidence resolving time (or equivalent) since they might place a limit on level lifetime, thereby enabling RUL to be used to reject $\Delta\pi$ = yes for a transition multipolarity
- For K = 1/2 rotational bands, the decoupling parameter may give a clear indication of the Nilsson orbital involved in the band configuration

(Heavy Ion, xnypγ)

• For near-spherical nuclei, if a cascade of ΔJ = 1 transitions is observed at high spin with regular energy progression, these transitions may be assigned as (M1) transitions within a common band. Exception: in rare cases, nuclei can have alternating parity bands (reflection asymmetry), and ΔJ = 1, Δπ = yes cascades occur

• For a well-deformed nucleus, if a cascade of ΔJ = 2 transitions is observed at high spin with regular energy progression, these transitions may be assigned as E2 transitions within a common band

• Octupole-deformed nuclei may exhibit an apparent band which is really two ΔJ = 2 rotational sequences of opposite parity, connected by cascading E1 transitions

Special Case:

Superdeformed band data are updated continuously in ENSDF by Balraj Singh (McMaster University). Check ENSDF at the conclusion of a mass chain evaluation to be sure no SD-band data have been added since the chain was downloaded for revision

Capture Reactions

(p, γ), (n, γ) E = thermal, (n, γ) E = res, etc.

• Use separate datasets for thermal and resonance n-capture data

• Primary and secondary transitions usually appear in the same dataset even if their intensities require different normalisations

• Jπ of the thermal neutron capture state(s) is Jπ(target) ± $1/2^+$ (i.e., s-wave capture assumed)

• Thermal neutron capture: multipolarity of a primary γ is E1, M1, E2 or M1+E2

• For resonance n capture, ENSDF does not include the resonances and their properties; list the bound states fed, their interconnecting gammas and any conclusions concerning level Jπ

• Average resonance n capture: inclusion of primary gammas and their reduced intensities (which carry information on final state Jπ) is optional; a list of final level E and deduced Jπ would suffice

Coulomb Excitation

• If authors give matrix element values, convert to B(Eλ) using

$B(E\lambda) = |\langle M(E\lambda)\rangle|^2/(2J_0+1)$ where J_0 is g.s. spin.

• If authors give B(Eλ)↓, convert to B(Eλ)↑ and include with level information

• In the strongly deformed region, a cascade of E2 transitions with enhanced transition probabilities ($B(E2)_W > 10$) provides definitive evidence for a rotational band and for the sequence of Jπ values, providing Jπ of one level is independently known

• Calculate level $T_{1/2}$ from B(Eλ) and adopted γ-ray properties when possible

ENSDF – Adopted Levels and Gammas: Model Exercises

Coral Baglin

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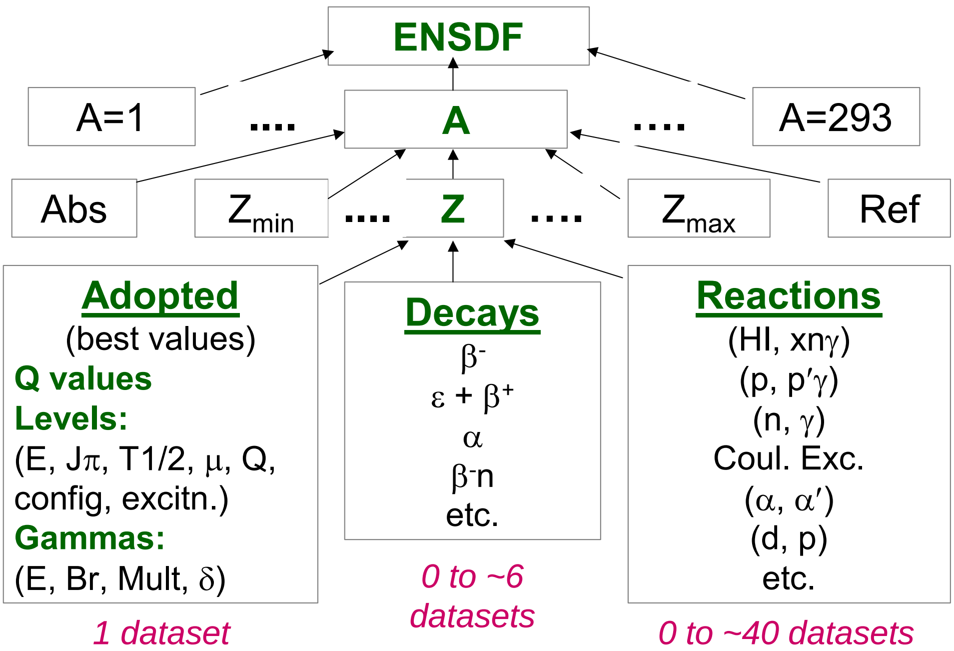
ENSDF Database Structure



Adopted Levels, Gammas

This dataset is the heart of any nuclide evaluation!

• Condensation of all the information from all the other datasets, and provides the **best values** known at the time of the evaluation

• Provides the information that goes into the summary database NUDAT

• May be the **only** dataset that some users will ever look at

• Sources of all data appearing here must be made transparent to the reader

General Information

Q values:

• Usually rounded values from latest mass table (presently 1995Au04)

• Add new S(p), Q(α) with keynumber, if available; compare with 1995Au04

• Optional: comment on uncertainties in 'SY' values; note newly-measured masses if very different from Audi prediction

General Comments:

e.g., Production/Identification, keynumber lists for major shell model calculations or isotope shift/hfs references (all optional)

Other Reactions:

Give reaction and keynumber for completeness, even though no data have been used and no reaction dataset has been created e.g., continuum gamma study (optional)

Define XREF Symbols:

Every DSID in nuclide must be listed here, even if not associated with a specific level

Example 1 ?

```
167IR    ADOPTED LEVELS
167IR C  Production: 92MO(78KR,p2n) E=357, 384 MEV (1997DA07).
167IR C  Identification: 1981HO10 unambiguously assign a new |a group to 167IR
167IR2C  by relating it to known transitions through a multi-dimensional
167IR3C  analysis correlating parent energies, daughter energies, and the
167IR4C  timing of events. The production reactions involved 58NI on
167IR5C  molybdenum-tin targets and 107AG on vanadium-nickel targets
167IR C  For calculation of proton decay widths for 167IR GS and isomer see
167IR2C  2000DA11.
167IR  Q          11760   SY-1070   6 6507     5     1995AU04,1997DA07
167IR CQ          |DS(n)=300 (1995AU04).
167IR CQ QA$from measured EA=6351 5 (1997DA07) for GS to GS transition; 1995AU04
167IR2CQ give QA=6495 50, reflecting lack of information concerning daughter
167IR3CQ state at that time.
167IR CQ SP       From measured EP=1064 6 (1997DA07) for GS to GS transition;
167IR2CQ SP=-1110 10 in 1995AU04.
167IR  XA171AU A DECAY (1.02 MS)
167IR  XB78KR(92MO,2NPG)
167IR  L 0           (1/2+)          35.2 MS   20
167IR2 L %A=48 6 (1997DA07)$%P=32 4 (1997DA07)$%EC+%B+=?
167IRX L XREF=B
167IR CL J         comparison of calculated and measured partial lifetimes for
167IR2CL p decay rule out d{-3/2} and h{-11/2} transitions, so 1997DA07 conclude
167IR3CL that an L=0 p is emitted to the 0+ GS of 166OS.
167IR CL %A,%P     From relative intensities of |a and p decay from level,
```

Level and Gamma Properties - General

• Every nuclide must have at least 1 level

• Document sources of <u>all</u> data (<u>dataset name</u>, not just keynumber)

•Comment on serious discrepancies

• Specify whether 'average' is weighted or unweighted (use larger of internal and external uncertainties in weighted averages)

• Remember to round off so that uncertainty <26

• Remember that 'level' and 'gamma' data appear in different tables in NDS; <u>unhelpful</u> to say "Jpi for levels with γ to 8+ isomer based on …" (in level table) or "multipolarity for γs observed in low spin reactions is from …" (in γ table)

• Do <u>not</u> include:

continuation G records giving CC, KC, etc
primary γ rays from neutron capture
neutron capture state(s)
coincidence 'C' from col. 78 of G records
unplaced γ rays listed in source datasets

Level Properties

Level Energy:

- Use GTOL to calculate from adopted Eγ in most cases.
- Include all discrete levels and giant resonances; identify analog resonances
- Adopt minimum number of levels consistent with source datasets

T1/2 (or Γ):

- Specify source, e.g., "from B(E2)↑ in Coulomb excitation", etc.
- Give bare-atom half-lives in comment (e.g., "$T_{1/2}$(52Fe26+) = …")
- Remember $\Gamma = \Gamma\gamma + \Gamma p + \ldots$ for resonance, so note any assumptions such as '$\Gamma = \Gamma\gamma_0 + \Gamma\gamma_1$' or '$\Gamma = \Gamma p$'.

Band Flag: (if relevant)

Give rotational band parameters in comment (if meaningful) from:

$E_K(J) = E_0 + A(J(J+1)-K^2) + B(J(J+1)-K^2)^2 + (-)^{(J+K)}(J+K)!/(J-K)!(A_{2K} + B_{2K}(J(J+1)-K^2)$

Isospin: very important for low A!

Level Decay Branches: for g.s. and T1/2 ≥ 0.1 s levels, include all modes that might reasonably be expected, even if not yet observed

```
 92RB   Q 8100      7  5099   10 10750  60              1995AU04
 92RB   L 0.0          0-               4.492 S   20
 92RB2  L %B-=100 $ $B-N=0.0107 5 $
 92RBX  L XREF=AB
--------------
192PO   Q              11.0E3 SY 2.2E3  SY 7320    7    1995AU04
192PO  CQ           |DS(n)=360, |DS(p)=450 (1995AU04).
192PO   L 0.0          0+               33.2 MS   14
192POX  L XREF=AB
192PO2  L %A AP 100$ %EC+%B+=?$
192PO  CL           %A: only A DECAY observed. %(EC+B+) AP 0.4 can be
192PO2CL estimated from gross B decay theory (partial T AP 8 S)
192PO3CL (1973TA30), or AP 0.54 from partial BETA T of 6.1 S
192PO4CL calculated by 1997MO25.
-------------
168RE   Q -5800     SY8960    SY830     SY5063    13    1995AU04
168RE  CQ           |DQ(|b)=400, |DS(n)=420, |DS(p)=510 (1995Au04).
168RE   L  0.0         (5+,6+,7+)       4.4 S      1
168RE2  L %EC+%B+=100$ %A AP 5E-3 $
168REX  L XREF=AB
168RE  CL           %A: deduced from IA/RI(199.3G in 168W) and EC decay
168RE2CL scheme for 168RE (1992Me10).
```

Example 2: decay branches

XREF Flags:

- Use 'X(*)' if level from dataset X cannot be uniquely identified with level in question
- Use 'X(energy)' to resolve any ambiguity due to poor energy match between adopted level and dataset X level

Example 3: XREFs

```
59NI    L 5821      10
59NIX L XREF= BN(*5830)
59NI CL          JPI=3/2+ FROM (POL P,D) AND L(P,D)=2 FOR 5821 AND/OR
59NI2CL 5844 LEVEL(S).
59NI    L 5844      10 (3/2+,5/2+)
59NIX L XREF=BN(*5830)
59NI CL  J       L(D,P)=(2). JPI=3/2+ FROM (POL P,D) AND L(P,D)=2 FOR 5821
59NI2CL AND/OR 5844 LEVEL(S).
```

- Watch for systematic energy scale deviations between various reaction studies

- Avoid associating transfer reaction level with an adopted level whose configuration would not be excited

Example 4

169Tm(d,p) Target: 1/2[411]p g.s.

n stripped from d

170Tm states populated must be 1/2[411]p⊗Ω[xxx]n

Populated:

1/2[411]p ± 1/2[521]n
1/2[411]p ± 5/2[512]n
1/2[411]p ± 7/2[633]n
1/2[411]p ± 3/2[521]n

Not populated:

7/2[404]p ± 7/2[633]n
1/2[541]p ± 5/2[512]n
1/2[541]p ± 7/2[633]n

B(Lλ)↑:

Give only when value measured, but branching or $T_{1/2}$ unknown (e.g., E3 Coulomb excitation measured, but no E3 transition observed)

Moments (μ, Q): static, model-independent values

• Summarized in 89Ra17 (evaluation) and 01StZZ (listing); add new references

• Specify method used

• Mention standards used, corrections applied (e.g., Sternheimer)

• Signs do matter

• Convert g-factor data to μ

Δ<r2> (DAVRSQ): include data in comment on g.s. (or isomer) if available

Example 5: μ, Δ<r2>, etc

```
167LU   L      0.0+X   1/2(+)          1 M       GE                        CM
167LUX L XREF=B
167LU2 L %EC+%B+=?$%IT=?
167LU3 L MOMM1=-0.0999 13 (1998GE13)$
167LU CL          DAVRSQ(170LU,167LU)=-0.291 (1998GE13); 10%
167LU2CL systematic uncertainty.
167LU CL          J,MOMM1: from collinear fast beam laser spectroscopy
167LU2CL (1998GE13). PI based on proximity of MOMM1 to value expected for
167LU3CL 1/2[411] orbital (-0.05) cf. that for the only other nearby J=1/2
167LU4CL orbital (viz. 1/2[541], |m AP +0.7).
167LU CL T        estimated by 1998GE13; based on known rare-earth diffusion …
```

Spin and Parity:

• An argument must be provided for every Jπ that is given

• Use fewest and best arguments for definite Jπ; more arguments the better for uncertain J or π. Try to <u>convince</u> reader; enable a quick check on the <u>impact</u> of any new data that may become available later

• Use flagged comments for long, repetitive arguments (e.g., “Jpi based on presence of primary γ from ½+ capture state in (n, γ) E = thermal and log$f^{1u}t$ < 8.5 from 1/2- in … EC decay”)

• If directly measured (e.g., atomic beam), state the method

• Note that μ no longer provides a <u>strong</u> Jπ argument (used to)

• Avoid using multiply-placed γs in “γ to Jπ” type arguments

• Note that “γs to 3/2+ and 5/2-“ (2 levels) differs from “γs to 3/2+, 5/2-“ (1 level) – avoid ambiguities

• “γ to Jπ” is a <u>weak</u> argument

• “γ to …” arguments: level Jπ matters; not E(level)

• Use “logft =…from <u>Jπ = 1/2-”</u> and L(d, p) = 2 for <u>9/2+ target</u>” type arguments; parent/target Jπ is part of the argument

Sample Jπ Arguments:

Argument(s)	**Jπ**
E2 737γ to 7/2+ g.s.; log*ft* < 5.9 from ½+.	3/2+
Primary γ from ½+ in (n,γ) E = thermal; E1 438γ from 7/2- 832 level.	5/2+
From (pol d, p) and L(d, p) = 3 for 0+ target.	5/2+
Log$f^{1u}t$ < 8.5 from 2-; M1 558γ from 4+ 1038 level.	3+
M1+E2 78γ to ½- 132 level.	3/2-
E1 122γ to 2- 244 level; 72γ to 4+ 50 level.	(2,3)+
Probable analog of 3/2- 358 level in ^{AA}ZZ.	(3/2-)
Unhindered α decay from (10-) parent.	(10-)
γ to 2- and γ to 4+.	(2+,3,4-)

Gamma-ray Properties

Energy:
If E derived from level energy difference, say so and recalculate after GTOL has been run (without that Eγ included, of course)

Relative Branching:
• Scale Iγ so strongest branch is 100;
Exceptions:
Strongest line is multiply placed (& in col. 77) (give as < I+ΔI)
Strongest line is given as a limit
Transition is within a superdeformed band
• Omit uncertainty if only one branch
• Give TI for E0 or fully converted transitions

Multipolarity:
• [mult] means 'deduced solely from level scheme'; use [E2], etc. only if needed to calculate transition probabilities or CC for line with no measured multipolarity
• Convert 'D' or 'Q' to '(E1)', '(E2)', etc., if preferred or if needed for calculation; specify how Δπ was deduced

• Remember that 'M1, E2' and 'M1+E2' are not equivalent

Mixing Ratio:
• Include sign, if known; absence of sign indicates modulus δ
• If two solutions, give both in comment, none in MR field
• Watch for cases where experiment gives higher limit than RUL allows

Conversion Coefficients (CC):
Give when significant

E0 Transitions:
Quote $\rho2(E0)$ from 1999Wo07 (or from authors of later papers)

Reduced Transition Probabilities:
• Give whenever calculable
• If δ overlaps 0 or ∞, calculate for D or Q only
• Calculate for [E1], [E2], [$\Delta J > 2$]
• Watch out for data given as a limit

Reduced Transition Probability Calculations (special cases)

I: Data given as limit:
$\delta(M1,E2) < 0.3$:
$B(E2)_W$: give as upper limit
$B(M1)_W$: give av. of $B(M1)_W(\delta=0)$ and $B(M1)_W(\delta=0.3)$
TI < i for non-dominant branch:
Assign 1/2i $\pm$ 1/2i to this transition to enable calculation of $B(L\lambda)_W$s for other branches
$T_{1/2} < t$:
Give resulting lower limits on $B(L\lambda)$Ws.
$T_{1/2} > t$:
Typically, forget it !
However, $B(E2)_W<0.005$ or $B(E1)_W< 2x10^{-10}$ might, for example, be worth mentioning

II: When $T_{1/2}$ was calculated directly from $B(L\lambda)$:
Calculate $B(L\lambda)_W\downarrow$ from measured $B(L\lambda)\uparrow$ and single-particle value (available from RULER)

Checking Your File

• Run FMTCHK and make necessary corrections

• Read through file (ENSDAT/ENSWIN output may be helpful); amazing what the eye can catch this way

• Check band drawings – typographical error in $J\pi$ or incorrect band flag may be extremely easy to detect in these drawings

• Run PANDORA.

- Use FILE.ERR output to identify physics errors.
- Use FILE.GLE to check for:

(i) inconsistencies in $J\pi$, MULT, δ between adopted and decay datasets

(ii) adopted photon branching that has not been renormalised so the strongest branch is 100

(iii) levels or transitions in decay or reaction datasets which were accidentally omitted from *Adopted Levels, Gammas* (or conversely)

Bibliographic Databases in support of NSDD Evaluations

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1. Introduction

Bibliographic databases useful to nuclear structure and decay data (NSDD) evaluators are briefly described, along with examples of their usage. Authors' reference listings are also discussed. Nuclear Science References is recognized as the major bibliographic resource, and therefore most of the presentation is devoted to this database.

2. Nuclear Science References

Nuclear Science References (NSR) is the primary bibliographic resource for NSDD evaluators. Originally known as Nuclear Structure References, the name was changed in 1995 to reflect the extended coverage. The primary scanning effort is concentrated at the National Nuclear Data Center (NNDC), with some contributions from Russian groups that cover various conferences and laboratory reports.

About 75 to 80 journals are regularly scanned, particularly journals devoted completely to nuclear physics (*e.g.*, European Journal of Physics A, Nuclear Physics A, and Physical Review C) that are comprehensively indexed in NSR. Relevant information from laboratory reports, conference proceedings, theses, *etc*. is also indexed. NSR is a reference-oriented bibliography; i.e., each entry represents one article. There are approximately 174000 entries with about 4500 added yearly. The database is considered "complete" for primary nuclear structure references (articles published in refereed journals) since 1967, and has references dating back to 1910.

HTML-formatted retrievals have links to other sources:

1. Journal link managers (American Physical Society, EDP Sciences, and Nuclear Physics Electronic
   43561 as of 9 October 2003
2. Evaluated Nuclear Structure Data File (ENSDF)
   229 as of 9 October 2003
3. Experimental Unevaluated Nuclear Data Library (XUNDL)
   960 as of 8 October 2003
4. Digital Object Identifiers (*doi*) for several journals

Use of the journal link managers is being phased out in favor of *doi*. At present, links to XUNDL are only available at the NNDC.

One issue of *Nuclear Data Sheets* is devoted to Recent References each year, reflecting the entries added to Nuclear Science References during the year. The following access *via* the Internet is available:

1. TELNET — IAEA-NDS and IAEA-NDS IPEN mirror,
2. Web — NNDC, IAEA-NDS, and IAEA-NDS IPEN mirror, (CODASYL database, and PERL)
3. Web — NNDC, IAEA-NDS and IAEA-NDS IPEN mirror (relational database, SQL, and Java Server Pages).

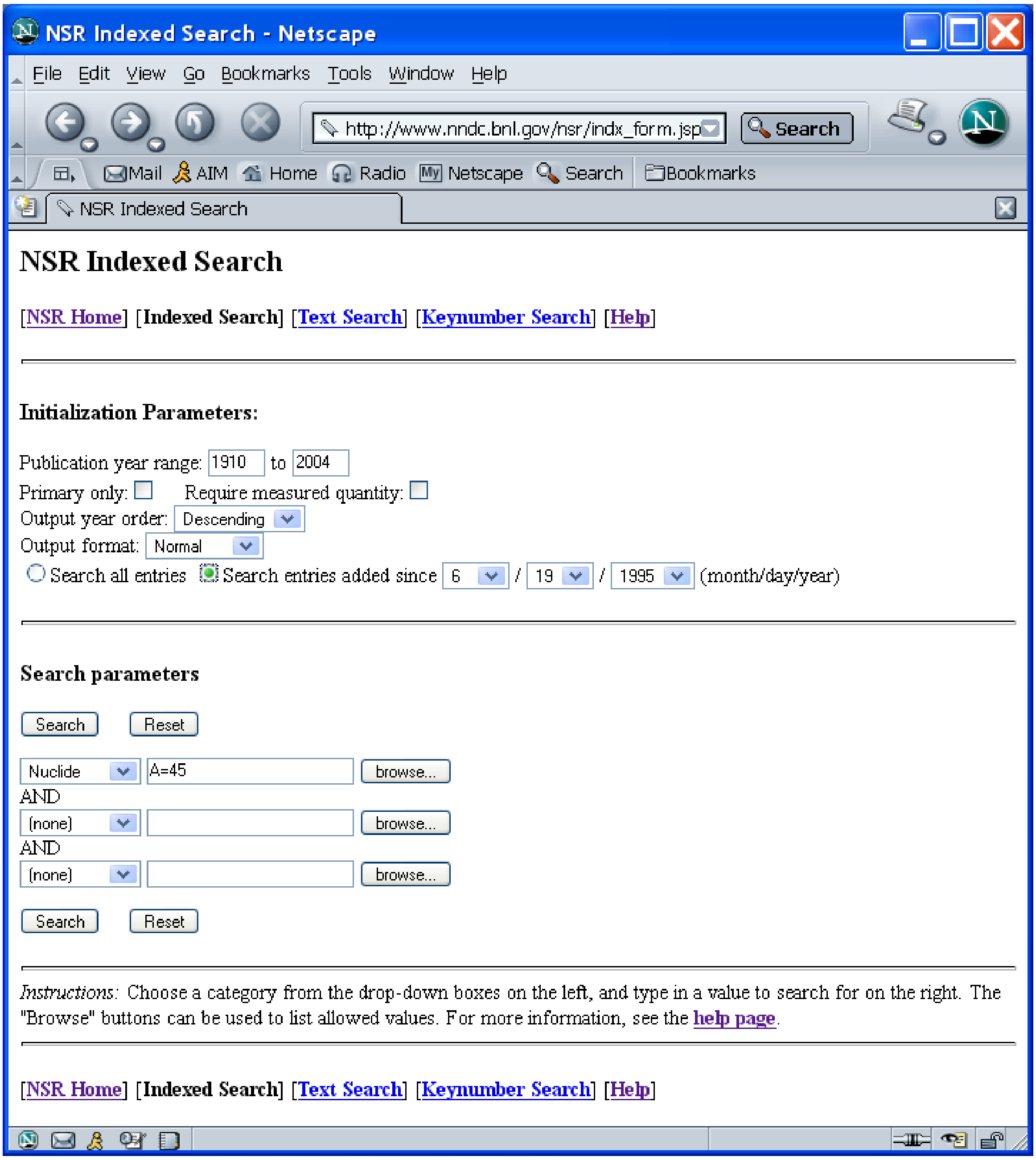
The older Web interface will be discarded by NNDC, probably before the end of 2004.

The master NSR database is updated as entries are added or modified, and the NNDC Web site is updated approximately weekly. Monthly updates are sent to the IAEA Nuclear Data Section. NSDD evaluation centers receive mass-chain-specific updates,and monthly updates in the exchange format are also sent to groups such as the Isotopes Project at LBNL and Sarov.

There are many ways to use NSR (*e.g.*, text searches of titles and keyword abstracts in the SQL version). The following five examples are relevant to ENSDF evaluators (all examples use SQL NSR, although similar capabilities are generally present in theolder interfaces).

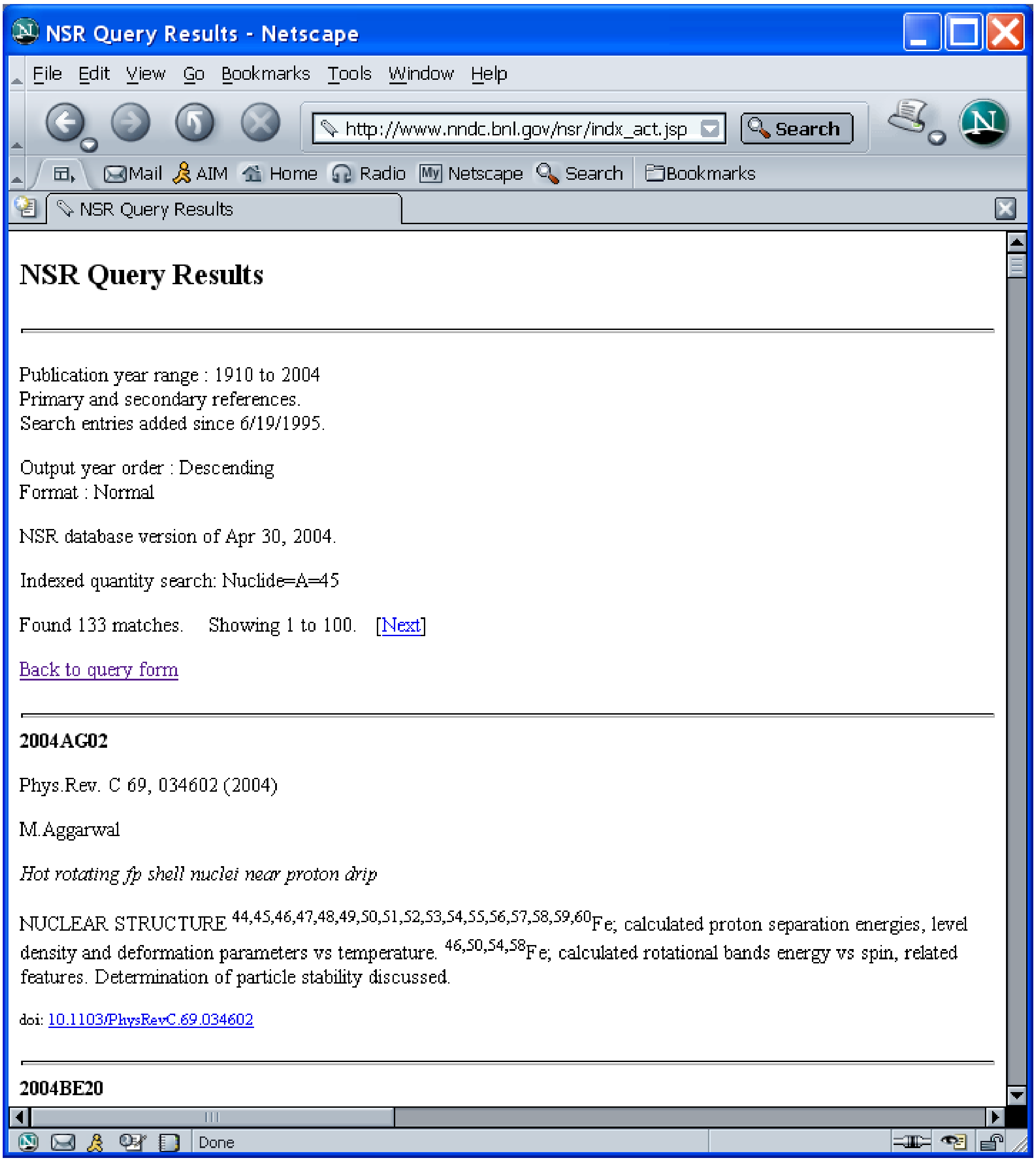
Example 1: Starting a New Mass Chain Evaluation

When starting a new mass chain evaluation, one should check NSR for entries added since the cut-off date of the previous evaluation, using the **Indexed search** option.



1. Uncheck primary only.
2. Selection of descending Output year order will list published references before earlier related preliminary results.
3. Select Search entries added since, and use the ENSDF cut-off date for the mass chain as the criteria.
4. Select Nuclide and specify the mass as A = mmm to obtain all entries for nuclides with mass mmm.

The resultant retrieval will look like:



NSR Query Results

Publication year range : 1910 to 2004
Primary and secondary references.
Search entries added since 6/19/1995.

Output year order : Descending
Format : Normal

NSR database version of Apr 30, 2004.

Indexed quantity search: Nuclide=A=45

Found 133 matches. Showing 1 to 100. [Next]

Back to query form

2004AG02

Phys.Rev. C 69, 034602 (2004)

M.Aggarwal

Hot rotating fp shell nuclei near proton drip

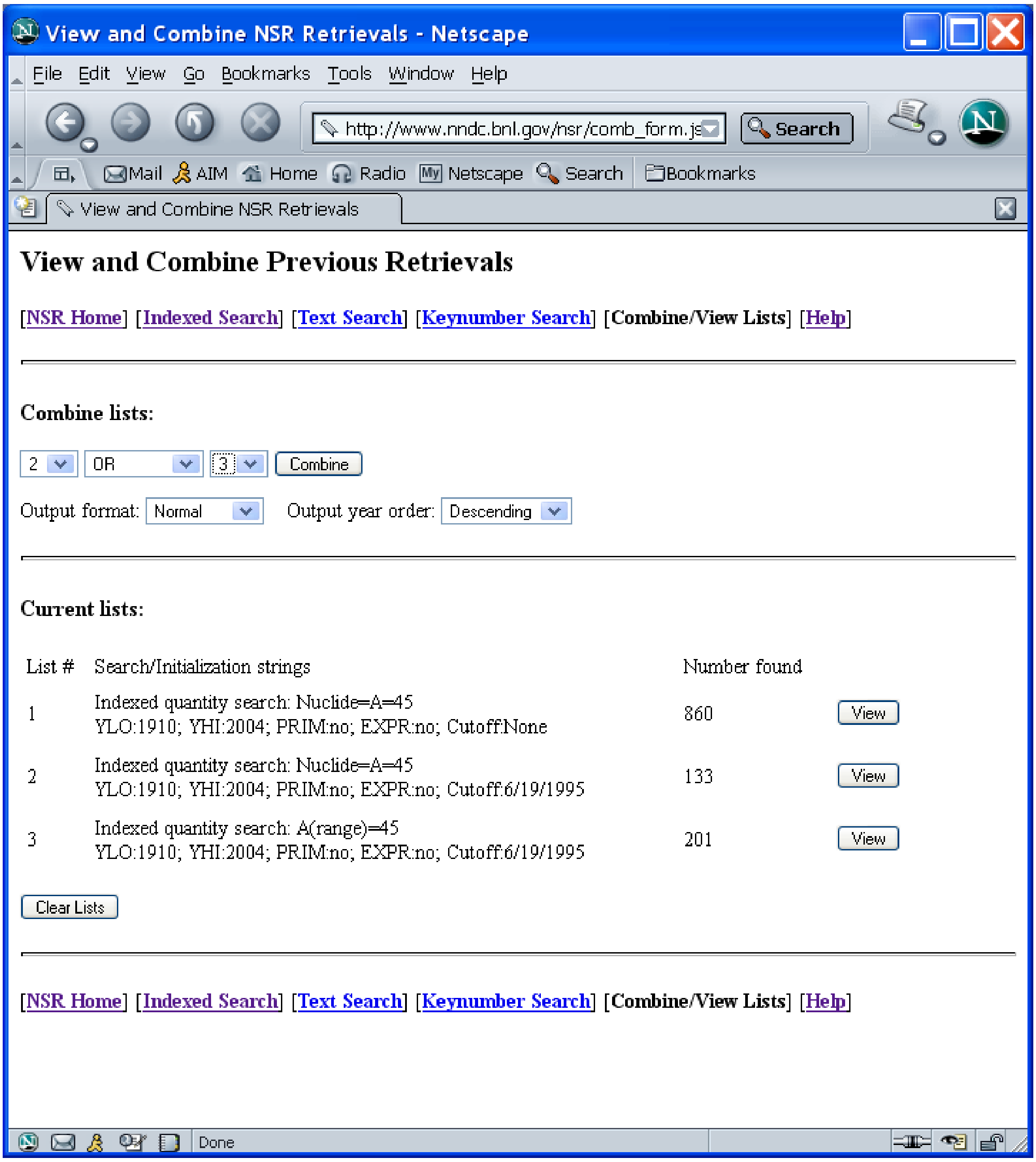
NUCLEAR STRUCTURE $^{44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60}Fe$; calculated proton separation energies, level density and deformation parameters vs temperature. $^{46,50,54,58}Fe$; calculated rotational bands energy vs spin, related features. Determination of particle stability discussed.

doi: 10.1103/PhysRevC.69.034602

2004BE20

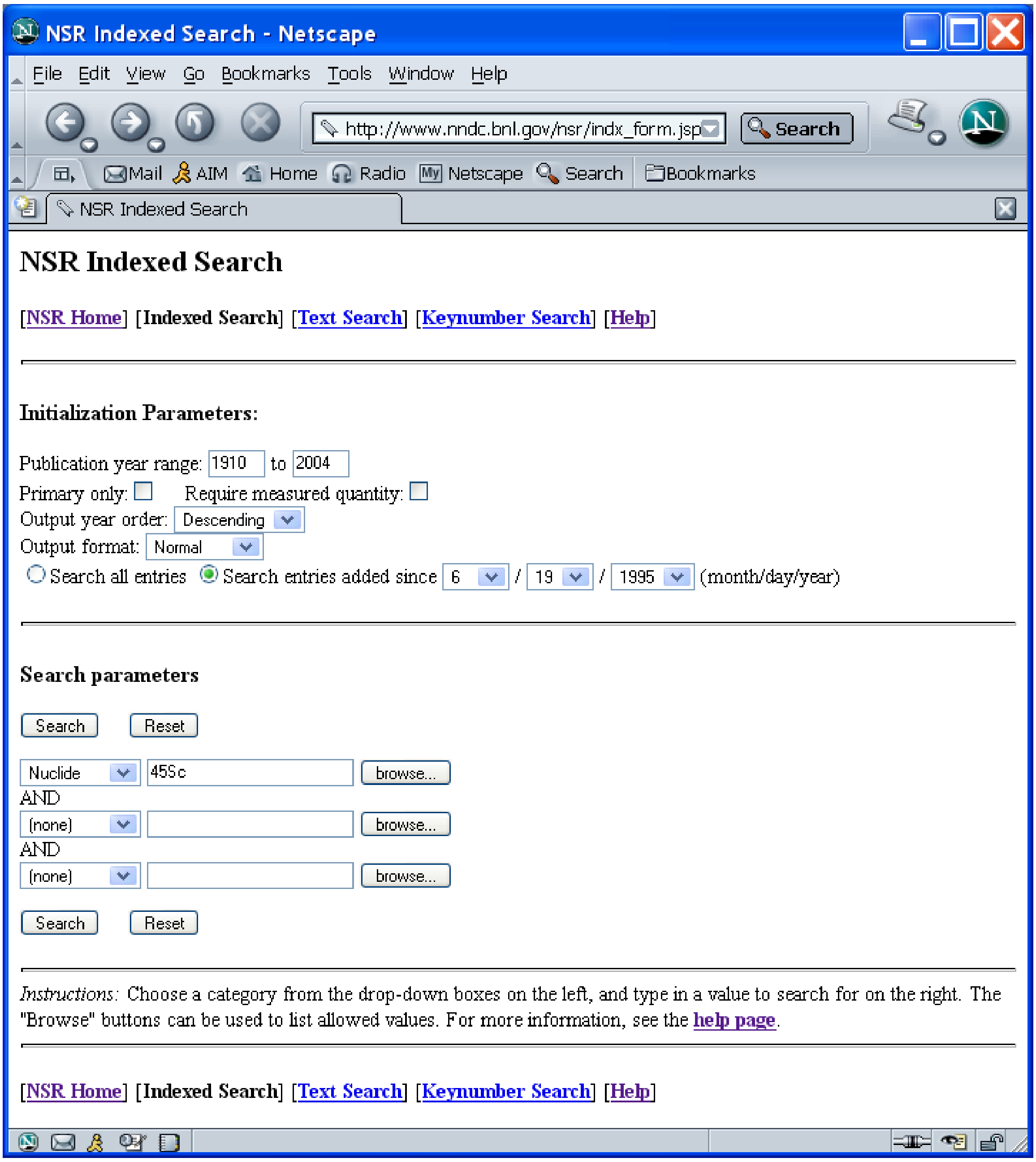
One should probably not check **Require measured quantity** in this initial survey, since you will want to check for relevant compilations and evaluations.

The retrieval should also be repeated by selecting A [range] instead of Nuclide and specifying the mass of interest. Such an approach is necessary to obtain NSR entries where the number of nuclides is too numerous to list, and again is useful to check for relevant compilations and evaluations. The two retrievals may be combined using a Boolean OR.

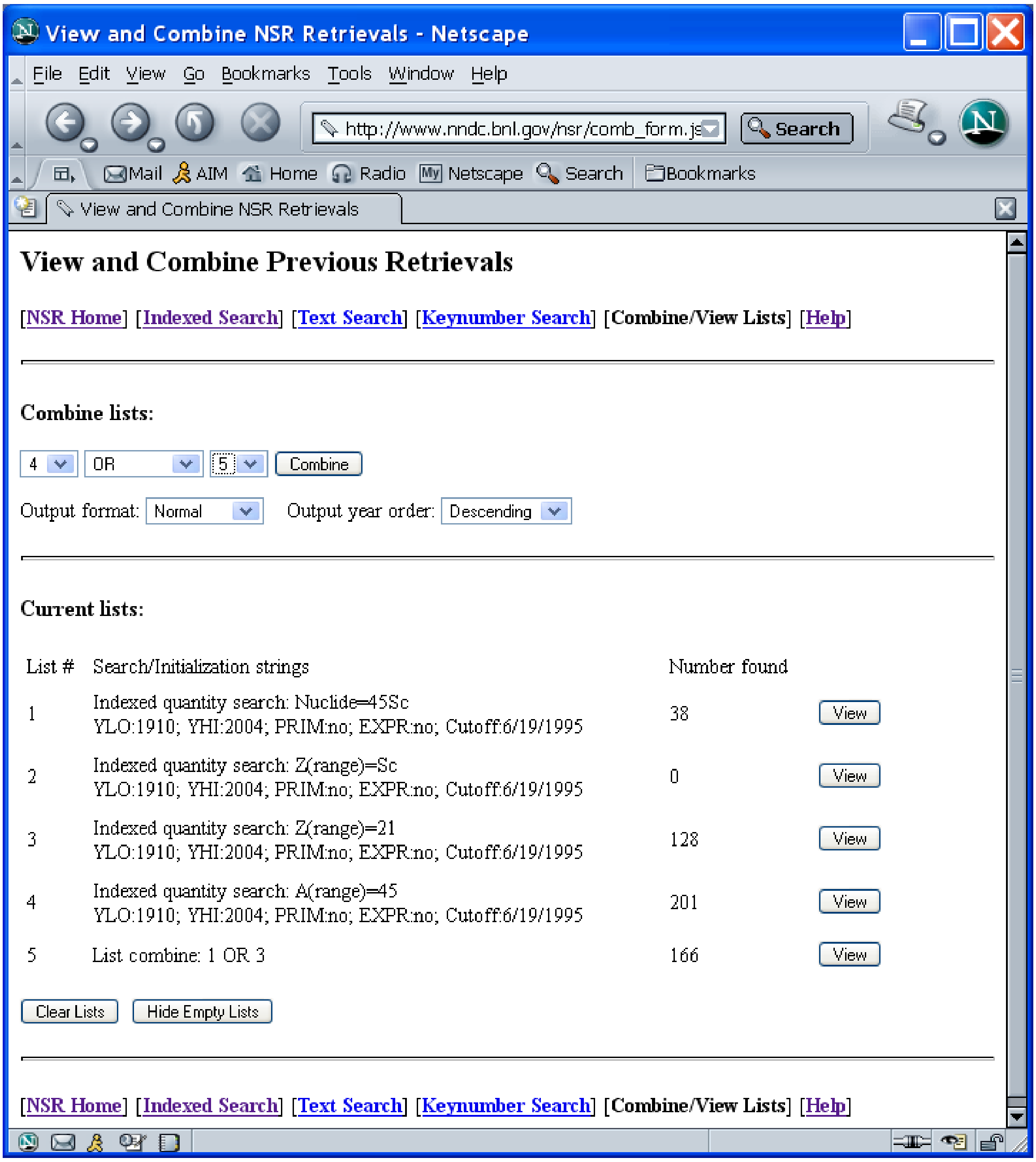

View and Combine NSR Retrievals - Netscape
File Edit View Go Bookmarks Tools Window Help
http://www.nndc.bnl.gov/nsr/comb_form.js
Search
Mail AIM Home Radio Netscape Search Bookmarks
View and Combine NSR Retrievals
View and Combine Previous Retrievals
[NSR Home] [Indexed Search] [Text Search] [Keynumber Search] [Combine/View Lists] [Help]
Combine lists:
2 OR 3 Combine
Output format: Normal Output year order: Descending
Current lists:
List # Search/Initialization strings Number found
1 Indexed quantity search: Nuclide=A=45
YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:None 860 View
2 Indexed quantity search: Nuclide=A=45
YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:6/19/1995 133 View
3 Indexed quantity search: A(range)=45
YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:6/19/1995 201 View
Clear Lists
[NSR Home] [Indexed Search] [Text Search] [Keynumber Search] [Combine/View Lists] [Help]
Done

Example 2: Starting an Evaluation of a Nuclide

The first step in starting an evaluation of a nuclide is similar to that for a mass chain. Instead of specifying A = mmm for the nuclide, define the nuclide. Also, the ENSDF cut-off date for the nuclide should be used.

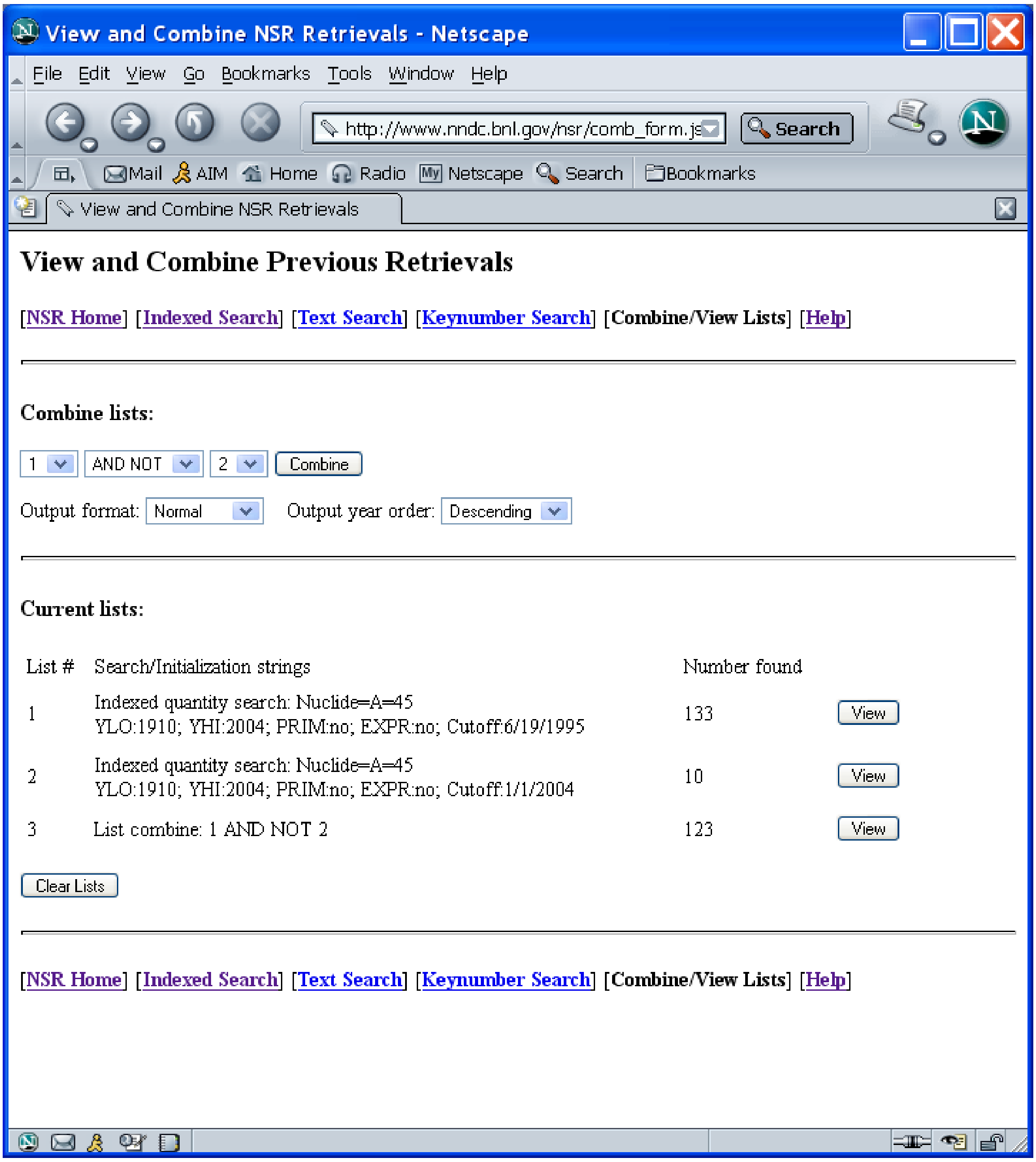


1 May also be useful to undertake retrievals for A [range] and Z [range] and use a Boolean OR. Note that the Z number (not chemical symbol) is required for the option.


View and Combine NSR Retrievals - Netscape
File Edit View Go Bookmarks Tools Window Help
http://www.nndc.bnl.gov/nsr/comb_form.js
Search
Mail AIM Home Radio Netscape Search Bookmarks
View and Combine NSR Retrievals
View and Combine Previous Retrievals
[NSR Home] [Indexed Search] [Text Search] [Keynumber Search] [Combine/View Lists] [Help]
Combine lists:
4 OR 5 Combine
Output format: Normal Output year order: Descending
Current lists:
List # Search/Initialization strings Number found
1 Indexed quantity search: Nuclide=45Sc YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:6/19/1995 38 View
2 Indexed quantity search: Z(range)=Sc YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:6/19/1995 0 View
3 Indexed quantity search: Z(range)=21 YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:6/19/1995 128 View
4 Indexed quantity search: A(range)=45 YLO:1910; YHI:2004; PRIM:no; EXPR:no; Cutoff:6/19/1995 201 View
5 List combine: 1 OR 3 166 View
Clear Lists
Hide Empty Lists
[NSR Home] [Indexed Search] [Text Search] [Keynumber Search] [Combine/View Lists] [Help]

Example 3: As an Aid in Reviewing an ENSDF Evaluation

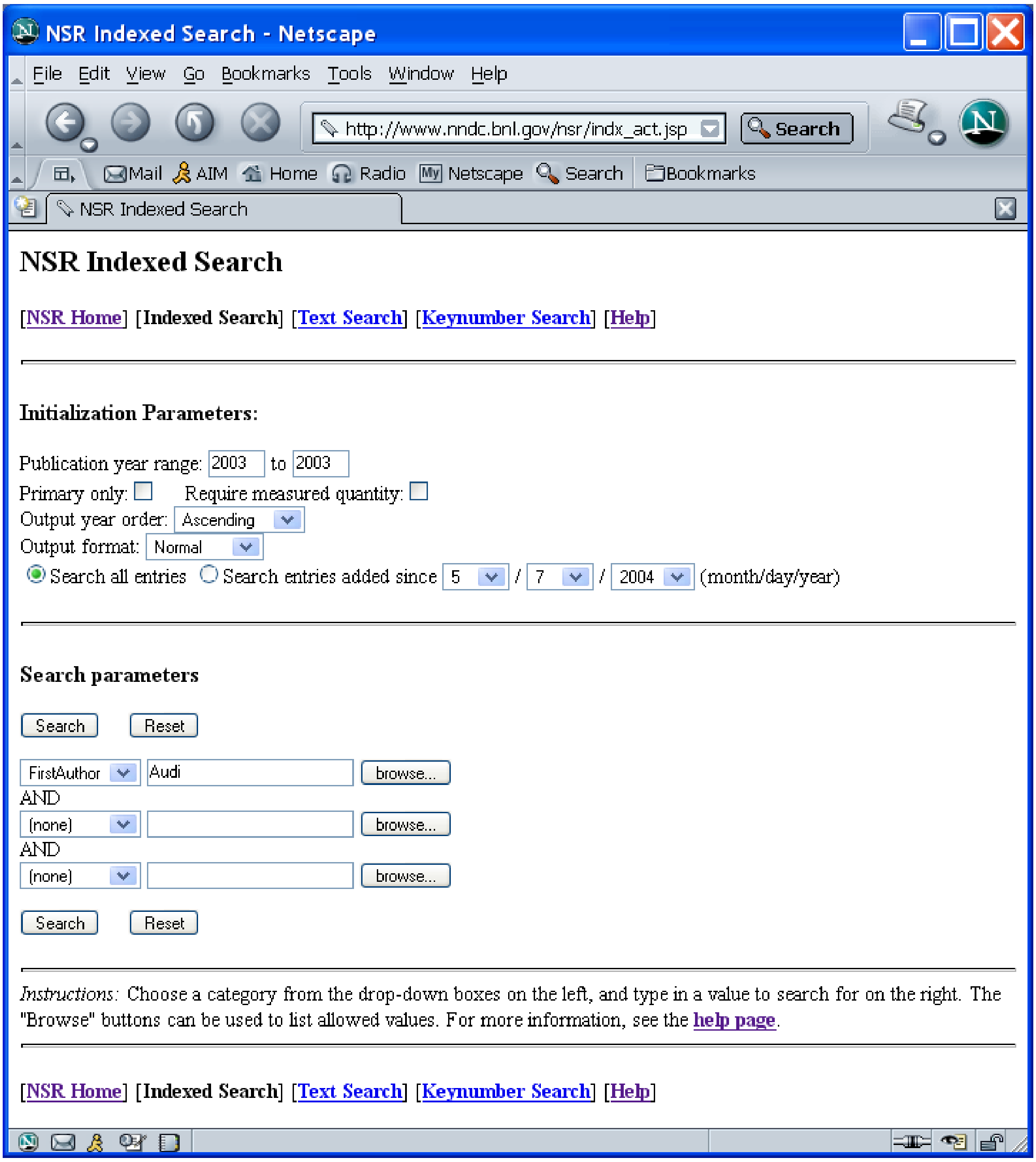
NSR may also aid the referee in checking for the completeness of an evaluation under review. Using the new cut-off date and the cut-off date of the previous evaluation, a Boolean NOT operation can be adopted to achieve this objective.



Again, one should check for relevant compilations and evaluations.

Example 4: Searches by Publication Year and First Author

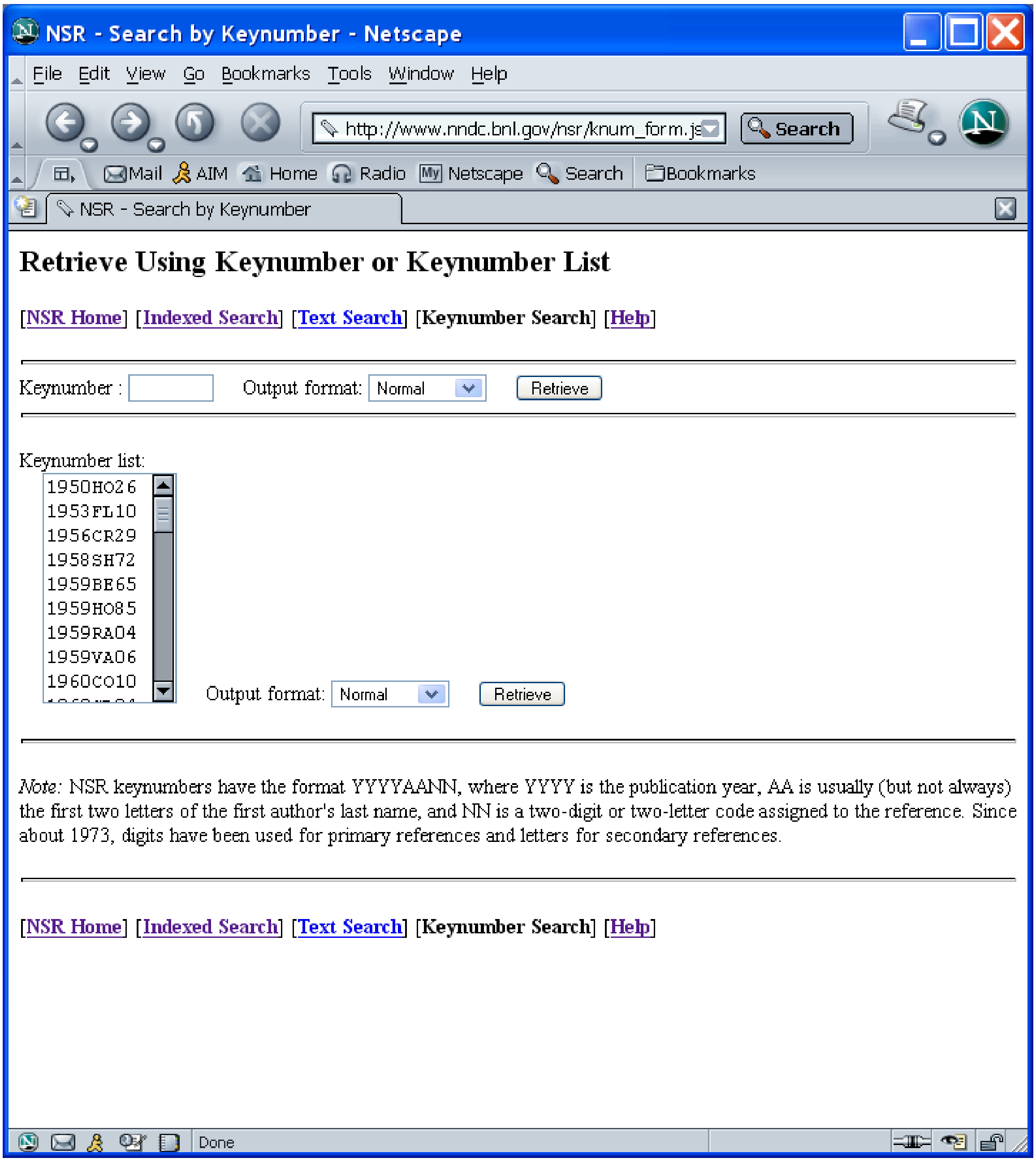
There may be instances when an evaluator finds a reference that does not seem to appear in NSR. This observation may occur if there is an error in NSR or if Selectors could not be generated for the NSR entry, and can be checked by means of the **Indexed search** option.



1. Specify the publication year range.
2. Deselect primary only.
3. Select **FirstAuthor**, and specify the last name of the first author.

Example 5: Checking Keynumber Lists

Useful to check the keynumbers in an ENSDF evaluation prior to submission to theNNDC for typographical errors. Use the keynumber list generated by the ENSDAT program (**E**valuated **N**uclear **S**tructure **D**rawings **a**nd **T**ables) and the**Keynumbersearch** option of NSR.



1. Copy the keynumber file generated by ENSDAT to the clipboard.
2. Paste into the Keynumber list.
3. Check the results for missing entries or entries that have no relationship to your evaluation.

When using NSR as an NSDD evaluator, there are three points worth noting:

1. If you encounter a possible error in an NSR entry, please check the entry using the exchange format option which allows one to see the Selectors that have been generated from the keyword abstract. If you confirm the problem, report your findings to Dave Winchell at Winchell@bnl.gov or nsr@bnl.gov.

2. All references cited in an ENSDF evaluation should have a keynumber assignment. If you encounter a reference which does not appear to be indexed in NSR, please note the following: Check NSR using first author and publication year.
   a. If a relatively recent secondary reference (*e.g.*, a private communication or preprint), may be useful to wait.
   b. Except for major journals and conference proceedings, a copy of the reference is required for a keynumber assignment. For theses, this would be complete bibliographic information and the pages of text relevant to your evaluation. Conferences require complete bibliographic information and the article. Authors'names, file creation/modification and download dates, and hard copy or the files are required for data downloaded from the Internet.
   c. Send the information to Jag Tuli (NNDC, BNL) with your submittal or update of an ENSDF evaluation.

3. If you have access to obscure laboratory reports, limited distribution conference proceedings, *etc.*, send a copy to the NNDC for inclusion in the library and scanning into NSR.

3. Computer Index to Neutron Data

The Computer Index to Neutron Data (CINDA) is the result of scanning efforts by four centers in the Nuclear Reaction Data network (National Nuclear Data Center - US and Canada, Nuclear Energy Agency Data Bank - OECD members, Russian Nuclear Data Center - former Soviet Union, and IAEA Nuclear Data Section - other countries). Coverage includes journals, conference proceedings, laboratory reports, theses, *etc.* Data compiled in the Exchange Format (EXFOR) and evaluations in various national or international nuclear reaction data libraries are also indexed.

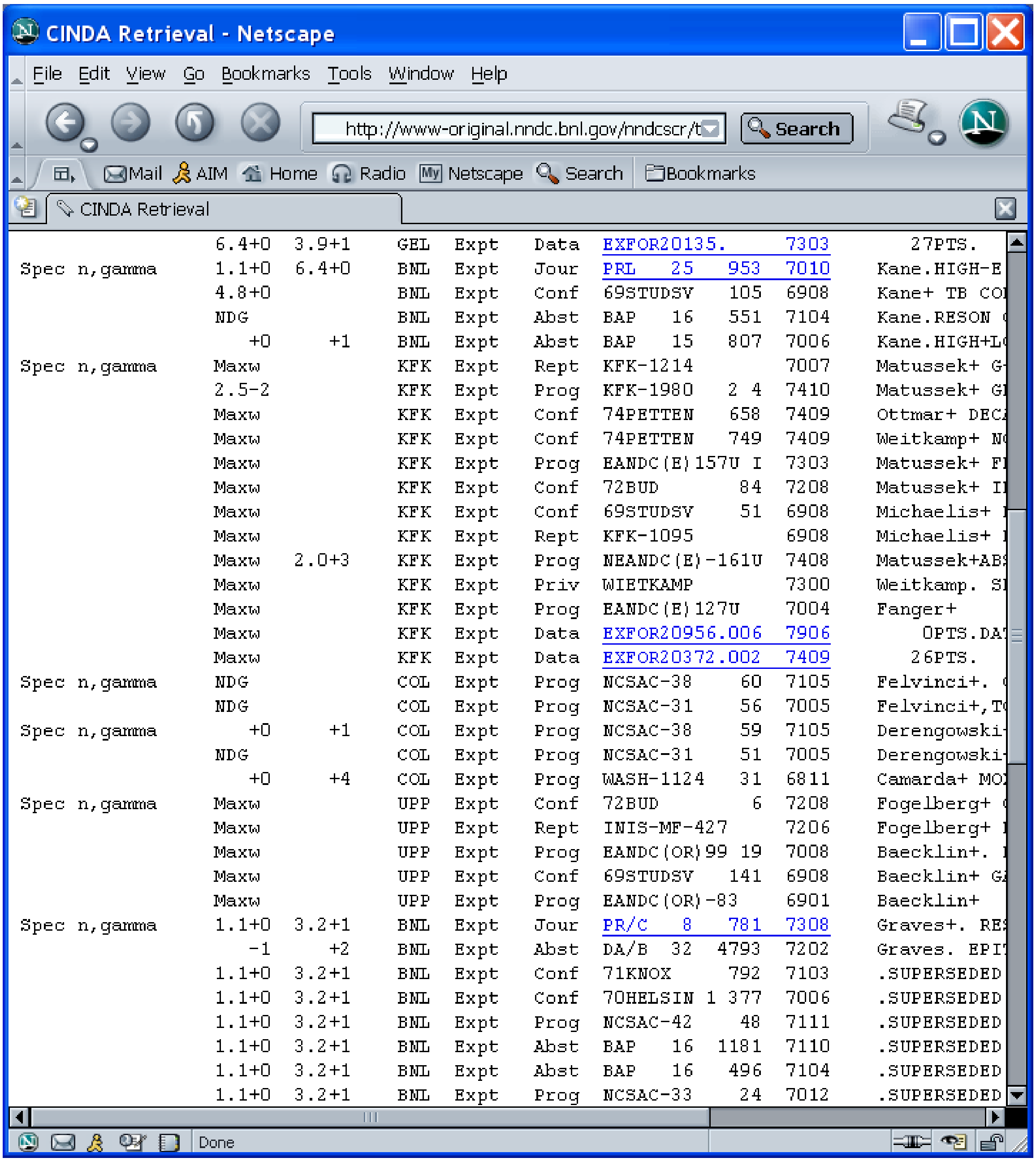
CINDA is a data-oriented bibliography in which information is blocked in terms of experimental quantity and laboratory: consists of about 265000 entries and is considered "complete" from the discovery of the neutron onwards.

HTML retrievals have links to other sources of data including the journal link managers listed above, EXFOR entries, and various evaluated nuclear reaction data libraries. The following access *via* the Internet is available:

1. TELNET — IAEA-NDS and IAEA-NDS IPEN mirror,

2. Web — NNDC, IAEA-NDS, and IAEA-NDS IPEN mirror (CODASYL database and PERL),
3. Web — NNDC, IAEA-NDS and IAEA-NDS IPEN mirror (relational database, SQL and
Java Servlets).

Historically, CINDA has proved useful for checking the completeness of reference coverage for NSDD evaluations. At present, the primary usefulness involves links to the data compiled in the EXFOR format. An example of such links for $^{235}U(n, \gamma)$spectral data is shown in the following figure.



		6.4+0	3.9+1	GEL	Expt	Data	EXFOR20135.	7303	27PTS.
Spec	n,gamma	1.1+0	6.4+0	BNL	Expt	Jour	PRL 25 953	7010	Kane.HIGH-E
		4.8+0		BNL	Expt	Conf	69STUDSV 105	6908	Kane+ TB CO
		NDG		BNL	Expt	Abst	BAP 16 551	7104	Kane.RESON
		+0	+1	BNL	Expt	Abst	BAP 15 807	7006	Kane.HIGH+L
Spec	n,gamma	Maxw		KFK	Expt	Rept	KFK-1214	7007	Matussek+ G
		2.5-2		KFK	Expt	Prog	KFK-1980 2 4	7410	Matussek+ G
		Maxw		KFK	Expt	Conf	74PETTEN 658	7409	Ottmar+ DEC
		Maxw		KFK	Expt	Conf	74PETTEN 749	7409	Weitkamp+ N
		Maxw		KFK	Expt	Prog	EANDC(E)157U I	7303	Matussek+ F
		Maxw		KFK	Expt	Conf	72BUD 84	7208	Matussek+ I
		Maxw		KFK	Expt	Conf	69STUDSV 51	6908	Michaelis+
		Maxw		KFK	Expt	Rept	KFK-1095	6908	Michaelis+
		Maxw	2.0+3	KFK	Expt	Prog	NEANDC(E)-161U	7408	Matussek+AB
		Maxw		KFK	Expt	Priv	WIETKAMP	7300	Weitkamp. S
		Maxw		KFK	Expt	Prog	EANDC(E)127U	7004	Fanger+
		Maxw		KFK	Expt	Data	EXFOR20956.006	7906	OPTS.DA
		Maxw		KFK	Expt	Data	EXFOR20372.002	7409	26PTS.
Spec	n,gamma	NDG		COL	Expt	Prog	NCSAC-38 60	7105	Felvinci+.
		NDG		COL	Expt	Prog	NCSAC-31 56	7005	Felvinci+,T
Spec	n,gamma	+0	+1	COL	Expt	Prog	NCSAC-38 59	7105	Derengowski
		NDG		COL	Expt	Prog	NCSAC-31 51	7005	Derengowski
		+0	+4	COL	Expt	Prog	WASH-1124 31	6811	Camarda+ MO
Spec	n,gamma	Maxw		UPP	Expt	Conf	72BUD 6	7208	Fogelberg+
		Maxw		UPP	Expt	Rept	INIS-MF-427	7206	Fogelberg+
		Maxw		UPP	Expt	Prog	EANDC(OR)99 19	7008	Baecklin+.
		Maxw		UPP	Expt	Conf	69STUDSV 141	6908	Baecklin+ G
		Maxw		UPP	Expt	Prog	EANDC(OR)-83	6901	Baecklin+
Spec	n,gamma	1.1+0	3.2+1	BNL	Expt	Jour	PR/C 8 781	7308	Graves+. RE
		-1	+2	BNL	Expt	Abst	DA/B 32 4793	7202	Graves. EPI
		1.1+0	3.2+1	BNL	Expt	Conf	71KNOX 792	7103	.SUPERSEDED
		1.1+0	3.2+1	BNL	Expt	Conf	70HELSIN 1 377	7006	.SUPERSEDED
		1.1+0	3.2+1	BNL	Expt	Prog	NCSAC-42 48	7111	.SUPERSEDED
		1.1+0	3.2+1	BNL	Expt	Abst	BAP 16 1181	7110	.SUPERSEDED
		1.1+0	3.2+1	BNL	Expt	Abst	BAP 16 496	7104	.SUPERSEDED
		1.1+0	3.2+1	BNL	Expt	Prog	NCSAC-33 24	7012	.SUPERSEDED

Future plans for CINDA include expanding the coverage to include charged-particle and photon-induced reactions (limiting indexing to experimental and evaluated data only), and closer linkages between CINDA and NSR that may allow links from NSR to EXFOR.

4. Authors' Reference Lists

The bibliography of an article should always be checked for relevant references that are not in NSR. These include private communications, preprints, obscure journal articles, conferences, laboratory reports, theses and URLs. Care should be taken when using some of these sources, particularly Web-based information and data. Any discrepancies between the supporting data on a Web site and the published article should be resolved with the authors. Also, since the Web is somewhat ephemeral in nature, the data should be saved locally along with sufficient information to identify such material (authors and file creation, modification, and download dates).

Evaluated Nuclear Structure Data File

A Manual for Preparation of Data Sets

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BNL-NCS-51655-01/02-Rev
Formal Report

Evaluated Nuclear Structure Data File

A Manual for Preparation of Data Sets

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February, 2001

Abstract

The structure and format for the Evaluated Nuclear Structure Data File (ENSDF) are described. ENSDF is used to store nuclear structure properties of nuclides and the results of various experiments to derive those properties.

Contents

Chapter I

I. INTRODUCTION

The organization and structure of the Evaluated Nuclear Structure Data File (ENSDF) are described in this manual.[1] This computer-based file is maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory for the international Nuclear Structure and Decay Data Network.[2]

For every mass number (presently $A \leq 293$), the Evaluated Nuclear Structure Data File (ENSDF) contains evaluated structure information. For masses $A \geq 44$, this information is published in the *Nuclear Data Sheets*; for $A < 44$, ENSDF is based on compilations published in the journal *Nuclear Physics*. The information in ENSDF is updated by mass chain or by nuclide with a varying cycle time dependent on the availability of new information.

The author gratefully acknowledges many suggestions and comments received during the revision of this manual. Special thanks are due to the following colleagues at NNDC: M. Blennau, T. Burrows, P. Dixon, C. Dunford, R. Kinsey, P. Oblozinsky, A. Sonzogni, and D. Winchell. This research was supported by the Office of Basic Energy Sciences, U. S. Department of Energy.

[1] The format for ENSDF was first designed by W. B. Ewbank and M. R. Schmorak at the Nuclear Data Project, Oak Ridge National Laboratory, and was described in the ORNL-5054/R1 (February 1978). The present report describes the current format and supersedes both the ORNL report and BNL-NCS 51655 (March 1983) and BNL-NCS-51655-Rev.87 (April 1987).

[2] Coordinated by the International Atomic Energy Agency, Vienna - see any issue of the *Nuclear Data Sheets* for list of evaluation data centers.

Chapter II

II. GENERAL ORGANIZATION AND STRUCTURE OF THE DATA FILE

A. General Organization

The Evaluated Nuclear Structure Data File (ENSDF) is made up of a collection of 'data sets' which present one of the following kinds of information:

1. The summary information for a mass chain giving information, *e.g.*, evaluators' names and affiliations, cutoff date, evaluators' remarks, and publication details, *etc*.
2. The references used in all the data sets for the given mass number. This data set is based upon reference codes (key numbers) used in various data sets for a given mass number and is added to the file by the NNDC.
3. The adopted level and gamma-ray properties for each nuclide.
4. The evaluated results of a single type of experiment, e.g., a radioactive decay or a nuclear reaction for a given nuclide.
5. The combined evaluated results of a number of experiments of the same kind, e.g., (heavy ion, xnγ), Coulomb excitation, etc. for a given nuclide.

The data sets in ENSDF are organized by their mass number. Within a mass number the data sets are of two kinds:

- Data sets which contain information pertaining to the complete mass chain. These data sets contain information of the type (1) and (2) given above.
- Data sets belonging to a given nuclide (Z-value).

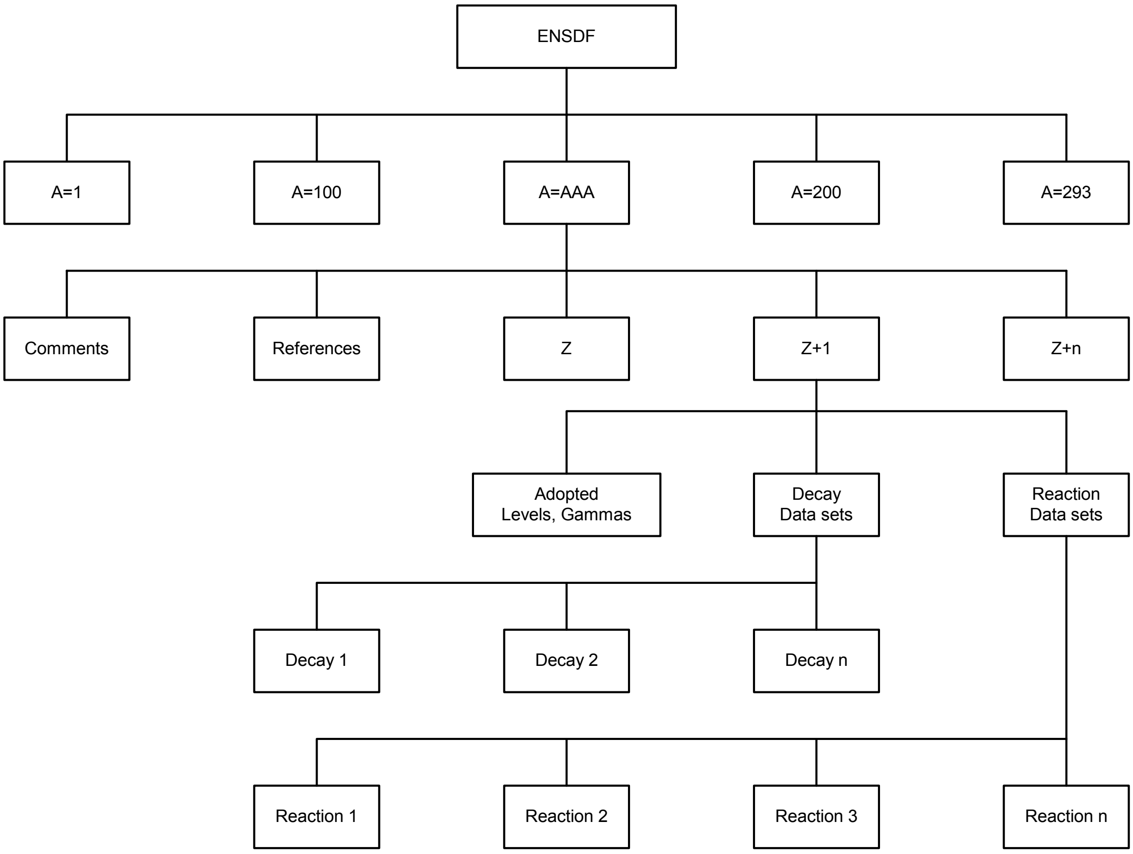
Latter data sets, i.e., for a given nuclide (Z-value), consist of the following:

- A Comments data set which gives abstract information for the nuclide. This data set contains summary information as described in (1) above. This data set exists only if the nuclide was evaluated or updated beyond the whole mass chain was evaluated.
- Adopted data set (only one per Z-value) giving adopted properties
- of the levels and gamma rays seen in that nuclide.
- Data sets giving information of the type (4) or (5) above.

If there is more than one data set of type (4) or (5) for a given nuclide, then an adopted data set is *required* for that nuclide. If there is only one data set for a given nuclide and no gamma-rays have been seen, then that data set is assumed also to present the adopted properties for that nuclide. However, if there is gamma information known for the nuclide, a separate Adopted Levels, Gammas data set must be given even though all the information may come from only one experiment (data set).

The general organization of ENSDF is shown in Fig. II.1.

Figure II.1: ENSDF Organization Chart



B. Data Set Structure

A data set is composed of 80-character records. A data set has at least two records, the beginning (DSID) and the endrecord. Data set structure is shown in Fig. II.2, and is described below:

A data set *must* begin with an IDENTIFICATION record and *must* end with an END record (a blank record). Between these two records, there can be as many additional records as are needed to describe fully the experimental or the evaluated information.

Immediately following the IDENTIFICATION record is a group of records which contain information about the entire data set (#1 and #2 in Fig. II.2). The History (H), general COMMENT (C), NORMALIZATION (N), Q-VALUE (Q), PARENT (P), and CROSS-REFERENCE (X) records are of this type. Not all of these records are included in every data set. For example, Q-VALUE (Q) and CROSS-REFERENCE (X) records normally appear only in adopted data sets while the PARENT (P) record is given only in radioactive decay data sets.

The body of a data set (#3 and #4 in Fig. II.2) is composed of numeric data records which describe the measured or deduced properties of levels, γ rays, α particles, etc. These records are associated with the level which decays (for GAMMA, records) or the level which is populated (for BETA, EC, ALPHA, PARTICLE, or DELAYED-PARTICLE records). Thus, each LEVEL record is followed by a group of records describing β, ε, or (delayed-) particle decay into the level and |-ray out of the level (#4 in Fig. II.2). The LEVEL records, and the corresponding radiation records, are placed in the data set in the order of increasing energy.

> If a GAMMA, ALPHA, EC, BETA, or (DELAYED-)PARTICLE record properly belongs in a data set but cannot be associated with any particular level, the record should be placed in the data set *before* any LEVEL records (#3 in Fig. II.2).
>
> The placement of COMMENT records is described in Section III.B.5.

C. File Storage and Transmittal

The data sets sent to NNDC for inclusion in ENSDF can be in any order, as the file is currently maintained using a data base management system which rearranges various data sets in their predetermined order. Copies of the file are transmitted in the form of a sequential file via various mass media. Unless requested otherwise the data sets in the sequential file are arranged by mass numbers in increasing numerical order. For a given mass number the data sets are organized as given in Fig. II.1, ordering them from left to right. Decay data sets are placed under the daughter nuclide and are ordered by A, Z and then the excitation energy of the parent nuclide. The reaction data sets are given under the residual nuclide and ordered by the A, Z of the target nuclide followed by the A, Z of the incident particle and then by the energy of the incident particle. These are followed by other data sets, e.g., Coulomb Excitation, (HI, XNG), etc.

Data Set Structure

Identification Record

1 H, X Records, General/Flagged Comments

Q record, Q comments

2 P record, P comments

N record, N comments

3 Unplaced Radiations, G, B, A, E

Level Record, Corresponding Radiations

. . .

4 Level Record, Corresponding Radiations

End Record

Fig. II.2

Chapter III

III. STANDARD ONE-CARD RECORD FORMATS

A. Introduction

In most cases, all information for a record can be placed on a single 80-column (byte) card (record)[3]. A 'standard' format has been defined for each one-card record, such that the most commonly used quantities can be placed on a single card. The standard formats are described in this section for each record. If a needed quantity is not included in the standard format or if a value will not fit within the field defined for the value by the standard format, or if a record cannot be contained on a single card, then additional cards can be prepared as described in Chapter IV (for examples, see Appendices C and D). Note that many of the analysis programs may not process standard fields when placed on the continuation records.

B. The Standard One-Card Record Formats

Record formats are given below in the same order in which they would normally be encountered in a data set. Conditions under which each record may appear or be required are given in parentheses. The format descriptions give the fields (in inclusive card-column numbers), the field names (the formal 'name' of the quantity that goes into the field), and a brief field description. Card columns not explicitly included in the fields are expected to be blank. A detailed description of each field can be found in the reference section noted. Any numerical field left blank usually implies that the numerical information is lacking. Numbers will usually be assumed to be positive unless stated otherwise. Numbers can be entered anywhere in the appropriate field (i.e., there is no need to left-adjust or right-adjust, unless stated otherwise.)

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[3] Throughput this manual an 80-byte record is referred to as a card of 80 columns. Column number refers to the byte number on the record, starting from the left.

1. Identification Record

Required for all data sets.
Must precede all other records.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide Identification	V.1
6-9		Must be blank	
10-39	DSID	Data set identification	V.2
40-65	DSREF	References to main supporting publications and analyses	V.3
66-74	PUB	Publication Information	V.4
75-80	DATE	Date (year/month) when the data set was placed in ENSDF (entered automatically by computer)	V.5

Note: In the rare case when DSID field is insufficient for dataset identification it may be continued on a second identification record with columns 1-39 defined as above except that col. 6 will contain an alphanumeric character and columns 40-80 will be blank. If there is a continuation record, the DSID field on the first IDENTIFICATION record *must* end with a comma ‘,’.

2. History Record

The history records follow the Identification record and should appear in reverse-chronological order, most recent being the first

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than ‘1’ for continuation records	
7		Must be blank	
8	H	Letter ‘H’ is required	
9		Must be blank	
10-80	History	Dataset history consisting of various field descriptors and their values in cols 10-80 continued on any number of continuation records. Field descriptor is followed by an ‘=’ (without spaces before or after ‘=’) and the value and a terminator ‘$’ (‘$’ is not needed for the last field descriptor)	V.25

3. Q-value Record

Required for adopted data sets.
If there is only one data set for the nuclide, the Q-value record shouldbe given in that data set.
Must precede ***L, G, B, E, A, DP*** *records.*
If signs are not given, they will be assumed to be +.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank	
7		Must be blank	
8	Q	Letter 'Q' is required	
9		Must be blank	
10-19	Q^-	Total energy (keV) available for β^- decay of the ground state. ($Q^- > 0$ if β^- decay is energetically possible. $Q^- < 0$ represents the Q_ε energy of the Z+1 (Z = proton number) isobar.)	V.10
20-21	DQ^-	Standard uncertainty in Q^-	V.11
22-29	SN	Neutron separation energy in keV	V.10
30-31	DSN	Standard uncertainty in SN	V.11
32-39	SP	Proton separation energy in keV	V.10
40-41	DSP	Standard uncertainty in SP	V.11
42-49	QA	Total energy (keV) available for α decay of the ground state	V.10
50-55	DQA	Standard uncertainty in QA	V.12
56-80	QREF	Reference citation(s) for the Q-values	V.3

4. Cross-Reference Record

Given only in adopted data sets.
Must precede ***L, G, B, E, A, DP*** *records.*

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank	
7		Must be blank	
8	X	Letter 'X' is required	
9	DSSYM	Any ASCII character that uniquely identifies the data set whose DSID is given in col. 10-39.	
10-39	DSID	*Must* exactly match one of the DSID's used	V.2
40-80		Blank	

NOTES:

1. In *Nuclear Data Sheets* the DSID on the first 'X' record in the data set will be identified with character 'A' and second DSID with 'B' and so on, irrespective of DSSYM on the X card. Only the first 14 DSIDs on 'X' records are given different symbols. All the rest are given the symbol 'O' (for others). By merely reshuffling the X-records, evaluators can ascertain the DSIDs that will be identified individually. This has no effect on the file and affects only the published output.
2. If the DSID for the data set is continued on to a second card, the DSID on XREF record must match the DSID on the first card, including the terminating ',' which will be translated into ellipses in the cross-reference table in the output.
3. There must be a data set corresponding every given X-record.

5. Comment Record

General Comments
Must precede all **L, G, B, E, A, DP** *records*.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than ‘1’ for continuation records	
7	C	Letter ‘C’, ‘D’, or ‘T’ is required *See notes 3 - 5 below*	
8	RTYPE	Blank or record type of records to which the comment pertains	V.6
9	PSYM	Blank, or symbol for a (delayed-)particle, e.g., N, P, etc.	
10-80	CTEXT	Text of the comment. [See ENSDF Translation Dictionary (Appendix F)]	V.7

NOTES:

1. The comment refers only to records of specified RTYPE given in that data set. The comment will normally appear only in the table for that RTYPE in the output. For example, if the comment is on levels (`L' in col. 8) it will appear only in the level properties table.

2. If col. 8 and 9 are blank then the comment refers to the whole data set. These general comments precede formatted level or the radiation records. See Appendix B for use of comment records in COMMENTS data set.

3. Letter ‘T’ in place of ‘C’ in col. 7 of a comment record indicates to the output programs that this record should be reproduced ‘as is’ and the blanks in the record should not be squeezed out.

4. Letter ‘D’ in place of ‘C’ in col. 7 of a comment record indicates to the output programs that this is a documentation record and can be ignored. This record will also be ignored by the various analysis programs.

5. Lower case letters ‘c’ and ‘t’ in col. 7 of a comment record indicate to the output programs that CTEXT in these records should not be translated. These will appear as written in the *Nuclear Data Sheets*. In this mode one must write special characters directly, for example, ‘|g’ for γ, ‘{+238}Pu’ for ^{238}Pu. See Appendix A for list of special characters.

Record Comments

Must follow the record to which the comment pertains.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7	C	Letter 'C' or 'D' is required *See notes 4 and 5 on General Comments*	
8	RTYPE	Record type being commented upon It can be blank for Particle records	V.6
9	PSYM	Blank, or symbol for a particle, e.g., N, P, etc.	
10-80	SYM$ or SYM, SYM…$	SYM = type of data being commented upon Specified SYMs must be followed by a '$' except as in note 1 below.	V.8
10-80	CTEXT	Text of comment follows the '$' On continuation comment records, CTEXT may start in col. 10, and SYM or SYMs are *not* repeated. [See ENSDF Translation Dictionary, Appendix F]	V.7

NOTES:

1. The old format, where SYM were specified in col. 10-19, will be accepted without the '$' delimiter as long as col. 19 is a blank, and comment text begins in col. 20.

2. Record comments placed following a record of the same **RTYPE** <u>refer only to that one record</u> (for example, a comment record with 'CL' in cols. 7-8 and 'T$' in col. 10-11 placed following the level record for the second-excited state refers to the half-life of *only* the second-excited state).

Footnote Comments
Must precede **L, G, B, E, A, DP** *records*

Field (Col.)	Name	Description	Reference
1-9		same as in ii (Record Comments)	
10-80	SYM$ or SYM, SYM…$or SYM(FLAG)$ or SYM(FLAG), SYM(FLAG)…$	SYM = see note 1 below FLAG = any ASCII alphanumeric character or string of alphanumeric characters *Field must end with a '$'* *See note 1 on Record comments for exception*	V.8
10-80	CTEXT	Text of comment follows '$' On continuation comment records SYM or SYM (FLAG) are *not* repeated. [See ENSDF Translation Dictionary (Appendix F)]	V.7

NOTES:

1. SYM can only be one of the following:
   - The fields defined in formatted L, G, B, E, A, DP records.
   - BAND. This SYM *must* be accompanied with a FLAG. Note also that text following '$' delimiter, or in col. 20-80 in old format, will appear as the band label in some of the drawings. Therefore any other information on that band should be given on continuation records.

2. Footnote without FLAG
   - This refers to all records of the specified RTYPE in the data set.
   - The footnote will normally appear only in the table for that RTYPE in the output. For example, if the footnote is on levels ('L' in col. 8) it will appear only in the level properties table.
   - Footnote with FLAG

     Only those records are footnoted for which footnote flags are given, see note 4 below.

     Only those data values of data types specified by SYM which is associated with a given FLAG are footnoted.

3. Footnote FLAG must be either a single character placed in col. 77 of the formatted record or a string of characters assigned to a special data type called FLAG on the following continuation record.

   Examples of flags on a continuation record:

   152EU2 G FLAG=ABCD$
   156GD2 L FLAG=KMP$

4. No footnotes are allowed for records of RTYPE: N, P, or Q.

5. To change the standard label heading of a formatted field, e.g., S to C^2S for L records, CTEXT should have the form LABEL=name, where 'name' is the new label desired. The new label should be kept as short as possible. Note that FLAG can not be specified with relabeling; also any other comment on the relabeled field must appear on a different record.

   Examples of field relabel:

   156GD CL S$LABEL=C2S
   156GD CL S$LABEL=DSIGMA/DOMEGA (45 DEG)

6. Parent Record

Required for all decay data sets.
Must precede ***L, G, B, E, A, DP*** *records.*

Field (Col.)	Name	Description	Reference
1-5	NUCID	Parent Nuclide identification	V.1
6		Must be blank	
7		Must be blank	
8	P	Letter 'P' is required	
9		Blank or an integer in case of multiple P records in the data set	
10-19	E	Energy of the decaying level in keV (0.0 for g.s.)	V.18
20-21	DE	Standard uncertainty in E	V.11
22-39	J	Spin and parity	V.20
40-49	T	Half-life; units *must* be given	V.14
50-55	DT	Standard uncertainty in T	V.12
56-64		Must be blank	
65-74	QP	Ground-state Q-value in keV (total energy available for g.s. → g.s. transition); it will always be a positive number. Not needed for IT and SF decay.	V.9
75-76	DQP	Standard uncertainty in QP	V.11
77-80	ION	Ionization State (for Ionized Atom decay), blank otherwise	

NOTES:

1. More than one parent card is allowed in a data set. If the decay scheme is due to more than one parent, separate P records should be given for each parent level.

2. Currently, publication program allows maximum of two parent cards.

3. Parent information, *namely*, E, J, T, QP must be identical to their values given in the Adopted Levels data set.

7. Normalization Record

*Must precede **L, G, B, E, A, DP** records.*
Required if an absolute normalization is possible;
used mainly with decay and (n, γ) reaction data sets.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide (Daughter/Product) identification	V.1
6		Must be blank	
7		Must be blank	
8	N	Letter 'N' is required	
9		Blank or an integer in case of multiple P records in the data set. It should correspond to the designator on the P record.	
10-19	NR	Multiplier for converting relative *photon* intensity (RI in the GAMMA record) to *photons* per 100 decays of the parent through the decay branch or to *photons* per 100 neutron captures in an (n, γ) reaction. *Required* if the absolute photon intensity can be calculated.	V.9
20-21	DNR	Standard uncertainty in NR	V.11
22-29	NT	Multiplier for converting relative *transition* intensity (including conversion electrons) [TI in the GAMMA record] to *transitions* per 100 decays of the parent through this decay branch or per 100 neutron captures in an (η, γ) reaction. *Required* if TI are given in the GAMMA record and the normalization is known.	V.9
30-31	DNT	standard uncertainty in NT	V.11
32-39	BR	Branching ratio multiplier for converting intensity per 100 decays through this decay branch to intensity per 100 decays of the parent nuclide. *Required if known*.	V.9
40-41	DBR	Standard uncertainty in BR	V.11
42-49	NB	Multiplier for converting relative β^- and ε intensities (IB in the β^- record; IB, IE, TI in the EC record) to intensities per 100 decays through this decay branch. *Required if known*.	V.9

Field (Col.)	Name	Description	Reference
50-55	DNB	Standard uncertainty in NB	V.11
56-62	NP	Multiplier for converting per hundred delayed-transition intensities to per hundred decays of precursor	V.9
63-64	DNP	standard uncertainty in NP	V.11
65-80		Must be blank	

Note: Normally β^- and ε intensities are given as per 100 parent decays. One should remember that the multiplier for conversion to per 100 decays is NB x BR, and therefore NB = 1/BR. Also, the uncertainties in $I(\beta^-)$ will be calculated from addition of three quantities $\Delta(I(\beta^-))$, DBR and DNB in quadrature. Unless the uncertainties are precisely known it is recommended that NB be given without uncertainty. See PN record.

If more than one P records exist in the data set then there should be corresponding N records giving the respective branching ratios.

8. Production Normalization Record

*Must follow **N** record, if **N** record present.*
*Should be given when **G** records with intensities are present.*

Field	Name	Description
1-5	NUCID	Nuclide (Daughter/Product) identification
6		Blank
7	P	Letter ‘P’ (for production) is required
8	N	Letter ‘N’ is required
9		Must be blank
10-19	NRxBR	Multiplier for converting relative *photon* intensity (RI in the GAMMA record) to *photons* per 100 decays of the parent (normally NRxBR). If left blank, (NR DNR)x(BR DBR) from N record will be used for normalization.
20-21	UNC[4]	Standard uncertainty in NRxBR
22-29	NTxBR	Multiplier for converting relative *transition* intensity (including conversion electrons) [TI in the GAMMA record] to *transitions* per 100 decays of the parent (normally NTxBR). If left blank, (NT DNT)x(BR DBR) from N record will be used for normalization.
30-31	UNC[1]	standard uncertainty in NTxBR
42-49	NBxBR	Multiplier for converting relative β^- and ε intensities (IB in the B- record; IB, IE, TI in the EC record) to intensities per 100 decays. If left blank, (NB DNB)x(BR DBR) from N record will be used for normalization.
50-55	UNC[1]	Standard uncertainty in (NB DNT)x(BR DBR)
56-62	NP	Same as in ‘N’ record
63-64	UNC[1]	standard uncertainty in NP
77	COM	Blank or ‘C’ (for comment) If blank, comment associated with the intensity option will appear in the drawing of *Nuclear Data Sheets*. If letter ‘C’ is given, the desired comment to appear in the drawing should be given on the continuation (‘nPN’) record(s), col. 10-80.
78	OPT	Intensity Option. Option as to what intensity to display in the drawings of *Nuclear Data Sheets*. The available options are given below (default option 3).

[4] If left blank no uncertainty will appear in the publication.

Option	Intensity displayed	Comment in drawing
1	TI or RI(1+α)	Relative I(γ+ce)
2	TIxNT or RIxNRx(1+α)	I(γ+ce) per 100 (mode) decays
3	TIxNTxBR or RIxBRxNRx(1+α)	I(γ+ce) per 100 parent decays
4	RIxNTxBR	I(γ) per 100 parent decays
5	RI	Relative I(γ)
6	RI	Relative photon branching from each level
7	RI	photon branching from each level

9. Level Record

Optional, although a data set usually has at least one.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than `1' for continuation records	
7		Must be blank	
8	L	Letter 'L' is required	
9		Must be blank	
10-19	E	Level energy in keV - m*ust not be blank*	V.18
20-21	DE	Standard uncertainty in E	V.11
22-39	J	Spin and parity	V.20
40-49	T	Half-life of the level; units *must* be given Mean-life expressed as the width of a level, in units of energy, may also be used	V.14
50-55	DT	Standard uncertainty in T	V.12
56-64	L	Angular momentum transfer in the reaction determining the data set (whether L_n, L_p, ΔL, etc., is determined from the DSID field of the IDENTIFICATION record).	V.22
65-74	S	Spectroscopic strength for this level as determined from the reaction in the IDENTIFICATION record (spectroscopic factor for particle-exchange reactions; β for inelastic scattering). Note: If a quantity other than spectroscopic factor is given in this field, a footnote relabelling the field is required.	V.21
75-76	DS	Standard uncertainty in S	V.11
77	C	Comment FLAG used to refer to a particular comment record	V.8
78-79	MS	Metastable state is denoted by 'M' or 'M1' for the first (lowest energy) isomer; 'M2', for the second isomer, etc. For Ionized Atom Decay, field gives the atomic electron shell or subshell in which β^- particle is captured	V.17
80	Q	Character '?' denotes an uncertain or questionable level Letter 'S' denotes neutron, proton, alpha separation energy or a level expected, but not observed	

10. Beta (β^-) Record

Must follow the LEVEL record for the level which is fed by the β^-.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than ‘1’ for continuation records	
7		Must be blank	
8	B	Letter ‘B’ is required	
9		Must be blank	
10-19	E	Endpoint energy of the β^- in keV *Given only if measured*	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IB	Intensity of the β^--decay branch[5]	V.13
30-31	DIB	Standard uncertainty in IB	V.11
42-49	LOGFT	log *ft* for the β^- transition for uniqueness given in col. 78-79	V.9
50-55	DFT	Standard uncertainty in LOGFT	V.12
56-76		Must be blank	
77	C	Comment FLAG (Letter ‘C’ denotes coincidence with a following radiation.	V.8
	A	‘?’ denotes probable coincidence with a following radiation.)	
78-79	UN	Forbiddenness classification for the β^- decay, e.g., ‘1U’, ‘2U’ for first-, second-unique forbidden (a blank field signifies an allowed transition; non-unique forbiddenness can be indicated in col 78, with col 79 blank)	V.16
80 Q		Character ‘?’ denotes an uncertain or questionable β^- decay Letter ‘S’ denotes an expected or predicted transition	

[5] Intensity units are defined by the NORMALIZATION record.

11. EC (or EC + β^+) Record

Must follow the LEVEL record for the level being populated in the decay.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than ‘1’ for continuation records	
7		Must be blank	
8	E	Letter ‘E’ is required	
9		Must be blank	
10-19	E	Energy for *electron capture* to the level Given only if measured or deduced from measured β^+ end-point energy	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IB	Intensity of β^+-decay branch[6]	V.13
30-31	DIB	Standard uncertainty in IB	V.11
32-39	IE	Intensity of electron capture branch[6]	V.13
40-41	DIE	Standard uncertainty in IE	V.11
42-49	LOGFT	Log ft for ($\varepsilon + \beta^+$) transition for uniqueness given in col. 78-79	V.9
50-55	DFT	Standard uncertainty in LOGFT	V.12
65-74	TI	Total ($\varepsilon + \beta^+$) decay intensity[6]	V.13
75-76	DTI	Standard uncertainty in TI	V.11
77	C	Comment FLAG (letter ‘C’ denotes coincidence with a following radiation.	V.8
	A	‘?’ denotes probable coincidence with a following radiation).	
78-79	UN	Forbiddenness classification for ε, β^+ decay e.g., ‘1U’, ‘2U’ for first, second unique forbidden (a blank signifies an allowed or a non-unique forbidden transition. Non-unique forbiddenness can be indicated in col 78, with col 79 blank)	V.16
80	Q	Character ‘?’ denotes an uncertain or questionable ε, $+\beta^+$ branch Letter ‘S’ denotes an expected or predicted transition	

12. Alpha Record

Must follow the LEVEL record for the level being populated in the decay.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank	
7		Must be blank	
8	A	Letter `A' is required	
9		Must be blank	
10-19	E	Alpha energy in keV	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IA	Intensity of α-decay branch in *percent* of the total α-decay	V.13
30-31	DIA	Standard uncertainty in IA	V.11
32-39	HF	Hindrance factor for α decay	V.9
40-41	DHF	Standard uncertainty in HF	V.11
42-76		Must be blank	
77	C	Comment FLAG (letter ‘C’ denotes coincidence with a following radiation. A ‘?’ denotes probable coincidence with a following radiation).	V.8
78-79		Must be blank	
80	Q	Character ‘?’ denotes uncertain or questionable α branch Letter ‘S’ denotes an expected or predicted α branch	

13. (Delayed-) Particle Record

Must follow the LEVEL record for the level which is fed by the particle. Records for particles which are unassigned in a level scheme should precede the first level of the data set.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7		Must be blank	
8	D	Blank for prompt-, letter 'D' for delayed-particle emission	
9	Particle	The symbol for the (delayed) particle (N = neutron, P = proton, A = alpha particle) is required)	
10-19	E	Energy of the particle in keV	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IP	Intensity of (delayed) particles in *percent* of the total (delayed-)particle emissions	V.13
30-31	DIP	Standard uncertainty in IP	V.11
32-39	EI	Energy of the level in the 'intermediate' (mass = A+1 for n, p; A+4 for α) nuclide in case of delayed particle	V.13
40-49	T	Width of the transition in keV	V.14
50-55	DT	Uncertainty in T	V.12
56-64	L	Angular-momentum transfer of the emitted particle	V.22
65-76		Blank	
77	C	Comment FLAG used to refer to a particular comment record.	V.8
78	COIN	Letter 'C' denotes placement confirmed by coincidence. Symbol '?' denotes probable coincidence.	V.15
79	Blank		
80	Q	Character '?' denotes an uncertain placement of the transition in the level scheme Letter 'S' denotes an expected, but as yet unobserved, transition	

NOTES:

1. The delayed-particle record will appear in a delayed-particle data set (e.g., B-N DECAY, ECP DECAY, etc.) which should be given under the A-chain for the final nuclide. For example, '95RB B-N DECAY' should be given as data set for ^{94}Sr.

2. The intensity units are defined by the NORMALIZATION record.

14. Gamma Record

Must follow the LEVEL record for the level from which the / ray decays. Records for / rays which are unassigned in a level scheme should precede the first level of the data set.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than ‘1’ for continuation records	
7		Must be blank	
8	G	Letter ‘G’ is required	
9		Must be blank	
10-19	E	Energy of the γ-ray in keV *Must not be blank*	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	RI	Relative *photon* intensity[1]	V.13
30-31	DRI	Standard uncertainty in RI	V.11
32-41	M	Multipolarity of transition	V.19
42-49	MR	Mixing ratio δ. (sign must be shown explicitly if known; if no sign is given, assumed to be unknown).	V.10
50-55	DMR	Standard uncertainty in MR	V.12
56-62	CC	Total conversion coefficient	V.9
63-64	DCC	Standard uncertainty in CC	V.11
65-74	TI	Relative total transition intensity[6]	V.13
75-76	DTI	Standard uncertainty in TI	V.11
77	C	Comment FLAG used to refer to a particular comment record. Symbol ‘*’ denotes a multiply-placed γ ray. Symbol ‘&’ denotes a multiply-placed transition with intensity not divided. Symbol ‘@’ denotes a multiply-placed transition with intensity suitably divided. Symbol ‘%’ denotes that the intensity given as RI is the branching in the Super Deformed Band.	V.8
78	COIN	Letter ‘C’ denotes placement confirmed by coincidence. Symbol ‘?’ denotes questionable coincidence.	V.15
79		Blank	
80	Q	Character ‘?’ denotes an uncertain placement of the transition in the level scheme. Letter `S' denotes an expected, but as yet unobserved, transition	

[7] Intensity units are defined by the NORMALIZATION record.

15. Reference Record

Record can occur only in Reference data set.
NNDC provides the Reference data set.

Field (Col.)	Name	Description	Reference
1-3	MASS	Mass Number	
4-7		Must be blank	
8	R	Letter ‘R’ is required	
9		Must be blank	
10-17	KEYNUM	Reference key number	V.3
18-80	REFERENCE	Abbreviated reference (from NSR file)	

16. End Record

Required for all data sets.
Must be the last record in a data set.

Field (Col.)	Description
1-80	All columns are blank

C. Summary

The following two pages summarize the standard one-card formats for all allowed record types.

SUMMARY OF STANDARD ONE-CARD RECORD FORMAT

Col	Record TYPE												
No.	R	I	X	C/D	Q	N	P	L	G	B	E	A	Particle
1-3	←-----------Mass-----------→												
4-5	←-----------Element symbol-----------→												
6		#		#	#	#	#	#	#	#	#	#	#
7				C/D									
8	R			@	Q	N	P	L	G	B	E	A	D(delayed)
9		#											P/N/A
10-39		ID	ID										
10-19	key#		SYM		Q-	NR	←-----------E-----------→						
20-21					DQ-	DNR	←-----------DE-----------→						
20-80	Ref		Com										
22-39						J	J						
22-29				SN	NT			RI	IB	IB	IA	IP	
30-31				DSN	DNT			DRI	DIB	DIB	DIB	DIP	
32-41									M				
32-39				SP	BR					IE	HF	ED	
40-41				DSP	DBR					DIE	DHF		
40-49							T	T					T
40-65	Ref												
42-49				QA	NB			MR	<-LOGFT->				
50-55				DQA	DNB	DT	DT	DMR	←DFT→				
56-62								CC					
56-64								L					L
56-80				Qref									
63-64								DCC					
65-74						QP	S	TI		TI			
66-74	PUB												
75-76						DQP	DS	DTI		DTI			
75-80	Date												
77								C	a	C	C	C	C
78-79							MS	C/?	UN	UN			
80								Q	Q	Q	Q	Q	Q

Any ASCII Character
@ L,G,B,A,E,N,Q,P for record comments following the respective record
* denotes multiply placed.
@ denotes multiply placed, intensity sitably divided.
& denotes multiply placed, undivided intensity given.
% denotes that the intensity given is % branching in SD band.

ENSDF Standard 80-character Formated Records

Record	1–5	6	7	8	9	10–19	20–21	22–29	30–31	32–39	40–41	42–49	50–55	56–62	63–64	65–74	75–76	77	78	79	80
IDENT	NUCID	&	blank			<— DSID —>					DSREF					<— PUB —>	<— DATE —>				
XREF	NUCID	blank		X	!	<— DSID —>					blank										
REF	AAA blank	blank		R	bl	KEYNUMBER	REFERENCE														
HIST	NUCID	&	bl	H	bl	<— HTEXT —>															
Q-VALUE	NUCID	blank		Q	bl	Q-	DQ-	SN	DSN	SP	DSP	QA	DQA	QREF							
G COMM	NUCID	&	†	#	bl	CTEXT															
F/R COMM	NUCID	&	†	#	‡	SYM(FLAG)	CTEXT														
PARENT	NUCID	blank		P	§	E	DE	<— J —>			<— T —>		DT	blank		QP	DQP	<— ION —>			
NORM	NUCID	blank		N	§	NR	DNR	NT	DNT	BR	DBR	NB	DNB	NP	DNP	blank					
P NORM	NUCID	&	P	N	§	NR*BR	UNC	NT*BR	UNC	blank		NB*BR	UNC	NP	DNP	blank					
LEVEL	NUCID	&	bl	L	bl	E	DE	<— J —>			<— T —>		DT	<— L —>		<— S —>	DS	F	MS		Q
BETA	NUCID	&	bl	B	bl	E	DE	IB	DIB	blank		LOGFT	DFT	blank				F	UN		Q
EC	NUCID	&	bl	E	bl	E	DE	IB	DIB	IE	DIE	LOGFT	DFT	blank				F	UN		Q
ALPHA	NUCID	&	bl	A	bl	E	DE	IA	DIA	HF	DHF	blank							F	bl	Q
PART	NUCID	&	bl	¶		E	DE	IP	DIP	ED	<— T —>		DT	<— L —>		blank		F	C	bl	Q
GAMMA	NUCID	&	bl	G	bl	E	DE	RI	DRI	<— M —>		MR	DMR	CC	DCC	TI	DTI	F	C	bl	Q

Notes:

blank	These fields must be blank.
&	Primary record must have a blank or "1" in this field. Continuation records should have any printable ASCII character except for blank or "1" (one).
!	Unique alphanumeric character identifying the source data set.
†	Allowed characters for this field are C, c, D, d, T, and t.
#	Character identifying the record being commented on. Allowed characters for this field are N, P, Q, L, G, B, E, A, D, and blank.
‡	Must be blank except for: 1) Particle code for a (delayed-)particle record. 2) Sequence number for normalization and parent records.
§	Must be blank except when there are multiple parent records then this field should contain an integer relating the parent record to the related normalization record.
¶	Byte 8 must either be blank for a prompt particle radiation or D for a delayed particle radiation. Byte 9 identifies the particle (N, P, D, or T).

Chapter IV

IV. RECORDS CONTAINING MORE THAN ONE CARD

A. Card Enumeration

Certain record types, namely, the Identification, History, Parent, and Normalization records can have multiple occurrence of records with qualifications as indicated in the descriptions of these record types. For other record types if all the information cannot be contained on a single card, additional cards can be used to describe the record fully. The first card of a record will have a blank in col. 6 and subsequent cards will have an ASCII character different from blank or 1 (usually running numbers: 2 to 9 or letters A to Z).

B. Format for Continuation Cards

CONTINUATION RECORD
Must follow the record of the same RTYPE.

Field	**Name**	**Description**
1-5	NUCID	Nuclide identification
6		Any alphanumeric character other than 1. Note: ‘S’ is reserved for computer-produced records which will usually be suppressed in *Nuclear Data Sheets*
7		Must be blank
8	RTYPE	Letter corresponding to the record type L, B, E, G or H
9		Must be blank
10-80	Data	< quant >< op >< value >[< op >< value >][< ref >]$ …

The following abbreviations have been used in the description of the data above:

< quant >: Standard symbol for a quantity as defined in IV.C below.
Notes:
1. Ratios of more than two quantities should be indicated by colons and not by slashes (e.g., K:L1:L2:L3 and not K/L1/L2/L3).
2. See Section V.24 for description of < value > when < quant >=XREF
3. See Section V.25 for description of items for H record

< op >: =, <, >, <=,>=, EQ, AP, LT, LE, GT, GE
Note: for the last 6 operators, blanks before and after them are required.

< value>: Numeric value with units as needed and optional uncertainty.
Uncertainty is as defined in Sections V.11 and V.12.
Note: For ranges, uncertainties should not be included.
To specify a bounded range of values a second operator (note that =, EQ, AP are not valid) and value are required.
See examples below.

[…]: Optional.
< ref >: 8 character key numbers, KEYNUM (see Section V.3), separated by commas and enclosed within parentheses, e.g., (1976TU01,1981BO01).
$: Delimiter (end of record is also a delimiter; thus '$' is not needed for the last item on a record)

<u>Examples</u>:

```
126TE 2   G       BE2W=25.3 7(1970LAZM)
126I  2 L  %EC+%B+=56.3 20 (1977JA04)$%B- EQ 43.7 20 (1977JA04)
126SN S   B       EAV=2030 60
126TE 2   L       G LE 0.19 GT 0.1 (1981SH15)$MOME2 AP -0.20$BE2=0.478 12
```

C. Allowed Data Types on Continuation Records

Each record type is permitted to contain only a limited (but extendable) set of data types. For example, a GAMMA record is not allowed to contain information of data type DTYPE = J (nuclear spin), similarly a LEVEL record is not allowed to contain LOGFT information.

For A and DP records only FLAG in addition to the quantities on the formatted records, can be given on a continuation record. The allowed data types for LEVEL, GAMMA, B-, and EC records are described below.

1. Level Record

Allowed data types E, DE, J, T, DT, L, S, DS, C, MS, Q are described with the standard formats in Section III.B.9. Additional allowed data types are:

TYPE	**Description**
%EC,%B+,%EC+%B+,	Percent decay of the level by ε, β^+, ε + β^+,
%B-,%IT,%SF	β^-, isomeric transition, spontaneous fission,
%A,%P,%N …	α, proton, or neutron decay, …
%B-N; %B-XN …	Percent delayed decay through n, xn emission,…. Similarly, for other particle emissions, e.g., p, xp, α, xα, etc., following β^-, β^+, or ε decays. *Note: Decay modes must be given on '2 L' card in adopted set and on an 'S L' card in decay and (n, γ) data sets*
ION	Ionization State (used in Ionized Atom Decay)
CONF	Nuclear configuration of the level
BE1, BE2 …	Reduced electric transition probability (upward) given in units e^2 x $(\text{barns})^L$, where L = 1, 2, … for the transition from the ground state to this level
B2, B3 …	2^L - pole (L=2,3,…) nuclear deformation parameter
FLAG	Additional footnote symbols
G	g-factor of the level
ISPIN	Isobaric spin
ISPINZ	Z-component of Isobaric Spin
MOME1, MOME2 …	Electric moments: dipole, quadrupole, …
MOMM1, MOMM2 …	Magnetic moments: dipole, quadrupole, …
WIDTH,WIDTHG,	Level width, Γ, Partial-γ , -γ0, -n, -p, -α widths,
WIDTHG0,WIDTHN,	Γ (γ), Γ(γ0), Γ(n),
WIDTHP, WIDTHA	Γ (p), Γ(α), respectively
XREF	Cross-reference to other data sets for that nuclide; this is generally given only in the adopted set.

2. Gamma Record

Allowed data types, E, DE, RI, DRI, M, MR, DMR, CC, DCC, TI, DTI, C, COIN, Q are described with the standard formats in Section III.B.14. Additional allowed data types are:

DTYPE	**Description**
BE1, BE2 …	Reduced electric transition probability (downward) given in units of e^2 x $(\text{barns})^L$, where L = 1, 2, …
BE1W, BE2W …	Reduced electric transition probability (downward) given in single-particle (Weisskopf) units
BM1,BM2 …	Reduced magnetic transition probability (downward) given in units of μ^2_N x $(\text{barns})^{L-1}$, where L = 1, 2 …
BM1W,BM2W …	Reduced magnetic transition probability (downward) given in single-particle (Weisskopf) units
CE	Total conversion electron intensity
CEK,CEL …	Conversion-electron (ce) intensity for K, L, …
CEL1 …	L_1 … conversion
ECC	Measured total conversion coefficient
EKC, ELC, EL1C …	Measured K-, L-, L1-… conversion coefficient
FL	Final level energy; must be either identical to a level energy in the data set optionally followed by a '?' (latter expresses uncertain placement) or a '?' (if the final level is not known)
FLAG	Additional footnote symbols
KC,LC,L1C …	Theoretical K-, L-, L_1-… conversion coefficient
K:L,M:L,L1:L2 …	Conversion-electron intensity ratios
K:T,L:T …	Ratio of K, L …ce-intensity to total (γ+ ce) intensity

3. Beta (β^-) Record

Allowed data types E, DE, IB, DIB, LOGFT, DFT, C, UN, Q are described with the standard formats in Section III.B.10. Additional allowed data types are:

DTYPE	Description
EAV	Average energy of the β^- spectrum
FLAG	Additional footnote symbols Note: 'C' and '?' may not be used - see Section III.B.10 for their special meaning

4. EC Record

Allowed data types, E, DE, IB, DIB, IE, DIE, LOGFT, DFT, TI, DTI, C, UN, Q are described with the standard formats in Section III.B.11. Additional allowed data types are:

DTYPE	Description
EAV	Average energy of the β^+ spectrum
CK,CL,CM … CL+	Calculated fraction of decay by electron capture from the K, L, M …, L+M+…shells
ECK,ECL,ECM … ECL+	Measured fraction of decay by electron capture from the K, L, M …, L+M+… shells
CK/T,CL/T ...	Ratio of K, L ... ε-intensity to total ε intensity
FLAG	Additional footnote symbols Note: 'C' and '?' may not be used - see Section III.B.11 for their special meaning

Chapter V

V. DETAILED FIELD DESCRIPTIONS

1. NUCID

The standard nuclide identification consists of two parts - mass number in cols. (1-3), right justified and element name (or Z – 100 for Z 109) in (col. 4-5), left justified. The nuclide identification must be contained within the field defined for it (cols. 1-5). The nuclide identification must be included on every card of a data set except the END record. Comments and reference data sets pertaining to the whole A-(mass) chain evaluation contain only the A-value in the NUCID field.

2. DSID

Data Set ID for an ENSDF data set serves as a unique, computer recognizable identification for the data set. There can not be two data sets with identical DSID and NUCID. In the rare circumstance two data sets with same DSID for a given NUCID can be accommodated by ending DSID with a colon (:) and following it with a unique identifier which will then be different for the various data sets with that DSID.

The following rules for DSID should be strictly observed for ENSDF entries. Single blanks have meaning and should be used according to the formats below. In the description below the optional fields are given in italics. General categories are given in upper and lower cases and further defined. DSID \underline must be confined to the 30 spaces allowed. The field may, however, be continued on to the DSID field on the second ID record as explained in Chapter III in which case the DSID on the first record \underline must end with a, comma ‘,’.

GENERAL IDs

REFERENCES

COMMENTS (see Appendix B for format for this data set)

ADOPTED LEVELS

ADOPTED LEVELS, GAMMAS

DECAY DATA SET IDs

Parent Mode Decay (Half-life)

<u>Parent</u> should be the parent nuclide symbol, e.g., 52CR

For SF decay more than one parent can be given separated by commas

For Ionized Atom Decay parent nuclide symbol is followed by ionization state in square brackets, e.g., 187RE[+75]

<u>Mode</u> may be one of B+, B-, EC, IT, A, P, B-N, ECP, SF ...

List of decay modes may be expanded.

<u>Half-life</u> can be of the form T defined in Section V.14.1

MUONIC ATOM

REACTION DATA SET IDs

Target(Reaction), (Reaction), Target(Reaction) E=Energy Qualifier

COULOMB EXCITATION

(HI,XNG)

<u>Target</u> should be the target (nuclide or element) symbol

<u>Reaction</u> should be given as (in,out), e.g., (N,P)

in is the incident particle, out are the outgoing particles

<u>Energy</u> may be one of the following

NUM, NUM Units (for definition of NUM see Section V.9.)

NUM-NUM Units

TH (for thermal)

RES (for resonance)

<u>Qualifier</u> may be one of the following

RES

IAR

IAS

EXAMPLES:

187RE B- DECAY	187OS IT DECAY (231 US)
187RE[+75] B- DECAY	187AU P DECAY:?
190PT A DECAY (6E11 Y)	95RB B-N DECAY
186OS(N,G) E=THERMAL	186W(N,G) E=TH: SECONDARY
RE(N,N'):TOF	238U(N,FG) E=TH
186W(N,G) E=RES: AVG	189OS(P,T) E=19 MEV
187OS(D,D') E=12, 17 MEV	185RE(A,2NG) E=23-42.8 MEV
187RE(D,2NG), 187RE(P,NG)	44CA(P,G) E=856, 906 KEV IAR
PB(238U,FXG)	PB(238U,XG)

3. DSREF, KEYNUM, QREF

The DSREF and QREF fields may include up to three key numbers (KEYNUM) each of which refers to a particular publication. Additional key numbers may be placed in COMMENT records. Key numbers must be left-justified and separated by commas with no blanks between the comma and the reference. A reference key number must be of the form YYYYAABB where YYYY is a four digit integer, AA are two alphabetic characters and BB is either a two digit integer or consists of two alphabetic characters. Examples: 1981TU01, 1981TUXY, etc.

4. PUB

Publication information generally consists of the year of the A-chain publication denoted by two digit year indicator followed by three-character code NDS for Nuclear Data Sheets and two-letter code NP for Nuclear Physics-A. This may optionally be followed by a comma and other updating information, e.g., the initials of the person modifying the data set after its publication. Example: 78NDS,TWB or 81NDS.

5. DATE

This field is of the form YYYYMM where YYYY and MM are four and two digit integers, respectively, within the following ranges: YY $\geq$ 1900 and 01 $\leq$ MM $\leq$ 12.

6. RTYPE

RTYPE is a two-letter code in col. 8-9 that gives a name to the RECORD type. Note that col. 9 is blank for most of the RTYPE tabbing

RTYPE	**Description**
blank	May be IDENTIFICATION, general COMMENT, or END record
H	HISTORY record
N	NORMALIZATION record Production Normalization record has 'P' in col 7.
P	PARENT record
Q	Q-VALUE record
L	LEVEL record
G	GAMMA record
B	BETA (β^-) record
E	EC (for ε, β^+ or Є + β^+) record
A	ALPHA record
R	REFERENCE record
X	CROSS-REFERENCE record
DP	DELAYED PARTICLE record, or PARTICLE (col.8=blank) record Particle symbol (e.g., 'P' for proton) is given in col. 9.

7. CTEXT

This field consists of free text. The various expressions used in CTEXT can be translated via dictionary lookup. The translation dictionary is given in Appendix F. The unit expression used in translation is the string of characters between adjacent ‘delimiters’. The characters presently used as ‘delimiters’ are:
b(blank) ,(comma) .b(period followed by a blank) ; : ( ) - = + < > / and $

In some cases the dictionary lookup programs look beyond the next delimiter for proper translation.

8. SYM(FLAG)

The SYM(FLAG) field (with FLAG given) is valid only for records with RTYPE: L, G, B, E, A, DP. However, SYM (without FLAG) may additionally be used for record types N, P, and Q.

FLAG can be a string of characters optionally separated by commas. Any character other than a comma and parentheses can be used as a FLAG symbol. For B and E records ‘C’ can not be used for a FLAG as ‘C’ in column 77 of B, E, and A records denotes coincidence. Similarly ‘*’, ‘@’, ‘%’, and ‘&’ for G records are reserved with special meaning (Section III.B.14). See notes on SYM and FLAG under description of COMMENT record. FLAG can be used only with SYMs which are valid data types on a formatted card or with BAND. In fact, for BAND FLAG must be given.

Allowed symbols to be used as SYM for various RTYPE are currently limited to the fields allowed on the formatted records.

9. BR, CC, HF, LOGFT, NB, NP, NR, NT, QP

These fields consist of either a blank or a single unsigned number (NUM) in one of the following forms:

1. An integer (e.g., 345)
2. A real number (e.g., 345.23)
3. An integer followed by an integer exponent (e.g., 345E-4, 4E+5)
4. A real number followed by an integer exponent (e.g., 345.E-4)

Note: desirable to write a number as ‘0.345’ rather than ‘.345’.

10. MR, Q-, QA, SN, SP

These fields have the same form as the quantities in Section V.9. above, with the difference that they are allowed to have signature (positive or negative).

11. DBR, DCC, DE, DHF, DIA, DIB, DIE, DIP, DNB

Includes DNR, DNP, DNT, DQP, DQ-, DS, DSP, DTI

These two character fields, represent uncertainty in the ‘standard’ form in the given quantity. The ‘standard’ numeric uncertainty denotes an uncertainty in the last significant figure(s), for example, NR=0.873, DNR=11 represent a normalization factor of 0.873 ± 0.011, similarly QP=2.3E6, DQP=10 stand for a Q-value of $(2.3 \pm 1.0) \times 10^6$ (see also General Policies given in Appendix H). The non-numeric uncertainty, e.g., <, >, or ≥, etc. is denoted by expressions LT, GT and GE, etc. The allowed forms for these fields are summarized below:

1. Blank
2. An integer <99, preferably <25, (left or right justified)
3. One of the following expressions:
   LT, GT, LE, GE, AP, CA, SY
   for <, >, ≤, ≥, ≈ , calculated, and from systematics, respectively.

12. DFT, DMR, DT, DNB, DQA

These fields allow for the specification of 'standard' asymmetric uncertainty. For example, T=4.2 S, DT=+8-10, represent a half-life=$4.2^{+0.8}_{-1}$ s, similarly MR=-3, DMR=+1-4 represent mixing ratio=-3^{+1}_{-4} meaning a range from -7 to -2 (note: asymmetric uncertainties add algebraically). When the +/- construction is missing from this field, the digits or the expressions given in this field represent either the numeric 'standard' symmetric or the non-numeric uncertainty as described in Section V.11 above.

Summarizing this field, there are two cases:

1. Symmetric uncertainty - the field consists of an integer number or an expression of the type described in Section V.11 above.

2. Asymmetric uncertainty - the field is of the form +x-y, where x and y are integers.

13. IA, IB, IE, IP, RI, TI

The following numbers/expressions are valid for these fields:

1. NUM (number as defined in Section V.9 above)

2. (NUM)

Note: Parentheses denote that the number given has been deduced (not directly measured) or taken from other experiment(s).

14. T

The field for half-life T must have one of the following forms:

1. NUM-Blank-Units (i.e., number as defined in Section V.9 above followed by a blank and units). Valid symbols for units are: Y, D, H, M, S, MS, US, NS, PS, FS, AS, EV, KEV, and MEV, for year, day, hour, minute, second(s), 10^{-3} s, 10^{-6} s, 10^{-9} s, 10^{-12} s, 10^{-15} s, 10^{-18} s, eV, 10^{3} eV, and 10^{6} eV, respectively.

2. Word `STABLE'

Note: A question mark following half-life denotes that the assignment to that level is not certain. A comment should be given to explain the exact meaning intended.

15. COIN

This one character field can either be blank or have character ‘C’ or ‘?’. The character ‘C’ denotes coincidence, while ‘?’ denotes questionable coincidence.

16. UN

This two character field can either be blank for allowed transitions, or have an integer between 1 and 9 indicating order of forbiddeness followed by a blank for ‘non-unique’ or a ‘U’ for unique transition.

17. MS

This two character field can either be blank or have character ‘M’ followed by a blank or a digit between 1 and 9.

18. E

An energy field (E) can have only one of the following forms:

1. NUM (as defined in Section V.9 above)

2. NUM+A or A+NUM, where A=X, Y, Z, U, V, W, A, B,... used in this order; i.e.,for the first occurrence an ‘X’ is used, for its second occurrence a ‘Y’ is used, and so on.

3. SN+NUM, SP+NUM. Resonance energies should be given in center-of-mass system, as far as possible.

4. A (as defined in 2. above)

Note: Parentheses are allowed for this field. They denote that the number given has been deduced (not directly measured) or taken from other experiment(s). Explanation as to what is intended should be given.

19. M

The multipolarity field can be one of the following:

1. Mult
2. Mult + Mult
3. Mult, Mult
4. NOT Mult

MULT

where Mult = E_L or M_L'
(where L, L' are single digits – $L \geq 0$, $L' \geq 1$)

$M_L' + E_L$ or
$E_L + M_L'$ or
D or Q

Note: Parentheses in the multipolarity field denote that the assignment is probable and not definite. Square brackets indicate assumed or derived assignment.

20. J

The spin-parity field can have only one of the following forms:

1. JPI (can be J, π, or Jπ)

2. PI OR JPI (‘,’ (comma) can be used in place of ‘OR’)

3. JPI AND JPI (‘&’ (ampersand) can be used in place of ‘AND’)

4. OP JPI (where OP is AP, LE, or GE)
Note: This will be interpreted as π = PI and J is OP J
Example: $\leq$ 5+ means π = + and J $\leq$ 5

5. NOT JPI

6. JPI TO JPI (‘:’ (colon) can be used in place of ‘TO’)
Note: If parity is given in the range it will be interpreted as follows:

a) J to J'PI means J $\leq$ J $\leq$ J' and π = PI

b) JPI to J'PI' means JPI, J = J+1 PI = $\pm$,...,J = J'-1 PI = $\pm$,J'PI'

c) JPI to J' means JPI, J = J+1 PI = $\pm$,...,J = J'-1 PI = $\pm$, J'PI = $\pm$

Examples:

a) 3 to 6- means Jπ = 3-, 4-, 5-, 6-

b) 3+ to 6- means Jπ = 3+, 4±, 5±, 6-

c) 3+ to 6 means Jπ = 3+, 4±, 5±, 6±

7. NATURAL/UNNATURAL

8. A or A+JPI (where A is one of the characters, J, K, L, M, N, O, P...)

In the above J = N or N/2 (N is a positive integer or zero)
PI(π) = + or -
JPI = J or PI or J followed by PI

Note:

1. Parentheses in the J^{π} field indicate that the parenthesized value(s) is (are) based upon weak arguments. See 'Bases for Spin and Parity Assignments' in Appendix H. Note that JPI = (3,4)- is interpreted as J = (3) or (4) and π =-.

2. As far as possible do not give more than three JPI values.

3. The ranges such as 3- to 5+ are better written as 3-, 4, 5+.

4. Square brackets around J^{π} value indicate assumed value.

21. S

This field may contain no more than three S-values, in the form of NUM defined in Section V.9, separated by a '+' or a comma, for corresponding L-values given in the L-field (col. 65-74). Parentheses are allowed and will be interpreted to mean probable values.

22. L

This field may contain no more than three integer numbers optionally preceded by LE or GE and separated by a '+' or a comma. Parentheses are allowed and will be interpreted to mean probable values. Square brackets indicate assumed or derived values.

For certain reactions the L value may be accompanied by its electric or magnetic character in the form similar to multipolarity (see Section V.19).

23. ION

This field is either blank or a signed integer, left justified, denoting order of ionization of the atom, e.g., +75. It is used in Ionized Atom Decay data sets.

24. Cross Reference

The cross referencing of a record (currently allowed only for the ‘L’ record in an ADOPTED data set) is done through specification on the continuation record and takes the following forms:

1. NUCID 2 L XREF=ABC$
   Above record indicates that the adopted level (specified by preceding ‘L’ record) has been seen in data sets ‘A’, ‘B’ and ‘C’ and that the corresponding levels are unambiguous.

2. NUCID 2 L XREF=A(E1)B(E2)C(E3)$
   This record indicates that the adopted level is the same as the E1 level in data set ‘A’, the E2 level in data set ‘B’, etc.

3. NUCID 2 L XREF=A(E1,E2)B(E3)$
   This record indicates that the adopted level is either the E1 or the E2 level in data set ‘A’, the E3 level in data set ‘B’.

4. NUCID 2 L XREF=A(*E1)B(E2)$
   This record indicates that a level with energy E1 in data set ‘A’ is associated with more than one adopted level. An ‘*’ must appear on all occurrences of a multiply assigned level. Alternatively, the notation A(*) may be used if the energy is apparent.

5. NUCID 2 L XREF=+$
   This record indicates that the adopted level has been seen in all data sets.

6. NUCID 2 L XREF=-(AB)$
   This record indicates that the adopted level has been seen in all data sets except the data sets ‘A’ and ‘B’.

Note: The symbols A, B, C relating to specific data sets must be defined through Cross-Reference records (see Section III.B.4).

25. History record

1. In all individual ENSDF data sets (excepting the REFERENCE and COMMENTS data sets), the following information will be presented (the information is required, unless indicated optional) on an H record every time changes are made to the data set (see Section III.B.2 for description of H record):

   TYP Type of change/evaluation (required)
   AUT Author's name (the person who makes or is responsible for the change not necessarily the evaluator of the data set) (required)
   DAT Date of change (optional, if cutoff date given)
   CUT Literature cutoff date (optional when changes do not involve fresh evaluation)
   CIT Citation (optional, if not published)
   COM Comments (optional)

2. Current list of evaluation types (can be expanded) are

   FUL Complete revision of the nuclide based on all information to the cutoff date indicated. Cutoff date required
   FMT Some format changes done
   ERR Errata (fix error(s) in the dataset, should be accompanied with COM)
   MOD Modified dataset for partial update of nuclide. Kind of modification done should be indicated as comment. Cutoff date is optional.
   UPD Update due to scan of new literature. Cutoff date is required.
   EXP Experimental (not evaluated) data set.

   There can be only one type specification per history record given.

3. Date and Cutoff date must be given as DD-MMM-YYYY (e.g., 31-MAY- 1996)

4. Citation (optional) gives the reference where the evaluation is published. CIT=ENSDF means included in ENSDF but not published.

5. Comments (optional) may give general remarks about evaluation/update.

6. The fields can be in any order on an 'H' record.

Note that history records indicate various revisions. These are wiped out at the next FULL evaluation.

For FULL evaluation NNDC will introduce 'H' records based on the COMMENTS data set.

Examples:

```
156DY H  TYP=MOD$AUT=B. Singh$DAT=31-DEC-1995$
156DY2H COM=Updated SDB data only$
156DY H  TYP=UPD$AUT=R. Helmer$CUT=15-DEC-1994$
156DY2H COM=Updated data set since last full evaluation$
156DY H  TYP=FMT$AUT=J. Tuli$DAT=1-DEC-1994$COM=FIXED T1/2$
156DY H  TYP=FUL$AUT=R. Helmer$CUT=01-May-1991$
156DY2H CIT=NDS 65, 65 (1992)$
```

Appendix A

Character Set

The base character set is the standard 7-bit ASCII character set up to octal 173. Characters with octal values of 173 and greater are used as control characters. An alternate character set consists primarily of the Greek alphabet and some special symbols. The backslash character (octal 134) is interpreted as a backspace command. An alternate character in the input file consists of two characters, a control character and the standard character equivalent of the alternate character. All available alternate characters and their standard equivalents are given in the table on the following page.

There are four control characters, | (octal 176), ~ (octal 176), { (octal 173), and } (octal 175). The vertical bar and the tilda are used to shift the next character into the first and second alternate character sets, respectively. The entire string of characters may also be modified from their standard form. In this case the string to be modified is enclosed by the open and close brace control characters. The character immediately following the open brace is interpreted as a control character. The available control character values and their meanings are given below. The modified character strings may be nested. The control characters may be in either upper or lower case.

Examples

|g will be displayed as γ
{B{+238}Puwill be displayed as ^{238}Pu

String Control Characters

|	first alternate character
~	second alternate character
+	superscript
-	subscript (+ and – are mutually exclusive)
I	italic
B	bold
U	underline

Note: Symbol ^ (caret) may be used before a word to preserve case, e.g., ^A for A (and not a).

Alternate Character Sets

Standard	1st alt.	2nd alt.	Standard	1st alt.	2nd alt.
!	©	!	N	N	N
"	-	"	O	O	Ö
#	§	⊗	P	Π	P
$	e	$	Q	⊇	Õ
%	√	%	R	Ρ	R
&	≡	&	S	Σ	S
'	°	Å	T	Τ	T
(	←	(	U	ϒ	Ü
)	→	)	V	∇	V
*	x	.	W	Ω	W
+	±	+	X	Ξ	X
’	½	’	Y	∇	Y
-	Ŧ	-	Z	Ζ	Z
.	∝	.	[	{	[
/	÷	/	]	}	]
0	(	0	^	↑	^
1	)	1	-	↓	-
2	[	2	ʿ	′	ʿ
3	]	3	a	α	ä
4	<	4	b	β	b
5	>	5	c	η	c
6	√	6	d	δ	d
7	∫	7	e	ε	é
8	∏	8	f	φ	f
9	∑	9	g	γ	g
:	†	:	h	©	h
;	‡	;	i	□	i
<	≤	<	j	ϵ	j
=	≠	=	k	κ	k
>	≥	>	l	λ	λ
?	≈	?	m	μ	m
@	∞	•	n	ν	n
A	Α	Ä	o	ο	ö
B	Β	B	p	π	p
C	Η	C	q	Θ	õ
D	Δ	D	r	ρ	r
E	Ε	É	s	σ	s
F	Φ	F	t	⎪	t
G	Γ	G	u	⎤	ü
H	Χ	H	v	?	v
I	Ι	I	w	ω	w
J	~	J	x	ξ	x
K	Κ	K	y	ψ	y
L	Λ	L	z	ζ	z
M	Μ	M			

Appendix B

Format for Comments Data Set

This data set consists only of general comment records (defined in III.B(4)). The format of the comment records is similar to general comments in other data sets except that the NUCID field will contain only the mass number, AAA, and that a SYM field is required as in a flagged comment. As in the flagged comments, the SYM field will either occupy columns 10 to 19 with column 19 being blank or the SYM will be followed by a '$'. Continuation records for a given comment are allowed with the additional feature that a new line will be started if the continuation character in column 6 is a '#' and that a new paragraph will be started if the character is a '@'. This feature is intended to facilitate the entry of information into the COMM comments.

SYM	Meaning
TITLE	Title of evaluation. Required if the evaluation spans several masses.
AUTH	Authors, a list of authors from the institution given in the following INST comment. A letter or number in parenthesis following an authors last name will signal a permanent address which is different from the institution. (See PERM)
INST	Institution, name and address of the authors' institution.
INST	comment must follow the appropriate AUTH comment. The # continuation character is used so the address does not run together into one line. More than one set of AUTH and INST comments can be given if more than one institution is involved.
ABST	Abstract, should be terse and to the point. Additional details should be given under COMM comments.
CUT	Cutoff data and associated comments.
COMM	General comments on techniques used in the evaluation or on other information common to many of the isotopes.
ACKN	Acknowledgments.
PERM(a)	Permanent address of an author. The letter or number 'a' within the parenthesis corresponds to the letter or number within the parenthesis which follows the authors last name in the AUTH comment.
FUND	Funding, an acknowledgment of funding which will result in a footnote being added to the title.
CIT	Citation. To be added by the NDS production staff so that the publication can be correctly cited by persons using a retrieval of the A chain. The authors may leave it out.

<u>EXAMPLE of a COMMENTS data set</u>

```
156         COMMENTS
156   C     TITL$  Nuclear Data Sheets for A=156
156   C     AUTH$R. G. Helmer
156   C     INST$Idaho National Engineering Laboratory
156   #C    EG&G Idaho, Inc.
156   #C    Idaho Falls, Idaho 83415 USA
156   C     ABST$The experimental results from the various reaction and decay
156   2C    studies leading to nuclides in the A=156 mass chain, and ALPHA decays
156   3C    from it, have been reviewed. These data are summarized and presented,
156   4C    together with adopted levels schemes and properties.
156   C     CUT$Data available prior to May 1991 have been evaluated.
156   C     ACKN$The evaluator wishes to thank C. W. Reich, the reviewer, and the
156   2C    editors for many helpful discussions.
156   C     FUND$Research sponsored by the U. S. Department of Energy.
156   C     CIT$R. G. Helmer, NDS 65, 65 (1992)
156   C     COMM$General Comments: In this evaluation, the following expression
156   2C    was used to define the rotational-band parameters a and B:
156   C     E(J)=E{-0} + a[J(J+1)-K{+2}] + B[J(J+1)-K{+2}]{+2}.
156   C     with the following terms sometimes added for K=1 and 2 bands
156   C     + (-1){+J+1}a{-2}J(J+1) for K=1
156   C     and
156   C     + (-1){+J}a{-4}(J-1)J(J+1)(J+2) for K=2.
156   C     In the determination of the values of these parameters, the energy
156   2C    spacings of only the lowest levels, and minimum number of levels, were
156   3C    used.
156   C     The ENSDF file (the computer data base from which these Data Sheets
156   3C    are produced), contains some information that is not printed in these
156   4C    Data Sheets. This includes the theoretical internal-conversion
156   6C    coefficients for each shell, where the values are significant, for
156   8C    each |g for which a multipolarity is given in the Data Sheets. Also, a
156   9C    short comment is made about the experimental methods for each
156   BC    reference.  This information would be available if a copy of the ENSDF
156   DC    file were obtained.
```

Output for above COMMENTS data set is shown on the following page

Nuclear Data Sheets for A = 156*

Nuclear Data Sheets 65, 65 (1992)

R. G. Helmer
Idaho National Engineering Laboratory
EG&G Idaho, Inc.
1.Idaho Falls, Idaho 83415 USA
(Received June 24, 1991; Revised August 20, 1991)

Abstract: The experimental results from the various reaction and decay studies leading to nuclides in the A=156 mass chain, and α decays from it, have been reviewed. These data are summarized and presented, together with adopted levels schemes and properties.

Cutoff Date: Data available prior to May 1991 have been evaluated.

General Policies and Organization of Material: See the January issue of Nuclear Data Sheets.

Acknowledgments: The evaluator wishes to thank C. W. Reich, the reviewer, and the editors for many helpful discussions.

General Comments: In this evaluation ,the following expression was used to Define the rotational–band parameters A and B:

$E(J)=E_0 + A[J(J+1)–K^2] + B[J(J+1)–K^2]^2$.

with the following terms sometimes added for K=1 and 2 bands

$+ (–1)^{J+1}A_2J(J+1)$ for K=1

and

$+ (–1)^J A_4(J–1)J(J+1)(J+2)$ for K=2.

In the determination of the values of these parameters ,the energy spacings of only the lowest levels ,and minimum number of levels, were used.

The ENSDF file (the computer data base from which these Data Sheets are produced), contains some information that is not printed in these Data Sheets. This includes the theoretical internal–conversion coefficients for each shell, where the values are significant ,for each γ for which a multipolarity is given in the Data Sheets. Also, a short comment is made about the experimental methods for each reference. This information would be available if a copy of the ENSDF file were obtained.

* Research sponsored by the U. S. Department of Energy.

Appendix C

Example of an Adopted Data Set

```
162TB    ADOPTED LEVELS, GAMMAS                         99NDS    199909
162TB  H TYP=FUL$AUT=R. G. Helmer and C. W. Reich$CIT=NDS 87, 317 (1999)$
162TB2 H CUT=1-Jan-1999$
162TB  Q  2506     36 6284   36 7457   36 -895   85     1995AU04
162TB C  Data are from 162GD B- decay (1982Ge07,1970Ch02) and 163DY(T,A)
162TB2C  reaction (1989BuZW,1988BuZP).
162TB CL E         Other levels up to 1600 keV are indicated by the 163DY(T,A)
162TB2CL spectrum in 1988BuZP.
162TB CL J         For the levels reported from the 163DY(T,A) reaction, the
162TB2CL JPI values are based on L=2 transfers and intensity patterns
162TB3CL within bands that indicate pickup of a 3/2[411] proton.
162TB CL BAND(A)   KPI = 1- band.
162TB2CL CONF=((P,3/2(411))(N,5/2(523))).
162TB@CL ^A=9.78
162TB DL           Levels: 1- (0), 2- (39), 3- (97), 4- (176), 5- (267).
162TB CL BAND(B)   KPI = 4- band.
162TB2CL CONF=((P,3/2(411))(N,5/2(523))).
162TB@CL ^A AP 10
162TB CL BAND(C)   Bandhead of KPI = 1+ band.
162TB2CL CONF=((P,7/2(523))(N,5/2(523)))
162TB  XY162GD B- DECAY
162TB  XZ163DY(T,A)
162TB PN                                              6
162TB  L   0         1-              7.60 M   15                 A
162TB2 L %B-=100 $ XREF=+
162TB CL T         Unweighted average of 7.43 MIN 4 (1965Sc24) and 7.76 MIN 10
162TB2CL (1977Ka08). Others: 7.48 M 3 (1965Sc24), 8.0 M 5 (1966Fu08),
162TB3CL 7.75 M 31 (1966Sc24), 7.5 M 10 (1967Gu03), and 7.6 M 2 (1968Ka10).
162TB4CL See 1951Bu25, 1960Wi10, and 1962Ta12 for half-life measurements
162TB5CL related to nuclide identification.
162TB CL J         Configuration is assigned as
162TB2CL CONF=((P,3/2(411))(N,5/2(523))) based on the ground-state
162TB3CL assignments of CONF=(P,3/2(411)) for 161TB and
162TB4CL CONF=(N,5/2(523)) for 161GD and 163DY.
162TB CL J         LOGFT=4.95 of the B- transition to the 2- level at 1148 keV
162TB2CL in 162DY indicates an allowed-unhindered B transition, which
162TB3CL must be CONF=(N,5/2(523)) to CONF=(P,7/2(523)). This confirms
162TB4CL the configuration assignment to this ground state as well as
162TB5CL helping establish the configuration assignment to the 1148-keV
162TB6CL level in 162DY as CONF=((P,3/2(411))(P,7/2(523))). See 162DY
162TB6CL Adopted Levels and 1995Be02 for further discussion.
162TB  L  39.10    9  2-                                   A
```

```
162TB2 L XREF=+
162TB CL J       From M1 component in G to 1- ground state, expected energy
162TB2CL spacing in rotational band, and (T,A) reaction results.
162TB  G  39.0     2  100       M1+(E2)
162TB CG M        From intensity balance at 39 level in 162GD B- decay,
162TB2CG transition is primarily M1 (1970Ch02); x/G intensity ratio and
162TB3CG ^L x-ray energy are consistent with this.
162TB  L   97      1  3-                                A
162TB2 L XREF=Z
162TB  L  176      1  4-                                A
162TB2 L XREF=Z
162TB  L  216      1  4-                                B
162TB2 L XREF=Z
162TB CL J       Configuration is assigned as that of the ground state,
162TB2CL namely, (PI 3/2[411])(NU 5/2[523]) recoupled. The systematics
162TB3CL of 1998Ja07 suggest a "theoretical" Gallagher-Moszkowski splitting
162TB4CL of 82 keV compared to the observed 216 keV, if this assignment
162TB5CL is correct.
162TB  L  267      2  5-                                A
162TB2 L XREF=Z
162TB  L  310      1  5-                                B
162TB2 L XREF=Z
162TB  L 341.41    9 (0-,1)
162TB2 L XREF=Y
162TB CL J       From LOGFT=5.9 in B- decay from 0+ 162GD.
162TB  G 302.30    15  58    9
162TB  G 341.42    10 100    9
162TB  L 442.11    8  1+                                  C
162TB2 L XREF=Y
162TB CL J       From allowed-unhindered (LOGFT=4.4) B- transition from the
162TB2CL 162GD ground state (0+). This also uniquely establishes the
162TB3CL configuration of this level as CONF=((N,5/2(523))(P,7/2(523))).
162TB  G 403.00    8   85    4
162TB  G 442.12    8  100
```

Output for above data set is shown in the following pages

Adopted Levels, Gammas

Q(β⁻)=2506 *36*; S(n)=6284 *36*; S(p)=7457 *36*; Q(α)=−895 *85* 1995Au04.
Data are from ^{162}Gd β⁻ decay (1982Go07,1970Ch02) and ^{163}Dy(t,α) reaction (1989BuZW,1988BuZP).

^{162}Tb Levels

Cross Reference (XREF) Flags

A ^{162}Gd β⁻ Decay
B ^{163}Dy(t,α)

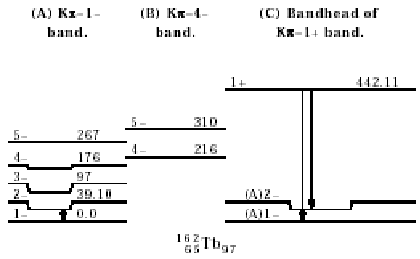
E(level)†	Jπ‡	XREF	$T_{1/2}$	Comments
0.0§	1−	AB	7.60 min *15*	%β⁻=100. $T_{1/2}$: Unweighted average of 7.43 min *4* (1965Sc24) and 7.76 min *10* (1977Ka08). Others: 7.48 min *3* (1965Sc24), 8.0 min *5* (1966Fu08), 7.75 min *31* (1966Sc24), 7.5 min *10* (1967Gu03), and 7.6 min *2* (1968Ka10). See 1951Bu25, 1960Wi10, and 1962Ta12 for half-life measurements related to nuclide identification. Jπ: Configuration is assigned as configuration=((π 3/2[411])(ν 5/2[523])) based on the ground-state assignments of configuration=(π 3/2[411]) for ^{161}Tb and configuration=(ν 5/2[523]) for ^{161}Gd and ^{163}Dy. Jπ: log *ft*=4.95 of the β⁻ transition to the 2− level at 1148 keV in ^{162}Dy indicates an allowed-unhindered β transition, which must be configuration=(ν 5/2[523]) to configuration=(π 7/2[523]). This confirms the configuration assignment to this ground state as well as helping establish the configuration assignment to the 1148-keV level in ^{162}Dy as configuration=((π 3/2[411])(π 7/2[523])). See ^{162}Dy Adopted Levels and 1995Be02 for further discussion.
39.10§ *9*	2−	AB		Jπ: From M1 component in γ to 1− ground state, expected energy spacing in rotational band, and (t,α) reaction results.
97§ *1*	3−	B		
176§ *1*	4−	B		
216# *1*	4−	B		Jπ: Configuration is assigned as that of the ground state, namely, (π 3/2[411])(ν 5/2[523]) recoupled. The systematics of 1998Ja07 suggest a "theoretical" Gallagher-Moszkowski splitting of 82 keV compared to the observed 216 keV, if this assignment is correct.
267§ *2*	5−	B		
310# *1*	5−	B		
341.41 *9*	(0−,1)	A		Jπ: From log *ft*=5.9 in β⁻ decay from 0+ ^{162}Gd.
442.11@ *8*	1+	A		Jπ: From allowed-unhindered (log *ft*=4.4) β⁻ transition from the ^{162}Gd ground state (0+). This also uniquely establishes the configuration of this level as configuration=((ν 5/2[523])(π 7/2[523])).

† Other levels up to 1600 keV are indicated by the ^{163}Dy(t,α) spectrum in 1988BuZP.
‡ For the levels reported from the ^{163}Dy(t,α) reaction, the Jπ values are based on L=2 transfers and intensity patterns within bands that indicate pickup of a 3/2[411] proton.
§ (A): Kπ=1− band. Configuration=((π 3/2[411])(ν 5/2[523])). A=9.78.
# (B): Kπ=4− band. Configuration=((π 3/2[411])(ν 5/2[523])). A=10.
@ (C): Bandhead of Kπ=1+ band. Configuration=((π 7/2[523])(ν 5/2[523])).

γ(^{162}Tb)

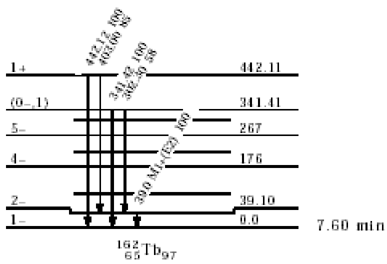
E(level)	Eγ	Iγ	Mult.	Comments
39.10	39.0 *2*	100	M1+(E2)	Mult.: From intensity balance at 39 level in ^{162}Gd β⁻ decay, transition is primarily M1 (1970Ch02); x/γ intensity ratio and L x-ray energy are consistent with this.
341.41	302.30 *15*	58 *9*		
	341.42 *10*	100 *9*		
442.11	403.00 *8*	85 *4*		
	442.12 *8*	100		

Adopted Levels, Gammas (continued)



Level Scheme

Intensities: relative photon branching from each level



Appendix D

Example of a Decay Data Set

```
162TB    162GD B- DECAY              1982GE07,1970CH02        99NDS    199909
162TB  H TYP=FUL$AUT=R. G. Helmer and C. W. Reich$CIT=NDS 87, 317 (1999)$
162TB2 H CUT=1-Jan-1999$
162TB C  162GD has been produced by double-neutron capture in enriched 160GD
162TB2C  with radiochemistry (1967Wa05,1970Ch02) and from spontaneous fission
162TB3C  of 252CF with radiochemistry (1982Ge07). Measurements include
162TB4C  G singles and GG, GX, and GB coincidences.
162TB CL          Decay scheme is from 1982Ge07, and is similar to those of
162TB2CL 1970Ch02 and 1967Wa05.
162TB CL          The consistency of the scheme is supported
162TB2CL by the fact that the sum of the energies of the radiations is
162TB3CL 1395 keV 56 which agrees with the Q value of 1400 100.
162TB CL E        From least-squares fit to G energies.
162TB CL J        From 162TB Adopted Levels. Rotational band and Nilsson
162TB CG          Data are from 1982Ge07, unless otherwise noted. Others:
162TB2CG 1970Ch02, 1967Wa05.
162TB CB E        From 1970Ch02.
162TB CB IB       From evaluators' assumption that 100% of the decays
162TB2CB depopulate the levels at 341 and 442 keV (that is, no B-
162TB3CB feeding of the ground state and 39 level) and no G feeding of
162TB4CB the 341-keV level. From LOGFT GE 5.9 for 0+ to 1- ground state
162TB5CB (1973Ra10), IB-(0) LE 13% and from LOGF1T GE 8.5 for 0+ to 2- at
162TB6CB 39 keV (1973Ra10), IB-(39) LE 0.15%.
162TB2CL configuration assignments are given there.
162TB D  Experimental methods:
162TB D  1967Wa05: 162GD from double-neutron capture in enriched (94%) 160GD
162TB2D      with radiochemistry.  G's measured with NAI(TL) detectors.
162TB D  1970Ch02: 162GD from double-neutron capture in enriched (94.8%) 160GD
162TB2D      with radiochemistry.  G's measured with Ge and Si(Li) detectors
162TB3D      and B's with Si(Li) detector.  GX and GB coincidences measured.
162TB D  1982Ge07: 162GD from 252CF spontaneous fission with radiochemistry.
162TB2D      G's measured with Ge detector.
162GD  P   0        0+             8.4 M    2            14E2     1
162TB  N   0.51    2          1.0       1.0
162TB CN NR       Based on evaluators' assumption that 100% of the decays
162TB2CN depopulate the levels at 341 and 442 keV.
162TB PN                                                  3
162TB  L   0        1-            7.60 M   15
162TB CL T        From 162TB Adopted Levels and based on 7.43 M 4 (1965Sc24)
162TB2CL and 7.76 M 10 (1977Ka08).
162TB  L  39.10    9  2-
162TB  G  39.0    2   10    2  M1+(E2)            8     2           C
162TBS G LC=6 2$ MC=1.4 3
162TB CG E        Average of 39.1 2 (1982Ge07) and 38.8 2 (1970Ch02).
```

```
162TB CG RI       Average of 9 2 (1982Ge07) and 14 3 (1970Ch02).
162TB CG M,CC     CC value deduced by evaluators from intensity balance at 39
162TB2CG level for current decay scheme; added G's feeding 39 level will
162TB3CG increase CC value. From CC(M1)=5.58 and CC(E2)=135, G is
162TB4CG primarily M1 with some E2 probable. Measured x/G intensity
162TB5CG ratio and L x-ray energy are consistent with this (1970Ch02).
162TB  L 341.41    9 (0-,1)
162TB  B             4.5  5          5.9    2
162TBS B EAV=362 14
162TB  G 302.30    15   3.1  5
162TB  G 341.42    10   5.3  5
162TB  L 442.11    8  1+
162TB  B  10E2     1   95.5  5          4.4    2                      C
162TBS B EAV=322 40
162TB  G 403.00    8   85    4  [E1]               0.008              C
162TBS G KC=0.0069$ LC=0.0010$ MC=0.0002
162TB  G 442.12    8  100       [E1]               0.007              C
162TBS G KC=0.0056$ LC=0.00076$ MC=0.0002
```

Output for above data set is shown in the following pages

^{162}Gd β^- Decay 1982Ge07,1970Ch02

Parent ^{162}Gd: E=0; Jπ=0+; $T_{1/2}$=8.4 min *2*; Q(g.s.)=14×10^2 *1*; %β⁻ decay=100.
^{162}Gd has been produced by double-neutron capture in enriched ^{160}Gd with radiochemistry (1967Wa05,1970Ch02) and from spontaneous fission of ^{252}Cf with radiochemistry (1982Ge07). Measurements include γ singles and γγ, γX, and γβ coincidences.

^{162}Tb Levels

Decay scheme is from 1982Ge07, and is similar to those of 1970Ch02 and 1967Wa05.
The consistency of the scheme is supported by the fact that the sum of the energies of the radiations is 1395 keV 56 which agrees with the Q value of 1400 *100*.

E(level)†	Jπ‡	$T_{1/2}$	Comments
0.0	1−	7.60 min *15*	$T_{1/2}$: From ^{162}Tb Adopted Levels and based on 7.43 min *4* (1965Sc24) and 7.76 min *10* (1977Ka08).
39.10 *9*	2−		
341.41 *9*	(0−,1)		
442.11 *8*	1+		

† From least-squares fit to γ energies.
‡ From ^{162}Tb Adopted Levels. Rotational band and Nilsson.

β^- radiations

Eβ⁻†	E(level)	Iβ⁻‡§	Log *ft*	Comments
1000 *100*	442.11	95.5 *5*	4.4 *2*	av Eβ=322 *40*.
(1060 *100*)	341.41	4.5 *5*	5.9 *2*	av Eβ=362 *14*.

† From 1970Ch02.
‡ From evaluators' assumption that 100% of the decays depopulate the levels at 341 and 442 keV (that is, no β⁻ feeding of the ground state and 39 level) and no γ feeding of the 341-keV level. From log *ft*≥5.9 for 0+ to 1− ground state (1973Ra10), Iβ⁻(0)≤13% and from log f^1t≥8.5 for 0+ to 2− at 39 keV (1973Ra10), Iβ⁻(39)≤0.15%. configuration assignments are given there.
§ For β⁻ intensity per 100 decays, multiply by 1.0.

γ(^{162}Tb)

Data are from 1982Ge07, unless otherwise noted. Others: 1970Ch02, 1967Wa05.
Iγ normalization: Based on evaluators' assumption that 100% of the decays depopulate the levels at 341 and 442 keV.

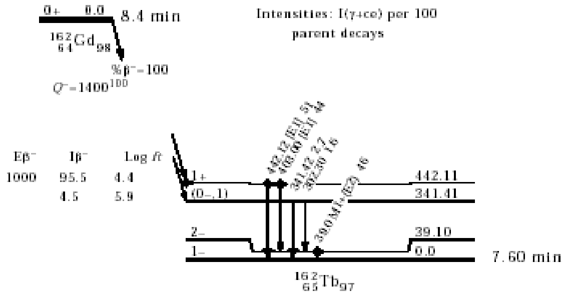
Eγ	E(level)	Iγ†	Mult.	α	Comments
39.0 *2*	39.10	10 *2*	M1+(E2)	8 *2*	α(L)=6 *2*; α(M)=1.4 *3*. Eγ: Average of 39.1 *2* (1982Ge07) and 38.8 *2* (1970Ch02). Iγ: Average of 9 *2* (1982Ge07) and 14 *3* (1970Ch02). Mult.,α: α value deduced by evaluators from intensity balance at 39 level for current decay scheme; added γ's feeding 39 level will increase α value. From α(M1)=5.58 and α(E2)=135, γ is primarily M1 with some E2 probable. Measured x/γ intensity ratio and L x-ray energy are consistent with this (1970Ch02).
302.30 *15*	341.41	3.1 *5*			
341.42 *10*	341.41	5.3 *5*			
403.00 *8*	442.11	85 *4*	[E1]	0.008	α(K)=0.0069; α(L)=0.0010; α(M)=0.0002.
442.12 *8*	442.11	100	[E1]	0.007	α(K)=0.0056; α(L)=0.00076; α(M)=0.0002.

† For absolute intensity per 100 decays, multiply by 0.51 *2*.

^{162}Gd β^- Decay 1982Ge07,1970Ch02 (continued)

Decay Scheme

Intensities: I(γ+ce) per 100 parent decays



Appendix E

ENSDF Coding for Ionized Atom decay

Decay Data Set

1. ID record

The ionization state of the atom would be in square brackets following the nuclide symbol in the DSID field.

2. Parent record
   - Energy field: level energy of the parent nucleus
   - Half-life field: half-life for the decay of the ionized itom
   - Q-value field: nuclear ground-state to ground-state value
   - New field (77-80): ionization state

3. Level records
   - Energy field: level energy of the daughter nucleus
   - MS field: atomic electron shell or subshell in which the emitted beta- particle is captured.
   - A new quantity, "ION", giving the ionization state would be required on an "S L" record following the level record.

4. Daughter Adopted Levels, Gammas

The adopted levels would be cross-referenced to the observed states in the ionized atom decay dataset.

5. Parent Adopted Levels, Gammas

The half-life and decay branching of the ionized atom decay would be given as comments (analagous to the current practice for half-lives which differ due to chemical effects). This should be regarded as an interim solution; after more experience is gained, methods of giving these data on level continuation records should be derived.

Examples:

187Re

```
187OS    187RE[+75] B- DECAY           96BO37
187OS C  BOUND STATE B- DECAY OF BARE 187RE (75+ CHARGE STATE)
187OS C  96BO37 (ALSO 97NO07,97KL06,97WE08): DECAY OF FULLY IONIZED
187RE
187OS2C  NUCLEI CIRCULATING IN A STORAGE RING.  ...............
187OS C  T1/2 OF 187RE ION (75+ CHARGE STATE)=32.9 Y 20
187RE  P  0          5/2+             32.9 Y 20            2.663     19+75
187OS  N                     1.0
187OS  L  0          1/2-                                   K
187OSS L ION=+75
187OS  B             WEAK               11  AP                       1U?
187OS  L  9.75        3/2-                                   K
187OSS L ION=+75
187OS  B             100              7.87  3
187OS  G  9.75                                               S
187OS  L  0          1/2-                                   L1
187OSS L ION=+75
187OS  B                                                    ?

187RE    ADOPTED LEVELS, GAMMAS
187RE CL BAND(A)$5/2[402]?
187RE  L       0.0   5/2+             4.35E10 Y 13                    A
187RE2 L %B-=100$%A LT 0.0001
187RE CL $%B-({+187}Re{++75})=100; T1/2({+187}Re{++75})=32.9 20 Y

187OS    ADOPTED LEVELS, GAMMAS
187OS CL BAND(A)$1/2[501] BAND
187OS CL BAND(B)$3/2[512] BAND
187OS  XA187RE B- DECAY
187OS  XB187IR EC DECAY
187OS  XC186OS(N,G) E=THERMAL
187OS  XD187RE(D,2NG), 187RE(P,NG)
187OS  XECOULOMB EXCITATION
187OS  XF189OS(P,T)
187OS  XG186OS(D,P)
187OS  XH187OS(D,D')
187OS  XI188OS(D,T),(T,A)
187OS  XJ187RE[+75] B- DECAY
187OS  L       0.0   1/2-            STABLE                         A
187OSX L XREF=ABCDEFGHIJ
187OS  L     9.746 24 3/2-              2.38 NS 18                    B
187OSX L XREF=BCDFJ
```

163Dy

163HO C BOUND STATE B- DECAY OF {+163}Dy{+66+} ION
163HO C 92JU01: T1/2 MEASURED BY STORING BARE 163DY 66+ IONS IN A HEAVY-ION
163HO2C STORAGE RING. ....
163HO C T1/2({+163}Dy{+66+})=47 +5-4 D
163DY P 0+Y   5/2-   47 D   +5-4   -2.565   14+66
163HO N   1.0
163HO L 0   7/2-   K
163HOS L ION=+66
163HO B   100

163DY   ADOPTED LEVELS, GAMMAS
163DY L 0.0   5/2-   STABLE
163DY CL $%B-({+163}Dy{+66+})=100; T1/2({+163}Dy{+66+})=47 +5-4 D
163HO XA163HO IT DECAY (1.09 S)
163HO XB163ER EC DECAY
163HO XC162DY(P,P) IAR
163HO XD162DY(3HE,D),(A,T)
163HO XE163DY(D,2NG),(P,NG)
163HO XG164ER(POL T,A)
163HO XI165HO(P,T)
163HO XJ163DY[+66] B- DECAY
163HO CL BAND(A)   7/2(523). A=11.12, B=-0.313 EV
163HO L 0.0   7/2-   4570 Y   25
163HO2 L %EC=100
163HO3 L FLAG=A$XREF=-(C)

Appendix F.

ENSDF Dictionary – Translation into True-type Character Set

<table>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>"A"</td><td>"A"</td></tr>
<tr><td>%12C</td><td>%{+12}C</td></tr>
<tr><td>%14C</td><td>%{+14}C</td></tr>
<tr><td>%2B-</td><td>%2|b{+-}</td></tr>
<tr><td>%A</td><td>%|a</td></tr>
<tr><td>%B+A</td><td>%|b{++}|a</td></tr>
<tr><td>%B+N</td><td>%|b{++}n</td></tr>
<tr><td>%B+P</td><td>%|b{++}p</td></tr>
<tr><td>%B+_</td><td>%|b{++}</td></tr>
<tr><td>%B-2N</td><td>%|b{+-}2n</td></tr>
<tr><td>%B-N</td><td>%|b{+-}n</td></tr>
<tr><td>%B-P</td><td>%|b{+-}p</td></tr>
<tr><td>%B-_</td><td>%|b{+-}</td></tr>
<tr><td>%BEC</td><td>%|b{++}|e</td></tr>
<tr><td>%E0</td><td>%E0</td></tr>
<tr><td>%E2</td><td>%E2</td></tr>
<tr><td>%EC</td><td>%|e</td></tr>
<tr><td>%ECA</td><td>%|e|a</td></tr>
<tr><td>%ECF</td><td>%|eF</td></tr>
<tr><td>%ECK</td><td>%|ek</td></tr>
<tr><td>%ECP</td><td>%|ep</td></tr>
<tr><td>%EWSR</td><td>%EWSR</td></tr>
<tr><td>%G</td><td>%|g</td></tr>
<tr><td>%I</td><td>%I</td></tr>
<tr><td>%IB</td><td>%I|b</td></tr>
<tr><td>%IG</td><td>%I|g</td></tr>
<tr><td>%IT</td><td>%IT</td></tr>
<tr><td>%M1</td><td>%M1</td></tr>
<tr><td>%N</td><td>%n</td></tr>
<tr><td>%P</td><td>%p</td></tr>
<tr><td>%RI</td><td>%I|g</td></tr>
<tr><td>%SF</td><td>%SF</td></tr>
<tr><td>(A)</td><td>(|a)</td></tr>
<tr><td>(B)</td><td>(|b)</td></tr>
<tr><td>(COUL.)</td><td>(Coul.)</td></tr>
<tr><td>(CV)</td><td>(CV)</td></tr>
<tr><td>(DOWN)</td><td>(|_)</td></tr>
<tr><td>(H,T)</td><td>(H,T)</td></tr>
</table>

<table>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>(IT)</td><td>(IT)</td></tr>
<tr><td>(T)</td><td>(t)</td></tr>
<tr><td>(THETA,H)</td><td>(|q,H)</td></tr>
<tr><td>(THETA,H,T,T)</td><td>(|q,H,t,T)</td></tr>
<tr><td>(THETA,T,H)</td><td>(|q,T,H)</td></tr>
<tr><td>(UP)</td><td>(|^)</td></tr>
<tr><td>*</td><td>\|*\</td></tr>
<tr><td>**(J+1/2)</td><td>{+(J+|,)}</td></tr>
<tr><td>**-1</td><td>{+-1}</td></tr>
<tr><td>**-3</td><td>{+-3}</td></tr>
<tr><td>**-4</td><td>{+-4}</td></tr>
<tr><td>**1/2</td><td>{+1/2}</td></tr>
<tr><td>**1/3</td><td>{+1/3}</td></tr>
<tr><td>**2</td><td>{+2}</td></tr>
<tr><td>**3</td><td>{+3}</td></tr>
<tr><td>**L</td><td>{+L}</td></tr>
<tr><td>*A**(1/3)</td><td>|*|A{+1/3}</td></tr>
<tr><td>*DS/DW</td><td>d|s/d|W</td></tr>
<tr><td>*E</td><td>|*E</td></tr>
<tr><td>*EG</td><td>E|g</td></tr>
<tr><td>*EKC</td><td>|a(K)exp</td></tr>
<tr><td>*G*WIDTHG0**2</td><td>g|G{+2}\{-|g0}</td></tr>
<tr><td>*G2</td><td>g{-2}</td></tr>
<tr><td>*IB-</td><td>|*I|b{+-}</td></tr>
<tr><td>*IE</td><td>|*I|e</td></tr>
<tr><td>*Q</td><td>|*Q</td></tr>
<tr><td>*R</td><td>R</td></tr>
<tr><td>*RI</td><td>I|g</td></tr>
<tr><td>*SIGMA</td><td>|*|s</td></tr>
<tr><td>*SUMOF</td><td>|S</td></tr>
<tr><td>*T1/2</td><td>|*T{-1/2}</td></tr>
<tr><td>*TAU</td><td>|t</td></tr>
<tr><td>*WIDTH</td><td>|G</td></tr>
<tr><td>*WIDTHP</td><td>|G{-p}</td></tr>
<tr><td>2B-</td><td>2|b{+-}</td></tr>
<tr><td>2J</td><td>2J</td></tr>
<tr><td>2N*SIGMA</td><td>2N|s</td></tr>
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<tr><td>4PIG</td><td>4|p|g</td></tr>
<tr><td>A DECAY</td><td>|a decay</td></tr>
<tr><td>A DECAYS</td><td>|a decays</td></tr>
<tr><td>A SYST</td><td>|a syst</td></tr>
<tr><td>A'</td><td>|a'</td></tr>
<tr><td>A(THETA)</td><td>A(|q)</td></tr>
<tr><td>A**1/3</td><td>A{+1/3}</td></tr>
<tr><td>A**2/3</td><td>A{+2/3}</td></tr>
<tr><td>A-DECAY</td><td>|a-decay</td></tr>
<tr><td>A-N</td><td>A-N</td></tr>
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<tr><td>AG</td><td>|a|g</td></tr>
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<tr><td>AP</td><td>|?</td></tr>
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<tr><td>AUGER</td><td>Auger</td></tr>
<tr><td>AUGUST</td><td>August</td></tr>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>AVRSQ</td><td>{ <r{+2}>}</td></tr>
<tr><td>AXK</td><td>(|a)(K x ray)</td></tr>
<tr><td>AY</td><td>Ay</td></tr>
<tr><td>B</td><td>|b</td></tr>
<tr><td>B(E0</td><td>B(E0</td></tr>
<tr><td>B(E1</td><td>B(E1</td></tr>
<tr><td>B(E2</td><td>B(E2</td></tr>
<tr><td>B(E3</td><td>B(E3</td></tr>
<tr><td>B(E4</td><td>B(E4</td></tr>
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<tr><td>B*R</td><td>|bR</td></tr>
<tr><td>B*RHO</td><td>B|*|r</td></tr>
<tr><td>B+</td><td>|b{++}</td></tr>
<tr><td>B-2N</td><td>|b{+-}2n</td></tr>
<tr><td>B-N</td><td>|b{+-}n</td></tr>
<tr><td>B-VIBRATIONAL</td><td>|b-vibrational</td></tr>
<tr><td>B-_</td><td>|b{+-}</td></tr>
<tr><td>B/A</td><td>B/A</td></tr>
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<tr><td>BCE</td><td>|bce</td></tr>
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<tr><td>BE-</td><td>|be{+-}</td></tr>
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<tr><td>BE3UP</td><td>B(E3)|^</td></tr>
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<tr><td>BE3WUP</td><td>B(E3)(W.u.)|^</td></tr>
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<tr><td>BE6UP</td><td>B(E6)|^</td></tr>
<tr><td>BE6W</td><td>B(E6)(W.u.)</td></tr>
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<tr><td>BE7W</td><td>B(E7)(W.u.)</td></tr>
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<tr><td>BGN</td><td>|b|gn</td></tr>
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<tr><td>BGT</td><td>|b(GT)</td></tr>
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<tr><td>BL</td><td>|b{-L}</td></tr>
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<tr><td>ISPIN</td><td>T</td></tr>
<tr><td>ISPINZ</td><td>T{-z}</td></tr>
<tr><td>IT BRANCHING</td><td>IT branching</td></tr>
<tr><td>IT DECAY</td><td>IT decay</td></tr>
<tr><td>IT DECAYS</td><td>IT decays</td></tr>
<tr><td>IT TRANSITION</td><td>IT transition</td></tr>
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<table>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>IT-</td><td>IT-</td></tr>
<tr><td>IT=</td><td>IT=</td></tr>
<tr><td>IX</td><td>I(x ray)</td></tr>
<tr><td>J</td><td>J</td></tr>
<tr><td>J**2</td><td>J{+2}</td></tr>
<tr><td>J0</td><td>J{-0}</td></tr>
<tr><td>J1</td><td>J{-1}</td></tr>
<tr><td>J2</td><td>J{-2}</td></tr>
<tr><td>JANUARY</td><td>January</td></tr>
<tr><td>JF</td><td>J{-f}</td></tr>
<tr><td>JI</td><td>J{-i}</td></tr>
<tr><td>JKP</td><td>JK|p</td></tr>
<tr><td>JMAX</td><td>Jmax</td></tr>
<tr><td>JMIN</td><td>Jmin</td></tr>
<tr><td>JOSEF</td><td>JOSEF</td></tr>
<tr><td>JPI</td><td>J|p</td></tr>
<tr><td>JULIE</td><td>JULIE</td></tr>
<tr><td>JULY</td><td>July</td></tr>
<tr><td>JUNE</td><td>June</td></tr>
<tr><td>K</td><td>K</td></tr>
<tr><td>K/L+M</td><td>K/L+M</td></tr>
<tr><td>K/LM</td><td>K/LM</td></tr>
<tr><td>K/T</td><td>ce(K)/(|g+ce)</td></tr>
<tr><td>KAPPA</td><td>|k</td></tr>
<tr><td>KC</td><td>|a(K)</td></tr>
<tr><td>KELSON</td><td>Kelson</td></tr>
<tr><td>KEV</td><td>keV</td></tr>
<tr><td>KEVIN</td><td>Kelvin</td></tr>
<tr><td>KG</td><td>kG</td></tr>
<tr><td>KL1L1</td><td>KL{-1}L{-1}</td></tr>
<tr><td>KL1L2</td><td>KL{-1}L{-2}</td></tr>
<tr><td>KL1L3</td><td>KL{-1}L{-3}</td></tr>
<tr><td>KL1M1</td><td>KL{-1}M{-1}</td></tr>
<tr><td>KL1M2</td><td>KL{-1}M{-2}</td></tr>
<tr><td>KL1M3</td><td>KL{-1}M{-3}</td></tr>
<tr><td>KL2L2</td><td>KL{-2}L{-2}</td></tr>
<tr><td>KL2L3</td><td>KL{-2}L{-3}</td></tr>
<tr><td>KL2M1</td><td>KL{-2}M{-1}</td></tr>
<tr><td>KL2M3</td><td>KL{-2}M{-3}</td></tr>
<tr><td>KL2M4</td><td>KL{-2}M{-4}</td></tr>
<tr><td>KL3L3</td><td>KL{-3}L{-3}</td></tr>
<tr><td>KL3LM1</td><td>KL{-3}LM{-1}</td></tr>
<tr><td>KL3M2</td><td>KL{-3}M{-2}</td></tr>
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<tr><td>KL3N</td><td>KL{-3}N</td></tr>
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<table>
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<tr><td>KLL</td><td>KLL</td></tr>
<tr><td>KLM</td><td>KLM</td></tr>
<tr><td>KM2M3</td><td>KM{-2}M{-3}</td></tr>
<tr><td>KM2N2</td><td>KM{-2}N{-2}</td></tr>
<tr><td>KM3M3</td><td>KM{-3}M{-3}</td></tr>
<tr><td>KNIGHT</td><td>Knight</td></tr>
<tr><td>KOE</td><td>kOe</td></tr>
<tr><td>KPI</td><td>K|p</td></tr>
<tr><td>KRANE</td><td>Krane</td></tr>
<tr><td>KRONIG</td><td>Kronig</td></tr>
<tr><td>KUO-BROWN</td><td>Kuo-Brown</td></tr>
<tr><td>KURIE</td><td>Kurie</td></tr>
<tr><td>KXY</td><td>KXY</td></tr>
<tr><td>L</td><td>L</td></tr>
<tr><td>L+/T</td><td>ce(L+)/(|g+ce)</td></tr>
<tr><td>L/T</td><td>ce(L)/(|g+ce)</td></tr>
<tr><td>L1</td><td>L1</td></tr>
<tr><td>L12</td><td>L12</td></tr>
<tr><td>L12C</td><td>|a(L12)</td></tr>
<tr><td>L1C</td><td>|a(L1)</td></tr>
<tr><td>L2</td><td>L2</td></tr>
<tr><td>L23</td><td>L23</td></tr>
<tr><td>L23C</td><td>|a(L23)</td></tr>
<tr><td>L2C</td><td>|a(L2)</td></tr>
<tr><td>L3</td><td>L3</td></tr>
<tr><td>L3C</td><td>|a(L3)</td></tr>
<tr><td>LA</td><td>|?<</td></tr>
<tr><td>LAMBDA</td><td>|l</td></tr>
<tr><td>LAMPF</td><td>LAMPF</td></tr>
<tr><td>LARMOR</td><td>Larmor</td></tr>
<tr><td>LASER</td><td>LASER</td></tr>
<tr><td>LBL</td><td>LBL</td></tr>
<tr><td>LC</td><td>|a(L)</td></tr>
<tr><td>LE</td><td>|<</td></tr>
<tr><td>LEGENDRE</td><td>Legendre</td></tr>
<tr><td>LI</td><td>Li</td></tr>
<tr><td>LITHERLAND</td><td>Litherland</td></tr>
<tr><td>LM</td><td>LM</td></tr>
<tr><td>LMN</td><td>LMN</td></tr>
<tr><td>LN</td><td>L(n)</td></tr>
<tr><td>LOGF1T</td><td>log| {If{+1}t}</td></tr>
<tr><td>LOGF1UT</td><td>log| {If{+1u}t}</td></tr>
<tr><td>LOGF2UT</td><td>log| {If{+2u}t}</td></tr>
<tr><td>LOGF3UT</td><td>log| {If{+3u}t}</td></tr>
<tr><td>LOGFT</td><td>log| {Ift}</td></tr>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>LOHENGRIN</td><td>LOHENGRIN</td></tr>
<tr><td>LORENTZIAN</td><td>Lorentzian</td></tr>
<tr><td>LP</td><td>L(p)</td></tr>
<tr><td>LT</td><td><</td></tr>
<tr><td>M</td><td>M</td></tr>
<tr><td>M+/T</td><td>ce(M+)/(|g+ce)</td></tr>
<tr><td>M+=</td><td>M+=</td></tr>
<tr><td>M-SHELL</td><td>M-shell</td></tr>
<tr><td>M-SUBSHELL</td><td>M-subshell</td></tr>
<tr><td>M/CE</td><td>M/total ce</td></tr>
<tr><td>M/T</td><td>ce(M)/(|g+ce)</td></tr>
<tr><td>M1</td><td>M1</td></tr>
<tr><td>M12</td><td>M12</td></tr>
<tr><td>M1C</td><td>|a(M1)</td></tr>
<tr><td>M2</td><td>M2</td></tr>
<tr><td>M23</td><td>M23</td></tr>
<tr><td>M2C</td><td>|a(M2)</td></tr>
<tr><td>M3</td><td>M3</td></tr>
<tr><td>M3C</td><td>|a(M3)</td></tr>
<tr><td>M4</td><td>M4</td></tr>
<tr><td>M45</td><td>M45</td></tr>
<tr><td>M4C</td><td>|a(M4)</td></tr>
<tr><td>M5</td><td>M5</td></tr>
<tr><td>M5C</td><td>|a(M5)</td></tr>
<tr><td>M6</td><td>M6</td></tr>
<tr><td>M8</td><td>M8</td></tr>
<tr><td>MARCH</td><td>March</td></tr>
<tr><td>MB</td><td>mb</td></tr>
<tr><td>MB/SR</td><td>mb/sr</td></tr>
<tr><td>MC</td><td>|a(M)</td></tr>
<tr><td>MC+</td><td>|a(M+..)</td></tr>
<tr><td>MEDLIST</td><td>MEDLIST</td></tr>
<tr><td>MEV</td><td>MeV</td></tr>
<tr><td>MEV**-4</td><td>MeV{E4-4}</td></tr>
<tr><td>MG/CM2</td><td>mg/cm{+2}</td></tr>
<tr><td>MHZ</td><td>MHZ</td></tr>
<tr><td>MILLI-EV</td><td>meV</td></tr>
<tr><td>MIT</td><td>MIT</td></tr>
<tr><td>ML</td><td>M+L</td></tr>
<tr><td>MNO</td><td>M+N+O</td></tr>
<tr><td>MOME2</td><td>Q</td></tr>
<tr><td>MOME3</td><td>Octupole mom(el)</td></tr>
<tr><td>MOMM1</td><td>|m</td></tr>
<tr><td>MOMM3</td><td>Octupole mom(mag)</td></tr>
<tr><td>MOMM5</td><td>2{+5} mom(mag)</td></tr>
</table>

ENSDF	Translation
MOMM7	2{+7} mom(mag)
MOSSBAUER	Mossbauer
MOSZKOWSKI	Moszkowski
MR	|d
MR**2	|d{+2}
MS	ms
MU	|m
MU-	|m{+-}
N*SIGMA	N|*|s
N+/T	ce(N+)/(|g+ce)
N-SHELL	N-shell
N-SUBSHELL	N-subshell
N-Z	N-Z
N/T	ce(N)/(|g+ce)
N1	N1
N12	N12
N123	N123
N1C	|a(N1)
N2	N2
N23	N23
N2C	|a(N2)
N3	N3
N3C	|a(N3)
N4	N4
N45	N45
N4C	|a(N4)
N5	N5
N5C	|a(N5)
N6C	|a(N6)
N<	N<
N=	N=
NAI	NaI
NB	I|b normalization
NB/SR	nb/sr
NBS	NBS
NC	|a(N)
NC+	|a(N+..)
NC2S	NC{+2}S
NDS	Nuclear Da Sheets
NE	|=
NE213	NE213
NG	n|g
NGG	n|g|g
NILSSON	Nilsson
NMR	NMR
NOTE:	Note:
NOVEMBER	November
NP	Particle normalization
NQR	NQR
NR	I|g normalization
NS*SIGMA	NS|s
NT	I(|g+ce) normalization
NU	|n
NX	NX
Ne	Ne
O	O
O/Q	O/Q
O/T	ce(O)/(|g+ce)
O1	O1
O123	O123
O1C	|a(O1)
O2	O2
O2C	|a(O2)
O3	O3
O3C	|a(O3)
O4C	|a(O4)
OCTOBER	October
ODD-A	odd-A
OMEGA	|w
OMEGA**2*TAU	|w{+2}|t
OMEGA*T	|w|t
ORNL	ORNL
OSIRIS	OSIRIS
P DECAY	p decay
P(THETA)	p(|q)
P+/T	ce(P+)/(|g+ce)
P-WIDTH	p-width
P0	P{-0}
P1	P1
P1/2	p1/2
P1C	|a(P1)
P2NG	p2n|g
PAC	PAC
PAD	PAD
PALPHA	p|a
PG	p|g
PGG	p|g|g
PHI	|F
PHI(P1)	|F(p{-1})
PHI(P2)	|F(p{-2})

<table>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>PI</td><td>|p</td></tr>
<tr><td>PI-</td><td>|p{+-}</td></tr>
<tr><td>PIB</td><td>|p|b</td></tr>
<tr><td>PIBG</td><td>|p|b|g</td></tr>
<tr><td>PIG</td><td>|p|g</td></tr>
<tr><td>PN</td><td>P{-n}</td></tr>
<tr><td>PNG</td><td>pn|g</td></tr>
<tr><td>PRI</td><td>|DI|g(%)</td></tr>
<tr><td>PSI</td><td>|Y</td></tr>
<tr><td>PWBA</td><td>PWBA</td></tr>
<tr><td>PWIA</td><td>PWIA</td></tr>
<tr><td>Q</td><td>Q</td></tr>
<tr><td>Q(</td><td>Q(</td></tr>
<tr><td>Q+O</td><td>Q+O</td></tr>
<tr><td>Q+_</td><td>Q(|e)</td></tr>
<tr><td>Q^{-}</td><td>Q(|b{+-})</td></tr>
<tr><td>Q/D</td><td>Q/D</td></tr>
<tr><td>Q22</td><td>Q{-22}</td></tr>
<tr><td>Q2D</td><td>Q2D</td></tr>
<tr><td>Q2DM</td><td>Q2DM</td></tr>
<tr><td>Q3D</td><td>Q3D</td></tr>
<tr><td>QA</td><td>Q(|a)</td></tr>
<tr><td>QDD</td><td>QDD</td></tr>
<tr><td>QDDM</td><td>QDDM</td></tr>
<tr><td>QDMDQ</td><td>QDMDQ</td></tr>
<tr><td>QMG</td><td>QMG</td></tr>
<tr><td>QP</td><td>Q(g.s.)</td></tr>
<tr><td>QQSP</td><td>QQSP</td></tr>
<tr><td>QS</td><td>Q{-s}</td></tr>
<tr><td>QSD</td><td>QSD</td></tr>
<tr><td>R</td><td>R</td></tr>
<tr><td>R(DCO)</td><td>R(DCO)</td></tr>
<tr><td>R**2</td><td>r{+2}</td></tr>
<tr><td>R**4</td><td>r{+4}</td></tr>
<tr><td>R**6</td><td>r{+6}</td></tr>
<tr><td>R0</td><td>r{-0}</td></tr>
<tr><td>RDDS</td><td>RDDS</td></tr>
<tr><td>RDM</td><td>RDM</td></tr>
<tr><td>RHO</td><td>|r</td></tr>
<tr><td>RHO**2</td><td>|r{+2}</td></tr>
<tr><td>RI</td><td>I|g</td></tr>
<tr><td>RITZ</td><td>Ritz</td></tr>
<tr><td>ROSE</td><td>Rose</td></tr>
<tr><td>RPA</td><td>RPA</td></tr>
<tr><td>RUL</td><td>RUL</td></tr>
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<tr><td>RUTHERFORD</td><td>Rutherford</td></tr>
<tr><td>RYTZ</td><td>Rytz</td></tr>
<tr><td>S VALUE</td><td>S value</td></tr>
<tr><td>S VALUES</td><td>S values</td></tr>
<tr><td>S'</td><td>S'</td></tr>
<tr><td>S(2N)</td><td>S(2n)</td></tr>
<tr><td>S(2P)</td><td>S(2p)</td></tr>
<tr><td>S(CE)</td><td>s(ce)</td></tr>
<tr><td>S-1</td><td>s{+-1}</td></tr>
<tr><td>S-FACTOR</td><td>S-factor</td></tr>
<tr><td>S-FACTORS</td><td>S-factors</td></tr>
<tr><td>S-VALUE</td><td>S-value</td></tr>
<tr><td>S-VALUES</td><td>S-values</td></tr>
<tr><td>S-WAVE</td><td>s-wave</td></tr>
<tr><td>S/</td><td>S/</td></tr>
<tr><td>S=</td><td>S=</td></tr>
<tr><td>SA</td><td>S(|a)</td></tr>
<tr><td>SAXON</td><td>Saxon</td></tr>
<tr><td>SCHMIDT</td><td>Schmidt</td></tr>
<tr><td>SD</td><td>SD</td></tr>
<tr><td>SDB</td><td>SDB</td></tr>
<tr><td>SE(LI)</td><td>Se(Li)</td></tr>
<tr><td>SELTZER</td><td>Seltzer</td></tr>
<tr><td>SEPTEMBER</td><td>September</td></tr>
<tr><td>SF</td><td>SF</td></tr>
<tr><td>SI(LI)</td><td>Si(Li)</td></tr>
<tr><td>SIGMA</td><td>|s</td></tr>
<tr><td>SIGMA(0)</td><td>|s{-0}</td></tr>
<tr><td>SIGMA*DE</td><td>|s|*|DE</td></tr>
<tr><td>SIGMAG</td><td>|s{-|g}</td></tr>
<tr><td>SIGMAN</td><td>|s{-n}</td></tr>
<tr><td>SIGMANU</td><td>|s|n</td></tr>
<tr><td>SIGNA</td><td>|s(n|a)</td></tr>
<tr><td>SIGNG</td><td>|s(n|g)</td></tr>
<tr><td>SILI</td><td>Si(Li)</td></tr>
<tr><td>SIO</td><td>SiO</td></tr>
<tr><td>SLIV-BAND</td><td>Sliv-Band</td></tr>
<tr><td>SN</td><td>S(n)</td></tr>
<tr><td>SOREQ</td><td>SOREQ</td></tr>
<tr><td>SP</td><td>S(p)</td></tr>
<tr><td>STEFFEN</td><td>Steffen</td></tr>
<tr><td>STOCKHOLM</td><td>Stockholm</td></tr>
<tr><td>SUMOF</td><td>|S\</td></tr>
<tr><td>SY</td><td>syst</td></tr>
<tr><td>Sn</td><td>Sn</td></tr>
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ENSDF	Translation
T	T{-1/2}
T)	t)
T,	t,
T/	T/
T1/2	T{-1/2}
T20	T20
T21	T21
T22	T22
TAU	|t
TDPAD	TDPAD
TELLER	Teller
TEMP	T
TG	t|g
TH	th
THETA	|q
THETA**2	|q{+2}
THETA1	|q{-1}
THETA2	|q{-2}
THETAA	|q|a
THETAA**2	|q|a{+2}
THETAG	|q|g
THETAP1**2	|q{-p1}{+2}
THETAP2**2	|q{-p2}{+2}
TI	I(|g+ce)
TOF	tof
TPAD	TPAD
TRISTAN	TRISTAN
TRIUMPH	TRIUMPH
Ti	Ti
U	U
U2A2	U{-2}A{-2}
UB	|mb
UB*MEV	|mb|*MeV
UB/SR	|mb/sr
UG	|mg
UG/CM	|mg/cm
UK	UK
UNISOR	UNISOR
UNIV	Univ
UNIVERSITY	University
US	|ms
USA	USA
USSR	USSR
V	V
VAP	VAP
W	W
W(THETA)*G*WIDTH	w(|q)g|G{-|g0}
W.U.	W.u.
WEISSKOPF	Weisskopf
WIDTH	|G
WIDTH**2	|G{+2}
WIDTHA	|G|a
WIDTHA0	|G{-|a0}
WIDTHA1	|G{-|a1}
WIDTHA2	|G{-|a2}
WIDTHA3	|G{-|a3}
WIDTHA4	|G{-|a4}
WIDTHG	|G{-|g}
WIDTHG0	|G{-|g0}
WIDTHG0**2	|G{+2}\{-|g0}
WIDTHG1	|G{-|g1}
WIDTHN	|G{-n}
WIDTHN0	|G{-n0}
WIDTHP	|G{-p}
WIDTHP'	|G{-p'}
WIDTHP0	|G{-p0}
WIDTHP1	|G{-p1}
WIDTHP2	|G{-p2}
WIGNER	Wigner
WINTHER	Winther
X(	X(
X-RAY	x-ray
X-RAYS	x-rays
XG	X|g
XK	K| x ray
XKA	K|a| x ray
XKA1	K|a{-1}| x ray
XKA2	K|a{-2}| x ray
XKB	K|b| x ray
XKB1	K|b{-1} x ray
XKB13	K|b{-13} x ray
XKB1P	K|b{-1}'| x ray
XKB2	K|b{-2} x ray
XKB2P	K|b{-2}'| x ray
XKB3	K|b{-3} x ray
XKB4	K|b{-4} x ray
XKB5	K|b{-5} x ray
XKB5I	K|b{-5}\{+I} x ray
XKB5II	K|b{-5}\{+II} x ray
XKG	(K| x ray)|g

<table>
<tr><th>ENSDF</th><th>Translation</th></tr>
<tr><td>XKO2</td><td>K-O{-2} x ray</td></tr>
<tr><td>XKO23</td><td>K-O{-23} x ray</td></tr>
<tr><td>XKO3</td><td>K-O{-3} x ray</td></tr>
<tr><td>XL</td><td>L| x ray</td></tr>
<tr><td>XL1</td><td>L{-1} x ray</td></tr>
<tr><td>XL2</td><td>L{-2} x ray</td></tr>
<tr><td>XL3</td><td>L{-3} x ray</td></tr>
<tr><td>XLA</td><td>L{-|a} x ray</td></tr>
<tr><td>XLA1</td><td>L|a{-1}| x ray</td></tr>
<tr><td>XLA2</td><td>L|a{-2}| x ray</td></tr>
<tr><td>XLB</td><td>L{-|b} x ray</td></tr>
<tr><td>XLB1</td><td>L|b{-1}| x ray</td></tr>
<tr><td>XLB10</td><td>L|b{-10}| x ray</td></tr>
<tr><td>XLB15</td><td>L|b{-15}| x ray</td></tr>
<tr><td>XLB2</td><td>L|b{-2}| x ray</td></tr>
<tr><td>XLB215</td><td>L|b{-215}| x ray</td></tr>
<tr><td>XLB3</td><td>L|b{-3}| x ray</td></tr>
<tr><td>XLB4</td><td>L|b{-4}| x ray</td></tr>
<tr><td>XLB5</td><td>L|b{-5}| x ray</td></tr>
<tr><td>XLB6</td><td>L|b{-6}| x ray</td></tr>
<tr><td>XLB9</td><td>L|b{-9}| x ray</td></tr>
<tr><td>XLC</td><td>L{-|c} x ray</td></tr>
<tr><td>XLG</td><td>L{-|g} x ray</td></tr>
<tr><td>XLG1</td><td>L|g{-1}| x ray</td></tr>
<tr><td>XLG2</td><td>L|g{-2}| x ray</td></tr>
<tr><td>XLG3</td><td>L|g{-3}| x ray</td></tr>
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<tr><td>XLG5</td><td>L|g{-5}| x ray</td></tr>
<tr><td>XLG6</td><td>L|g{-6}| x ray</td></tr>
<tr><td>XLL</td><td>L{-{Sl}} x ray</td></tr>
<tr><td>XM</td><td>M x ray</td></tr>
<tr><td>XPYNG</td><td>xpyn|g</td></tr>
<tr><td>XX</td><td>XX</td></tr>
<tr><td>YTTRIUM</td><td>Y</td></tr>
<tr><td>Z</td><td>Z</td></tr>
<tr><td>Z>N</td><td>Z>N</td></tr>
<tr><td>[E2]</td><td>[E2]</td></tr>
<tr><td>[RI</td><td>[I|g</td></tr>
<tr><td>a0</td><td>a{-0}</td></tr>
<tr><td>|D</td><td>|D</td></tr>
</table>

Appendix G

ENSDF Dictionary Ordered by Output

Translation	ENSDF
(α)(ce)	ACE
(β)	(B)
(θ,H,t,T)	(THETA,H,T,T)
(θ,H)	(THETA,H)
(θ,T,H)	(THETA,T,H)
2J	2J
2Nσ	2N*SIGMA
2^5mom(mag)	MOMM5
2^7mom(mag)	MOMM7
$2\beta^-$	2B-
4π	4PI
4πβγ	4PIBG
4πβ	4PIB
4πγ	4PIG
<	LT
>	GT
A(θ)	A(THETA)
A-N	A-N
A=	A=
AAS	AAS
AB	AB
AJ	AJ
Aa_0	AA0
Alaga	ALAGA
April	APRIL
Auger	AUGER
August	AUGUST
Ay	AY
$A^{1/3}$	A**1/3
$A^{2/3}$	A**2/3
A_0	A0
A_{11}	A11
A_1	A1
A_{22}	A22
A_2/A_0	A2/A0
A_2	A2
A_2P_2	A2P2
A_3	A3
A_{44}	A44
A_4	A4
A_5	A5
A_6	A6
A_7	A7

Translation	ENSDF
B(E0	B(E0
B(E0)	BE0
B(E0)(W.u.)	BE0W
B(E1	B(E1
B(E1)(W.u.)	BE1W
B(E1)↑	BE1UP
B(E1)	BE1
B(E2	B(E2
B(E2)	BE2
B(E2)↑	BE2UP
B(E2)↓	BE2DWN
B(E2)(W.u.)	BE2W
B(E3	B(E3
B(E3)↑	BE3UP
B(E3)(W.u.)↑	BE3WUP
B(E3)	BE3
B(E3)(W.u.)	BE3W
B(E4	B(E4
B(E4)↑	BE4UP
B(E4)(W.u.)	BE4W
B(E4)	BE4
B(E5)	BE5
B(E5)(W.u.)	BE5W
B(E6)(W.u.)	BE6W
B(E6)↑	BE6UP
B(E6)	BE6
B(E7)(W.u.)	BE7W
B(E7)	BE7
B(E8)	BE8
B(EL)(W.u.)	BELW
B(EL)	BEL
B(J	B(J
B(M1)	BM1
B(M1)↑	BM1UP
B(M1)(W.u.)	BM1W
B(M2)	BM2
B(M2)↑	BM2UP
B(M2)(W.u.)	BM2W
B(M3)(W.u.)	BM3W
B(M3)	BM3
B(M4)	BM4
B(M4)(W.u.)	BM4W
B(M5)(W.u.)	BM5W

Translation	ENSDF
B(M8)↑	BM8UP
B(ML)	BML
B(ML)(W.u.)	BMLW
B/A	B/A
B=	B=
BCS	BCS
BE(L)	BE(L)
BF_3	BF3
BGO	BGO
BJ^2	BJ**2
BM(L)	BM(L)
Be	Be
Berkeley	BERKELEY
Bessel	BESSEL
Bethe	BETHE
Biedenharn	BIEDENHARN
Blair	BLAIR
Bohr	BOHR
Born	BORN
Branching	BR
Breit	BREIT
Brink	BRINK
B_4C	B4C
Bxρ	B*RHO
C	C
CCBA	CCBA
CCC	CCC
CERN	CERN
CP	CP
CRC	CRC
Ca(OH)	CA(OH)
Cerenkov	CERENKOV
Clebsch	CLEBSCH
Cm	Cm
Co	CO
Compton	COMPTON
Coriolis	CORIOLIS
Coster	COSTER
Coul	COUL
Coulomb	COULOMB
CsI	CSI
Curie	CURIE
C^2S	C2S
D)	D)
D+(Q)	D+(Q)

Translation	ENSDF
D+Q	D+Q
DCO	DCO
DCOQ	DCOQ
DPAC	DPAC
DPAD	DPAD
DSA	DSA
DSAM	DSAM
DWBA	DWBA
DWIA	DWIA
DWUCK	DWUCK
Davydov	DAVYDOV
December	DECEMBER
Doppler	DOPPLER
Dubna	DUBNA
E	E
E(ce)	ECE
E(d)	ED
E(d)	E(D)
E(e)	E(E)
E(n)	E(N)
E(n)	EN
E(p)	EP
E(p)	E(P)
$E(p_2)$	E(P2)
$E(p_1)$	E(P1)
E(t)	ET
E(t)	E(T)
E(α)	E(A)
E-E	E-E
E/ΔE	E/DE
E0	E0
E1	E1
E10	E10
E2	E2
E3	E3
E4	E4
E5	E5
E6	E6
E7	E7
E8	E8
E9	E9
EL	EL
ENDF/B-V	ENDF/B-V
ENDF/B	ENDF/B_
ENDOR	ENDOR

Translation	ENSDF
EPR	EPR
ESR	ESR
EWSR	EWSR
Ee	EE
Enge	ENGE
E	E
$E^{1/2}$	E**1/2
E^{2}	E**2
EΔE	EDE
Eα	EA
Eβ	EB
Eβ	EB_
$E\beta^{-}$	EB_
Eε	EEC
Eγ	*EG
Eγ	EG
$E\gamma^{3}$	EG**3
$E\gamma^{5}$	EG**5
F+B	F+B
F-K	F-K
F/B	F/B
FWHM	FWHM
February	FEBRUARY
Fermi	FERMI
Feshbach	FESHBACH
Fock	FOCK
Fourier	FOURIER
G-M	G-M
GDR	GDR
GM	GM
GMR	GMR
GQR	GQR
GSI	GSI
GTOL	GTOL
Gallagher	GALLAGHER
Gamow	GAMOW
Garvey	GARVEY
Gaussian	GAUSSIAN
Ge(Li)	GE(LI)
Ge(Li)	GELI
GeV	GEV
Geiger-Muller	GEIGER-MULLER
Geiger	GEIGER
H(	H(
H,	H,
H=	H=
HERA	HERA
HF	HF
HI	HI
HP	HP
HPGE	HPGE
Hager	HAGER
Hartree	HARTREE
Hauser	HAUSER
I	I
I(xray)	IX
I(γ+ce)	TI
I(γ+ce) normalization	NT
IAR	IAR
IAS	IAS
IBA	IBA
IBM	IBM
IBS	IBS
IGISOL	IGISOL
IMPAC	IMPAC
IPAC	IPAC
ISOLDE	ISOLDE
IT branching	IT BRANCHING
IT decay	IT DECAY
IT decays	IT DECAYS
IT=	IT=
Ice	ICE
Ice(K)	ICE(K)
Ice(N)	ICE(N)
In(	IN(
Iα	IA
Iβ	IB
Iβ normalization	NB
$I\beta^{-}$	IB-
$I\beta^{+}$	IB+
Iε	IE
Iε	IEC
Iγ	IG
Iγ	*RI
Iγ	RI
Iγ normalization	NR
IγEγ	IG*EG
J	J
JKπ	JKP
JOSEF	JOSEF

Translation	ENSDF
JULIE	JULIE
January	JANUARY
Jmax	JMAX
Jmin	JMIN
July	JULY
June	JUNE
J^2	J**2
J_0	J0
J_1	J1
J_2	J2
J_f	JF
J_i	JI
Jπ	JPI
K	K
K-O_2 xray	XKO2
K-O_3 xray	XKO3
K-O_{23} xray	XKO23
K/L+M	K/L+M
K/LM	K/LM
KLL	KLL
KLM	KLM
KL_1L_1	KL1L1
KL_1M_2	KL1M2
KL_1L_3	KL1L3
KL_1M_3	KL1M3
KL_1M_1	KL1M1
KL_1L_2	KL1L2
KL_2M_1	KL2M1
KL_2L_2	KL2L2
KL_2L_3	KL2L3
KL_2M_3	KL2M3
KL_2M_4	KL2M4
KL_3L_3	KL3L3
KL_3LM_1	KL3LM1
KL_3N	KL3N
KL_3M_3	KL3M3
KL_3M_2	KL3M2
KM_2M_3	KM2M3
KM_2N_2	KM2N2
KM_3M_3	KM3M3
KXY	KXY
Kelson	KELSON
Kelvin	KEVIN
Knight	KNIGHT
Krane	KRANE

Translation	ENSDF
Kronig	KRONIG
Kuo-Brown	KUO-BROWN
Kurie	KURIE
K xray	XK
$K\alpha_2$ xray	XKA2
$K\alpha_1$ xray	XKA1
Kα xray	XKA
$K\beta_2$ xray	XKB2
$K\beta_2'$ xray	XKB2P
$K\beta_4$ xray	XKB4
$K\beta_3$ xray	XKB3
$K\beta_1$ xray	XKB1
$K\beta_1'$ xray	XKB1P
$K\beta^{I}_5$x	XKB5I
$K\beta^{II}_5$x	XKB5II
$K\beta_{13}$ xray	XKB13
$K\beta_5$ xray	XKB5
Kβ xray	XKB
Kπ	KPI
L	L
L(n)	LN
L(p)	LP
L1	L1
L12	L12
L2	L2
L23	L23
L3	L3
LAMPF	LAMPF
LASER	LASER
LBL	LBL
LM	LM
LMN	LMN
LOHENGRIN	LOHENGRIN
Larmor	LARMOR
Legendre	LEGENDRE
Li	LI
Litherland	LITHERLAND
Lorentzian	LORENTZIAN
L_1xray	XL1
L_2xray	XL2
L_3xray	XL3
$L_l$xray	XLL
$L_\alpha$xray	XLA
$L_\beta$xray	XLB
$L_\eta$xray	XLC

Translation	ENSDF
L_{γ}xray	XLG
L xray	XL
$L\alpha_1$ xray	XLA1
$L\alpha_2$ xray	XLA2
$L\beta_3$ xray	XLB3
$L\beta_4$ xray	XLB4
$L\beta_1$ xray	XLB1
$L\beta_5$ xray	XLB5
$L\beta_2$ xray	XLB2
$L\beta_{215}$ xra	XLB215
$L\beta_9$ xray	XLB9
$L\beta_{15}$ xray	XLB15
$L\beta_6$ xray	XLB6
$L\beta_{10}$ xray	XLB10
$L\gamma_3$ xray	XLG3
$L\gamma_4$ xray	XLG4
$L\gamma_6$ xray	XLG6
$L\gamma_5$ xray	XLG5
$L\gamma_2$ xray	XLG2
$L\gamma_1$ xray	XLG1
M	M
M x ray	XM
M+=	M+=
M+L	ML
M+N+O	MNO
M-shell	M-SHELL
M-subshell	M-SUBSHELL
M/total ce	M/CE
M1	M1
M12	M12
M2	M2
M23	M23
M3	M3
M4	M4
M45	M45
M5	M5
M6	M6
M8	M8
MEDLIST	MEDLIST
MHZ	MHZ
MIT	MIT
March	MARCH
MeV	MEV
MeV{E4-4}	MEV**-4
Mossbauer	MOSSBAUER

Translation	ENSDF
Moszkowski	MOSZKOWSKI
N-Z	N-Z
N-shell	N-SHELL
N-subshell	N-SUBSHELL
N1	N1
N12	N12
N123	N123
N2	N2
N23	N23
N3	N3
N4	N4
N45	N45
N5	N5
N<	N<
N=	N=
NBS	NBS
NC^{2}S	NC2S
NE213	NE213
NMR	NMR
NQR	NQR
NSσ	NS*SIGMA
NX	NX
NaI	NAI
Ne	Ne
Nilsson	NILSSON
Note:	NOTE:
November	NOVEMBER
NuclearDataSheets	NDS
Nxσ	N*SIGMA
O	O
O/Q	O/Q
O1	O1
O123	O123
O2	O2
O3	O3
ORNL	ORNL
OSIRIS	OSIRIS
October	OCTOBER
Octupole mom(mag)	MOMM3
Octupole mom(el)	MOME3
P1	P1
PAC	PAC
PAD	PAD
PWBA	PWBA
PWIA	PWIA

Translation	ENSDF
Particle normalization	NP
P_0	P0
P_n	PN
Q	MOME2
Q	Q
Q(	Q(
Q(g.s.)	QP
Q(α)	QA
$Q(\beta^-)$	Q-
Q(ε)	Q+_
Q+O	Q+O
Q/D	Q/D
Q2D	Q2D
Q2DM	Q2DM
Q3D	Q3D
QDD	QDD
QDDM	QDDM
QDMDQ	QDMDQ
QMG	QMG
QQSP	QQSP
QSD	QSD
Q_{22}	Q22
Q_s	QS
R	*R
R	R
R(DCO)	R(DCO)
RDDS	RDDS
RDM	RDM
RPA	RPA
RUL	RUL
Ritz	RITZ
Rose	ROSE
Rutherford	RUTHERFORD
Rytz	RYTZ
S values	S VALUES
S value	S VALUE
S'	S'
S(2n)	S(2N)
S(2p)	S(2P)
S(n)	SN
S(p)	SP
S(α)	SA
S-factors	S-FACTORS
S-factor	S-FACTOR
S-value	S-VALUE
S-values	S-VALUES
S/	S/
S=	S=
SD	SD
SDB	SDB
SF	SF
SOREQ	SOREQ
Saxon	SAXON
Schmidt	SCHMIDT
Se(Li)	SE(LI)
Seltzer	SELTZER
September	SEPTEMBER
Si(Li)	SI(LI)
Si(Li)	SILI
SiO	SIO
Sliv-Band	SLIV-BAND
Sn	Sn
Steffen	STEFFEN
Stockholm	STOCKHOLM
T	TEMP
T	ISPIN
T/	T/
T20	T20
T21	T21
T22	T22
TDPAD	TDPAD
TPAD	TPAD
TRISTAN	TRISTAN
TRIUMPH	TRIUMPH
Teller	TELLER
Ti	Ti
$T_{1/2}$	T1/2
$T_{1/2}$	T
T_z	ISPINZ
U	U
UK	UK
UNISOR	UNISOR
USA	USA
USSR	USSR
Univ	UNIV
University	UNIVERSITY
U_2A_2	U2A2
V	V
VAP	VAP
W	W

Translation	ENSDF
W.u.	W.U.
Weisskopf	WEISSKOPF
Wigner	WIGNER
Winther	WINTHER
X(	X(
XX	XX
Xγ	XG
Y	YTTRIUM
Z	Z
Z>N	Z>N
[E2]	[E2]
[Iγ	[RI
°	DEG
x	*
avEβ	EAV
a_0	a0
branching uncertainty	DBR
c.m.	C.M.
ce	CE
ce(K)/(γ+ce)	K/T
ce(K)	CEK
ce(L)/(γ+ce)	L/T
ce(L)	CEL
ce(L+)/(γ+ce)	L+/T
ce(L1)	CEL1
ce(L12)	CEL12
ce(L23)	CEL23
ce(L2)	CEL2
ce(L3)	CEL3
ce(M)/(γ+ce)	M/T
ce(M)	CEM
ce(M+)/(γ+ce)	M+/T
ce(M1)	CEM1
ce(M2)	CEM2
ce(M23)	CEM23
ce(M3)	CEM3
ce(M45)	CEM45
ce(M4)	CEM4
ce(M5)	CEM5
ce(N)/(γ+ce)	N/T
ce(N)	CEN
ce(N+)/(γ+ce)	N+/T
ce(N1)	CEN1
ce(N2)	CEN2
ce(N3)	CEN3

Translation	ENSDF
ce(N45)	CEN45
ce(N4)	CEN4
ce(N5)	CEN5
ce(O)	CEO
ce(O)/(γ+ce)	O/T
ce(O)+ce(P)	CEO+CEP
ce(O1)	CEO1
ce(P+)/(γ+ce)	P+/T
ceβ	CEB
ceγ	CEG
cm^2	CM2
cm^3	CM3
configuration=	CONF=
configuration	CONF
$cos^2θ$	COS2TH
dE/dx	DE/DX
d^3He	D3HE
dΩ	DOMEGA
dγ	DG
dσ	DSIGMA
dσ/dΩ	DS/DW
dσ/dΩ	*DS/DW
e'(θ)	E'(THETA)
eV	EV
even-A	EVEN-A
ex.	EX.
e+	E+
e±	E+-
fm	FM
fm^{-1}	FM-1
fm^{-1}	FM**-1
fm^2	FM**2
fm^4	FM**4
g factor	G FACTOR
g factors	G FACTORS
g(2+	G(2+
g-factors	G-FACTORS
g-factor	G-FACTOR
g.s.	GS
g=	G=
gT	G*T
$gT_{1/2}$	GT1/2
$gWΓ_0^2$	G*W*WIDTHG0**2
$gwΓ_{γ0}$	G*W*WIDTHG0
$g_1Γ$	G1*WIDTH

Translation	ENSDF	Translation	ENSDF
g_1	G1	s-wave	S-WAVE
$g_2\Gamma$	G2*WIDTH	syst	SY
g_2	*G2	s^{-1}	S-1
g_2	G2	t)	T)
$g^2{}_A$	GA2	t,	T,
$g\Gamma$	G*WIDTH	th	TH
$g\Gamma^2{}_{\gamma 0}$	*G*WIDTHG0**2	tof	TOF
$g\Gamma^2{}_{\gamma 0}$	G*WIDTHG0**2	tγ	TG
$g\Gamma_n$	G*WIDTHN	$w(\theta)g\Gamma_{\gamma 0}$	W(THETA)*G*WID
$g\Gamma_{\gamma 0}$	G*WIDTHG0	x-ray	X-RAY
$g\Gamma_0\Gamma\gamma$	GWIDTH0WIDTHG	x-rays	X-RAYS
h'ω	HOMEGA	xpynγ	XPYNG
h^2	H**2	$<r^2>$	AVRSQ
is D	ISD	$<\beta^2>^{1/2}$	BAVRSQ
kG	KG	$\Delta<r^4>$	DAVRSQ4
kOe	KOE	$\Delta<r^2>$	DAVRSQ
keV	KEV	$\Delta<r^6>$	DAVRSQ6
log $f^{1u}t$	LOGF1UT	(J+½)	**(J+1/2)
log $f^{3u}t$	LOGF3UT	$^{-1}$	**-1
log $f^{2u}t$	LOGF2UT	$^{-3}$	**-3
log $f^{1}t$	LOGF1T	$^{-4}$	**-4
log ft	LOGFT	$^{1/2}$	**1/2
mb	MB	$^{1/3}$	**1/3
mb/sr	MB/SR	$^{12}C\gamma$	C12G
meV	MILLI-EV	^{2}	**2
mg/cm^2	MG/CM2	^{3}	**3
ms	MS	^{L}	**L
nb/sr	NB/SR	e.g.	E.G.
nγ	NG	i.e.	I.E.
nγγ	NGG	xE	*E
odd-A	ODD-A	$xI\beta^-$	*IB-
p decay	PDECAY	xIε	*IE
p(θ)	P(THETA)	xQ	*Q
p-width	P-WIDTH	$xT_{1/2}$	*T1/2
p1/2	P1/2	$x\alpha^{1/3}$	*A**(1/3)
p2nγ	P2NG	xσ	*SIGMA
pnγ	PNG	≤	LE
pα	PALPHA	≠	NE
pγ	PG	≥	GE
pγγ	PGG	≈	AP
r^2	R**2	≈<	LA
r^4	R**4	≈>	GA
r^6	R**6	∞	INFNT
r_0	R0	Δ	Δ
s(ce)	S(CE)	Δ(HF)	DHF

Translation	ENSDF
Δ(logft)	DFT
Δ(β-normalization)	DNB
Δ(γ-normalization)	DNR
Δ(γ+ce-normalization)	DNT
ΔA	DA
ΔA_2	DA2
ΔA_4	DA4
ΔE	DE
ΔI(γ+ce)	DTI
ΔIα	DIA
ΔIβ	DIB
ΔIε	DIE
ΔIγ	DRI
ΔIγ(%)	PRI
ΔJ	DJ
ΔJπ	DJPI
ΔK	DK
ΔL	DL
ΔN	DN
ΔQ(ε)	DQ+
$\Delta Q(\beta^-)$	DQ-
ΔQ(α)	DQA
ΔS	DS
ΔS(n)	DSN
ΔS(p)	DSP
ΔT	DISPIN
$\Delta T_{1/2}$	DT
$\Delta T_{1/2}$	DT1/2
Δ	DELTA
Δα	DCC
Δ™	DMR
Δπ	DPI
Φ	PHI
$\Phi(p_2)$	PHI(P2)
$\Phi(p_1)$	PHI(P1)
Γ	*WIDTH
Γ	WIDTH
$\Gamma^2_{\gamma 0}$	WIDTHG0**2
Γ^2	WIDTH**2
Γ_n	WIDTHN
Γ_{n0}	WIDTHN0
Γ_{p0}	WIDTHP0
Γ_{p1}	WIDTHP1
Γ_p	*WIDTHP
$\Gamma_{p'}$	WIDTHP'

Translation	ENSDF
Γ_{p2}	WIDTHP2
Γ_p	WIDTHP
$\Gamma_{\alpha 4}$	WIDTHA4
$\Gamma_{\alpha 1}$	WIDTHA1
Γ_γ	WIDTHG
$\Gamma_{\gamma 1}$	WIDTHG1
$\Gamma_{\alpha 2}$	WIDTHA2
$\Gamma_{\alpha 0}$	WIDTHA0
$\Gamma_{\gamma 0}$	WIDTHG0
$\Gamma_{\alpha 3}$	WIDTHA3
Γα	WIDTHA
Σ	*SUMOF
Σ	SUMOF
Ψ	PSI
α	ICC
α	ALPHA
α	CC
α decay	ADECAY
α decays	ADECAYS
α syst	ASYST
α'	A'
α's	ALPHAS
α(K)exp	*EKC
α(K)exp	EKC
α(K)	KC
α(L)exp	ELC
α(L)	LC
α(L12)exp	EL12C
α(L12)	L12C
α(L1)exp	EL1C
α(L1)	L1C
α(L2)	L2C
α(L23)exp	EL23C
α(L23)	L23C
α(L2)exp	EL2C
α(L3)exp	EL3C
α(L3)	L3C
α(M)exp	EMC
α(M)	MC
α(M+..)	MC+
α(M1)	M1C
α(M1)exp	EM1C
α(M2)	M2C
α(M2)exp	EM2C
α(M3)	M3C

Translation	ENSDF
α(M3)exp	EM3C
α(M4)	M4C
α(M4)exp	EM4C
α(M5)	M5C
α(M5)exp	EM5C
α(N)exp	ENC
α(N)	NC
α(N+..)	NC+
α(N1)exp	EN1C
α(N1)	N1C
α(N2)exp	EN2C
α(N2)	N2C
α(N23)exp	EN23C
α(N3)	N3C
α(N3)exp	EN3C
α(N4)exp	EN4C
α(N4)	N4C
α(N5)	N5C
α(N6)	N6C
α(O1)	O1C
α(O2)	O2C
α(O3)	O3C
α(O4)	O4C
α(P1)	P1C
α(exp)	ECC
α-decay	A-DECAY
α-syst	A-SYST
α_0	ALPHA0
α_1	ALPHA1
α_2	ALPHA2
α_3	ALPHA3
αα	AA
αγ	AG
β	BETA
β	B
β's	BETAS
β(GT)	BGT
β(IS	B(IS
β-vibrational	B-VIBRATIONAL
βR	B*R
βR	BETA*R
βc	BC
βce	BCE
βe^-	BE-
βn	BN

Translation	ENSDF
βp	BP
β^+	B+
$\beta^+\varepsilon$ Decay	BECDECAY
β^-2n	B-2N
β^-	B-_
β^-n	B-N
β_0	B0
β_{04}	B04
β_{03}	B03
β_{02}	B02
β_{00}	B00
β_{12}	B12
β_1	B1
β_{20}	B20
β_{24}	B24
β_{22}	B22
β_2R	B2*R
β_2	B2
β_3	B3
β_3R	B3*R
β_{30}	B30
β_4	B4
β_{42}	B42
β_4R	B4*R
β_5	B5
β_5R	B5*R
β_6	B6
β_6R	B6*R
β_7	B7
β_L	BL
$\beta_LRA^{1/3}$	BL*R*A**(1/3)
β_L^2	BL**2
β_LR	BL*R
βα	BA
ββ	BB
βγ	BG
βγn	BGN
βγγ	BGG
δ	MR
δ^2	MR**2
ε	EPSILON
ε	EC
ε2p	EC2P
εB	EPSILONB
εB(E2)↑	EBE2UP

Translation	ENSDF
εB(E3)↑	EBE3UP
εK	CK
εK(exp)	ECK
εL	CL
εL(exp)	ECL
εL1(exp)	ECL1
εL2(exp)	ECL2
εL3(exp)	ECL3
εM	CM
εN	CN
εp	ECP
εα	ECA
γ	GAMMA
γ	G_
γ/α	G/A
γX	GX
γce	GCE
γe^{-}	GE-
γn	GN
γp	GP
γp'	GP'
γp(t)	GP(T)
γ±	G+-
γ_0	G0
γβ	GB
$\gamma\beta^{-}$	GB-
γγ	GG
γγn	GGN
$\gamma\gamma^{\Gamma}$	GGT
γγγ	GGG
χ	CHI
χ^2	CHI**2
εM(exp)	ECM
εN(exp)	ECN
κ	KAPPA
λ	LAMBDA
μ	MOMM1
μ	MU
μb	UB
μb/sr	UB/SR
μbxMeV	UB*MEV
μg	UG
μg/cm	UG/CM
μs	US
μ^{-}	MU-

Translation	ENSDF
ν	NU
π	PI
π^{-}	PI-
πβ	PIB
πβγ	PIBG
πγ	PIG
θ	THETA
θ^2	THETA**2
θ_1	THETA1
θ_2	THETA2
θ_{p1}^2	THETAP1**2
θ_{p2}^2	THETAP2**2
θα	THETAA
$\theta\alpha^2$	THETAA**2
θγ	THETAG
ρ	RHO
ρ^2	RHO**2
σ	SIGMA
σ(nγ)	SIGNG
σ(nα)	SIGNA
σ_0	SIGMA(0)
σ_n	SIGMAN
σ_γ	SIGMAG
σxΔE	SIGMA*DE
σν	SIGMANU
Γ	*TAU
Γ	TAU
ω	OMEGA
$\omega^2\Gamma$	OMEGA**2*TAU
ωΓ	OMEGA*T

Appendix H

ENSDF Policies

GENERAL POLICIES - Presentation of Data

The Nuclear Data Sheets are prepared from the Evaluated Nuclear Structure Data File (ENSDF), a computer file maintained by the National Nuclear Data Center on behalf of the International Network for Nuclear Structure and Decay Data Evaluations. See page iii for a list of the members of this network and their evaluation responsibilities. The presentation of material in the Nuclear Data Sheets reflects the organization of ENSDF, which is a collection of "data sets". For each nuclear species, these data sets present the following types of information:

The adopted properties of the nucleus.

The evaluated results of a single type of experiment, such as a radioactive decay, a single nuclear reaction, or the combined results of a number of similar types of experiments, such as (HI,xnγ) reactions. The data given in ENSDF are primarily derived from experimental information.

The general policies and conventions followed in the preparation of these data sets and in the presentation of material in the Nuclear Data Sheets (NDS) are discussed below.

General

The following policies apply to the adoption or presentation of data. Deviations from these policies will be noted by the evaluator.

1. The excitation energies of levels connected by γ transitions are from a least-squares fit to the adopted γ energies.

2. Dominant decay branches (*i.e*., for the decay of ground states and isomeric states) are rounded off to 100 when the competing branches total less than approximately 0.001%. When only one branch has been observed and no estimate can be made for expected competing branches, the observed branch is given as ≤100 and the competing branch(es) as "%branching=?".

3. Total internal-conversion coefficients (α) for each transition are theoretical values corresponding to the listed radiation character (*i.e.*, multipolarity) and mixing ratio (δ). For a transition of mixed character (two or more multipolarities) and unknown mixing ratio, α is the average of the possible extremes and the uncertainty overlaps the full range of values.

In all calculations by the evaluator involving internal-conversion coefficients, a 3% uncertainty is assumed for the theoretical coefficients.

4 The cross reference flags (XREF), defined in the Adopted Levels table are given for each adopted level. When a level in an individual reaction or decay data set may correspond to more than one adopted level, the flag for that data set is given in lower case. In case of ambiguity, the energy from a particular data set is given as a comment.

Adopted Levels, Gammas data set

The Adopted Levels and γ radiations tables in the NDS are generated from an Adopted Levels, Gammas data set in ENSDF. This data set represents the best values for the level and γ properties as determined by the evaluator on the basis of all the available information.

The following information is included in an Adopted Levels, Gammas data set.

For the nuclide:

1. **Q** (β^-): β^- decay energy [always presented as Q(β)=M(A,Z)−M(A,Z+1)] and α decay energy [Q(α)] for the ground state.
2. **S(n) and S(p)**: Neutron and proton separation energies.
3. **XREF**: Cross-reference symbol assignments for the various experimental data sets.

For each level:

1. **E(lev)**: Excitation energy (relative to the ground state).
2. **J^{Π}**: Spin and parity with arguments supporting the assignment.
3. **$T_{1/2}$ or Γ**: Half-life or total width in center of mass.
4. **Decay branching** for the ground state and isomers (an isomer is defined as a nuclear level with $T_{1/2}$□0.1 s or one for which a separate decay data set is given in ENSDF).
5. **Q**,μ: Static electric and magnetic moments.
6. **XREF Flags** to indicate in which reaction and/or decay data sets the level is seen.
7. **Configuration assignments** (*e.g*., Nilsson orbitals in deformed nuclei, shell-model assignments in spherical nuclei).
8. **Band assignments** and possibly band parameters (*e.g.*, rotational bands in deformed regions).
9. Isomer and isotope shifts (usually only a literature reference is given).
10. Charge distribution of ground states (usually only a literature reference is given).
11. Deformation parameters.
12. **B(E2)↑,B(M1)↑**,..: Electric or magnetic excitation probabilities when the level half-life or the ground-state branching is not known.

For γ-ray and E0 transitions:

1. **Placement** in level scheme.
2. **Eγ**: Measured γ-ray or E0 transition energy.
3. **Iγ**: Relative photon intensity from each level.
4. **Mult**,δ: Electric or magnetic multipole character, the mixing ratio, and nuclear penetration parameter.
5. **CC**: Total internal-conversion coefficient (when significant).
6 **(EL)(W.u.),B(M1)(W.u.)**,..: Reduced transition probabilities in Weisskopf units.

GENERAL POLICIES - Presentation of Data (cont.)

Reaction and decay data sets

These data sets include information about different types of experiments and may include data sets for β decay, α decay, isomeric transition (IT) decay, Coulomb excitation, charged-particle reactions [such as (d,p) and (t,p)], heavy-ion reactions [such as ^{40}Ar,xnγ)], (γ,γ'), and mesonic atoms.

The following policies apply to the presentation of data in reaction and decay data sets. Any deviation from these policies will be noted by the evaluator.

1. The J^{Π} values in the decay data sets and reaction data sets with gammas are taken from the associated Adopted Levels, Gammas data set. For other reaction data sets the J^{Π} values are from the reaction data. The J^{Π} value to the capture state in thermal-neutron capture is assigned assuming s-wave capture.
2. The character of a γ ray and its mixing ratio are from the associated Adopted γ radiation table.
3. The term "absolute intensity" has the same meaning as the term "emission probability", and the term "relative intensity" is equivalent to "relative emission probability" or "relative emission rate." The former are given as intensities per 100 decays.
4. Beta and electron-capture intensities are per 100 decays of the parent and are usually deduced from γ intensity imbalance for the levels fed. The separation of $I(\varepsilon+\beta^+)$ into $I(\varepsilon)$ and $I(\beta^+)$ is based on theoretical ε/β^+ ratios. The log *ft* values for nonunique transitions are calculated as for allowed transitions.
5. Particle transition intensities (other than β's) are per 100 particle decays. The total particle branching is given both in the drawings and in the tables.
6. Tabular γ-ray intensities are relative values. The normalization factor to convert them to absolute intensities [photons per 100 decays of the parent for decay data sets, or photons per 100 neutron captures for (n,γ) data sets, *etc*.] is given in a footnote.
7. Radiations from the decay of neutron or proton resonances are not presented. The energies and other level properties for bound levels deduced from resonance experiments are included. Primary as well as secondary γ's following thermal-neutron capture are generally included.
8. BEλ, BMλ for the excitation of levels are generally given.
9. Up to three references that make major contributions to the information in a specific data set are given in the data set heading. These major references also appear in the drawings.

Organization of material

Within each A chain, information is presented by nuclides which are arranged in order of increasing Z. There is an index for each evaluation which is followed by an isobaric diagram. A table of properties for the ground state and isomeric levels for all nuclides of the A chain is given following or with the isobaric diagram.

For each nuclide, ^{A}Z, the arrangement of material and conventions for inclusion in tables are described below.

1. Adopted levels in ^{A}Z - All adopted level properties are shown for each level, together with explanatory comments.
2. Adopted γ radiations in ^{A}Z.
3. Band structure is shown where known.
4. Levels and radiations in ^{A}Z from radioactive decays - Decays are ordered by increasing A, Z, and excitation energy of the parent.
   a. Table of levels deduced from the decay.
   b. Tables of radiations observed in the decay.
   c. Decay Scheme
5. Levels and γ rays in ^{A}Z from nuclear reactions - Reactions are ordered by increasing A, Z of the target, then by increasing A, Z of the incident nucleus. A heading is given for each reaction.
   a. Table of levels deduced from the reaction.
   b. Table of γ rays observed in the reaction, if any.
   c. Level Scheme, if γ rays were observed and placed.

GENERAL POLICIES – "THEORY"

A reference "Theory 1967Xy01" indicates theoretical predictions computed by the authors of 1967Xy01. A reference "Theory" alone indicates a determination by the evaluator of theoretical predictions described below.

Internal Conversion Coefficients

Theoretical conversion coefficients are obtained by spline interpolation (1968Ha53) from tables of Hager and Seltzer (1968Ha53) for the K–, $L_{1...3}$–, $M_{1...5}$–shells and of Dragoun, Plajner, and Schmutzler (1971Dr11) for the (N+O+...) –shells. For the $N_{1...5}$–subshells, values are obtained by graphical interpolation from tables of Dragoun, Pauli, and Schmutzler (1969Dr09). For K–, $L_{1...3}$ shells, conversion coefficients for transitions outside the E_γ, A, or Z ranges of Hager and Seltzer are obtained as follows: for $E_\gamma \leq 6000$ keV and for Z=3,6,10 and $14 \leq Z \leq 30$ interpolation from tables of Band, *et al.* (1976Ba63); for $E_\gamma > 2600$ keV, by graphical interpolation from tables of Trusov (1972Tr09). For E0 transitions, K/L_1 and L_1/L_2 ratios are obtained by graphical interpolation from tables of Hager and Seltzer (1969Ha61).

Angular Distribution and Correlation Coefficients

The coefficients required for analysis of directional correlation, polarization correlation, directional distribution, and polarization distribution data are obtained as described by Steffen (1971St47, 1971St48). In particular, we adopt the phase convention for the mixing ratio, δ, defined by Krane and Steffen (1970Kr03). Particle parameters required for the analysis of correlation and distribution data involving conversion electrons are obtained by graphical interpolation from tables of Hager and Seltzer (1968Ha54). The expression for the deorientation coefficient required to account for intermediate unobserved mixed radiations is given by Anicin (1972An20).*
A tabulation of gamma-gamma directional-correlation coefficients is given by Taylor, *et al.* (1971Ta32). These authors use the Steffen phase convention.

Penetration Parameters

Penetration parameters required for the analysis of internal conversion data and angular correlation or distribution data involving electrons are obtained by graphical interpolation from tables of Hager and Seltzer (1969Ha61).

Internal Pair Conversion Coefficients

Theoretical internal pair conversion coefficients for Λ=E1, M1, E2 are obtained by graphical interpolation in Z, E from tables of Lombard, *et al.* (1968Lo16).

* As pointed out by these authors, most earlier references which discuss this coefficient define it incorrectly.

β-Decay Rate Probabilities

Log *ft* values, capture-to-positron ratios, and electron-capture ratios for allowed, first-forbidden unique, and second-forbidden unique transitions are obtained as described by Gove and Martin (1971Go40). This reference also contains a tabulation of log *ft* values and total capture-to-positron ratios for allowed and first-forbidden unique transitions.

Atomic Processes

X-ray fluorescence yields are obtained from Bambynek, *et al.* (1972Bb16) for $Z \leq 92$ and from Ahmad (1979Ah01) for Z>92.
Electron binding energies for Z<84 are taken from Bearden and Burr (1967Be73) and from Porter and Freedman (1978Po08) for Z>84.

α-Decay Hindrance Factors

The α-hindrance factors (the ratio of the measured partial half-life for α-emission to the theoretical half-life) are obtained from the spin-independent equations of Preston (1947Pr17). The nuclear radius for each even-even nucleus is determined by defining, for the g.s. to g.s. α-transition, the hindrance factor (HF)□1. For odd-A and odd-odd nuclei, the radius parameters are chosen to be the average of the radii for the adjacent even-even nuclei (1998Ak04). In cases where only one adjacent even-even radius is known, the extrapolated/interpolated value for the unknown radius is used in the calculation. A survey of the dependence of α-hindrance factors on asymptotic quantum numbers and the variation of α-hindrance factors within rotational bands is given for A□229 in 1972El21.

Electromagnetic Transition Rates

The Weisskopf single-particle estimates for the half-lives of electric and magnetic multipole radiation of energy E_γ are (1952Bl97)

$$T_{1/2W}(EL)=0.190 \left(\frac{L}{L+1}\right)\left(\frac{3+L}{3}\right)^2 \frac{[(2L+1)!!]^2}{A^{2L/3}} \left(\frac{164.44}{E\gamma\ (\mathrm{MeV})}\right)^{2L+1} \mathrm{x}10^{-21}\ \mathrm{s}$$

$$T_{1/2W}(ML)=3.255\ A^{2/3}\ T_{1/2W}(EL)$$

for a nuclear radius of $1.2\ A^{1/3}\mathrm{x}10^{-13}$ cm.

Unweighted and Weighted Averages

If $x_1 \pm \Delta x_1$, $x_2 \pm \Delta x_2$, ...$x_n \pm \Delta x_n$ are n independent measurements of a given quantity, Δx_i being the uncertainty in x_i, then the weighted average of these measurements is $\bar{x} \pm \Delta\bar{x}$, where

$$\bar{x} = W\Sigma x_i/(\Delta x_i)^2,$$
$$W = 1/\Sigma\ (\Delta x_i)^{-2},$$

and $\Delta\bar{x}$ is the larger of
$(W)^{1/2}$
and $[W\Sigma(\Delta x_i)^{-2}(x-x_i)^2/(n-1)]^{1/2}$.

The unweighted average of these same measurements is given by $\bar{x} \pm \Delta\bar{x}$, where

$$\bar{x} = \Sigma x_i/n,$$
$$\Delta\bar{x} = [\Sigma\ (\bar{x} - x_i)^2/n(n-1)]^{1/2}.$$

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED

Ground States

1. The ground state of an even-even nucleus has $J_\pi = 0^+$.
2. Spin determinations by such techniques as atomic-beam resonance, paramagnetic resonance, electron-spin resonance, and optical spectroscopy give correct values.

Gamma Transitions

3. The agreement of the measured value of a single conversion coefficient with the theoretical value for a multipolarity which is well separated from the value for any other multipolarity determines the transition multipolarity.
4. In all other cases if there is no other evidence for multipolarity, agreement of two or more measured conversion coefficients or ratios with theoretical values is necessary in order to establish the multipolarities of a transition and its mixing ratio.
5. Since an E0 transition can proceed only by conversion or pair production, pure E0 is ruled out if photons are observed.
6. Recommended upper limits for γ-ray strengths (Γ_γ/Γ_w,Γ_w-Weisskopf stimate) for various A values are given below.

	Γ_γ/Γ_W (Upper Limit)		
Character*	A=6–44[a§]	A=45–150[b,c]	A>150[d]
E1 (IV)	0.3[#]	0.01	0.01
E2 (IS)[e]	100	300	1000
E3	100	100	100
E4	100	100[†]	
M1 (IV)	10	3	2
M2 (IV)	3	1	1
M3 (IV)	10	10	10
M4		30	10

* 'IV' and 'IS' stand for isovector and isoscalar
† Γ_γ/Γ_w(Upper Limit)=30 for A=90–150
\# Γ_γ/Γ_w(Upper Limit)=0.1 for A=21–44
§ Γ_γ/Γ_w(Upper Limit)=0.003 for E1 (IS),
10 for E2 (IV), 0.03 for M1 (IS), 0.1 for M2 (IS)
[a] From 1979En05
[b] From 1979En04
[c] From 1981En06
[d] Deduced from **ENSDF** by M. J. Martin
[e] In super-deformed bands the E2 transitions can have Γ_γ/Γ_w>1000.

Beta Transitions§

7. If log *ft* < 5.9, the transition is allowed: ΔJ=0 or 1, Δπ=no (no change in parity). Superallowed (ΔT=0) 0^+□0^+ transitions have log *ft* in the range 3.48 to 3.50. Isospin forbidden (ΔT=1) 0^+□0^+ transitions have log *ft*>6.4. If 3.6<log *ft*<6.4, the transition is not 0^+□0^+.
8. If log $f^{1u}t$<8.5 (log *f't* < 7.4), ΔJ=0,1; Δπ=yes or no.
9. If log *ft*<11.0, ΔJ=0,1; Δπ=yes or no or ΔJ=2, Δπ=yes.
10. If log *ft*<12.8, ΔJ=0,1,2; Δπ=yes or no.
11. If log $f^{1u}t$≥8.5 (log *f't* ≥ 7.4) and if the Fermi plot has the curvature corresponding to a shape factor (p^2+q^2), then the transition is first-forbidden unique (ΔJ=2, Δπ=yes).

See "β-Decay Rate Probabilities" on page vii.
Note that log $f^{1u}t$=log f't+1.079.

Note: For nuclei at, or very near to, closed shells values may be smaller. For example, in the mass region around Z=82, the upper limit of 5.9 given in #7 above could be 5.1.

§ See 1973Ra10

γγ Directional Correlation

$$W(\theta) = \sum_{k\text{-even}} A_k P_k (\cos\theta)$$

12. If a gamma-gamma directional-correlation experiment yields A_2≈+0.36 and A_4≈+1.1, then the spin sequence is 0 □ 2 □ 0.
13. Results of γγ(θ) are strong evidence for excluding spin sequences for which the theoretical A_2 or A_4 falls well outside the experimental range.

βγ Directional Correlation

$$W(\theta) = \sum_{k\text{-even}} A_k(\beta)A_k(\gamma)P_k(\cos\theta)$$

14. If $|A_2(\beta)|\geq 0.1$(A_4=0), the transition is not allowed. The converse is not true.
15. If $A_4(\beta)\neq 0$, the transition is neither allowed nor first forbidden.
16. If $A_4(\beta)=0$, the transition is allowed or first forbidden.

βγ Polarization Correlation

$$P(\theta) = \frac{\sum_{k-odd} A_k(\beta)A_k(\gamma)P_k(\cos\theta)}{W(\theta)}$$

17. In allowed transitions,

β^- $A_1(\beta)<0$ if $J_i=J_f$
β^+ $A_1(\beta)>0$ if $J_i=J_f$

β^- $A_1(\beta)\geq 0$ if $J_i=J_f+1$
$A_1(\beta)<0$ if $J_i=J_f-1$

β^+ $A_1(\beta)\leq 0$ if $J_i=J_f+1$
$A_1(\beta)>0$ if $J_i=J_f-1$

18. If $A_3(\beta)\neq 0$, the β-transition is not allowed. The converse is not always true.

γ Angular Distribution

19. In the angular distribution of gamma rays from deexcitation of states populated in high-spin reactions (for a typical value of σ/J=0.3, where σ is the magnetic substate population parameter):

a. If A_2≈+0.3 and A_4≈–0.1, the transition is generally ΔJ=2 (stretched quadrupole). (The same A_2 and A_4 values are possible for ΔJ=0, D+Q transitions also, but such transitions are N less common. A_4=0 for ΔJ=0, dipole transition).
b. If A_2≈–0.2 and A_4≈0, the transition is generally ΔJ=1 (stretched dipole).
c. If A_4>0 (A_2≈+0.5 to –0.8), the transition is ΔJ=1, D+Q.

γ DCO Ratio

In the angular correlation (DCO) of gamma rays from deexcitation of states populated in high-spin reactions (for a typical value of σ/J=0.3, where σ is the magnetic substate population parmeter):
20. For ΔJ=2, stretched quadrupole as a gating transition:
a. R(DCO)≈1.0, the transition is generally ΔJ=2 (stretched quadrupole). (The same value is possible for ΔJ=0, dipole but such transitions are less common).
b . If R(DCO)≈0.5, the transition is generally ΔJ=1 (stretched dipole).
c . If R(DCO) differs significantly from ≈0.5 or ≈1.0, the transition is ΔJ=1 (or 0), D+Q

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS – continued

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED continued

γ DCO Ratio continued

21. For ΔJ=1, stretched dipole as a gating transition:
a. If R(DCO)≈2.0, the transition is generally ΔJ=2 (stretched quadrupole). (The same value is possible for ΔJ=0, dipole transitions, but such transitions are less common).
b. If R(DCO)≈1.0, the transition is generally ΔJ=1 (stretched dipole).
c. If R(DCO) differs significantly from ≈2.0 or ≈1.0, the transition is ΔJ=1 (or 0), D+Q.

Reactions

22. Low-energy Coulomb excitation is predominantly E2 excitation.
23. Coulomb excitation determines J^{π} if the excitation probability agrees with the calculated values of Alder (1960Al23).
24. The spin of the compound nuclear state resulting from thermal-neutron capture is equal to the spin of the target nucleus plus or minus 1/2.
25. Primary γ's from neutron capture are E1, M1, E2, or M1+E2.
26. If the angular distribution in a single-nucleon transfer reaction can be fitted with a unique L value, the spin of the final state J_f is related to the spin of the initial state J_i by

$$\vec{J}_f = \vec{J}_i + \vec{L} + 1/2$$

with parity change if L is odd.
27. If the vector analyzing power for a single-nucleon transfer reaction shows a clear preference between J=L+1/2 and J=L−1/2 and if the L value is known, then the J value is determined.
28. Generally for the states populated in high-spin reactions, spins increase with increasing excitation energy. This is a result of the fact that these reactions tend to populate yrast or near yrast states.
29. If the angular distribution can be fitted with a unique L-value the J^{π} of the final state is related to the J^{π} of the initial state by $\vec{J}_f = \vec{J}_i + \vec{L}$, $\pi_f\pi_i = (-1)^L$, for the following cases
 a. A strong group observed in (p,t), (t,p), and (^{3}He,n) reactions (strong groups are assumed to result from two identical nucleons transferred in a relative s state)
 b. A strong group observed in the α-particle transfer reaction (^{6}Li,d).
 c. (e,e') and (α,α') inelastic scattering.
30. In reactions with $J^{\pi}=0^+$ target, projectile, and ejectile, if the yield of a group at 0º or 180º is
 a. non-zero, the parity of the final state is $(-1)^{J_f}$
 b. zero at several uncorrelated energies, the parity of the final state is $(-1)^{J_f+1}$
31. In reactions with a polarized $J^{\pi}=1$ projectile in the m=0 substate, with $J^{\pi}=0^+$ ejectile and target, if the yield of a group at 0º or 180º is
 a. non-zero, the parity of the final state is $(-1)^{J_f+1}$
 b. zero at several uncorrelated energies, the parity of the final state is $(-1)^{J_f}$

Regions of Strong Nuclear Deformation

The systematic occurrence of rotational-band structure in the strongly deformed nuclides can be a considerable help in making Jπ assignments, since one can also use the level energy as one of the considerations. This frequently makes it possible to assign a Jπ value to a level with confidence from data which, absent such structure, might yield an ambiguous assignment.

32. Level-energy considerations. If the couplings among the states are not too strong, the energies of the lower members of a band can be expressed by the relatively simple relation (see, *e.g.*, 1971Bu16 and references therein):

$$E(J,K)=AX+BX^2+CX^3+\ldots$$
$$+(-1)^{J+K}\prod_{i=1-K}^{K}(J+i)\ \{A_{2K}\}+B_{2K}X+\ldots\} \qquad (1)$$
where $X=J(J+1)-K^2$

The **inertial parameter**, A, exhibits a systematic behavior in the various regions of strongly deformed nuclei, which can be helpful in assigning levels to rotational bands. In some instances (*e.g.*, strong Coriolis coupling) where the A values depart significantly from systematic trends, this observation can itself be useful, since it can help establish the presence of such effects and, hence, provide evidence for the relevant nucleonic configurations.

For the case of K=1/2 bands, the **decoupling parameter**, a, which is characteristic for each such band, is given by the ratio A_1/A in (1). Establishing a value for the decoupling parameter of a proposed band can be useful in assigning a nucleonic configuration to it - and *vice-versa*.
33. Allowed-unhindered beta transitions. In this region, beta transitions having log *ft* values <5.0 are classified as "allowed unhindered" (*au*). Such transitions take place between one-quasiparticle orbitals having the same asymptotic quantum numbers. In the "rare-earth" region (90 ≤ N ≤112, 60 <≈ Z <≈76), four such orbital pairs are known: [532], near the beginning of this region; [523], near the middle of this region; [514], above the middle of this region; and, at the high end, [505]. Observation of an *au* transition is definitive evidence for the presence of the particular pair of orbitals.
34. Coulomb excitation. If a sequence of levels having "rotational-like" energy spacings is found to be excited with enhanced probabilities, this is evidence that this sequence (at least below the first "backbend") forms the ground-state rotational band for the nuclide involved. If the E2 transition probabilities involved are large (tens of Weisskopf units or larger) and comparable to each other, then this is definitive evidence for both a band structure and the sequence of Jπ values, assuming one of the spins Nis known.
35. Alpha decay. Observation of a "favored" α transition (HF<4) indicates that the two states involved have the same nucleonic configuration. If a sequence of levels having "rotational-like" energy spacings is associated with the level fed by this favored transition and these levels have HF's that vary according to the established trend within rotational bands (1972El21), then this sequence can be considered to form a rotational band whose nucleonic configuration is the same as that of the alpha-decaying state. If the Jπ value of this latter state and its configuration are known, then the corresponding quantities can be considered to be known for the band in the daughter nuclide or *vice versa*.
36. Single-nucleon-transfer reactions (light-ion-induced). For a single-nucleon transfer reaction induced by light ions (^{4}He and lighter), the characteristic pattern of cross sections among rotational-band members ("fingerprint") can be used to assign a set of levels as specific Jπ members of a band based on a particular Nilsson configuration, if the fingerprint agrees well with that predicted by the Nilsson-model wavefunctions and is distinct from those expected for other configurations in the mass region. (This method is even stronger if angular distributions giving unique L values, or vector analyzing powers, support the assignments for one or more of the levels.)

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS – continued

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED continued

High-spin states

In the decay of high-spin states, commonly produced in heavy-ion induced compound nuclear reactions or in highly excited nuclides created as products of nuclear fission or in Coulomb excitation, the multipolarities of the deexciting γ transitions and the relative spins and parities of the levels are generally determined from angular distributions, angular correlations (DCO ratios), linear polarizations and internal-conversion coefficients. In addition, relative energy-level spacings and the increase of γ intensity with decreasing excitation energy are important clues.

37. For a well-deformed nucleus when a regular sequence of ΔJ=2 (stretched quadrupole) transitions is observed at high spins as a cascade, the sequence may be assigned to a common band with E2 multipolarity for all the transitions in the cascade. A similar but somewhat weaker argument holds for less deformed nuclei where a common sequence of levels is connected by a regular sequence of ΔJ=2 (stretched quadrupole) transitions in a cascade.

38. For near-spherical nuclei, when a regular sequence of ΔJ=1 (stretched dipole) transitions is observed at high spins as a cascade, then the sequence may be assigned to a common band with (M1) multipolarity for all the transitions in the cascade. (Cascades of ΔJ=1, E1 transitions occur in rare cases of nuclides which show alternating-parity bands or reflection asymmetry.)

39. In the absence of angular distribution/correlation data, a regular sequence of transitions in a cascade may be assigned to a common structure or a band if (a) the low-lying levels of this structure have well established spin and parity assignments and (b) there is good evidence that, at higher energies and spins, the band has not changed in its internal structure due to band crossings or other perturbations.

Alpha Decay

40. The hindrance factor for an α transition from the ground state of an even-even nucleus to the ground state of the daughter nucleus is 1.0 by definition. For odd-A and odd-odd nuclei, hindrance factors ≤4 identify favored α transitions, and these connect states having the same spin, parity and configuration.

41. For α-decay between two states, one of which has J=0, the parity change is given by $\Delta\pi=(-1)^{\Delta J}$.

PROPOSITIONS ON WHICH WEAK ARGUMENTS ARE BASED

1. In cases where gammas of one multipolarity "cluster" in one time region in the half-life vs. energy plot, as is true for M4's, other γ's whose half-lives fall in this cluster may be assigned the corresponding multipolarity.
2. In cases where a cluster of two multipolarities, *e.g.* M1 and E2 occupies one time region, a new gamma of which the half-life falls in this region may be assigned one of the two multipolarities or a mixture of the two.
3. Whenever ΔJ≥2, an appreciable part of the gamma transition proceeds by the lowest possible multipole order.

This statement is based on the scarcity of counter-examples and the observation that few E2 γ's are as slow as M3's, few E2's as slow as E3's, *etc*.

4. The spin and parity of a parent state may be inferred from the measured properties of its assumed isobaric analog resonance, and vice versa.
5. Low-lying states of odd-A nuclei have shell-model spins and parities, except in the regions where deformations appear. This argument is much stronger when supported by expected cross-section strengths (C^2S) in single-nucleon transfer reactions.

It is recognized that some shell-model predictions are stronger than others. For example, the shell model would mildly deny that the ground-state J^π of the 39th proton be $3/2^-$, but emphatically deny its being $3/2^+$. However, we have not included this distinction here and consider all shell-model arguments to be weak.

6a. For low-lying states of odd-odd spherical nuclei, the Nordheim Nrules (1950No10):

$$J = j_p + j_n, \text{ if } j_p=l_p + -1/2 \text{ and } j_n = l_n + -1/2;$$
$$J = |j_p - j_n|, \text{ if } j_p = l_p + - 1/2 \text{ and } j_n=l_n -+ 1/2.$$

may be helpful in obtaining the ground-state spins and parities, if there is supporting evidence.
6b. For excited states of strongly deformed odd-odd nuclei, the Gallagher-Moszkowski rules (1958Ga27) may be helpful in deducing the relative positions of the two two-quasiparticle states formed by the two different couplings of the quasiparticle constituents, if there is supporting evidence. Here, the state corresponding to the parallel alignment (Σ=1) of the projections (=1/2) of the intrinsic spins of the two odd particles is expected to lie lower than that produced by the antiparallel (Σ=0) alignment. This can be particularly useful in establishing the ground state Jπ values and nucleonic configurations forn odd-odd nuclei.

(In the strongly deformed even-even nuclei, the opposite is expected to obtain, i.e., the Σ=0 coupling should lie lower than that with Σ=1. In these nuclei, however, the experimental situation is less clear since the two-quasiparticle excitations occur at or above the pairing gap, where the level densities are high and couplings to vibrational excitations can affect the two two-quasiparticle states differently.)
7. Statements similar to 5 and 6 based on other models.
8. Statements based on interpolation or extrapolation of regional trends, such as shown in 1971Bu16, 1972El21, 1977Ch27, 1990Ja11 and 1998Ja07 for the rare-earth and heavy-mass regions.
9. All statements connected with the nonobservation of expected transitions.
10. Rules extracted in the survey by 1972El21 for unfavored α transitions can be used to deduce the configuration of the parent or the daughter level, if the configuration of the other is known.
11. For magnetic moments, the extreme rarity of pure single-particle states and observation of large deviations from free-nucleon g-factors in nuclei means that comparison between the experiment and the 'Schmidt Limit' estimates (based on such pure states) is not a sound basis for spin or parity assignment. The magnetic moments or g-factors, however, can give supporting, and in some cases decisive, evidence for assignments where predictions for possible alternatives, using g-factors based on local systematics of measured moments, differ widely.

For excited states, the 'collective' aspects of the state frequently make substantial contribution to the magnetic moment. The correct g-factor for this contribution, however, is a matter of detailed theory and any potential assignment based on assumed g(collective)=Z/A must be viewed with caution.

CONVENTIONS USED IN NUCLEAR DATA SHEETS

Units
Energies keV
Cross Sections barns
Magnetic dipole moments nuclear magnetons (μ_N)
Electric quadrupole moments barns
B(EL) e^2b^L
B(ML) $\mu_N^2\, b^{L-1}$

Uncertainties ("Errors") The uncertainty in any number is given one space after the number itself:
4.623 *3* means 4.623 $\pm$0.003
4.6 h *12* means 4.6 $\pm$1.2 h
$5.4\text{x}10^3$ *2* means 5400 $\pm$200
4.2 *+8–10* means $4.2^{+0.8}_{-1.0}$
–4.2 *+8–10* means –(4.2 *+10–8*)=$-4.2^{+0.8}_{-1.0}$

? Question Mark given after a quantity often indicates doubt as to the existence or the value of the quantity. For example, a "?" given after the $T_{1/2}$ value indicates that the assignment of that half-life to the associated level is not certain.

( ) Parentheses have the following interpretation for different quantities in the tabular data:

Quantity	Meaning of parentheses
Jπ	Jπ based upon weak arguments. See SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS.
L transfer or Mult.	Possible value but not definitely established experimentally.
Other	Value deduced (*i.e.*, is not directly measured) or taken from other sources.

Examples:

J^π =(1/2,3/2)$^-$
Weak arguments limit the spin to 1/2 or 3/2. Strong arguments indicate negative parity.

J^π=4$^{(+)}$
Strong arguments show the spin is 4; weak arguments suggest positive parity.

L=(3)
L value tentatively established as 3.

Mult.=(M1)
Radiation character tentatively established as M1.

Mult.=M1(+E2)
Radiation character includes E2 with a mixing ratio, |δ|, that may be >0.

[ ] Brackets

7/2$^-$[2514] Nilsson asymptotic quantum numbers, K^π [N n_z Λ]

Assumed quantity, *e.g.*, [M1+

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Nuclear Data Sheets Symbols and Abbreviations

A	mass number*, A=Z+N
A_2, A_4	coefficients of Legendre polynomials in angular- correlation or angular-distribution measurement
av	average
B(EL), B(ML)	reduced EL, ML transition probability in e^2x(barn)^L, μ_N^2 x(barn)$^{L-1}$
calc, CA	calculated, calculation
CCBA	coupled-channel Born approximation
ce	conversion electron
chem.	chemical separation
circ	circular
c.m.	center of mass
coef	coefficient
coin	coincidence
Coul. ex .	Coulomb excitation
CP	circular polarization
cryst	crystal-diffraction spectrometer
C^2S, C^2S'	one-nucleon spectroscopic strength for pickup, stripping reactions
d	day
D	dipole
DSA	Doppler shift attenuation
DWBA	distorted-wave Born approximation
DWIA	distorted-wave impulse approximation
E	energy
E(ε)	energy of electron-capture transition(endpoint of γ-continuum + K-electron eparation nergy of daughter)
E1, E2, EL	electric dipole, quadrupole, 2^L-pole
excit	excitation function
expt	experiment, experimental
F	fission
F-K	Fermi-Kurie (plot)
FWHM	energy resolution, full width at half maximum
g	gyromagnetic ratio*
GDR	giant dipole resonance
GQR	giant quadrupole resonance
g.s.	ground state
h	hour
H	magnetic field
HF	hindrance factor
hfs	hyperfine structure
HI	heavy ion
I	intensity
IAR	isobaric analog resonance
IAS	isobaric analog state
IBS	internal bremsstrahlung spectrum
IMPAC	ion implantation perturbed angular correlation technique
inel	inelastic
ion chem.	chemical separation by ion exchange
IT	isomeric transition
J	total angular momentum quantum number*
K	projection of nuclear angular momentum J on nuclear symmetry axis
K, L, M	K-, L-, M-shell internal conversion
K/L	K-, L-conversion electron ratio
L	(1)orbital angular momentum quantum number*, (2)multipolarity
L(n), L(p)	L-transfer in neutron, proton transfer reaction
min	minute
M+	M+N+O+...
M1, M2, ML	magnetic dipole, quadrupole, 2^L-pole
mag spect	magnetic spectrometer
max	maximum
Moss	Mossbauer effect
ms	(1)mass spectrometer, (2)millisecond
mult	multipolarity/character
N	neutron number*, N=A-Z
NMR, NQR	nuclear magnetic, quadrupole resonance
norm	normalization

PAC	perturbed angular correlation
pc	proportional counter
p,γ(θ)	angular distribution of γ-rays with respect to a proton beam
p,γ(t)	time distribution of photons with respect to a pulsed proton beam
pol	polarized, polarization
priv comm..	private communication
PWBA	plane-wave Born approximation
Q	(1)reaction energy*, (2)disintegration energy*, (3)quadrupole moment*, inunits of barns, (4)quadrupole
Q(ε)	total disintegration energy in ε decay
Q(β-)	total disintegration energy in β- decay
Q(α)	total disintegration energy in α decay, E(α) + E(recoil)
R	$r_oA^{1/3}$, nuclear radius*
RDM	recoil distance measurement
RUL	recommended upper limit for γ-ray strength
rel	relative
res	resonance
s	second
S	spectroscopic factor
S'	$[(2J_f+1)/(2J_i+1)]$S
S(n) or S_n ,	energy necessary to separate a
S(p) or S	neutron, proton from nucleus
scatt	scattering
scin	scintillation counter
semi	semiconductor detector
SF	spontaneous fission
Spall	spallation
Sr	steradian
syst, SY	systematics
t	triton
T	(1)isobaric spin, (2)temperature
Tz	Z-Component of isobaric spin, (N-Z)/2
$T_{1/2}$	half-life*
th	thermal
thresh	threshold
tof	time-of-flight measurement
vib	vibrational
W.u.	Weisskopf single-particle transition speed
Y	year
Z	atomic number*, Z=A-N
α	total γ-ray internal conversion coefficient N(ce)/N(γ)*
α(K), α(L)	γ ray internal conversion coefficient for electrons ejected from the K-, L-shell
αγ,βγ,γγ,	coincidences of α's and γ's, β's and γ's, γ's and γ's
αγ(θ,H,t)	αγ-, βγ-, γγ-coincidences as
βγ(θ,H,t),	function of angle, magnetic γγ(θ,H,t) field, time
β_2, β_3, βL	quadrupole, octupole, 2^L-pole nuclear deformation parameter
βγ(pol),	polarization correlation of γ's
γγ(pol)	in coinc idence with β's,γ's
Γ, Γ(γ), Γ(n)	level width*, partial width for γ-, n-emission
γ(θ,H,T)	γ-intensity as function of angle, magnetic field, temperature
γ±	annihilation radiation
δ	ratio of reduced matrix elements of (L+1)- to L-pole radiation with sign convention of Krane and Steffen, Phys.Rev. C2, 724 (1970)
ε	electron capture
εK, εL, εM	electron capture from K-, L-, M-shell
ε(γ)B(E2) ,	partial B(E2) for photon,
ε(ce)B(E2)	conversion electron detection
θ	indicates angular dependence
λ	(1)projection of particle angular momentum on nuclear symmetry axis, (2)radiation type, e.g., M1, M2..

μ	magnetic moment of particle*, given in nuclear magnetons (μ_n)
ν	neutron shell-model configuration
π	parity, proton shell-model configuration
σ	cross section*
Σ(γγ)	coincidence summing of γ-rays
ω(K), ω(L)	K, average-L fluorescence yield
%α	percent α branching from level
%β-	percent β- branching from level
%β+	percent β+ branching from level
%ε	percent ε branching from level
%IT	percent (γ+ce) branching from level
%SF	percent spontaneous fission from level
<r²>	root-mean-square of nuclear radius

Prefixes*

T	tera	$(=10^{12})$	μ	micro	$(=10^{-6})$
G	giga	$(=10^{9})$	n	nano	$(=10^{-9})$
M	mega	$(=10^{6})$	p	pico	$(=10^{-12})$
k	kilo	$(=10^{3})$	f	femto	$(=10^{-15})$
c	centi	$(=10^{-2})$	a	atto	$(=10^{-18})$
m	milli	$(=10^{-3})$			

Symbols for Particles and Quanta*

N	neutron	π	pion
p	proton	μ	muon
d	deuteron	e	electron
t	triton	ν	neutrino
α	α-particle	γ	photon

* Recommended by Commission on Symbols, Units, and Nomenclature of International Union of Pure and Applied Physics

ENSDF Analysis and Utility Codes

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ENSDF Analysis and Utility Codes

Their Descriptions and Uses

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Summary

The ENSDF analysis and checking codes are briefly described, along with their uses with various types of ENSDF datasets. For more information on the programs see "Read Me" entries and other documentation associated with each code (Hhttp://www.nndc.bnl.gov/nndc/ensdfpgm/H). The current status and platform
availability may be obtained at Hhttp://www.nndc.bnl.gov/nndcscr/ensdf_pgm/code_status.htmlH.

Disclaimer

Contents

How to Use the Programs

FMTCHK

FMTCHK should be run every time the ENSDF formatted file has been manually changed before executing any of the other programs. All fatal errors (indicated by “<F>”) should be corrected. If possible, all errors (indicated by “<E>”) should be corrected. Warning messages (indicated by “<W>”) should be checked to see if there are problems that may need correction. For small input files, use of the default options is recommended. For larger files, the user may wish to make several iterations, starting with fatal errors only. This program should also be run on the final version before submittal to the NNDC.

Notes:

1. It is sometimes difficult to judge whether a message should be flagged as an error or warning. If you disagree with an error message, please indicate this along with your reasons on submittal or before. In some instances, error messages are given because of the possible effects on other programs. Two examples are:
   a. It is considered an error when a mixing ratio is given and there is no associated mixed multipolarity. This is a problem since programs such as RULER or HSICC will be unable to perform the proper calculations. Note that the converse (*i.e.*, a mixed multipolarity given with no mixing ratios) may be addressed by assuming a 50%/50% admixture of the two multipolarities.
   b. It is considered an error when an “FL=” is not given and there are no final levels with a certain limit or there are more than one level which may be considered the final level based on E_{level}-E_{γ}. This is a problem, particularly for complex level schemes such as in the adopted dataset, for level scheme programs such as ENSDAT or Isotope Explorer and programs such as GTOL, which do a least-squares adjustment of the level energies, or programs such as PANDORA.

ENSDAT and TREND

ENSDAT produces level schemes, bands, and tables in a format similar to that of the *Nuclear Data Sheets* and may be used to visual expect the results. TREND provides a simpler ASCII presentation of the tabular data that does not require a PostScript printer or viewer. One should also be able to copy the list of keynumbers generated by ENSDAT into the clipboard and paste this into the keynumber form of the NNDC Web NSR to obtain the NSR entries corresponding to these keynumbers.

Adopted Levels, Gammas Datasets

As well as ENSDAT, FMTCHK, and TREND, applicable programs for these datasets are ADDGAM, GTOL, HSICC, PANDORA, and RULER. ADDGAM and PANDORA are useful in constructing the dataset. In addition, PANDOR may be used iteratively to aid in physics decisions, checking assignments, and updating source datasets based on changes in the adopted data. GTOL is useful only in obtaining the least-squares adjustment of the level energies; for complex datasets, the matrix to be inverted may be singular (see Additional notes under GTOL for methods of handling this problem). RULER may be used in the comparison mode to provide additional information in obtaining γ-multipolarity assignments. HSICC and RULER should also be run to provide the internal conversion coefficients and BEλWs and BMλWs, respectively; note that HSICC should be executed before RULER. HSICC should also be run to provide the internal conversion coefficients; note that there is no need to delete the "S G" records generated by HSICC; the publication program automatically suppresses these when the evaluation is prepared for submission to Academic Press. Figure 1 shows the approximate order in which the programs are run. Note that this is an iterative process and, as changes are made, various programs will need to be rerun (in particular, FMTCHK).

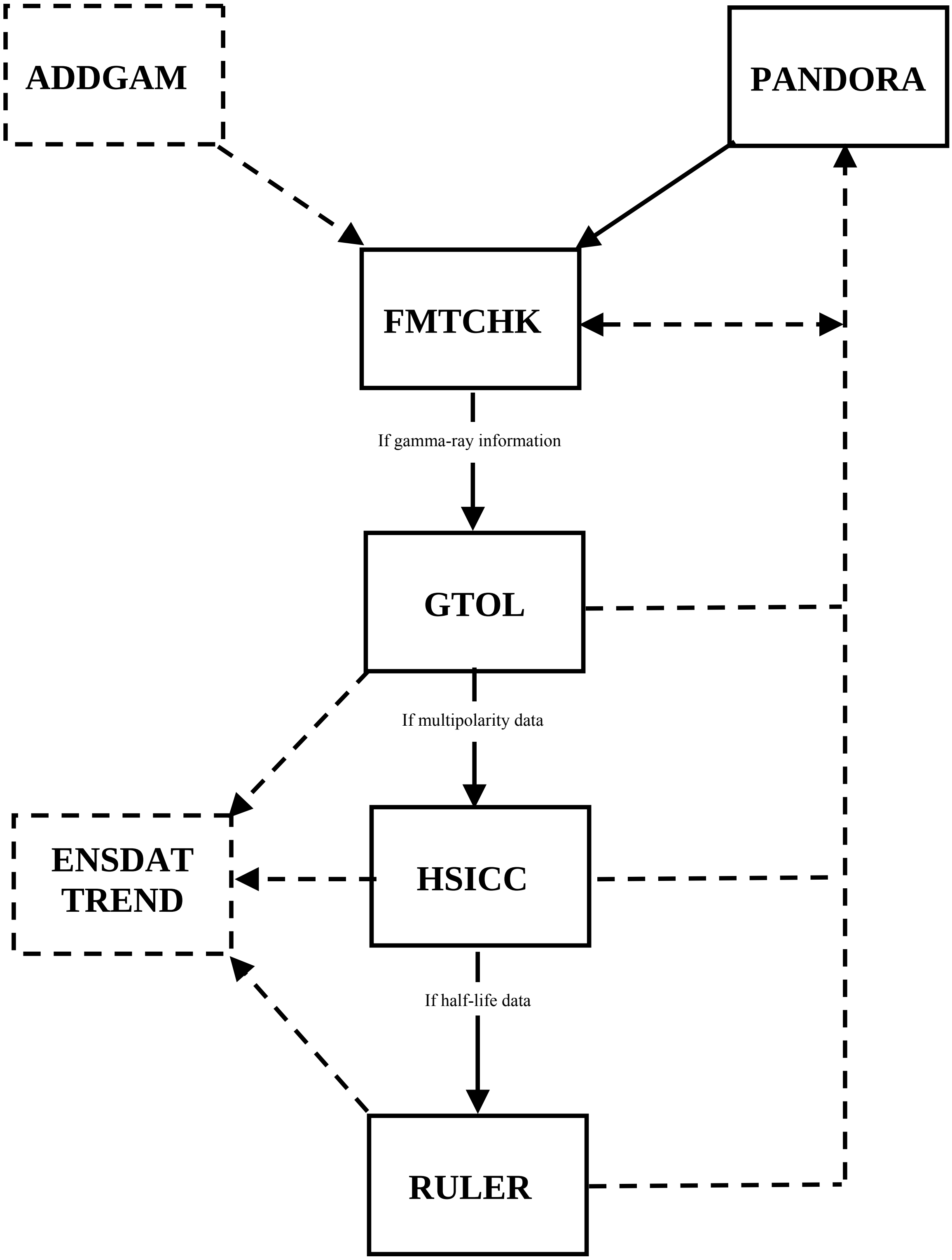

Figure 1: Flowchart of programs for Adopted Levels, Gammas datasets

Decay Datasets

Along with ENSDAT, FMTCHK, and TREND, applicable programs for these datasets are ALPHAD (for α decay), GABS, GTOL, HSICC, LOGFT (for $\beta^{\pm}/\varepsilon$ decay), RadList, and RULER. Figure 2 shows the approximate order in which the programs are run. Note that this is an iterative process and, as changes are made, various programs will need to be rerun (in particular, FMTCHK).

1. ALPHAD should be used to obtain the hindrance factors and, for even-even ground-state nuclei, r_0. For other nuclei, an r_0 must be supplied.
2. GABS may be used to combine the data from up to three sources to obtain I_γ-normalization (NR), the branching ratios (BR), and absolute I_γs. HSICC should run on the input data or the internal conversion coefficients from the adopted dataset should be used.
3. GTOL may be used to provide a least-squares adjustment of the level energies. It should be used to check the uncertainties and placement of the γs. If there are a large number of γs and few whose energies deviate from the calculated energies, the experimental uncertainties may be overestimated; on the other hand, if there are a large number of deviations, the uncertainties may be underestimated. Also, for any deviation of over $\approx 3\sigma$, the placement of the transition should be carefully checked. GTOL should also be used to obtain the intensities of particles feeding the levels; this should be done before ALPHAD and LOGFT are employed and may be useful in deriving I_γ-normalization (NR).
4. HSICC may be used to check experimentally measured internal conversion coefficients against theory. If the adopted internal conversion coefficients are not used, HSICC should be executed to produce this information for the data set. This should be done before GABS, GTOL, or RadList are used.
5. LOGFT is required to obtain the log *ft*s, $I_{\beta+}$ and I_ε, and partial electron-capture fractions. This should be done before using RadList. If one is not using measured intensities, GTOL should be used to obtain $I_{\beta-}$ and $I_{\varepsilon+\beta+}$.
6. RadList should be used to check the calculated energy deposited with that predicted by the Q-value and branching ratios. If X-ray intensities are measured, these should be compared to those calculated by the program. If discrepancies cannot be resolved, these should be noted in the dataset. ALPHAD, HSICC, and LOGFT should have been used before doing these checks.
7. If $T_{1/2}$s have been measured, RULER may be used to check or further limit multipolarities based on other methods (*e.g.*, from experimental conversion coefficients).

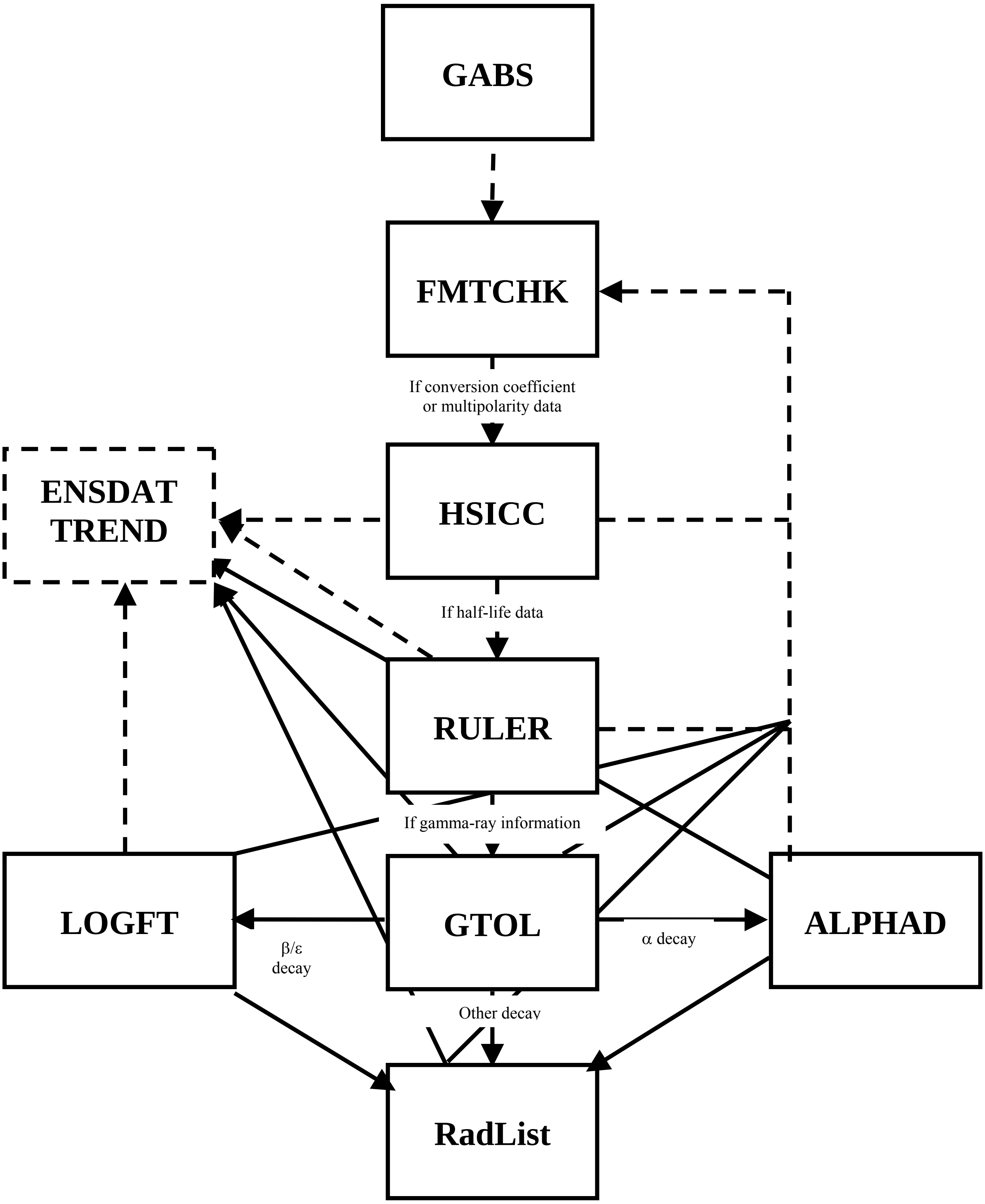

Figure 2: Flowchart of programs for decay datasets

Reaction Datasets

Along with ENSDAT, FMTCHK, and TREND, applicable programs for these datasets are GTOL, HSICC, and RULER. For (thermal n, γ) datasets, RadList may also prove of use. Figure 3 shows the approximate order in which the programs are run. Note that this is an iterative process and, as changes are made, various programs will need to be rerun (in particular, FMTCHK).

1. GTOL's primary use is to do a least-squares adjustment of the level energies and to check the uncertainties and placement of the γs as described above. Note that it is now common for authors to omit the Δγs; if the evaluator cannot obtain a good estimate of these, it may be better to use the author's level energy values. It is also useful for checking for intensity imbalance problems if relative intensities are given.
2. HSICC may be used to check experimentally measured internal conversion coefficients against theory. While it is generally not required to include the conversion and partial conversion coefficients for reaction datasets, it is very useful to do this for (thermal n, γ) datasets.
3. If half-lives ($T_{½}$) have been measured, RULER may be used to check or further limit multi-polarities based on other methods (*e.g.*, from experimental conversion coefficients).
4. RadList may be used to check the energy balance of (thermal n, γ) datasets by tricking it into believing the dataset is an IT decay dataset. This is done by changing the DSID on the ID record, adding an appropriate Parent record (level energy equal to the neutron separation energy) and a BR of 1.0 on the Normalization record.

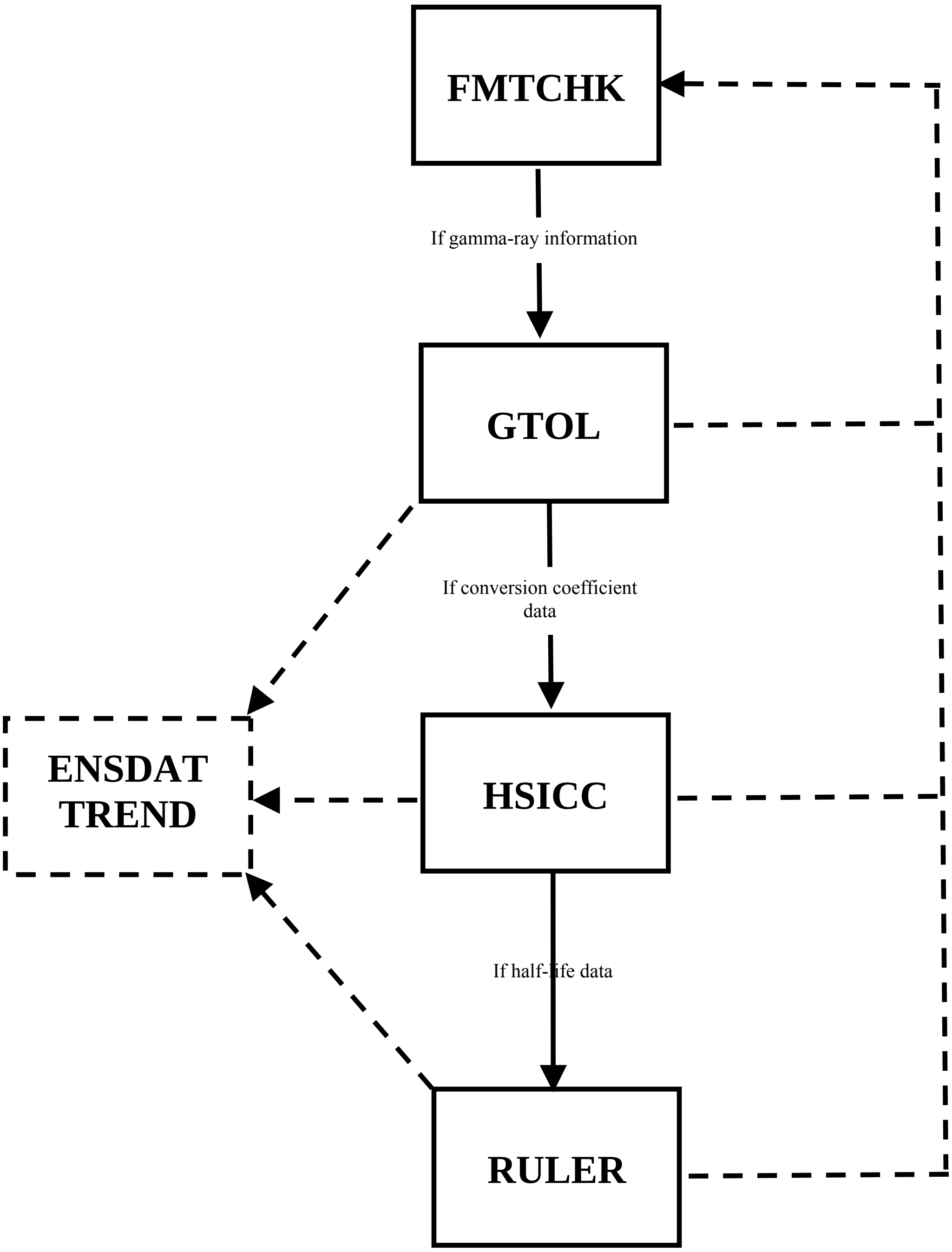

Figure 3: Flowchart of programs for reaction datasets

ADDGAM

Version 1.4 [Feb. 7, 2001]

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This program adds γs to the Adopted Levels when all γs come from one data set. If γs come from more than one data set but are non-overlapping, the program may be run successively with different γ data sets as input.

Input files (ENSDF format):

1) Data set containing the adopted levels. Sample input file: ADDGAML.DAT
2) Data set containing the gammas to be added. Sample input file: ADDGAMG.DAT

Output file: Merged set containing the information in (1) and the γs from (2). Sample output file: ADDGAM.NEW

Terminal dialog: The user will be asked to provide the file names for the data set containing the adopted levels, the file for the gammas to be added, and the file for the new data set.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: None

ALPHAD

Version 1.6 [Feb. 7, 2001]

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(Original Authors: H.V. Michels, Y. Sanborn, R.C. Ward)

This program calculates the α hindrance factors and theoretical $T_{½}$ and, for even-even ground state to ground state transitions, r_0 using Preston's spin-independent equations (M.A. Preston. Phys. Rev. 71, 865 (1947)).

The program reads an ENSDF-formatted file and produces a report of the hindrance factors, theoretical $T_{½}$s, and r_0s calculated by the program. This report will also summarize any problems encountered or assumptions made. There is also an option to produce a new file using containing the HFs calculated. r_0s may be specified on an ALPHA comment record by "HF" in columns 10 and 11 and a dollar sign ("$") in column 12 or blanks in columns 12 through 19. The first value and uncertainty in columns 20 through 80 preceded by an R ("R") and an equal sign ("=") or approximate sign ("AP") will be taken as r_0.

<u>Sample input file:</u> ALPHAD.DAT

<u>Sample output files:</u>
1. ALPHAD.RPT - Report of calculations
2. ALPHAD.NEW - New ENSDF file containing the hindrance factors (HFs) calculated by the program.

<u>Terminal dialog:</u>
1. **Input data file (Default: ALPHAD.DAT):**
2. **Output report to file (Y/N):**
   The default is "Y". If NO is answered, the report will be displayed on the terminal. If YES is answered, the following query will appear:
   Output report file (Default: ALPHAD.RPT):
3. **Echo input (Y/N):**
   The default is "Y". In this case the input file will be copied to the report file.
4. **Rewrite input with hinderance factor (Y/N):**
   The default is "Y". If YES is answered, the following query will appear:
   Output data set file (Default: ALPHAD.NEW):

If the report output is to a file, the terminal output will note the progress in the calculations and report warning messages.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional notes:

1. Calculation of Δr_0: Five values are calculated: $r_0(T_{½}(\alpha),E_\alpha)$, $r_0(T_{½}(\alpha)+\Delta T_{½}(\alpha),E_\alpha)$, $r_0(T_{½}(\alpha)-\Delta T_{½}(\alpha),E_\alpha)$, $r_0(T_{½}(\alpha),E_\alpha+\Delta E_\alpha)$, and $r_0(T_{½}(\alpha),E_\alpha-\Delta E_\alpha)$. $\Delta r_0 = \sqrt{}(((|r_0(T_{½}(\alpha)+\Delta T_{½}(\alpha),E_\alpha)-r_0(T_{½}(\alpha)-\Delta T_{½}(\alpha),E_\alpha)|)/2)**2 + ((|(r_0(T_{½}(\alpha),E_\alpha+\Delta E_\alpha)-r_0(T_{½}(\alpha),E_\alpha-\Delta E_\alpha)|)/2)**2)$. r_0 and Δr_0 as calculated are output in the report file and so are $r_0(T_{½}(\alpha)+\Delta T_{½}(\alpha),E)$, $r_0(T_{½}(\alpha)-\Delta T_{½}(\alpha),E)$, $r_0(T_{½}(\alpha),E+\Delta E)$, and $r_0(T_{½}(\alpha),E-\Delta E)$.
2. If either the value or the uncertainty for E_{parent}, Q_α, or E_{level} is non-numeric and E_α and ΔE_α are numeric, E_α and ΔE_α are used in the calculations. NOTE: For systematic uncertainties in Q_α from the Audi-Wapstra Mass Tables, the input data should be modified to use the estimated uncertainty and the new output edited to change DQP back to "SY".
3. If there is more than one non-numeric uncertainty involved, the order of precedence is limits (*e.g.,* GT or LT) and then "AP", "CA", and "SY" for the new output.

Additional documentation: None.

Acknowledgements: I thank Y. Akovali and M.J. Martin for many useful discussions on the physics involved, for their many suggestions on improving the output, and for testing various versions of this code.

COMTRANS (COMment TRANSlation)

Version 7.0 [August 8, 2003]

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The program COMTRANS is a nuclear structure evaluator tool for translating comments in the Evaluated Nuclear Structures Data File (ENSDF) from the all upper case form to the upper/lower case form. In addition, translations of code words found in the NSD dictionary are made into a rich text type of format (*e.g.*, |a replaces ALPHA and {+56}Fe replaces 56FE). These comments no longer need to be used with the NSD dictionary. However, evaluators should note that adding a code word to such a translated comment means they must change the lower case comment flag (c or t) in column 7 to an upper case comment flag (C or T) or rerun the file using COMTRANS. Otherwise, ENSDAT (and the publication code), which do not translate lower case comment (c or t) cards), will output the code word unchanged. Finally, the input file is converted into an Y2K compliant form if it is not in that form. All keynumbers are changed from the old six-character keynumber (85AU01) into the new eight-character Keynumber (1985AU01). The keynumbers fields of the ID and Q cards are also changed to comply with the Y2K formats.

The program asks for an input file name, an output file name and options. The ENSDF translation dictionary file must be in the same directory from which the program is executed. The input and output files may include a disk and directory path.

Program files:
1. comtrans_sl.exe
2. ensdf_dic.exe - dictionary creation program.

Text files:
1. ensdf_dic.dat - sequential text file of the dictionaries used to create ra_ensdf_dic.dat.

Input files:
1. An ENSDF formatted file. Sample input file: comtrans.tst
2. ra_ensdf_dic.dat - (direct access binary file) contains the ENSDF translation dictionaries used by ENSDAT and COMTRANS; must be in the execution directory.

Sample output file: comtrans.out (Y2K compliant)

Terminal dialog: The program will request the following information:
1. Input
2. Output

Compilation and loading instructions: Only the executable is supplied.

Additional notes:

1). Should **not** be run on ENSDF or XUNDL files submitted to the NNDC.

^A4 → A4 → A{-4} → a{-4}

A4 A_4 a_4

2). Useful to run before using Isotope Explorer 2 or ENSDAT.

a. Isotope Explorer 2 assumes that the comments have been translated into a “rich text” format and does not carry out a dictionary lookup.
b. ENSDAT may be faster since it will not have to do a dictionary lookup for the comments.

DELTA

Version 1.01 [April 15, 1993]

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This program analyses angular correlation and conversion coefficient data, and calculates the best values of mixing ratios. the sign convention is that of Krane and Steffen, Phys. Rev. C2, 724 (1970).

The gamma-gamma cascade studied is:

```
--------- J(1)
    |
    |  DELTA(1)    (TRANSITION NUMBER 1)
    |
    V
--------- J(2)
    |                  .
    |  DU(1)           .
    |                  .
    V                  .
--------- J(3)         .
                       . UNOBSERVED TRANSITIONS
--------- J(NLEV-2)    .      (MAXIMUM 3)
    |                  .
    |  DU(NLEV-3)      .
    |                  .
    V                  .
--------- J(NLEV-1)
    |
    |  DELTA(2)    (TRANSITION NUMBER 2)
    |
    V
--------- J(NLEV)
```

DELTA(1) and DELTA(2) can be varied. The mixing ratios of the unobserved transitions are fixed. Possible data items are:

1. A_2 and A_4 for $\gamma\gamma$-correlation (corrected for solid angle effects).
2. δ values from other independent measurements ($\tan^{-1}(\delta)$ is used internally).
3. Conversion coefficient or conversion ratio data.

All data items are treated as independent, and uncertainties as statistical. Note that a measured A_2 only gives very little information if both mixing ratios are unknown. A measured internal conversion coefficient helps a lot! Note that δ values may be suspect when minimum is not approximately parabolic. The default step size in $\tan^{-1}(\delta)$ is 2 degrees. This is normally small enough, but for very accurate data a smaller step size (set with option ST) may be necessary.

Limitations:

1. No triple correlations.
2. Spins up to 20 are allowed, except when unobserved transitions are involved. For unobserved transitions the maximum spin is 10. These limitations are valid if the computer can handle double precision reals of up to 10^{76}.
3. Effects of internal conversion on the deorientation coefficients for mixed transitions are neglected. See Anicin *et al.*, Nucl. Instrum.Meth. 103, 395 (1972) for this usually very small effect.

NOTE: Except for the changes made in input and output units and to conform to ANSI-77 standard, this code is as provided by the author.

Input file: All records have the following format:

COL. 1-2 Symbol that determines type of card.
COL. 3-72 Free format reals or integers. Separator: any character different from '0-9', '.' and '-'. Everything following a '$' is ignored. This can be used for comments on the data cards. Only DATA and GO cards are necessary. Uncert. = 0 for δ means that δ is kept fixed. new data with same name as existing data replace the latter.

Options (parameters in ( ) are optional):

CL	Clear data
DU	Dump common blocks (for debugging)
OU A	A = 0 short output (default) A > 0 FULL OUTPUT
ST ST1(,ST2)	Step size (in degrees) for $\tan^{-1}(\delta_1)$ and $\tan^{-1}(\delta_2)$, respectively
EN	End of run
GO RJ1,RJ2(,RJ3)	Read spins and go. RJ's are reals or integers (*e.g.*, 5/2- = -2.5, 2+ = 2, 0- = -0) Maximum 6 spins.
HE ANY TEXT	Header
LI A,B,C,D	Limits $\tan^{-1}(\delta_1)$ to A to B and $\tan^{-1}(\delta_2)$ to c to d
UN (DU(1), DU(2), DU(3))	Unobserved transitions, δs. Defaults = 0.0
Correlation and DELTA data	
A2 A2,DA2	A_2, ΔA_2
A4 A4,DA4	A_4, ΔA_4
D NTR (,DELTA,DDELTA)	Transition number, δ, Δδ. Defaults: none, 0, 0
Conversion coefficient data (maximum 5 items)	

** NTR, EXP, DEXP, L1, H1(,L2,H2)	where ** is any unique combination of symbols (e.g., CC, AK) NTR The number of the transition (1 or 2) EXP Experimental value DEXP Uncertainty L1 Theoretical value for the lower multipole (SHELL1) H1 Theoretical value for the higher multipole (SHELL1) For ratios SHELL1/SHELL2: L2 Theoretical value for the lower multipole (SHELL1) H2 Theoretical value for the higher multipole (SHELL2)

Sample input data set: DELTA.DAT

Output file (Short output marked with an asterisk (*)):

For each spin combination (each GO card):
* Option and data cards read
* Header
* Data
Header
χ^2 and best theoretical values of data (step in δ_1)
* Best δ_1
Header
* Plot of χ^2 *versus* $\tan^{-1}(\delta_1)$
Header
χ^2 and best theoretical values of data (step in δ_2)
* Best δ_2
* Plot of χ^2 *versus* $\tan^{-1}(\delta_2)$
* 'END OF ANALYSIS FOR THIS SPIN COMBINATION'

Optionally a dump of common block variables can be obtained.

Sample output: DELTA.RPT

Terminal dialog: The user will be requested to supply the input file name and the output file name.

Compilation and loading instructions: No special instructions

Additional documentation: DELTA - A computer program to analyze gamma-gamma correlations from unaligned states. L.P. Ekstrom. Nuclear Physics LUNFD6/(NFFR-3048) 1-27,(Lund University. 1983).

ENSDAT (Evaluated Nuclear Structure Drawings and Tables)

Version 9.7 [Sep. 11, 2000]

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The program ENSDAT (Evaluated Nuclear Structure Drawings And Tables) is similar to the production program for the Nuclear Data Sheets but more limited in its application. Only ENSDF data files can be used as input and a PostScript file, list of keynumbers in NSR, and a report file are output. As the default, all possible tables, band drawings, and gamma drawings are done for each dataset encountered in the input file. However, it is possible to choose one or more of these groups of output (see below). In addition, it is possible to modify the default tables and drawings by adding commands to the input file using control cards. (see the file enscomds.txt.) A final page is output to the PostScript file, which gives a listing of all the keynumbers, encountered in the input file.

Program files:

1. ensdat.exe
2. ensdf_dic.exe - dictionary creation program.

Text files:

1. enscomds.txt - instructions for using commands in the input file.
2. ensdf_dic.dat - sequential text file of the dictionaries used to create ra_ensdf_dic.dat.

Input files:

1. An ENSDF formatted file. Sample input file: adopted.186.
2. ra_ensdf_dic.dat - contains - translation dictionaries. ensdf_dic.exe must be run to create the ISAM files used by ENSDAT and COMTRANS.

Outputs:

1. PostScript file of tables and drawings in a form similar to the Nuclear Data Sheets.
2. Report file summarizing work done and any errors noted.
3. File listing the keynumbers (NSR) found in the input file.

Sample output files: ad_186.log and ad_186.ps.

Terminal dialog: The program will request the following information:

1. Input - input file specification
2. Output - output file name
3. Options - one or more of the following options can be entered, separated by a blank:

TABLE Level, gamma, and radiation information will be output in tabular format.
BAND Band drawings will be output. Radplot type drawings are also output.
DRAW Gamma drawings will be output.

NOAUTO No drawings or tables will be generated except those that are specified by the user on control cards, added to the input file.If none of these options are used, all tables, band drawings (if any), and gamma drawings (if any) will be output to the PostScript file.

4. View output - Yes or No (optional - see installation instructions for details)

Command Line dialog: ENSDAT *input output [option]*
Compilation and loading instructions: Only the executable is supplied.

Additional documentation: Following the output file name, several options are available to the user. The output file name must be followed by a blank and then, if desired, one or more of the following options:

TABLE	Level, gamma, and radiation information will be output in tabular format.
BAND	Band drawings will be output.
DRAW	Gamma drawings will be output.
NOAUTO	No drawings or tables will be generated except those, which are specified by the user on control cards added to the input file.

As before, if none of these options are used, all tables, band drawings (if any), and gamma drawings (if any) will be output to the PostScript file.

FMTCHK

Version 9.0g [August 4, 2003]

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(Original author: Bruce J. Barton)

This program analyzes the format of an ENSDF formatted file to verify that it conforms to "Evaluated Nuclear Structure Data File. A Manual for Preparation of Data Sets" by J.K. Tuli, Brookhaven National Laboratory Report BNL-NCS-63155-01/02 (2001) and subsequent memos.

Input file (ENSDF format): Sample input file is DATA.TST

Output file: A report file indicating possible errors or warnings is generated. Sample output file: FMTCHK.RPT. Brief explanations of the fatal error (prefix <F>), error (prefix <E>), warning (prefix <W>), and informational (prefix <I>) messages are given in READFMTC.ME or READFMTC.HTML.

Terminal dialog: The user will be asked to supply the input and output file names, if errors only should be reported or the complete file reported (default: errors only), if continuation records should be checked (default: check continuation records), if only fatal errors should be reported (default: no), if warning messages should be suppressed (default: no suppression). This query will be suppressed if only fatal errors are to be reported), and if the checking of the XREF *versus* DSID should be suppressed.

As the data sets in the input file are processed, this will be indicated on the terminal. After each data set is processed, the total number of fatal error, error, and warning messages will be reported. If both adopted data sets and "source" data sets are in the file, the X records and IDENTICATION records will be compared and any discrepancies listed.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: None.

Additional notes:

1. For level energies of the form X, Y, Z, *etc.* or E + X, E + Y, E + Z, *etc.*, an arbitrary energy is assigned to the first occurrence of the character based on the energy of the previous level energy. This is reported as an informational message in the report file and is used to see if the levels are in the proper energy order.

GABS

Version 9.2 [Feb. 7, 2001]

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GABS calculates absolute gamma-ray intensities and a decay-scheme normalizing factor (NR) for converting relative intensities to absolute values per 100 decays of the parent nucleus. The program calculates the decay mode branching ratios (BR) for radionuclides that decay through several decay modes. It also calculates the uncertainties in all these quantities.

Input file: GABSPC reads up to three data sets (ENSDF format). See the documentation for modifications to the standard ENSDF format for use by this program. Sample input: GABS.IN.

Output files:

1. Report file summarizing the results of the calculations (default: GABSPC.RPT).
2. New ENSDF formatted file containing the results of the calculations (may not already exist). Sample output: GABS.OUT

Terminal dialog: The program will ask for an input file name, a report file name, if a new file should be created ("Y"; default is no, case insensitive), and, optionally, the name of the output file.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: PROGRAM GABSPC (Version 9, May 2000). Edgardo Browne, Lawrence Berkeley National Laboratory. Adapted for IBM PC by Coral M. Baglin (September 1991).

GTOL

Version 6.4a [July 11, 2001]

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In this program, gamma-ray energies are used to derive a set of least-squares adjusted level energies. The net feeding at each level is calculated from the input γ intensities and conversion coefficients. Unplaced or questionable γs, or γs whose final level is ambiguous or unknown are ignored.
The program parses the DSID of each data set and, if there is no indication of possible gamma records within the data set, skips it. In addition, the program will not calculate the intensity balancing for adopted data sets.

Input file: An ENSDF formatted file with the following optional information:

An option record with 'OPTION' in col. 1-6 may precede any data set and contain any of the following options in free format:

Option	Meaning
NOREC	No recoil correction, *i.e.*, recoil correction has already been applied to E_γ
RECOIL	Perform recoil correction (DEFAULT)
MARKED	Process onlydata sets preceded by a card with '*GTOL' in col. 1-5
ALL	Process all data sets (DEFAULT)
DEG=	For the current data set, override default assumption of 1 keV where no uncertainty on the gamma energy is given. Following the equal sign may be either a number or a number followed by a percent sign. A number alone indicates the uncertainty on E_γ in keV while a number followed by a percent sign indicates the fractional percent uncertainty to be assigned.
DRI=	For the current data set, assume a default uncertainty for the relative I_γ when none given. A number alone indicates the uncertainty on I_γ in the current relative units while a number followed by a percent sign indicates the fractional percent uncertainty to be assigned.
DTI=	For the current data set, assume a default uncertainty for when none given. A number alone indicates the uncertainty on $I_{\gamma+ce}$ in the current relative units while a number followed by a percent sign indicates the fractional percent uncertainty to be assigned.

Note that an option card resets the defaults.

A level energy can be held fixed by adding the letter 'F' somewhere in the energy field (columns 10 - 21). If the output option to create a new file containing the adjusted level energies is chosen, 'F' will be removed and a level documentation record will be added (LEVEL ENERGY HELD FIXED IN LEAST-SQUARES ADJUSTMENT).

If DRI= or DTI= are specified on an OPTION record, the assumed uncertainty may be overridden for an individual intensity, by adding an "E" separated from the intensity in either the RI or TI fields.

If DEG=, DRI=, or DTI= are specified on an OPTION record and a new file is created, FOOTNOTE COMMENTS will be generated and inserted as necessary.

Sample input file: DATA.TST

<u>Output files:</u>

1. Report file. The report file will contain a summary of the data input and actions taken by the program (*e.g.*, unplaced or questionable γs ignored) and the following optional outputs for each data set:
   a. Comparison of input gamma energies to those calculated based on the adjusted level energies.
   b. Comparison of calculated net feedings to each level with values input on B, E, or A records

Note: if the calculated net feeding overlaps zero within three standard deviations, the program will calculate estimated upper limits (90% confidence level) using two methods suggested by Louis Lyons in Statistics for Nuclear and Particle Physicists (Cambridge University Press) and report these estimates if they differ by more than 0.01. The two methods are:

i. (Integral of gdB from 0 to Bl)/(Integral of gdB from 0 to infinity)=0.9 where g is the normal (Gaussian) distribution.

    ii. Bl < Bm + 1.28σ.
  c. If a new file is generated a comparison of the old and new records will also be generated.

  Sample output file: GTOL.RPT

2. New file containing the adjusted level energies (optional). Sample output file: None

Terminal dialog: The program will request the input and report (default: GTOL.RPT) file names and ask if you wish a new file created (default: no new file) and for the new file name, to suppress the gamma-energy comparison (default: no suppression), and to suppress the intensity comparison (default: no suppression). The progress of the program will be noted on the terminal as well as possible problems.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation:

B.J. Barton and J.K. Tuli. Physics analysis programs for nuclear structure evaluation. Brookhaven National Laboratory Informal Report BNL-NCS-23375/R (1977).

L.P. Ekstrom and P. Andersson. FORTRAN 77 versions of string handling subprograms and the programs GTOL and MEDLIST. Nuclear Physics Report LUNFD/(NFFR-3049)/1-27, (Lund University, Sweden. 1983).

Additional notes:

1. If the level energies are of the form X, Y, Z, *etc.* or E + X, E + Y, *etc.*, the least-squares fit is done separately for each group of states and merged back into the final results. Similar to FMTCHK, an arbitrary energy is assigned to the level based on the energy of the previous energy. This is used to sort the levels in the energy comparison but is not used when creating the new output file.
2. FMTCHK should be rerun if a new file is created since the order of the level energies may have changed as a result of the least-squares adjustment. This may occur when there are two closely lying levels or if there is a series of levels with unknown energies (*e.g.*, E + X) interspersed with levels of known energy.
3. If the connecting information is too sparse, the matrix created may be singular and cannot be inverted (this generally occurs for adopted datasets and other datasets where there are levels with no de-exciting γs). In such instances, check the report file for levels that do not de-excite and fix these levels.
4. As noted above, uncertainly placed γs are ignored in the least-squares fit and the intensity balance calculations. This means possible additional iterations to obtain an estimate of the excitation energies and their possible contributions to the uncertainties of the intensity balances:

   a. To obtain an estimate of the excitation energies of levels only connected by such transitions, modify the input by removing the "?" in column 80 of the relevant gamma records and adding "F" in the energy fields of any connected level records which also are fed or de-excited by other γs. Factor the results of the new least-squares fit into the original file.

b. To obtain an idea of the effect of uncertainly placed γs on the intensities, modify the input file by removing all “?” in column 80 of the gamma records. By comparing the original intensity balance calculations with the new one, you will be able to estimate the effect of these transitions on the balance uncertainties.

HSICC Program Package

The HSICC program package consists of the programs HSICC (calculates internal conversion coefficients), HSMRG (merges new gamma records created by HSICC with the original input data), BLDSHST (builds a direct access file of the internal conversion coefficient table), and SEQHST (recreates a sequential file of the internal conversion table from the direct access file). These are described separately on the following pages.

<u>Compilation and loading instructions:</u> HSICC requires subroutines from the NSDFLIB package; the others do not.

HSICC Program Package — HSICC

Version 11.13f [Oct. 9, 2001]

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(Original authors: R.S. Hager and E.C. Seltzer, California Institute of Technology; W.B. Ewbank and J.B. Bell, Nuclear Data Project, Oak Ridge National Laboratory; B.J. Barton, National Nuclear Data Center, Brookhaven National Laboratory; and G. De Smet and M. Verboven, Nuclear Physics Lab., Belgium)

This program calculates internal conversion coefficients by spline (cubic) interpolation tabulated values from Hager and Seltzer for the K, L, and M shells and from Dragoun, Plajner, and Schmetzler for the N + O +... shells.

Input files:
1. ENSDF formatted file. Sample input file: DATA.TST. NOTE: The input data should not be modified before running the code HSMRG.
2. ICC index file (created by the program BLDHST).
3. Binary file of ICCs (created by the program BLDHST).

Output files:
1. Complete report of calculations. Sample output file: HSCALC.LST.
2. New G/2G records generated by the program. This is used as input to the program HSMRG. Sample output file: CARDS.NEW.
3. Comparison of new and old G/2G records. Sample output file: COMPAR.LST.

Terminal dialog: The program will ask for the following information:
1. Input files
   a. Name of input ENSDF file (default: DATA.TST)
   b. Name of ICC index file (default: ICCNDX.DAT)
   c. Name of ICC binary table file (default: ICCTBL.DAT)
2. Output files
   a. Name of file from complete report (default: HSCALC.LST)
   b. Name of file containing new G/2G records (default: CARDS.NEW)
   c. Name of comparison file (default: COMPAR.LST)

Additional documentation:

R.S. Hager and E.C. Seltzer. Internal Conversion Tables. Part 1: K-, L-, M-Shell Conversion Coefficients for Z = 30 to Z = 103. Nucl. Data A4, 1 (1968).

O. Dragoun, Z. Plajner, and F. Schmutzler. Contribution of Outer Atomic Shells to Total Internal Conversion Coefficients. Nucl. Data Tables A9, 119 (1971).

B.J. Barton and J.K. Tuli. Physics analysis programs for nuclear structure evaluation. Brookhaven National Laboratory Informal Report BNL-NCS-23375/R (1977).

Additional notes: If E_γ is near the threshold for internal conversion, new records are not created.

HSICC Program Package — HSMRG

Version 7.1a [Sept. 17, 2001]

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(Original author: Bruce J. Barton)

This program merges the new (corrected) G-records created by HSICC with the input dataset file to create an updated dataset file.

Input files:
1. Input data file (ENSDF format). This must be the same input file used by HSICC. Sample input file: DATA.TST
2. Correction file of G-records created by HSICC. Sample input file: CARDS.NEW

Output file: Updated file (ENSDF format). Sample output file: CARDS.MRG

Terminal dialog: The program will ask for the names of the input file used by HSICC (default: DATA.TST), the correction file created by HSICC (default: CARDS.NEW), and the merged data file (default: CARDS.MRG).

Additional documentation: none

HSICC Program Package — BLDHST

Version 3.6 [Feb. 9, 2001]

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(Original author: Bruce J. Barton)

This program builds the Hager-Seltzer direct access table plus index from a sequential file.

Input file: A sequential access symbolic file of 80 character records (Z, SHELL, EG, E1, E2, E3, E4, M1, M2, M3, M4) = (I3, A2, F7.2, 8E8.2). Data file included: ICCSEQ.DAT. For MS-DOS, four additional files, H1.DAT through H4.DAT, are included covering Z = 3 - 34, Z = 35 - 59, Z = 60 - 82, and Z = 83 - 103, respectively.

Output files:

1. Direct access table consisting of a binary file of 11 word (44 bytes) records. 13004 records in the file if ICCSEQ.DAT is used as input.
2. An index consisting of a direct access binary file of one word (4 bytes) records. The Zth record is the integer record number pointer to the direct access table.

Terminal dialog: The program will first ask for the sequential input file name (default: ICCSEQ.DAT) and then the output table and index file names (defaults: ICCTBL.DAT and ICCNDX.DAT).

Additional documentation: none

HSICC Program Package — SEQHST

Version 3.4 [Feb. 9, 2001]

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(Original author: Bruce J. Barton)

This program converts the Hager-Seltzer direct access table to a sequential text file format.

Input file: The direct access table is a binary file of 11 word records. 13004 records in the file.

Output file: The text file is a sequential access symbolic file of 80 character records (Z, SHELL, EG, E1, E2, E3, E4, M1, M2, M3, M4) = (I3, A2, F7.2, 8E8.2). Data file included: ICCSEQ.DAT.

Terminal dialog: The program will first ask for the binary table file name (default: ICCTBL.DAT) and then the sequential output file name (default: ICCSEQ.DAT).

Additional documentation: none

LOGFT

Version 7.2a [Mar. 20, 2001]

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(Original authors: N.B. Gove and M.J. Martin, Nuclear Data Project, Oak Ridge National Laboratory, and B.J. Barton, National Nuclear Data Center, Brookhaven National Laboratory)

This program calculates log *ft* for beta decay. It also calculates the partial capture fractions for electron capture, the electron capture to positron ratio for positron decay, and the average beta energies. It will do special calculations for first and second forbidden unique; all other categories are treated as allowed.

Input files:
1. ENSDF formatted file. Sample input included: DATA.TST
2. Radial wave function data. Data file included: LOGFT.DAT

Output files:
1. Report file. Sample output included: LOGFT.RPT
2. New ENSDF formatted file with appropriate values for B and E cards updated. Sample output included: LOGFT.NEW

Terminal dialog: The program will ask for the names of the input data file (default: DATA.TST), the report file (default: LOGFT.RPT), the file containing the wave function data (default: LOGFT.DAT), and the file to be created (default: LOGFT.NEW).

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: N.B. Gove and M.J. Martin. Log-f tables for beta decay. Nuclear Data Tables A10, 206 (1971).

Additional notes:
1. New records will not be created if there are non-numeric parent or level energies, Q-values, or associated uncertainties.
2. If Lyon's method 1 has been used to estimate the intensity, LOGFT should also be run using the original values.

NSDFLIB

Version 1.5d [June 28, 1999]

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This subroutine package consists of three subroutine packages F77STR (Fortran 77 String Processing Library), NSDCNV (Fortran 77 Conversion Routines), and NSDMTH (Fortran 77 Mathematical Routines). All elements of the package have been written to conform to the ANSI standard for Fortran 77, and are therefore machine independent. The version number and date given in this "read me" is for F77STR.

Input file: none

Output file: none

Terminal dialog: none

Compilation and loading instructions: This subroutine package is required by most of the ENSDF analysis and utility codes and should be compiled and linked as necessary with them.

Additional documentation: Internal National Nuclear Data Center memo NSDFLIB.MEM

PANDORA

Version 6.6a [Mar. 28, 2001]

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This program provides the following physics checks for an ENSDF file.

1. Decay data sets have a P-card
2. An L-CARD with T1/2 > 0.1 S should have MS FLAG.
3. Check consistency of spin/parity of levels with multipolarity connecting transitions.
4. For a transfer reaction with even-even target J = L+-1/2.
5. For 3.6 < log *ft* < 5.9, $J^{i-1} \leq J^f \leq J^{i+1}$, no parity change. For 1U in cols. 78-79 and log *ft* ≥ 8.5 J^f=$J^{i\pm2}$, parity change.
6. For alpha decay, if the mass is odd and HF < 4, J^f=J^i, no parity change. If J^f or J^i = 0, parity change = $(-1)^{(Jf-Ji)}$
7. Levels out of order.

Input files: ENSDF formatted file. Sample input file: PANDIN.DAT.

Output files:

1. FILE.ERR. Errors and warnings about the input data. Sample output file: FILE.ERR.
2. FILE.GAM. Report of the γs in the input file arranged by A, Z, E_γ, and DSID. Sample output file: FILE.GAM.
3. FILE.GLE. Report of the γs in the input file arranged by A, Z, $E_{(parent\ level)}$, E_γ, and DSID. I_γ given are branching ratios ($I_{(strongest\ \gamma)}$ = 100). Sample output file: FILE.GLE.
4. FILE.LEV. Report of the levels in the input file arranged by A, Z, E_{level}, and DSID. Sample output file: FILE.LEV.
5. FILE.RAD. Report of β/ε in input file arranged by A, Z, $E_{\beta/\varepsilon}$, and DSID. Sample output file: FILE.RAD.
6. FILE.REP. Reports ignored records, levels that have no match in adopted levels, frequency of XREF symbols, new XREF symbols, *etc*. Sample output file: FILE.REP.
7. FILE.XRF. Reports the cross-reference records. The cross-reference symbols are also given in FILE.LEV. Sample output file: FILE.XRF.
8. New ENSDF formatted file with XREFs added or modified. Sample output file: PANDOR.OUT.

Generation of the files reporting on the gammas, levels, and radiations and the new ENSDF formatted file is optional. There is no option to specify file names for the FILE.* outputs.

Terminal dialog: The program will ask for the input file name and then if the user wishes the level, gammas, and radiation reports (default: 0 for no) and a new file generated (default: 0 for no). If new output is specified, the user will be queried for the output file name. As generation of the various output files is completed, this will be noted on the terminal.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: Internal document (PANDOR.PSC).

RadList

Version 5.5 [October 5, 1988]

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(Original authors: W.B. Ewbank and M.J. Kowalski, Nuclear Data Project, Oak Ridge National Laboratory; B.J. Barton, National Nuclear Data Center, Brookhaven National Laboratory; and L.P. Ekstrom and P. Andersson, Department of Nuclear Physics, Lund University)

This program is designed to calculate the nuclear and atomic radiations associated with the radioactive decay of nuclei. It uses as its primary input nuclear decay data in the ENSDF format. Listings or computer files containing the energies, intensities, and dose rates for various nuclear radiations are produced. These outputs also contain the energies, intensities, and dose rates of the associated atomic radiations. Optionally the continua spectra for $\beta^{\pm}$ decay and for internal bremsstrahlung associated with $\beta^{\pm}$ and electron-capture decay may be calculated.

Input files:
1. ENSDF formatted file. The following optional records as defined in cols. 1-9 of the record are allowed:
   a. MERGE/ENDMERGE Specifies that the radiations from the data sets contained between them will be merged on output (ignored if the data-base option is selected)
   b. PAGE Causes the radiation listing output to begin on a new page for the following data set.
   c. PARAMETER Various parameters affecting the calculations or output of the program may be given in cols. 10 - 80 of this record which immediately precedes a data set and only affects that data set. The parameters are:
      i. ALLGAM Overrides the minimum intensity cutoff for radiations and outputs all gammas. No value should be given for this parameter.
      ii. MAXEC Specifies the number of electron-capture branches to be listed in the radiation listing (default = 0).
      iii. MAT Specifies a material number for ENDF-6 output (default is based on the Z and A of the parent).
      iv. RIMIN Specifies the minimum intensity cutoff (in percent) for radiations (default = 0.001% except for the data-base option [10^{-12}%]).
      v. WEIGHT Specifies an arbitrary weighting fraction. Not allowed with database and ENDF-6 options.

Sample input file: RADLST.INP. See the report for an explanation of what is tested within this sample input.

2. Atomic electron binding energies, fluorescence and Auger-electron yields: One of the following two data files must be present:
   a. Direct access binary file (ATOMIC.DAT). The program will generate this file if it does not exist and the following file is available.
   b. Sequential file (default name: MEDNEW.DAT). Data file provided with distribution.
3. Atomic mass data: If neither of the two following files is present, the program will calculate atomic masses based on the Garvey-Kelson formalism.
   a. Direct access binary file (WAPSTB.DAT). The program will generate this file if it does no exist and the following file is available.
   b. Sequential file (default name: RADMAS.DAT). Data file provided with distribution.

Output files: With the exception of the report file, these files are options.

1. Report file: The input data are listed in cols 2-81 and messages reporting possible problems or assumptions made are given in cols 82-133. Possible severe errors are noted on a line following the record in question.
   After all relevant radiation data have been analyzed, there will be a summary of the energy deposited by the radiations and recoiling nuclei and a comparison between the sum of these deposited energies and the energy expected from the branching ratios and Q values.
2. Radiations listing: Fortran-formatted file containing the nuclear and atomic radiations obtained by the program. See the report for additional details.
3. Database file: Presents the data generated by the program in a fixed computer-readable format. See the report for additional details.
4. ENDF-6 format file: MT = 1, MF = 451 (comments) and MT = 8, MF = 457 (decay data) sections are generated.

Either the ENSDF-6 file or the database file may be generated but not both.

Terminal dialog:

1. The program will ask which output files should be generated (defaults: radiation listing; no ENDF-like file or database file).
2. Unless the database option is chosen, the user will be asked if the continua should be calculated (default: no).
3. The names of the input and report files will be requested (defaults: RADLST.INP and RADLST.RPT).
4. If the binary data files are not present, the user will be asked for the names of the sequential files.
5. The user will be asked the names of the various output files to be generated (defaults: ENSDF.RPT, NUDAT.OUT, and ENDF.RAW).
6. The source of the atomic data and the mass data will be noted.
7. As each data set or group of data sets are processed, a summary of the results will be displayed on the terminal.

Sample terminal dialogs and outputs: Following are descriptions of the sample files included in the distribution. NOTE: This supersedes Appendix B of the report. The various outputs in these files are separated by "%%%%%" followed by the type of output and in some cases only show those outputs where there are major differences.

1. RADLST1.OUT: Normal options
2. RADLST2.OUT: ENDF option

3. RADLST3.OUT: Database file option
4. RADLST4.OUT: Continua with bremsstrahlung chosen
5. RADLST5.OUT: ENDF with continua with bremsstrahlung chosen

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: T.W. Burrows. The program RADLST. Brookhaven National Laboratory Report BNL-NCS-52142 (1988).

RULER

Version 1.31a [July 15, 2002]

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This program either calculates the reduced electromagnetic transition strengths and compares these to the Recommended Upper Limits (RUL) or calculates BELW and BMLW for inclusion in ENSDF data sets. Primarily designed to work on ADOPTED LEVELS, GAMMAS datasets but will process any dataset whose DSID indicates the presence of gammas.

Input file: ENSDF formatted file. Sample input file: RULER.IN

Output files:

1. The report file will list the datasets and note any problems or assumptions by the program. Comparison mode: will show the calculations and compare the results to the RULs noting possible violations; calculation mode: will show the calculations and compare the old and new values for BELWs and BMLWs. Sample output files: RULER1.RPT (comparison) and RULER2.RPT (calculation).
2. Optionally a new file will be created containing the calculated BEλWs and BMλWs. Sample output file: RULER.OUT.

Terminal dialog: The program will request the input and report file specifications, the mode of operation (answer is case sensitive), and, optionally, the new file specifications.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: Distribution memo (RULER.PSC)

TREND

Version 8.3 [Feb. 7, 2001]

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(Other author: Bruce J. Barton)

This program generates ENSDF data tables report and allows the user to view and control the output file on the screen.

Input file: An ENSDF formatted file. Sample input file: DATA.TST.

Outputs: Tabular representations of the ENSDF data similar in organization to the Nuclear Data Sheets are generated either as a report file or as a file capable of being viewed interactively on an ANSI (VT100 equivalent) or VT52 terminal.

Sample output file: TREND.RPT (132 columns; 66 lines per page)

Terminal dialog: The program will request the following information:
1. Input file name
2. Output file name
3. If the output file exists, does the user wish to view it?
4. 80 or 132 column display (no defaults)
5. Lines per page (defaults: 60 if 80 column display; 66 if 132 column display). The user should specify 24 for screen display.

If the user has specified "TT:" or "TTY:" (case insensitive) as the output file name, answered yes to viewing an existing file, or 24 lines per page, the tables will be displayed on the screen with a prompt line at the bottom. The user may scroll up and down through the tables.

Compilation and loading instructions: This program requires subroutines from the NSDFLIB package.

Additional documentation: None

GUIDELINES FOR EVALUATORS

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April, 1988

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CONTENTS

GUIDELINES FOR DECAY AND REACTION DATA SETS

A. Extraction of Data

1. In any experiment, the author's basic measured quantities should be quoted, unless these data can be converted to more usual or convenient forms by applying known numerical factors (for example, mean-life to half-life, BE2(sp) to BE2).

Quote what was actually measured in an experiment and not necessarily what the authors quote, in cases where these are different.

> Note: A measurement of Iγ/ΣIβ might be quoted by an author as Iβ(gs), which, for the author's decay scheme should be equivalent to the absolute Iγ determination, but is not as fundamental a quantity. If the decay scheme is changed, the Iβ(gs) could change, whereas the absolute Iγ measurement should still be valid. Failure to make such an important distinction is a particularly common source of confusion when normalization conditions are being stated.
>
> A measurement of $I\gamma^{+-}/I\gamma$ might be quoted by an author as $I\beta^{+}/I\gamma$. The ratio should be expressed in terms of the annihilation radiation, since $I\beta^{+}/I\gamma$ could imply that the positron spectrum was measured.

2. Document any and all changes made in data quoted from an author. When correcting an author's value for a quantity, for example an error due to a misprint, give the corrected value in the appropriate field, and mention the uncorrected value in a comment. Do not give the uncorrected value in the field, and rely on the comment to define and explain the correct value.

3. When extracting data from an author's paper, note any assumptions, standards, or constants that enter into a derived value, and correct the data for any changes in these assumed values. For example, an ε/α ratio for one nucleus might depend on the value assumed for another nucleus, or a conversion coefficient might be normalized to a standard value. Such data should be presented in such a way that the effect of changes in any of the assumed values is clearly displayed; thus, "α_k = 0.0324 12 if α_k = 0.0324 12 if $\alpha_k(^{137}Cs)$-……". Better values for the assumed quantities might be available at the time the mass chain is being revised.

4. Check the bibliography in each article against the reference list provided by BNL. This action is a valuable cross-check to help ensure that references have not been overlooked. Also, authors will sometimes quote data received as private communications; these data should be tracked down if possible if they seem important.

5. Do not rely on an author to extract older data correctly. Even if an author collects such data in a table, the original article should be checked. This checking procedure is especially important in view of 3, above.

6. Be sure to distinguish between values measured by an author and those deduced by the same author. For example, in a transfer reaction, an author might adopt L values for some transitions based on known Jπ in order to extract values for other levels. Such a distinction should be made clear.

B. Manipulation and Presentation of Data

1. Comments

(a) For data sets in which the data appear in two or more separate sections in the data sheets output, namely decay data sets and reaction data sets involving gammas, the comments should always be written in such a way that they are clearly separated into general comments, comments on levels, comments on gammas etc. This "separation" of comments avoids the problem of having comments appear where they are not appropriate (of course these comments can be edited out where they are not appropriate, but this is a step that should be avoided).

> Note 1: A single comment such as "the level scheme is that of . . . based on. . . The Eγ and Iγ are from …, with Iγ normalized so that... The Iβ are from the I(γ+ce) imbalance at each level" should be rewritten as separate general comments on levels, gammas and betas, or as specific data-type comments on Eγ, Iγ, Iβ, as appropriate.
>
> Note 2: Comments on γγ(θ), γγ(t), γ(θ,H,T) etc. in a given data set should normally be given with levels rather than with gammas since it is usually under the levels listing that one wants to see comments on the values of J, T½, or μ etc., deduced in that data set from measurements of these types. If the γγ(θ) data also yield δ values, the comment on δ in the gamma listing can simply state that the relevant γγ(θ) data are discussed in the levels listing.

(b) General comments of a descriptive nature at the head of individual data sets should be kept to a minimum. In particular, comments for each keynumber that describe what was measured (such as Eγ, Iγ), or what detection method was used (such as semi, Ge(Li)) are not required, but can be given at the evaluator's discretion. The only required comments are the specification of bombarding energy and energy resolution for reaction data sets. Projectile energy and experimental resolution should be given for each reference from which data are quoted, even if not a major source. Such information may also be useful for other references. For grouped reactions, such as (HI, xnγ) or Coulomb excitation, the bombarding particle would of course also need to be specified for each keynumber. In addition, for Coulomb excitation, the distinction between particle detection, (x, x'), and gamma detection, (x, x'γ) should be made. Examples are given in (e) below.

> Note 1: The bombarding energy and resolution for reference "A" are of interest in a case where, although most of the excitations energies are from some other source, reference "A", whose data are not otherwise included, reports a level not seen by the other sources, and the evaluator chooses to include this level. In many cases, evaluators refer to reference "A" only in a comment on the specific level in question; however, reference "A" should be included explicitly with the other references in the heading.
>
> Note 2: The specification of "s" for spectrometer is an example of the additional type of information that is probably not worth giving, since such an entry conveys only partial information on the experimental setup while giving the analyzer the fact that photographic plates and aluminum absorbers, for example, were used may be of equal importance. In most cases it would be very difficult to write exhaustive comments such that the reader would not have to look at the paper to obtain the necessary experimental details, so there is no strong reason for giving just part of the picture. The specification of "semi" or "Ge(Li)" is also not really needed. Few modern papers contain "scin" data. Probably useful to specify "cryst", since such measurements can be very precise, and the calibration uncertainties are then known to be proportional to Eγ.

Note 3: Specific comments such as "Eγ are weighted averages from 77Sc02 and 79Fell. Others: 72Go04, 78Hi23" specify the important references for Eγ, and are more informative than a set of keywords presented uncritically.

Note 4: The specification of the angular range might be useful in a case such as the assigning of L = 0 as opposed to L = 2 in (α, α') for a giant resonance. This assignment requires knowledge of the angular yield variation at angles near zero. An indication that this range was measured lends credence to an author's conclusion that L = 0. However the same information could be given instead in a comment discussing the author's conclusion.

c) Do not put E = … on the ID record, except when needed to distinguish otherwise identical data sets, for example, (n, γ) E = th and (n, γ) E = res. The bombarding energy should be put in a comment; see examples in (e) below.

d) Except for even-even targets, Jπ(target) should be given for particle transfer reactions in which L values were determined. A general comment such as "Jπ(^{139}La) = 7/2^{+}" is recommended; see examples in (e) below.

e) For readability of the comments referred to above, each keynumber followed by the appropriate comments should be given on a separate line with the keynumber first. The following are some examples.

^{208}Pb Levels from ^{208}Pb(d, d'), (pol d, d')

71Un0l E = 13 MeV, FWHM = 3-10 keV, θ = 125°-150°
80Mo18 E = 86 MeV, FWHM = l x l0^{-3}
80Wi12 E = 108 MeV, θ = 4°-14° (partial data also reported in 80Dj02)
Others: 62Jo05, 68Hi09

^{208}Pb Levels from Coulomb Excitation

69Ba51 (x, x') X = α, E = 17-l9 MeV; x = ^{16}0, E = 69.1 MeV
71Gr3l (x, x'γ) x-α, E = 15,18 MeV

^{208}Bi Levels from ^{207}Pb(^{3}He, d), (α, t) 71Al05

E(^{3}He) = 30 MeV, FWHM AP 20 keV, θ = 10°-70°
E(α) = 30 MeV, θ = 20°, 50°
Jπ(^{207}Pb) = 1/2^{-}

^{208}Bi Levels from ^{208}Pb(p, n), (p, np') IAS

(p, n)	74Fi14	E - 25.8 MeV	
	80Ho21	E = 120 MeV, FWHM AP 670 keV; 160 MeV, FWHM AP 1200 keV	
		Others:	72Wo23, 71Wo04
(p, np')		73Wo04	E = 30.5 MeV
		77Bh02	E = 25 MeV, n-p' coin
		Others:	79LiZU, 71Wo04

2. Combining data sets

Do not combine reactions that are of fundamentally different character, for example (p, p') and (n, n'), or one-and two-particle transfer reactions.

Except for Coulomb excitation, separate data sets should be created for particle and gamma reactions, for example (d, p) and (d, pγ), or (p, p') and (p, p'γ). Attempting to combine the different types of information usually presented in the two reactions leads to confusion in the presentation. Typically, one wants to present the L (and/or J) and S information from the particle work, and adopted Jπ for the gamma drawings.

The reaction (X, X') is intended to include (X, X); there is no need to include explicitly the special case of elastic scattering.

> Note: In general, we do not include in the data sheets the type of information extracted from elastic scattering, so it is rare that the reaction (X, X) would appear alone. One exception is the case of resonance work, where information on resonances in the compound nucleus can be obtained and may be of importance (see Section F, below). Information on nuclear shapes and charge densities, etc., deduced from elastic scattering can be given, or referred to, in adopted levels without the need for the (X, X) source data set.

3. Sources of data

Sources of data for all headings, for example E(level), Iγ, δ, L, S, should be given unless "obvious". The final decision as to whether a source is obvious or not will reside with the editors. Keep in mind that each evaluator has the responsibility to ensure that the data presented are traceable to their source.

When more than one keynumber is included on an ID record, the keynumber from which the individual pieces of data are taken should be stated. If a reader wants to check an E, Iγ, or S, for example, that reader should be able to go directly to the relevant reference or references.

> Note: A comment on Iγ, stating "from X" or "weighted average of data from X and Y" is preferable to requiring the reader to deduce the sources of data based on the keywords in the general comments described in (1) above.

4. Placement of gamma records

Gammas should be placed in order of increasing energy following each level for consistency in presenting drawings (and for convenience in reading data bank listings). This same order should be followed in the unplaced gammas listing.

5. Significant digits

When converting values from one set of "units" to another (for example, half-life to mean-life, or renormalizing Iγ values), enough digits should be retained so that the inverse operation will reproduce the original values. Note that in some cases this exercise will result in more digits being quoted in the converted value than in the original value. This procedure is especially important when dealing with quantities determined with fairly high precision. For example, from BE2 = 0.384 4, one should report T1/2 = 7.27 ps 8, not 7.3 ps 1, and from a mean-life of 32 ps 1, one should report T1/2 = 22.2 ps 7, not 22 ps 1. Another way of stating this principle is that the fractional uncertainty in the original value should be preserved (to the same number of significant digits) in the converted value.

When taking a weighted or unweighted average, quote a sufficient number of digits to correspond to our round-off procedure; that is, whenever possible, quote two digits for uncertainties up to 25. For example, a weighted average of 6.0 1 and 6.1 1 should be quoted as 6.05 7.

6. Multiplets

(a) Unless a complex peak in a reaction spectrum is resolved in a given experiment, a single "level" entry should be made. For example, in the case of a peak suspected of being made up of two levels with Jπ = a and Jπ = b, respectively, on the basis of work from other experiments, a single level with "Jπ = a and b" in the Jπ field should be introduced. Inclusion in this data set of two levels involves making an explicit assumption that is not necessary. The probable level association can be adequately explained in a comment; this same approach should be used with gammas. A multiply-placed transition seen as a single peak in the spectrum should appear in the output as one transition with multiple placements. Do not introduce additional transitions (with artificially altered energies, or energies taken from the level scheme).

Note: If the intensity of a gamma multiplet is not divided among the several placements, the full intensity, with uncertainty, should be given for each placement, along with "&" in column 77. Do not enter the intensities as limits in source data sets; converse is true in adopted gammas, where multiply-placed Iγ should be entered as upper limits; see Note under Section E. 2. in GUIDELINES FOR ADOPTED LEVELS. If the intensities are divided, for example on the basis of γγ, "@" should be entered in column 77. These entries will automatically generate footnotes explaining that the transitions are multiply placed and that the intensities are not divided (for "&"), or are suitably divided (for "@").

(b) If a gamma transition or a peak in a reaction spectrum is claimed to be a multiplet, the basis for this claim should be given. For example, the gamma peak might be broad, or coincidence data might suggest that a peak is a multiplet. In the case of a peak in a reaction spectrum, experimental arguments such as "peak is broad" should be distinguished from theoretical arguments such as "C2S is too large for a single level on the basis of shell model expectations".

(c) Consider gamma-ray multiplets where Iγ (peak) in a specific data set cannot be decomposed on the basis of data available in that data set, but branchings involving one or more of the members of the multiplet are available from other data sets; Iγ for members of the multiplet should be deduced where possible using such branchings. Appropriate comments, such as "Iγ: From Iγ(326γ)/Iγ(432γ) in Adopted Gammas", are of course required, and "@" should be entered in column 77.

d) A multipolarity determined for a multiplet will not necessarily be correct for each, or perhaps even any, member of the multiplet. For example, depending on the relative strengths of the components, I(γ) and I(cek) for a doublet consisting of an El and Ml component could yield mult = E2. The multipolarity for the doublet should be given in a comment, but should not be entered in the multipolarity field of the individual components, unless additional information is available that justifies the assignments.

Note: When I(γ) but not I(cek) (or vice-versa) is resolved, and the multipolarity of one component of a doublet is known from other sources, the multipolarity for the other component may possibly be deduced.

7. Cross sections and analyzing-power should not be given explicitly - sufficient simply to mention that such measurements were made, in the context of justifying any conclusions based on such data. The conclusions themselves should be given.

Note: If an evaluator feels that the angular distribution coefficients do need to be given, they should be defined in the form A2, A4, not A2/Ao, A4/Ao; i.e., we define the angular distribution function as W(θ) = 1+ A2P2(cos θ) +..., not as Ao + A2P2(cos θ) +...

8. (γ, γ') experiments

Some confusion and a lack of consistency in the presentation of data exists in experiments on resonant fluorescence. Scattering experiments are the most common type of measurement that, for the case of photons scattered elastically from a thin target, yields the quantity $gW(\theta)\Gamma(\gamma 0)^2/\Gamma$, where g = (2J + 1)/(2Jo + 1), with J-resonance level spin, Jo = gs spin, and W is the usual angular correlation function. For inelastic scattering, the term $\Gamma(\gamma 0)^2$ in the numerator should be replaced by Γ(γ0)Γ(γi) where Γ(γi) refers to the de-exciting transition to an excited level with J = Ji. The quantity $gW\Gamma(\gamma 0)^2/\Gamma$, or just $\Gamma(\gamma 0)^2/\Gamma$, should be given in this type of experiment. When J and W are known, the adopted value for Γ(γ0)/Γ (= I(γ0)/ΣI(γ) in the case of bound states) should be used where available to deduce the level width (or T1/2). For the inelastic case, the corresponding intensity ratio I(γi)/ΣI(γ) would be needed.

Note 1: Measurements are usually undertaken at 127° where W = 1 for all dipole transitions, independent of Jo, J, or Ji (P2(cos θ) = 0 at this angle). For mixed transitions, W depends on the mixing ratio and on the J values.

Note 2: Occasionally, self-absorption experiments are performed to yield gWΓ(γ0)/Γ.

The quantity $\Gamma(\gamma 0)^2/\Gamma$ can be given in the “S" field, with the field suitably relabelled (see Section G. 1. below). This procedure eliminates considerable typing at the input stage. The quantity Γ(γ0)/Γ can be given in the RI field for the relevant γ or as a comment on the corresponding level.

9. BEλ and βλ

Consider Coulomb excitation and (e, e'), where electromagnetic excitation probabilities can be determined, in which the quantities BE2, BE3, etc. , should be quoted on continuation level records. Data quoted as matrix elements should be converted to BE2 etc. A matrix element has been determined and this fact could be added as a comment. Note that $BE\lambda = (2Jo + I)^{-1}|\langle ME\lambda \rangle|^2$, where <MEλ> is the matrix element, and Jo is the target spin.

Note: Do not give BEλ data with the gammas. BEλ(down) data, given by an author for gammas, should be converted to BEλ(up) and given with the corresponding level. The appropriate place for BEλ(down) data is in adopted gammas where we give such values in single-particle units based on adopted T1/2, branching, etc., data.

For inelastic reactions other than those governed by the electromagnetic interaction, the appropriate interaction strengths to quote are the deformation parameters, βλ or βλR. Authors sometimes convert the deformation parameters to BEλ, but this is a model-dependent procedure and unless the authors quote only BEλ the deformation parameters should be entered into ENSDF.

10. Delayed gammas

For an in-beam reaction in which both prompt and delayed Iγ from level X are available, there are two methods of accounting for the data.
(a) If only one reaction (or more than one but grouped together such as in (HI, xnγ) contains data on the delayed transitions from level X, two data sets can be created: one labelled with the modifier "prompt gammas" and the other with the modifier "delayed gammas".

(b) Preferred method is to create an IT decay data set for level x.
This alternative is especially recommended if there is more than one source of data. A single IT data set which combines the results from all the relevant reactions is preferable to creating several delayed-gamma data sets from the several reactions for the same level X.

> Note: The prompt data should always be presented; however, the separation into prompt and delayed data sets can be particularly useful when the delayed-gamma intensities are used to obtain multipolarities based on intensity balance arguments.

If the delayed data are rather sparse, and the results from the data, such as multipolarity information or T1/2, can be conveniently quoted in the prompt data set, (for example "Mult: from α deduced from intensity balance in the delayed spectrum"), the evaluator may choose to combine all the data in a single data set.

11. Data sets without level information

Separate data sets for reactions studied, but for which no specific level information is given, can be included at the evaluator's discretion if the experiment yielded some useful information. Such a data set would consist only of comments. The following are examples.

^{208}Po from ^{204}Pb(^{16}O, ^{12}C) 76Da18

E = 93 MeV
The authors deduce $\Gamma(\alpha)$ for the ^{208}Po ground state and compare with the corresponding α-decay value via R-matrix theory using the same target-plus-α nuclear potential.

^{208}Pb from ^{208}Pb(p, n) 74Sc0l,74Sc3l

E = 25.8 MeV
Authors deduce rms neutron/proton radius ratio = l.07 3

> Note: The information contained in such data sets in many cases could also be included as comments in adopted levels. This is especially true for the second example; however, unless a data set is created for a reaction, there is no convenient way to search and retrieve that reaction and thus to indicate to the reader that such a reaction was studied. If a reaction was studied but no "useful" information is available, the best approach would be to simply list the reaction under "Other reactions" in a comment on adopted levels.

12. β- and $\varepsilon + \beta$ + feedings, and logft

Logft values should be made consistent with the deduced β^- or $\varepsilon + \beta^+$ feedings. In particular,
when I $\pm$ ΔI is consistent with zero (for example 3% 3), the corresponding logft should be expressed as a lower limit corresponding to a feeding of I + ΔI(6% in this case). Branches that overlap zero (for example, - 3% 6), should be shown with the feeding given as an upper limit (<3%), with the corresponding logft given as a lower limit.

> Note 1: The above holds for cases where the feeding can be expected to be non-negligible, i.e., where the transition is ΔJ = l, $\Delta\pi$ = yes or no, or ΔJ = 2, $\Delta\pi$ = yes. Where Jπ change implies negligible feeding, feeding should be set to zero. Any deduced feeding not consistent with zero should be commented on and an explanation for the inconsistency given if possible.

An exception to this policy of omitting "unphysical" branches occurs when the initial or final Jπ is in question; there is no clear evidence whether Jπ or the feeding is in error. Under such circumstances , the β^- or $\varepsilon + \beta^+$ branch should be shown, perhaps with "?", and the problem should be pointed out in a comment.

Note 2: Summed feeding to two levels connected by a transition whose TI is not known, or is known only as a limit, can sometimes be determined even though the feeding cannot be divided between the two levels. Such combined feedings should be given in a comment.

13. Normalization

The normalization condition should always be given. Be sure to account for both NR and BR.

Note 1: If the normalization condition involves a measured quantity for which no uncertainty is quoted by the authors (for example, I(β^- gs) = 30%), try to assign an uncertainty. If you can not do so, or choose not to do so, the resulting NR (or NR x BR) should be given as approximate. If NR is given with no uncertainty, GTOL will generate level feedings, and MEDLIST will generate absolute intensities that reflectonly the uncertainties in the relative intensities. If ΔI(β^-) is assigned in the given example, the uncertainty can be explicitly added to I(β^-) in the listing, with an appropriate comment, or simply referred to in the normalization statement, for example, "NR:...the evaluator hasassigned an uncertainty of x% to the intensity of the gs β^- branch in order to get an overall uncertainty for NR". The former approach is recommended. Note that when the gs branch has a small intensity (say a few percent), even a large assigned uncertainty can result in a rather precise NR as calculated from ΣTI(gs) = 100 - Iβ^-(gs).

Note 2: When Iγ in the RI field already include all the uncertainty appropriate for absolute intensities, such as when an author determines and quotes absolute values (including absolute uncertainties), NR and BR should introduce no additional uncertainty and should be given on the "N" record with no uncertainty (there is no requirement that the uncertainty in BR, as given in adopted levels, be carried over to the "N" record in a decay data set, although the value must be the same).

14. Parent records

Fields where data are known should be completed in the parent record, and the data should be the same as in the adopted data set. Comments on the "P" record should not be given unless necessary. The appropriate place for comments on any of the quantities appearing on the "P" record is in the adopted data set for the parent nuclide.

15. Miscellaneous

(a) The symbol "/" should not be used when proportionality of more than two values is defined The expression K/L/M is mathematically equivalent to KM/L, even though few readers would interpret the term in this way. Use ":" instead: to give K:L:M.

(b) Do not replace numerical values with large uncertainties by approximate values.

Note: An "isomer" energy of 230 300 keVallows for the possibility that the isomer may lie below the "ground state" by 70 keV. If the energy is replaced by ~230 Kev, this possibility (while not ruled out) will not be conveyed to most readers.

(c) Try to resolve discrepancies - if they cannot be resolved, state this lack of resolution.

Note: If $\delta = +0.38$ is adopted for a certain transition, the value $\delta = +2$ appears in one of the source data sets, and the reason for the discrepancy cannot be determined, the evaluator should comment on the discrepancy. These comments can be logged in the source data set by pointing out that the value differs from the adopted value, or in adopted γs where the discrepant value can be mentioned in a comment. If something of this nature is not done, the reader might think that the discrepant value had been overlooked and may question the adopted value. If there are several such "discrepant" δ values in a certain data set, a general comment rather than a comment on each case could be given.

(d) Use the word "uncertainty" rather than "error" to refer to what we call the standard deviation in a measuredquantity. The word "error" should be reserved for mistakes, such as in the sentence "The authors apparently made an error when they ...".

(e) Note that TI is translated as I(γ+ce), not I($\varepsilon+\beta^+$), even though the fields have the same name in ENSDF. When I($\varepsilon+\beta^+$) is meant, this definition must be spelt out.

(f) A level designated as an isomer in one data set should be treated as an isomer in all data sets (that is, columns 78 and/or 79 should be completed).

(g) Do not comment on correction factors for a quantity when such correction factors are negligible relative to the uncertainty quoted for the quantity. For example, μ = +3.8 5 does not require a comment stating “diamagnetic correction has not been applied".

(h) Avoid the use of "CA" in the uncertainty field when a numeric uncertainty can be calculated.

Note: If Iγ is calculated from TI and α, the uncertainty in Iγ (from the uncertainty in TI and α), rather than "CA", should be placed in the uncertainty field.

(i) When calculating or correcting quantities that depend on other properties (for example, calculating conversion coefficients which depend on Eγ, calculating T1/2 from BE2 which depends on Eγ, branching, δ, and α, or correcting g factors for their dependence on T1/2), adopted values of all other relevant quantities should be used.

(j) When working with an author's proposed decay scheme, the evaluator should make a search for possible alternative gamma placements between known levels.

(k) Enter data in E(ε) or E(β^-) fields only when they are of sufficient accuracy that in the evaluator's judgement they should be considered as input to the mass adjustment. Values that are of somewhat lesser accuracy but still "significant" could be mentioned in comments. Very imprecise values are probably not worth recording. All the network analysis programs that require these energies obtain them from the appropriate Q-value and level energy.

Note: A measurement of β^+ endpoint must be entered as E(ε) = E(β^+) + 2mc^2. For example, a comment such as "E(ε): From E(β^+)=...(keynumber)" would be appropriate.

(l) Alpha-decay data sets: if the energies of the daughter levels being fed are not known, E(level) = 0 + X style should be used rather than listing the alphas as unplaced. With this procedure, relative level energies can be presented in the daughter-nucleus mass chain. Alternatively, a level energy from systematics can be given (see Section C. c), below). Note that there is no such thing as an unplaced alpha, unless one is referring to an alpha with uncertain parent assignment.

(m) Measurements of $P_k\omega_k$ (= I(K-x ray)) should be given. Adopted values can be entered on a continuation "E" record. These quantities are of direct interest to some researchers, and provide a direct measurement of the K-x rays, either for ε branches to individual levels, or an average for the whole decay scheme. When possible, $P_k\omega_k$ should be compared with I(K-x ray) as calculated by RADLIST.

(n) If numerical data are quoted in comments, the uncertainty should be included unless the value is only being used as a label; thus, "T1/2: From BE2 = 0.240 6", or "μ: From g = 1.62 3 in (α, 2nγ)". Even though the actual numerical value is not needed in all cross references, the uncertainty should be included.

(o) When changing the sign of a mixing ratio which has an asymmetric uncertainty, note that
δ = A + a-b becomes δ = -A + b-a (not -A + a-b).

(p) The ground state should be included in all data sets of the type (X, X'), i.e., inelastic scattering.

C. Systematics

Use should be made of systematics whenever possible, the extent to which they can be applied in any given case being determined by their reliability. The evaluator is usually in a better position to know how and when to apply systematics of a given quantity than the typical reader who is generally looking at just one or perhaps a few mass chains at a time.

> Note: Network evaluators make extensive use of systematics. Strong arguments for Jπ assignments which rely on logft values, strong arguments for multipolarities that rely on RUL, and extrapolations from the measured data in the mass adjustment (which are called systematics values) are prime examples.

One area in which systematics are particularly valuable is the estimation of ground and isomeric state branching ratios.

(a) Plots of Log T1/2(α) vs log E(α) for nuclides with the same Z are usually linear. For a nuclide whose alpha branching has not been experimentally determined, use of T1/2(α) vs E(α) systematics can sometimes yield a reliable estimate of T1/2(α) which, along with the measured total T1/2, yields the alpha branching. On more than one occasion, such an estimate has been invoked to show that an experimental value must be incorrect; see also (c), below.

(b) Gross beta decay T1/2(β^-) and T1/2($\varepsilon + \beta^+$) estimates from (for example) Takahashi et al., Beta-Decay Half-lives Calculated on the Gross Theory, At. Data Nucl. Data Tables 12 (1973) 101, can be used to estimate β^- or $\varepsilon + \beta^+$ branching fractions. These estimates are considered to be reliable to better than a factor of approximately 3; thus, while an estimate of %β^- ≈50 and branching for the alternate modes of ≈50% should be considered as very approximate, an estimate of %β^- ≈ 0.1 can be used to assign the alternate mode(s) as essentially 100% with a high degree of reliability.

Additional areas where systematics arguments should at least be explored include the following.

(c) Systematics of alpha-decay hindrance factors can be used to deduce a variety of quantities (depending on what is known about the decay branch). These include Jπ and configurations, total alpha branching and branchings of individual groups, and the excitation energy of the level fed in the daughter nucleus. Each evaluator (or centre) responsible for a mass region in which alpha decay occurs is encouraged to build up such a set of systematics. See Schmorak, Systematics of Nuclear Level Properties in the Lead Region, Nucl. Data Sheets 31 (1980) 283; and Schmorak, α-Decay Hindrance Factors in the ENSDF procedures manual for further discussion of these and other types of systematics.

(d) When a certain pair of shell- or Nilsson-model orbitals gives rise to the appearance of an isomeric transition over a reasonably large mass range, the reduced transition probabilities for the isomeric transition usually fall within a narrow range of values. Such data can be used to estimate properties for the "same" transition where one piece of information is missing, such as T1/2, IT branching, or Eγ.

(e) When a ground-state β^- branch is not known and there is no other way to determine the gamma normalization, logft values for similar transitions may exhibit local systematics. Even if the evaluator decides not to give an explicit normalization factor, a comment would be of value to the reader that points out what this factor would be if the transition had a logft value similar to other such transitions in the same region.

> Note: From logf^{1u}t > 8.5 one might derive Iβ^-(gs) < 10%. While this estimate might be the best one can do, systematics of logf^{1U}t values for other transitions of similar type (i.e., transitions between similar configurations) might suggest that the probable intensity is < 5%, or even close to zero. In such cases, the evaluator can adopt the systematics value for the limit on the β^- feeding in order to obtain the normalization. Justification for the chosen value must be stated. The systematics value could also be entered directly in the Iβ field, with an explanation for the source of that parameter instead of (or in addition to) the value derived from the normalization factor.

D. Uncertainties

1. Estimation of uncertainties.

When an experimental value is quoted by an author without an uncertainty, the evaluator should attempt to estimate and assign an uncertainty to that quantity if that quantity is required in further calculations, or if that value is a quantity that needs to be adopted and no other value is available.

> Note 1: The normalization of a decay scheme may sometimes involve a measurement quoted with no uncertainty; see Note 1 in Section B. 13, above for a discussion of a ground-state beta transition with no quoted uncertainty that is needed for the normalization of the decay scheme.

> Note 2: When one or more excitation energies in a reaction data set (quoted with no uncertainty) need to be included in the adopted levels, the evaluator should attempt to estimate the uncertainty for these excitation energies. Uncertainties can sometimes be estimated by comparing the author's values with adopted energies in regions where there is overlap. Occasionally, comparison with data for other nuclei included in the paper can also be helpful.

2. Adoption of uncertainties

Weighted average program GTOL and all other analysis programs that calculate uncertainties when individual values with uncertainties are combined, treat the individual uncertainties as statistical in nature. When the uncertainties are known to have a significant systematic component, the output from the above programs should be modified as necessary, particularly in cases where the quoted uncertainty is mainly and clearly systematic (due to a calibration uncertainty) so that the adopted uncertainty should be no smaller than the smallest of the input uncertainties. No result obtained from a weighted or unweighted average program or by any other method can have an uncertainty smaller than the uncertainty (or uncertainties) in the calibration standard(s) used to determine the input values.

3. All uncertainties in extracted data (for example, Eγ, Iγ, E(level) and T1/2) should be accounted for, either explicitly or in comments. Authors occasionally quote peak-fitting uncertainties and then

state that an additional x% should be included to account for other sources of uncertainty, or they quote the value for some quantity relative to a standard value.

> Note I: Consider Iγ in which these additional uncertainties, if independent of Eγ or Iγ, can either be included in NR, or explicitly combined for each transition with the partial uncertainties given by the authors. Since the intensity ratios of transitions close in energy may be nearly independent of the additional uncertainties, there may be an advantage in accounting for these through their inclusion in NR, although additional uncertainties that have been folded in can always be folded out if necessary.

> Note 2:, Additional uncertainties should be included explicitly in the case of data describing other quantities, at least for quantities that are used in adopted levels and gammas. Neither network analysis nor listing programs are capable of making use of a comment such as "an additional uncertainty of x eV should be added in quadrature to the Eγ to account for uncertainties in the calibration". If an author quotes a value of T1/2 or a g factor relative to a standard, the uncertainty in the standard should be included when the value is adopted or combined with other measurements.

4. When undertaking calculations, the evaluator should attach an uncertainty to all theoretical α values (3% is recommended). For example, calculations of TI = Iγ(l+α) (or Iγ = TI/(l+α) or T1/2 from BE2) should include this uncertainty. The contribution of this uncertainty to the total uncertainty is negligible in many cases, but in normalizing 100% IT decay to Iγ(l+α) = 100, or normalizing a decay scheme in which only a single transition feeds the ground state and Iγ for this transition is given by the authors with no uncertainty, the uncertainty in α will be the only uncertainty in the normalized Iγ (assuming that the decay scheme is known with confidence). A comment should be included to explain what was done, and this uncertainty should not be entered in the Δα field. Our analysis programs already assign 3% uncertainty to α when performing calculations involving this quantity.

5. Numerical uncertainties larger than 25 should, normally be rounded off.

> Note: Data should be quoted in units such that this round-off convention can be applied. For example, T1/2 = 250 ps 50 should be quoted as 0.25 ns 5, and a set of Iγ data given by an author normalized to $I_{\gamma I}$ = l000 70 should be renormalized to $I_{\gamma i}$ = 100 7. Energies: since the standard energy unit is keV, values such as Q^- = 2000 150, or E(β^-) = 2450 80 do not have to be converted to 2.00 15 MeV, or 2.458 MeV.

E. Resonances

Although the data coverage in ENSDF is limited to the bound-state region, any properties of the bound levels deduced from resonance work should be included. Eγ and 1γ data from (p, γ) and (n, γ) reactions do not need to be included in ENSDF except as noted below.

> Note: A typical case of interest involves the study of average resonance neutron capture in which Jπ values have been deduced on the basis of reduced transition intensities. The resulting data set needs to contain only the bound levels fed from the resonances, along with the deduced Jπ values; Iγ presented typically as Iγ/Eγ are not required. In fact, they should not be given since they are just average quantities, and are only significant from the point of view of ENSDF for their use in deducing Jπ (in this sense, they are analogous to angular distribution coefficients).

Resonance data should be included in the following cases.

a) Isobaric analog resonance data should be included; they should also be included in adopted levels.

b) Giant resonance data should be included, although data of this type are available for only a few nuclides.

c) Eγ, Iγ (and other relevant data) from thermal neutron capture should be included.

Note: Excitation data for isobaric analog resonances should appear with the nucleus in which the resonances occur. Branchings to daughter levels (for example, in (p, np')), should also be given. Comments that include the deduced energies of the parent states (energies relative to E = 0 for the analog of the ground state), or comments labelling the resonance with the appropriate parent level are useful.

Other situations may arise where the inclusion of resonance data is important (for example, near closed shells where the resonances occur at excitation energies low enough that they may "overlap" adjacent bound states that have been studied). The inclusion of data in this and other special cases is at the evaluator's discretion.

Note: Energies for resonance data can be entered in the form SN+X, SP+X, where X is the neutron- or proton-resonance energy, usually given in laboratory units (lab, or c.m. coordinates should be specified in either case). These resonances should be converted to excitation energies in the adopted levels.

F. L Transfers

1. A brief comment is required on the method used for obtaining L values; for example, L values "from DWBA analysis" should be distinguished from L values obtained "from comparison of σ(θ) with shapes for levels with known Jπ".

2. Parentheses are used to denote questionable or uncertain values. As described in the introductory section, square brackets can be used to indicate an assumed value, i.e., a value adopted by an experimenter (or by an evaluator) on the basis of known Jπ. This procedure might be adopted for the purpose of extracting S, or for determining empirical angular distribution shapes so that L values for other levels can be determined.

Note: When quoting L values, the evaluator has the option of quoting the author's values and then applying his/her own judgement as to their reliability when incorporating them into Jπ assignments, or of quoting the author's values as modified by the evaluator. For example, an author's L = 2 which in the evaluator's judgement should be L = (2), could appear as L = 2 in the source data set, but as L = (2) if used as a J1I' argument. Alternatively, a value of L = (2) could be entered in the source data set. In either case, a comment is required explaining that the evaluator feels that the L assignment is tentative.

G. Spectroscopic Factors

1. The exact label for the given quantity should be defined by using the "LABEL=name" format described in the manual; thus, "LABEL = C2S".

2. An explicit definition of S should be given if there is any ambiguity about what is meant; thus, "S is defined by "dσ/dΩ(exp) = Nsdσ/dΩ(DWBA) with N=..."

3. The method for obtaining the scale of S should be given, and it is important to distinguish between absolute and relative values. Thus, a comment such as "from DWBA", which implies that the values are "absolute", or "from DWBA normalized to X for the y level" for relative S values, should be given.

4. The shell-model (or other) orbital involved in the transfer should be specified if needed for the extraction of S.

> Note: This orbital can usually be specified in terms of a general comment such as "L-l, 2, and 3 are assumed to be p3/2, d5/2, and f5/2 except where noted otherwise". An alternative method is to give Jπ for the relevant levels along with a comment such as "Jπ: value assumed by the authors for the extraction of S"; the former approach is preferred when practical.

5. When Jπ adopted by an author differs from the evaluator's value, the S value (which will be incorrect) should not be entered in the S field, but given only in a comment. The reason for recommending that the incorrect value be given at all is that a knowledgeable reader can often estimate the value for the correct orbital from the value calculated for the incorrect orbital .

H. Jπ

1. Jπ values from adopted levels should be included where known; the introductory section states that this is our standard policy. For reaction data sets with no gammas, Jπ values should not be given unless they are determined in the reaction in question, or unless they are important in explaining some other aspect of the experiment. Jπ values should be given in reaction data sets with gammas. Note that the introductory section states that Jπ values appearing in the γ reaction data set are adopted values unless noted otherwise.

> Note 1: Reactions that do not involve gammas - Jπ values, such as from L values and analyzing powers in (d, p) reaction, should be given in the Jπ field along with a comment stating how they were determined. Jπ values that come directly from the L values, such as J = L ± 1/2 for single-particle transfer on an even-even nucleus, or L = J in (p, t) on an even-even target, are redundant, and should not routinely be given. Exceptions occur, for example, where the evaluator wishes to indicate the Jπ value used to extract the spectroscopic factor, or to show explicitly the band structure.

> Note 2: Reactions involving gammas, e.g., average resonance neutron capture - deduced Jπ values can be given in the Jπ field, or in comments. The latter procedure is recommended since adopted Jπ can then be placed in the Jπ field, in line with the accepted policy of including adopted Jπ values for any reaction data set involving gammas.

2. Arguments used in the Jπ assignments in adopted levels must be documented in the source data sets. The following represent a few examples.

	Jπ	argument
a)	3/2-	L(d, p) = l, 392γ to 5/2- is Ml
b)	1-	Average Resonance (n, γ), γ to 0+
c)	3+	El γ to 2-, γγ(θ)
d)	(5/2)+	L = 2, C2S in (d, p)

(a) (d, p) data set should contain the relevant L value, with any explanation deemed necessary to justify or explain the adoption. Recommended γ data set should contain the justification for the Ml assignment to the 392γ.

(b) Average Resonance (n, γ) data set should contain the value deduced in that data set (Jπ = 0-, l- in the present case), given in either the Jπ field, or as a comment; see also Note 2 under 1, above.

(c) enough detail of the γγ(θ) experiment should be given in the source data set to justify the conclusions. Briefly, this section should mention the assumptions (i.e., what J values for other levels and what δ values for relevant gammas in the cascade were adopted, and should clearly state which values of J are allowed and which are ruled out. For the above example: only necessary to state that γγ(θ) is consistent with J = 3, and rules out J = l and 2.

(d) (d, p) data set should contain L and C2S values for the level in question, and a comment justifying the basis for the C2S argument. For example: "d3/2 strength exhausted by known 3/2+ levels. C2S for the L = 2, E=...level suggests d5/2".

I. Iγ, TI

1. Relative TI data (or absolute, for example, for (n, γ) in preference to branching ratio data) should be given when available.

> Note: If both relative Iγ and branching ratios are available, and if the branching ratios are more accurately known than the relative TI, both sets of data should be given. Relative Iγ should be given in the RI field, and the branching ratios can be given as comments on the relevant levels.

2. Reaction γ s: projectile energy and angle at which the quoted Iγ were measured should be specified unless obvious from the keywords given in the general comments. Relative Iγ values measured under different experimental conditions, such as at a different bombarding energy or angle, should not be combined in the RI field, except where an Iγ from level "X" is deduced from branchings relative to other transitions from level "X".

3. Gamma intensities reported as upper limits are important data measurements; and should be included (a comment to the effect that the transition was not seen could be included). Iγ given as "weak" by an author should be noted as such in a comment; also important to distinguish between cases where a missing Iγ is weak, and where such an emission is obscured by an impurity (and therefore could be strong).

> Note: One could distinguish between observed and unobserved transitions expressed as limits by the use of "≤" for the former, and "<" for the latter; however, the distinction between these two non-numeric uncertainties is not universally agreed upon, and is probably too subtle a distinction.

4. The TI field should be used only if TI, rather than Iγ, is the quantity measured or deduced. Two common cases where this occurs are when TI is deduced from intensity-balance arguments, or TI is given by summing I(ce). When TI is given and α is known, the corresponding Iγ should be calculated and entered into the Iγ field, unless the value is negligibly small. The uncertainty given for Iγ should include the uncertainties in both TI and α; a comment should be given stating that Iγ comes from TI and α.

Note 1: Iγ deduced from TI and α may be given in the RI field even when a direct measurement of Iγ is available, if the evaluator concludes that the deduced value is more reliable than the measured value.

Note 2: When TI rather than Iγ is the basic measured or deduced quantity, K/T(= αk/(l+α)) =... etc. , rather than αk-... etc. format on the continuation record should be used. For example, K/T operates directly on TI to generate the cek intensity (via MEDLIST) and the resulting x-ray intensities. This format avoids including some uncertainties twice, since Iγ (if calculated from TI and α) will already have an uncertainty combined from these two quantities.

5. Do not put TI values in the RI field, even if a comment is included to explain what is being done, and even if all the entries are TI values. RI and TI must not be mixed in the same field.

6. RI (or TI) field should be left blank for a transition which de-excites a daughter nucleus isomer whose T1/2 value is such that the intensity is time-dependent. A computer-retrievable comment should be included that defines % feeding of the isomer, and a comment is also required to explain why the intensity is missing.

7. I(x ray) and I(γ±) data of good quality should be given as comments in the form I(x ray)/Iγ(γi), where γi is the transition to which the γs are normalized. This procedure avoids the necessity of changing the comments if the Iγ are renormalized. The program MEDLIST should be run to compare the measured x ray and γ± intensities with those calculated on the basis of the adopted decay scheme. If the I(x ray))/Iγ or I(γ±)/Iγ measurements are needed to obtain decay scheme normalization, note that MEDLIST can be used in an iterative fashion to deduce NR.

8. Internal conversion intensities are not needed, and they should not be given except in the following cases.

a) I(ce) ratios measured to a precision of better than about 3% should be included. At this level of precision, it is useful to compare such values to the theoretical data.

b) Where no Iγ is given, or where I(ce) are more precise, the I(ce) values should be quoted.

c) I(ce) are needed for E0 transitions, and should also be given for anomalously converted transitions.

9. A limit on a transition intensity (I < A) should be converted to I = 1/2A ± 1/2A for the purpose of calculating quantities that require the intensity of this transition, such as normalization factors, β^- and $\varepsilon + \beta^+$ feedings, or branchings (for branchings, see Note 4 under G. in GUIDELINES FOR ADOPTED LEVELS).

Note 1 : Where $I\beta^-$(gs) is determined to be < 6% and the evaluator has no further information to suggest that this value should be closer to 0 than to 6, the intensity should be expressed as 3% 3 for the purpose of obtaining the gamma intensity normalization; one should set sum TI(gs) = 97 3 and explain what is being done. This procedure is preferable to any of the alternatives, namely setting ΣTI(gs) = l00, or ΣTI(gs) > 97. There is no justification for adopting the first alternative, and adopting the second alternative leads to lower limits being given for all the intensities. The usefulness of the procedure depends on the value of the limit - if I(β^-) is known only to be < 50%, perhaps normalizing the decay scheme is not worthwhile, although setting sum TI(gs) - 75% 25 is still better than doing nothing (if no normalization is adopted, a comment could be given stating what the normalization factor would be for the extreme cases, namely for $I\beta^- = 0$, and $I\beta^- = 50$). Note that the intensity of the gs β^- group should still be given as a limit in the β^- listing.

Note 2: Iγ values given as limits should be converted to 1/2Iγ ± 1/2Iγ for the purpose of obtaining β^- and/or ε feedings from intensity imbalances. This procedure may lead to some feedings with rather large uncertainties, but this approach reflects correctly the state of knowledge of the decay scheme. The procedure is analogous to setting mult = [Ml+E2] for a highly converted transition in order to estimate the total intensity. Again, there is no implied suggestion that the intensities themselves should be changed from their limit form in the Iγ field. GTOL program has been modified to treat limits automatically in this manner.

If the evaluator feels that the limit in a given case should not be treated in this fashion, a comment should be given justifying whatever approach is taken.

10. For the purpose of obtaining β and/or ε feedings, gamma transitions whose placements are uncertain (that is, transitions that have a "?" in column 80) should be handled in the same manner as for transitions given as limits discussed in Note 2 under 9, above. One should take Iγ = ΔIγ = 1/2(A + ΔA), where Iγ = A ± ΔA is the measured value. GTOL has been modified to treat uncertain transitions in this manner, but the evaluator will also be responsible for ensuring that the input to GTOL is modified as discussed here.

J. Mult, δ, α

1. As stated in the introductory section, the multipolarity and δ entries (and thus α) for decay data sets should be adopted values. The inclusion of such data is mandatory, while for reaction gamma data sets such information should be included as needed or if measured.

Note: TI values are not needed in many reaction data sets, nor δ and α. However, the multipolarity should be defined. If TI values are required, adopted values for multipolarity and δ should also be used.

2. When multipolarity and/or δ values are determined, the basis for such determinations should be stated. Sources for the multipolarity data used by the evaluator (such as γ(θ), αk), along with the normalization required in αk data determined from relative Iγ and I(cek), should be given whether or not the experimental data (e.g., A2 and A4, αk, etc.) are explicitly given. Multipolarity assignments from ce data should originate from the evaluator based on the output from HSICC. Multipolarities deduced by the authors (or by the evaluator) on the basis of "stretched" γ(θ) should be noted as a comment in the style of "ΔJ = 1, or ΔJ = 2".

Note I: γ(θ) data determine only the L component of the gamma character (i.e., mult = D, D + Q, etc). Further assumptions are needed to establish the change in π, and should be stated when D is converted to M1, or D + Q to M1 + E2, etc. In particular, Q = E2 should not be considered an "obvious" conclusion. If T1/2 is known, RUL can sometimes be invoked to eliminate specific possibilities, particularly Q = M2, and D + Q = E1 + M2 when δ is known. If known values of Jπ are used to establish any part of the character of a gamma, that part should be placed in parentheses. Remember that one of the implied uses of a non-parenthesized multipolarity is as a strong argument to assign Jπ values, so one must avoid circularity.

Note 2: If any multipolarity = D, D + Q, etc. can be assigned as M1, M1 + E2, etc., only by the use of level scheme arguments, the designation mult = D should be retained in the source data set unless the complete designation (mult = (MI)) is needed to determine α. The mult = (M1) assignment can be adopted when choosing the multipolarity for the adopted γs section. The main advantage in following this procedure (other than the such assumptions should be made onlv when necessary) is that a transition known to have mult = D (strong assignment) may be more useful in defining a Jπ value than having only the parenthesized mult = (M1) (weak assignment). When such an argument is used, the reference for the multipolarity should be to the source data set, and not to adopted γs if the adopted value is mult = (M1).

3. Entries in the multipolarity, δ and α fields should be mutually consistent, and the following guidelines should be followed.

(a) If a single multipolarity is adopted, the δ field should be blank.

(b) If only a limit on δ is available and this limit is significant and worth giving, there are two options.

(i) Give the dominant multipolarity with corresponding α, and give the δ limit in a comment.

(ii) Give both multipolarities and the δ limit in the δ field. The value of α should correspond to 1/2δ(max), with an uncertainty chosen to overlap the 0 to δ(max) range.

Note: Option (i) is recommended when (in the evaluator's judgement) the admixed component is likely to be smaller than the experimental limit; thus, E2 + M3 with δ <0.5 should probably be entered as E2, while M1 + E2 with δ < 0.5 should probably be retained as a mixed multipolarity entry.

(c) If two multipolarities are given but no δ is known, the corresponding α value should be the value calculated as described in 7(a), below.

(d) If the multipolarity field contains more than two multipolarities (e.g. E0 + M1 + E2), the E2/M1 or E2/E0 etc., mixing ratios should be given if known on a continuation record rather than in the δ field.

(e) If δ overlaps zero or infinity, the corresponding multipolarity component should be in parentheses. For δ values with experimental limits that do not overlap zero or infinity, the evaluator may still choose to adopt the corresponding component in parentheses if they feel that the difference from zero or infinity is not significant (equivalent to interpreting the author's uncertainty as being somewhat larger than quoted).

4. The mixing ratio notation (M1 + x%E2) used occasionally by authors should be converted to δ.

5. Mult = M1, E2 is not equivalent to mult = M1 + E2. The first designation refers to the case where the experimental data overlap the theoretical values for both multipolarities. The second designation refers to the situation where the experimental data lie between the theoretical values for the two multipolarities. The designation M1 (+E2) is an intermediate case where the experimental data overlap M1 but not E2 values.

6. If αk, etc. data or conclusions from such data are included, the bases for the adopted values should be given. Thus, the basis for the normalization of the relative scales should be stated for relative I(ce) and 1γ, and the multipolarity for any transition used in this scale normalization should be independently established.

7. When internal conversion is significant but the multipolarity is unknown (apart from level scheme considerations) and TI is otherwise unobtainable and required, the following procedures can be followed.

(a) If ΔJ, Δπ are known, one can enter mult = [M1], [E1 + M2], etc., in the multipolarity field and choose α accordingly. For example if mult = [M1 + E2], one should enter α = 1/2[α(M1) + α (E2)] and Δα = |α-α(M1)| - |α - α(E2)|.

(b) If ΔJ and/or Δπ are not known, one can still follow the procedure described in (a) and set mult = [D, E2] (or mult = [E1, M1, E2]). Mult = M2 or higher are assumed to be less probable, but can be included.

The usefulness of either (a) or (b) depends on the range of α values for the possible multipolarities.

> Note 1: If ΔJ = l, Δπ = no, mult = [M1 + E2] should be adopted rather than mult = [M1] or mult = (E2] , unless there are good arguments for believing that one of the two possible multipole components dominates. Thus, α from M1 + E2 is always "correct" even with a large uncertainty, whereas α(M1) may lead to misleading conclusions. The possible large uncertainty in α for M1 + E2 when δ is not known reflects the correct state of knowledge concerning the total intensities.

> Note 2: The use of the mult = [ ] convention should be restricted to cases in which the internal conversion is significant. Do not assign mult = [ ] simply because the mult can be deduced from the level scheme; see also F. 5. in GUIDELINES FOR ADOPTED LEVELS, below.

8. Experimental αk, etc., and ce ratios that are used to determine multipolarities can be given at the evaluator's discretion; however, values measured with a precision of better than approximately 3% should be given, as well as values for transitions within 2 keV of the binding energy (and thus outside the range of values given by Hager and Seltzer). Except in these cases, the evaluator should state that "Mult and δ are from αk(exp) calculated from relative Iγ, and I(ce) normalized so that ..."; also important to point out when conversion electron intensity ratios rather than just αk have been used, since αk data alone do not always uniquely define a single multipolarity or combination of multipolarities. The references used as sources for the I(ce) data must be given, either in the footnote explaining the source for the multipolarity and δ, or in the general comments.

9. Note the distinction between ( ) and [ ] for multipolarities. These are discussed in the introductory section. Parentheses are used when there are some experimental data, but the data are not conclusive. The square brackets are used to denote a value deduced solely from level scheme considerations. Note that for the case where γ(θ) determines mult = D + Q and the level scheme is used to assign M1 + E2 rather than E1 + M2, the multipolarity should be in parentheses, mult = (M1 + E2), with a comment stating that "mult: D + Q from γ(θ) in ... Δπ = no from the level scheme". Square brackets are not appropriate for this case, since the level scheme argument forms only part of the assignment.

10. Do not define α with a lower limit; Iγ(l + α) could then appear incorrectly as a lower limit whereas there must be an upper bound. The situation arises almost exclusively in connection with transitions that have an E0 component in their multipolarity. Basic data are usually measured I(cek) and an upper limit on Iγ which leads to TI = I(ce) + < Iγ, where I(ce) = Σ_i(cei), i.e., TI has an upper bound. This situation is best addressed by giving I(cek) in a comment, along with the Iγ limit in the RI field. TI should be also be defined, and αk can be given in a comment. Only TI = I(ce) will be given for a transition adopted as pure E0.

Note: Recommended procedure for obtaining TI will depend on the relative magnitude of I(ce) and the limit of Iγ . The most useful quantity to quote for I(ce) >> Iγ is TI = I(ce) ± 1/2Iγ, with an uncertainty calculated in the usual way from ΔI(ce) and ΔIγ = 1/2Iγ; TI < [Iγ + I(ce)] is an appropriate choice for I1 >> I(ce); the first alternative is recommended for the intermediate case,.

K. g Factors, μ, Q

Values of μ should be taken from 78LeZA/2001StZZ where possible and entered directly into adopted levels. The μ values, or the corresponding values of the g factor, do not need to be repeated in the source data set. However, when the value of T1/2 used in 78LeZA is different from your adopted value, the value of μ should be corrected for this difference if possible. A comment should be included if not readily corrected, giving the T1/2 value to which μ in 78LeZA corresponds.

More recent g-factor data should be given in the appropriate source data sets with the corresponding value of μ given in adopted levels (based on the adopted g factor). These values should be corrected for the adopted T1/2 where necessary. When corrected, adopt a comment such as "g: For T1/2=... The authors report g=... for T1/2=... ". A comment is also required stating whether or not the diamagnetic and Knight-shift corrections have been applied (if the data are accurate enough to be affected by these corrections); this comment should be given both in the source data sets and in adopted levels.

Similarly, Q values should be taken from 78LeZA/200StZZ where possible, and quoted in adopted levels. More recent values should be given in the appropriate source data sets, with the adopted value also given in adopted levels. A comment should be given stating whether or not the Sternheimer correction (or some other polarization correction) has been applied, if the accuracy of the measured value warrants such a correction.

GUIDELINES FOR ADOPTED LEVELS, GAMMAS DATA SETS

A. General

1. All distinct levels that are observed in any of the individual data sets and the evaluator feels are firmly established should be included in adopted levels. Uncertain levels (shown with "?" in one or more of the individual data sets) can be included or not included at the evaluators discretion. Isobaric analog states (resonances) should be included; neutron and proton separation energies should not be included.

Note 1: The calibration and general trend of energies compared with adopted values should be checked for each data set to avoid the introduction of "extraneous" levels,. Corrections should be made for systematic shifts of energies in one or more data sets when the energies from such data sets are used to obtain the adopted value:

(a)to avoid the assignment of level "a" in one reaction as corresponding to level "b" in another reaction based only on the energy difference, and,

(b) to ensure that the energy adopted for level "a", if seen in only one reaction, is as correct as possible.

Note 2: When levels from two (or more) reactions lie close in energy (values agree within the uncertainties) and the evaluator chooses to adopt both (or all) levels, the justification for assuming that the levels are distinct should be given, unless obvious from XREF or other adopted level properties.

Consider the following cases:

E = 5000 10, Jπ = 3/2+ and E = 5010 10, Jπ = 5/2+ are known from reactions, and E = 5005.3 2 is known from a gamma reaction; however, there is considerable uncertainties as to which of the two reaction levels this level corresponds, and there is no evidence to suggest that the gamma-reaction level is a separate and distinct level. The reaction levels should be adopted, with a comment on each stating that probably the more accurate value of 5005.3 corresponds to one of the two adopted levels. Note that there is no unambiguous way to include the accurate energy as an adopted energy. The evaluator should not adopt three levels, unless there is definite evidence that the gamma-deduced level is distinct from the others.

E-596.7 5 with Jπ = 0+, 1, 2 and E-597.1 3 with Jπ = l+, 2, 3 are known to be different levels, and l(p, d) = 2, leading to Jπ = l-, 2-, 3- with E = 598 2 is also known. Unless there is evidence to suggest that the (p, d) level is distinct, just two levels should be adopted, with a comment on each stating that l(p, d) = 2, Jπ = l-, 2-, 3- for one or both of the levels.

2. Do not unnecessarily adopt values different from those that appear in the literature when the differences are small relative to the quoted uncertainty, and if the literature value has been widely quoted in other sources.

Note: Consider a situation in which an author recommends T1/2 = 6.54 s 22 as an average from several determinations, and this value has subsequently been used by other researchers. The evaluator determines that the value should be 6.56 s 20. Such a small difference does not merit the introduction of a different recommended value into the literature. The slight error in the recommended value should be noted - this warning would be useful in case someone recomputes a recommended value on the basis of some new values, and relies on the earlier quoted recommendation as a single input value representing the old data.

3. Make use of the XREF entries so that unnecessary comments can be avoided. For example, a comment such as "seen only in (d, p)" is not needed since XREF should already convey that information. However, an exception could arise if the evaluator wishes to emphasize some doubt about the level. XREF can also convey "one level corresponds to many levels", so that comments that convey only this information are not needed. However, comments such as "L(d, p) = l for E = 3450" can be given for two or more adopted levels to which the (d, p) level could correspond, and are still needed.

4. Important comments on level properties which appear in source data sets should be repeated in the adopted levels data sets - "doublet", "possible contaminant", "not resolved from X" are usually just as important in adopted levels.

5. If the evaluator adopts a Q value, (Q^-) that is different from the value given in the most recent mass adjustment, the mass adjustment value should be given in a comment for comparison. Furthermore, when the mass links are not too complicated, the other entries on the Q record could be adjusted to reflect the change in Q^- value. Under such circumstances, and if the change in Q^- is significant (considerably outside the limits given by the mass adjustment), listings of the adjusted S(n), S(p), and Q(α) values would represent a valuable contribution. However, the inclusion of these data is left to the discretion of the evaluator.

Note: When a re-adjustment is not feasible, a comparison between the mass adjustment value and the adopted value allows the reader to judge qualitatively what the effect on the other Q values might be.

6. All available first-card data should be included for gamma-records; however, continuation-record data generated from the HSICC program are not required.

7. Since the data in adopted levels, gammas are the evaluator's recommended values, discrepant data should not be adopted.

Note 1: If a gamma multipolarity disagrees with the adopted Jπ, and Jπ are considered to be well established, the discrepant multipolarity should not be adopted. The discrepancy should be noted in a comment, and a flagged comment should be used so that a footnote symbol appears in the multipolarity field.

Note 2: Since BE2 and T1/2 are equivalent data (if all quantities needed to convert from one to the other are known) and T1/2 is more basic, adopted values for both quantities should not be shown for the same level. The adopted T1/2 will normally be based on all of the available data, including any reliable BE2 measurements. By definition, the best BE2 value will be that deduced from this adopted T1/2 value and the adopted branchings, Q etc. If T1/2 comes from BE2, quoting both values is a redundant exercise; if T1/2 does not come solely from BE2, quoting both T1/2 and BE2 is essentially adopting two different values for the same quantity. A BE2 or BE3, etc. value is best adopted if T1/2 is not known, and cannot be calculated from these same BE2 or BE3 etc. values.

B. E(level)

The introductory section to Nuclear Data Sheets includes the statement "The excitation energies for levels connected by gamma transitions are taken from a least-squares fit to the adopted gamma energies. Other excitation energies are based on best values from all available reactions". No further comment is needed for any adopted levels section for which this statement is appropriate. When this statement may not be appropriate, the evaluator should add a comment explaining the source for the excitation energies.
Uncertainties should be included where available, and should be estimated if the authors do not provide them (see D. 1. under GUIDELINES FOR DECAY AND REACTION DATA SETS).

C. Jπ

1. Assignments should be based on the fewest and best arguments. There are two main advantages to this "fewest and best" approach:

(a) Jπ arguments are easier to read and follow when redundancy is eliminated,

(b) alternate arguments can be used to build up systematics.

For example, consider the assignment of 1+ to a level based on the arguments "Ml γ to 0+. Logft = 4.4 from 0+". Either argument alone is sufficient: if the multipolarity argument is used, the logft value can be combined with the values from which the logft arguments are derived, thus helping to build up confidence in the application of such systematics to cases where other strong arguments are not available.

Note: The above approach refers to strong arguments. When only weak arguments are available, the more arguments that can be marshalled, the more valid the assignment. However, no combination of weak arguments constitutes a strong argument.

2. "Direct" measurements of J (e.g., atomic beam) should be referenced as 76Fu06. More recent values should be referenced directly. The method should be stated in either case, thus "atomic beam", "NMR". Note that these methods give J only; a separate argument is required for π.

3. Arguments should be detailed enough to convince the reader that the assignments are reliable, and allow judgement to be made as what the consequences would be if new data were to become available.

(a) The argument "From (α, xnγ)" is not much use, especially if the (α, xnγ) data set contains no details. Statements such as "Excit. in ((α, xnγ)", "γ(θ) in (α, xnγ)" are needed. If such arguments appear frequently, they can be included in a flagged comment on Jπ such as "From (α, xnγ) based on...", or "Member of band X based on energy fit and inertial parameter". An alternative method is to write a Jπ footnote which states "Assignments from (α, xnγ) are based on excit. and 1(0). Assignments from (d, p) are based on L values and analyzing powers. etc". The Jπ argument can then be simply "From (α, xnγ)", "From (d, p)", etc. for the relevant levels. This approach is particularly useful when the arguments are somewhat lengthy.

(b) Gamma-decay arguments should be specific: thus "Ml γ to 2+", "γs to 3/2+, 5/2+", while the gamma energy is optional: thus "326γ to 2+ is Ml". A vague statement such as "JP is based on 'γ-decay modes" is not much use to the reader.

An argument for Jπ = 2-, 3- could be expressed as "L(d, p) = l gives 0- to 3-. γ to 4-". If the γ transition were to be subsequently determined as Ml, the reader can quickly determine that Jπ would be 3-. If the argument had only been given as a general statement such as "From L values in (d, p) and γ feedings", the consequences of the new piece of evidence would not be so transparent.

Note that Jπ values and γ-ray multipolarities referred to in these comments should be adopted values: "Ml γ to (3/2+)", "(E2) γ to (4)-".

Give Jπ(parent, target) in the specific Jπ arguments when the target is not even-even; for example, "logft = 5.4 from 1/2+", or "L(p, t) = 2 from 9/2+".

4. Jπ arguments for two or more levels can be linked if they are interconnected in such a way that giving separate arguments for each level can be awkward, or can give the appearance of circularity. As an example, consider the sequence 7-(β-)A(Ml)B(El)C(E2)2+: the argument "Logft = 5.1 from 7- and the Ml-El-E2 cascade to 2+ uniquely establishes Jπ(A) = 6-, Jπ(B) = 5- and Jπ(C) = 4+" can be given for one of the relevant levels (say C), and then one can say "Jπ: See C level" for the others.

5. Consider an L = 0 component in a particle-transfer reaction in which S = 0 can be assumed: leads to ΔJ-0, Δπ = no, even if other L components are present, and the same is true of an E0 component in a gamma transition. A level connected via an Ml + E2 γ to a level with J = l/2 must have J = 3/2.

6. Jπ arguments for the ground state of an even-even nucleus are not needed. For example L(p, t) = 0 gives only ΔJ = 0 and relies on the assumption of J = 0 for the even-even target nucleus. The absence of hyperfine structure is also not conclusive, since a small μ or Q value can lead to the same result.

7. Maintain consistency between the source data and the conclusions. For example, L(p, t) = 2 (S = 0 assumed) from an even-even target gives Jπ = 2+, not (2)+ or 2(+); if the L value is considered to

be a strong argument for J, this same argument applies to π. Similarly, if the argument is not considered to be strong for J, such an argument should not be considered strong for π; thus, L(p, t) = (2) gives Jπ = (2+).

> Note: A reaction such as (Q, d) with a measured L value can be used as a strong argument for π, namely, $\pi = (-)^L$, even though J is determined only as J = L-l, L, or L+l.

8. Expressions such as "preferred" or "consistent with" are not strong arguments. Avoid these expressions since they leave open the question of whether other alternative Jπ values have been ruled out; however, such expressions are valid for weak arguments.

9. Configurations

"Conf = 3/2[521]" is not a valid argument for Jπ; this argument only shifts the burden of proof from establishing Jπ = 3/2- to establishing conf = 3/2[521]. The configuration is normally deduced from Jπ, not vice-versa, although sometimes the reverse is true and the same argument for Jπ can be used to assign the configuration (sometimes a measured μ will also determine a specific configuration).

Knowledge of L and the analyzing power in a transfer reaction may give Jπ = 1/2- (and assign this level as a pl/2 orbital), but the Jπ argument should be "From L and analyzing power in (d, p)", not "From conf = pl/2". The configuration should be treated as a separate data type from Jπ, and be placed on a continuation record. Comments on "Conf" should normally be treated as distinct from comments on Jπ.

> Usually in the deformed regions, the cross sections and cross section ratios (e.g., (d, p) and (d, t) reactions) determine directly the combination JπK[ ], rather than Jπ (such as 5/2- 3/2[521]) or just Jπ = 5/2- alone. Under such circumstances, the configuration must be included in the Jπ argument.

10. Do not use multiply placed transitions in Jπ arguments unless the connection with the level in question is definite.

> Note: A multipolarity determined for a multiplet will not necessarily be the correct multipolarity for each member of the multiplet (see B. 6. (d)) under GUIDELINES FOR DECAY AND REACTION DATA SETS). If part of the multiplet is definitely established as being connected with the level in question, Jπ of the connected level can be used as a Jπ argument in the usual way, (e.g., "γ to 3/2+").

11. When choices of Jπ are limited to three or fewer, they should be clearly specified rather than given as a range; thus Jπ = 5/2-, 7/2-, 9/2- rather than Jπ = 5/2- to 7/2-. There is less chance of values being misinterpreted when they are written out completely, and the extra space required is not significant (which is the only good argument for quoting Jπ values as a range).

12. RUL is an argument for multipolarity, not for Jπ.

13. Note the difference between "Jπ = 5/2+ and 7/2-" (or 5/2+&7/2-) and "Jπ = 5/2+, 7/2-". The first notation indicates the presence of two unresolved levels with Jπ = 5/2+ and 7/2-, respectively; while the second notation indicates two alternate Jπ values for a single level.

D. Other Level Properties

1. Cross referencing of data should give the data set, and not just the keynumber, because the data sources are much easier to locate with this information. The method and keynumber are optional except in the following cases where this information is needed.

(a) μ, Q etc., values for stable or long-lived states should be taken from 78LeZA where possible. The method should be given since these data will normally not appear anywhere else in the mass chain. More recent data can be quoted directly, along with the method and keynumber. For values of μ not taken from 78LeZA and when warranted by the accuracy, a comment stating whether or not the diamagnetic and Knight-shift corrections have been applied should be included. Similarly for Q values, a comment should be given stating whether or not the Sternheimer correction (or other polarization correction) has been applied.

b) If T1/2 is obtained from BE2, this fact should be stated: "T1/2: From BE2 in Coul. ex.".

2. "g factor" quoted in a source data set should be converted to "μ" in adopted levels if J is known.

3. When branching modes are given (e.g., "%IT="), the bases for the values can be given here or in the source data sets. There is no need to repeat the arguments, but they must appear in one place or the other. Also, all possible modes of decay should be accounted for, unless the reason for omitting a mode is obvious.

> Note: Where "%ε+%β+ = 99.0 1; %IT = l.0 l" exists but β^- is also energetically allowed, there should be a comment explaining why the β^- branch is considered negligible; for example, "%β^- is negligible since the only available decay branch has ΔJ = 2, Δπ = yes, for which, from logflut>8.5, one derives %β-<lxl0^{-4}". An experimentally determined limit of this magnitude should be included explicitly in the branching statement. One can state simply "ΔJ = 4 for possible β^- branch so %β^- is negligible" for more obviously negligible branches such as where the only available branch has ΔJ = 4.

4. BEλ values should be included in adopted levels where T1/2 is not independently known and cannot be calculated from BEλ.

E. Eγ, Iγ, TI

1. Sources of data should be stated unless obvious (i.e., if there is only one or possibly two sources (small mass chain)). General comments are usually sufficient; thus, "From X unless noted otherwise" or "Weighted average of values from A, B, and C".

2. The introductory section to Nuclear Data Sheets includes the explanation that I_γ are "photon branchings (normalized to 100 for the most intense transition from each level)". Note that an uncertainty should be included in the value "l00" if there is an uncertainty given for the original intensity; however, when there is only one transition de-exciting the level, the uncertainty has no meaning and should not be given. Any major deviation from this policy should be stated, such as quoting branching ratios in %. There are some situations in which this policy should not be followed (i.e., where a transition other than the strongest should be chosen and for which no explanation is needed):

(a)strongest transition is an unresolved multiplet;

(b)strongest transition is given as an upper limit.

Note: Iγ for multiply-placed transitions where the intensity has not been divided should be given as limits (Iγ < A + ΔA if Iγ = A ± ΔA), with "&" in column 77.

3. Where possible, TI should be given for transitions that have no measured Iγ, or for which only a limit on Iγ is available. The most common cases would be for E0 transitions or low-energy transitions when I(ce) but no Iγ (or α) are available; see Note under J. 10. in GUIDELINES FOR DECAY AND REACTION DATA SETS .

Note: When TI is the "measured" quantity from an intensity balance and α is known so that Iγ can be determined, TI as well as Iγ should be given if known more accurately than TI calculated from Iγ(1+α). This approach allows the most accurate branching ratios to be obtained for the transitions from the level in question.

F. Mult, δ, α

1. Data sources should be stated unless obvious. Note that the introductory section states that the α values are theoretically determined on the basis of the given multipolarity and δ. The origins of any α value which is not based on this procedure should be explained in a comment. Sources for multipolarity and δ can usually be quite general: "Mult are based on αk and subshell measurements in and γγ(θ) data in ...". When multipolarities are based on measurements that yield only L, such as γ(θ) or γγ(θ), and M1 + E2 is adopted rather than El + M2, the basis for this choice must be stated.

2. See J. 3. in GUIDELINES FOR DECAY AND REACTION DATA SETS for requirements on consistency among the multipolarity, δ and α entries. α is not needed for transitions with mixed multipolarity and unknown δ, even though such values may have been used in a data source.

3. The relationship between BE2 and T1/2 allows δ (and/or α) to be deduced in cases where BE2 and T1/2 are independently known, and the ground-state branch is known (the ground-state branch could be deduced if all other quantities are known).

4. γ(θ) and γγ(θ) normally lead to two solutions for δ, and both should be noted. In particular, both should be placed in a comment if the correct one is not known; do not adopt one value in the δ field and the alternate value in a comment.

5. As well as using [ ] to indicate multipolarities deduced solely on the basis of the level scheme for transitions for which you want to list α, this convention may also be adopted in cases where α is negligible, but you wish to show the multipolarity because you are recommending a reduced transition probability. However, as noted earlier, do not assign mult=[ ] simply because the multipolarity can be deduced from the level scheme.

G. Reduced Transition Probabilities

Reduced transition probabilities are required whenever calculable, i.e., when T1/2, branching, multipolarity and δ are known. Note that for mixed transitions, values for both multipole components should be given.

Note 1: When δ is consistent with zero or infinity, the reduced transition probability for only the dominant component is required. The limit for the other component is optional and can be given in certain cases: BE2(W.u.) < l000 is not of interest, but BE2(W.u.) < 10^{-3} might be significant.

Note 2: Values should be given for transitions that have not been experimentally characterized, but can be determined from the level scheme as $\Delta J = 1$, $\Delta\pi$ = yes; $\Delta J = 2$, $\Delta\pi$ = no, or $\Delta J \geq 3$ (i.e., cases where significant mixing is not expected).

Note 3: When one or more of the relevant pieces of information required to calculate reduced transition probabilities is/are missing, the calculation should be carried out if reasonable assumptions can be made that fill the gaps. For example, a branch with a small gamma fraction of known multipolarity should be estimated (if the multipolarity would lead to a relatively small total branching) so that reduced transition probabilities for the other branches can be calculated.

Note 4: When only limits are available for some of the relevant data, special care must be taken.
(a) Transition with mult = Ml + E2 and $\delta < 0.1$: while BE2(W.u.) can only be given only as an upper limit, assigning BM1(W.u.) as a lower limit would be incorrect since an upper bound occurs for $\delta = 0$. BM1(W.u.) should be given as an average of the values corresponding to $\delta = 0$ and $\delta = 0.1$, with an uncertainty chosen to overlap the two values.
(b) Consider a transition with a total intensity known only as an upper limit: provided that this intensity limit is not the dominant branching mode, the branching for this transition should be treated as 1/2TI ± 1/2TI for the purpose of calculating the reduced transition probabilities for the other transitions.
(c) When T1/2 is only available as an upper limit, the resulting lower limits on the reduced transition probabilities should be given. When T1/2 is a lower limit, the resulting upper limits on the reduced transition probabilities are not of much interest, except perhaps as noted in Note 1, above.

Note 5: Consider the reduced transition probability of a transition for which the corresponding Coulomb excitation probability has been determined (BE2 being the most common case): this parameter can be deduced directly from the measurement and the appropriate single particle value. This procedure should be followed when the level T1/2 has been adopted from a measured BE2 (to avoid including the uncertainty in BE2 twice), or where BE2 is known but branches and/or mixing ratios are not known so that T1/2 for the corresponding level cannot be calculated.

Note 6: When $E\gamma$ is poorly known, the factor $E\gamma^{2L+1}x(1 + \alpha)$ appearing in the formula for the reduced transition probabilities may exhibit a smaller range of values than the factors $E\gamma^{2L+1}$ and $(1 + \alpha)$ taken separately. The correlation in $E\gamma$ and α should always be taken into account when calculating uncertainties for $BE\lambda$(W.u.) and $BM\lambda$(W.u.).

Note 7: $BE\lambda$(W.u.) and $BM\lambda$(W.u.) are not needed for mixed multipolarities when δ is not known. However, if an evaluator chooses, these parameters can be given as upper limits.

DRAFT

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NUCLEAR STRUCTURE AND DECAY DATA: INTRODUCTION TO RELEVANT WEB PAGES

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Summary

A brief description is given of the nuclear data centres around the world able to provide access to those databases and programs of highest relevance to nuclear structure and decay data specialists. A number of Web-page addresses are also provided for the reader to inspect and investigate these data and codes for study, evaluation and calculation. These instructions are not meant to be comprehensive, but should provide the reader with a reasonable means of electronic access to the most important data sets and programs.

1. Introduction

A network of international/national nuclear data centres constitutes the infrastructure for the provision of a wide range of atomic and nuclear data services to scientists worldwide (Table 1). More than 100 data libraries are readily available cost-free from these centres through the Internet, CD-ROM and other media.

Two nuclear data centres of particular note are the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory and the Nuclear Data Section at the International Atomic Energy Agency (IAEA-NDS) in Vienna, Austria. Access to the most relevant databases and associated codes through their web addresses are described below (both main directional web pages are shown in the Annex):

National Nuclear Data Center, Brookhaven - http://www.nndc.bnl.gov/

IAEA Nuclear Data Section: http://www-nds.iaea.org/
(also http://www-nds.iaea.or.at),

and IAEA-NDS mirror sites at IPEN, Brazil, http://www-nds.ipen.br/
and BARC, Mumbai, India, http://www-nds.indcentre.org.in/
that are maintained by NDS staff.

All libraries and related documentation held by the Nuclear Data Section are available free of charge to scientists in IAEA Member States. Overviews are given by Schwerer and Obložinský (2001) and in the document *Index of Nuclear Data Libraries Available from the* IAEA *Nuclear Data Section* (Schwerer and Lemmel, 2002) – also available on:

http://www-nds.iaea.org/indg_intro.html
http://www-nds.iaea.org/reports/nds-7.pdf to download as PDF file.

Brief descriptions of the contents and format of most libraries are published in the IAEA-NDS-report series (Lemmel and Schwerer, 2002), while an introduction to NDS database projects and services can be found at http://www-naweb.iaea.org/napc/nd/index.asp

2. Nuclear Structure and Decay Data Evaluators' Network

A network of centres has been established that specialize in nuclear structure and decay data (Pronyaev *et al.*, 2004); see also Table 2 for a list and access addresses through the Web and e-mail contacts. These laboratories and institutes are involved in all facets of compilation and production of recommended nuclear structure and decay data (*i.e.*, review, evaluation and processing), sharing the evaluation work by mass chain, and meeting biennially to discuss their common problems and interests under the auspices of the IAEA Nuclear Data Section.

3. Worldwide Web (WWW)

The web page of the IAEA Nuclear Data Services can be found at the web addresses http://www-nds.iaea.org/ (IAEA, Vienna, Austria), http://www-nds.ipen.br/ (IPEN, Brazil), and http://www-nds.indcentre.org.in/ at BARC, India; the equivalent web page for NNDC is http://www.nndc.bnl.gov/. These pages contain interactive access to the major databases, as well as overviews of all nuclear data libraries and databases available from the IAEA *(IAEA Nuclear Data Guide)* and NNDC, and access to various reports, manuals, nuclear data utility programs, Nuclear Data Newsletters and other informative documentation.

The web addresses specified above provide links with the following highly relevant databases (see also Section 4):

- ENSDF - evaluated nuclear structure and decay data
- MIRD - medical internal radiation dose tables
- Wallet cards - Ground and metastable state properties
- NUDAT - selected evaluated nuclear data
- NSR (Nuclear Science References)
- Masses (Atomic Mass Evaluation Data File)

For example, NSR bibliographic information can be explored through:

Known author name,

Keynumber (*e.g.,* 1970Ya02 consists of the first two letters of the lead author (Ya (of Yamazaki)), year (1970), and number designation (02)); also to be found in *Recent References, Nuclear Data Sheets* (Tuli, 2005)), and

Nuclide,

as well as through other criteria.

The reader is encouraged to access all of these databases, codes and information manuals through an explorative process, and assess their user-friendliness and usefulness. Your feedback is also welcome, and would help us to improve our web services.

4. Access to Relevant Databases and Programs

The data in some of the nuclear structure databases have been evaluated and assembled through the combined efforts of specialists within the international nuclear structure and decay-data evaluators' network (Section 2), while others are effectively more user-friendly derivatives and subsets of these same data files (*e.g.*, Nuclear Wallet Cards and NuDat).

4.1 Primary databases

NSR: Nuclear Science References is a bibliographic database for low and intermediate energy nuclear physics; published in *Nuclear Data Sheets* (Tuli, 2005) and available on-line (see both http://www-nds.iaea.org/nsr/ and http://www.nndc.bnl.gov/nsr/).

ENSDF: Evaluated Nuclear Structure Data File is the 'master' library for nuclear structure and decay data maintained through the evaluators' network co-ordinated by the IAEA (see Section 2), and containing evaluated experimental data for most known nuclides in the mass range from 1 to 293; published in *Nuclear Data Sheets* (Tuli, 2005) and *Nuclear Physics A* (Bakker, 2005) and available on-line (see both http://www-nds.iaea.org/ensdf/ and http://www.nndc.bnl.gov/ensdf/). The full library is also available as zipped files from the NDS open area.

4.2 Other specialised and derived databases

Atomic masses 2003 (Wapstra *et al.*, 2003): mass evaluations for over 2900 nuclides; available on-line (see both http://www-nds.iaea.org/masses/ and http://www.nndc.bnl.gov/masses/).

Nuclear Wallet Cards (Tuli, 2000): basic properties of ground and metastable states; available as pocket book and on-line (see both http://www-nds.iaea.org:8080/wallet/ and http://www.nndc.bnl.gov/wallet/). The NNDC site also contains Nuclear Wallet Cards for Radioactive Nuclides (Tuli, 2004), available as a pocket book and online, and Palm Pilot versions of both books.

NuDat: Nuclear Data contains user-friendly extracts of applications data from ENSDF and the Nuclear Wallet Cards, plus thermal neutron data; available on-line (see both http://www-nds.iaea.org/nudat/ and http://www.nndc.bnl.gov/nudat/).

MIRD: Medical Internal Radiation Dose is based on ENSDF and data processed by RADLST to generate, for example, tables of energies and intensities for X-rays and Auger electrons (Burrows, 1988); available on-line (see both http://www-nds.iaea.org/mird/ and http://www.nndc.bnl.gov/mird/).

XUNDL: experimental Unevaluated Nuclear Data Library is a compilation of experimental nuclear structure and decay data in ENSDF format – oriented primarily to high-spin data, but also contains some reaction and decay data (see both http://www-nds.iaea.org/ensdf/ and http://www.nndc.bnl.gov/ensdf/).

4.3 Programs

Useful computer codes for the calculation of specific nuclear structure and decay-data parameters include the following:

GABS: calculates absolute γ-ray intensities;
GTOL: undertakes least-squares fits to γ-ray energies, and calculates net feeding to nuclear levels;
HSICC: calculates internal conversion coefficients based on the theoretical values of Hager and Seltzer (1968), and Dragoun *et al* (1969 and 1971);
LOGFT: calculates *log ft* values for β and electron-capture decay, average $\beta^{\pm}$ energies and capture fractions;
PANDORA: checks "correctness" of the physics in ENSDF;

and others are available through the NNDC web page http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/.

4.4 Interactive calculational tools

Users can perform calculations interactively over the web by means of two processing tools:

> **Nuclear Structure Calculational Tools**: calculates internal conversion coefficients based on the theoretical values of Hager and Seltzer (1968), and Dragoun *et al.* (1969 and 1971), and *log ft* values for β and electron-capture decay, average $\beta^{\pm}$ energies and capture fractions (see http://www.nndc.bnl.gov/nndc/physco/).
>
> **Atomic Masses, Q-values and Threshold Energies**: calculates reaction Q-values, threshold energies and decay Q-values based on the 1995 Update to the Atomic Mass Evaluation (Wapstra *et al.*, 2003), and retrieves other quantities contained in this evaluation (see http://www.nndc.bnl.gov/qcalc2/).

4.5 Other network web sites

Web sites of other members of the Nuclear Structure and Decay-data Network (Table 2) contain much useful information, for example:

> **Energy Levels of Light Nuclei, A = 3 - 20**: evaluations, preprints, lists of recent references, reprints for A = 3 - 20 nuclides, and Palm Pilot applications and databases (see http://www.tunl.duke.edu/NuclData/);
>
> **jvNubase**: ground and metastable state properties, based primarily on ENSDF with some additions derived from more recent data
> (see http://www.nndc.bnl.gov/amdc/jvnubase/);
>
> **RadWare**: software package for interactive graphical analysis of gamma-ray coincidence data library of level scheme files in the RadWare ASCII-gls format that have been derived from ENSDF, XUNDL and contributed level schemes
> (see http://radware.phy.ornl.gov/).

4.6 Nuclear structure and decay-data evaluator's corner

http://www.nndc.bnl.gov/nndc/evalcorner/ is primarily designed for ENSDF evaluators and currently contains:

- an interface to ENSDF which allows evaluators to retrieve ENSDF mass chains and nuclides in a basic format (*i.e.*, comments have not been translated into a “rich text” format),
- simplified NSR retrieval system designed for ENSDF evaluators,
- new ENSDF analysis and utility codes in β testing, and
- links to materials from previous ENSDF or NSDD workshops.

5. Concluding Remarks

The contents of this report represent a brief introduction to the means of accessing a powerful set of compiled and evaluated nuclear structure and decay-data libraries, as well as codes for the analysis and development of such data. Useful applications of these data and tools are wide ranging, and the reader is encouraged to explore their potential through the various routes outlined above, and so develop a much greater understanding of their capabilities.

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see also *http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/analysis/radlst/radlstdoc.pdf*.

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Table 1. International/National Nuclear Data Centres.

IAEA Nuclear Data Section, Vienna, Austria *http://www-nds.iaea.org/*
US National Nuclear Data Center, Brookhaven, USA *http://www.nndc.bnl.gov/*
OECD, NEA Data Bank, Paris, France *http://www.nea.fr/*
Russian Federation Nuclear Data Centre, Obninsk, Russian Federation *http://www.ippe.obninsk.ru/podr/cjd/*
9 co-operating specialised centres: PR China, Hungary, Japan, Republic of Korea, Russian Federation and Ukraine

Table 2. Nuclear Structure and Decay Data Evaluators' Network.

US National Nuclear Data Center, Brookhaven, USA (maintenance of master ENSDF database) *http://www.nndc.bnl.gov/* Contact: J. K. Tuli (network co-ordinator) e-mail: Tuli@bnl.gov
Nuclear Data Project, Oak Ridge National Laboratory, USA *http://www.phy.ornl.gov/ndp/* Contact: M. S. Smith e-mail: MSmith@mail.phy.ORNL.gov
Isotope Project, Lawrence Berkeley National Laboratory, Berkeley, USA *http://ie.lbl.gov/* Contact: C. M. Baglin e-mail: baglin@lbl.gov
Idaho National Engineering and Environmental Laboratory, Idaho Falls, USA Contact: C. W. Reich e-mail: CWReich@interplus.net
Triangle University Nuclear Laboratory, Duke University, USA *http://www.tunl.duke.edu/NuclData/* Contact: J. H. Kelley e-mail: kelley@tunl.duke.edu
Argonne National Laboratory, Argonne, U.S.A. http://www.td.anl.gov/NDP/ Contact: F.G. Kondev e-mail: kondev@anl.gov
Nuclear Data Centre, Petersburg Nuclear Physics Institute, Russian Federation Contact: I. A. Mitropolsky e-mail: mart@pnpi.spb.ru
Institute of Atomic Energy, Beijing, PR China Contact: Ge Zhigang e-mail: gezg@iris.ciae.ac.cn
Jilin University, Physics Department, Changchun, PR China Contact: Huo Junde e-mail: jdhuo@mail.jlu.edu.cn
Centre d'Études Nucléaires, Grenoble, France Contact: J. Blachot e-mail: jean.blachot@wanadoo.fr
JAERI Nuclear Data Centre, Tokai-Mura, Japan *http://wwwndc.tokai.jaeri.go.jp/* Contact: J. Katakura e-mail: Katakura@bisha.tokai.jaeri.go.jp
Nuclear Data Centre, Physics Department, Kuwait University, Kuwait Contact: A. Farhan e-mail: Ameenah@kuc01.kuniv.edu.kw
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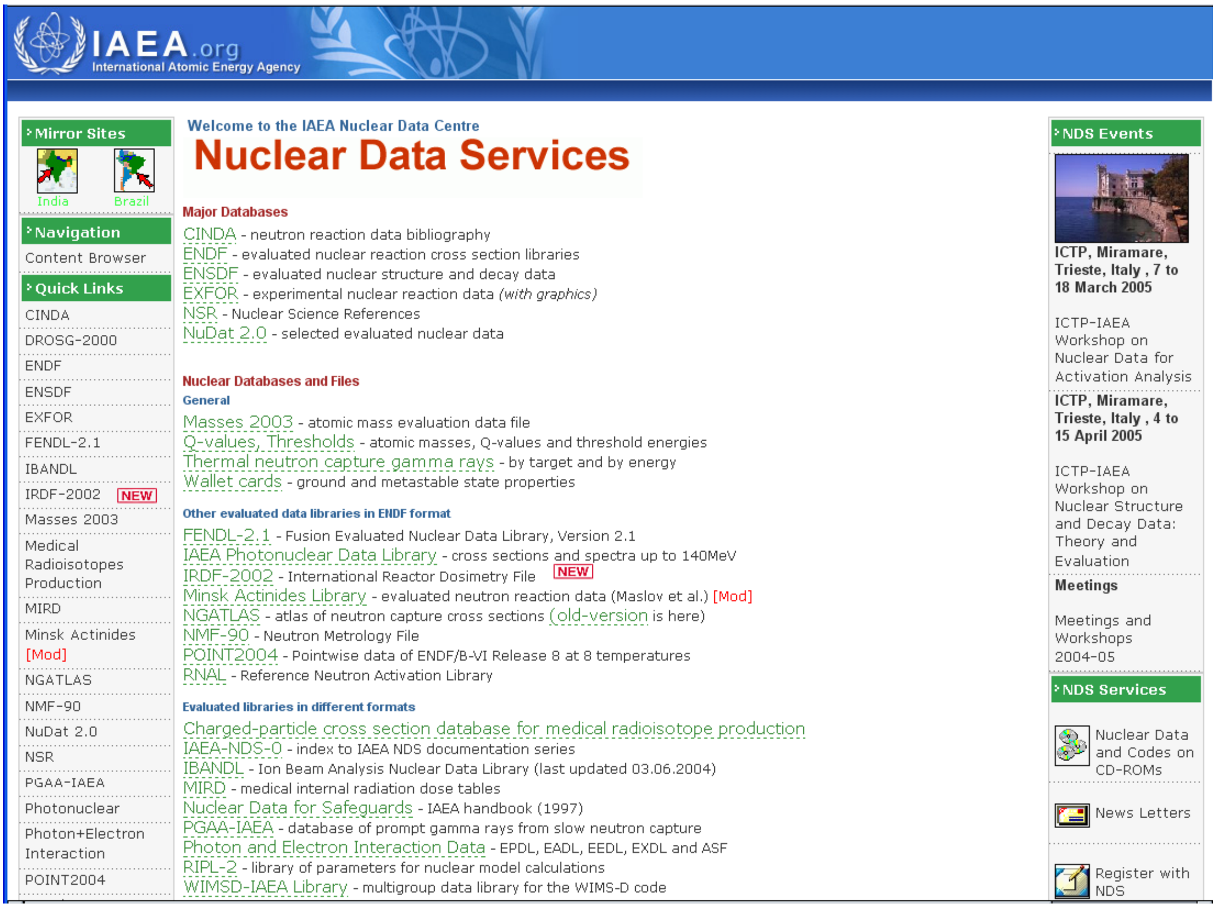
Department of Physics and Astronomy, McMaster University, Hamilton, Canada *http://physwww.physics.mcmaster.ca/~balraj/* Contact: J. C. Waddington e-mail: JCW@mcmaster.ca
Department of Nuclear Physics, Australian National University, Canberra, Australia *http://wwwrsphysse.anu.edu.au/nuclear/* Contact: T. Kibédi e-mail: Tibor.Kibedi@anu.edu.au
Atomic Mass Data Center, Centre de Spectrométrie Nucléaire et de Spectrométrie Masse, Orsay, France *http://www.nndc.bnl.gov/amdc/* Contact: Georges Audi e-mail: *mailto:audi@csnsm.in2p3.fr*
IAEA Nuclear Data Section, Vienna, Austria (co-ordination of network meetings) *http://www-nds.iaea.org/* Contact: A. L. Nichols e-mail: *a.nichols@iaea.org*

ANNEX

Directional Web pages for NDS and NNDC


IAEA.org
International Atomic Energy Agency
Mirror Sites
India
Brazil
Navigation
Content Browser
Quick Links
CINDA
DROSG-2000
ENDF
ENSDF
EXFOR
FENDL-2.1
IBANDL
IRDF-2002 NEW
Masses 2003
Medical Radioisotopes Production
MIRD
Minsk Actinides [Mod]
NGATLAS
NMF-90
NuDat 2.0
NSR
PGAA-IAEA
Photonuclear
Photon+Electron Interaction
POINT2004
Welcome to the IAEA Nuclear Data Centre
Nuclear Data Services
Major Databases
CINDA - neutron reaction data bibliography
ENDF - evaluated nuclear reaction cross section libraries
ENSDF - evaluated nuclear structure and decay data
EXFOR - experimental nuclear reaction data (with graphics)
NSR - Nuclear Science References
NuDat 2.0 - selected evaluated nuclear data
Nuclear Databases and Files
General
Masses 2003 - atomic mass evaluation data file
Q-values, Thresholds - atomic masses, Q-values and threshold energies
Thermal neutron capture gamma rays - by target and by energy
Wallet cards - ground and metastable state properties
Other evaluated data libraries in ENDF format
FENDL-2.1 - Fusion Evaluated Nuclear Data Library, Version 2.1
IAEA Photonuclear Data Library - cross sections and spectra up to 140MeV
IRDF-2002 - International Reactor Dosimetry File NEW
Minsk Actinides Library - evaluated neutron reaction data (Maslov et al.) [Mod]
NGATLAS - atlas of neutron capture cross sections (old-version is here)
NMF-90 - Neutron Metrology File
POINT2004 - Pointwise data of ENDF/B-VI Release 8 at 8 temperatures
RNAL - Reference Neutron Activation Library
Evaluated libraries in different formats
Charged-particle cross section database for medical radioisotope production
IAEA-NDS-0 - index to IAEA NDS documentation series
IBANDL - Ion Beam Analysis Nuclear Data Library (last updated 03.06.2004)
MIRD - medical internal radiation dose tables
Nuclear Data for Safeguards - IAEA handbook (1997)
PGAA-IAEA - database of prompt gamma rays from slow neutron capture
Photon and Electron Interaction Data - EPDL, EADL, EEDL, EXDL and ASF
RIPL-2 - library of parameters for nuclear model calculations
WIMSD-IAEA Library - multigroup data library for the WIMS-D code
NDS Events
ICTP, Miramare, Trieste, Italy , 7 to 18 March 2005
ICTP-IAEA Workshop on Nuclear Data for Activation Analysis
ICTP, Miramare, Trieste, Italy , 4 to 15 April 2005
ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation
Meetings
Meetings and Workshops 2004-05
NDS Services
Nuclear Data and Codes on CD-ROMs
News Letters
Register with NDS

POINT2004
Q-values, Thresholds
RIPL-2
RNAL
Safeguards data
Thermal Neutron Capture Gamma Rays
Wallet cards
WIMS-D Library

Documents

ENDF Manual
ENDF/B-6 Summary
ENSDF, NSR Manuals
INDC Reports

Computer codes

EMPIRE-II
ENDF Utils NEW
ENDVER
ENSDF Utilities
PREPRO NEW
SIGACE
ZVVIEW

WIMSD-IAEA Library - multigroup data library for the WIMS-D code

Electronic Documents

Citation Guidelines - online data service manual and citation guidelines
ENDF Format Manual - April 2001 version
ENSDF and NSR Manuals - ENSDF Feb. 2001 version & NSR Aug. '96 version
Selected INDC Reports - selected INDC reports, INDC(AUL) to INDC(VN)

Computer codes

EMPIRE-II - system of codes for nuclear reaction calculations (Version 2.18)
ENDF Utility Codes - Release 7.0 NEW
ENSDF programs - ENSDF Analysis and Utility programs (ALPHAD, LOGFT, etc.)
ENDVER - ENDF File Verification Support Package
PREPRO - ENDF Preprocessing Codes. Version - November 2004 NEW
SIGACE - package for generating high temperature ACE files
ZVVIEW - interactive plotting of nuclear data

General information

NDS information

Co-ordinated Research Projects (CRPs) - recently completed and ongoing CRPs
IAEA Nuclear Data Guide - catalogue of all nuclear data available from IAEA NDS
Index of nuclear data libraries - comprehensive index of NDS libraries
Nuclear Data Section - introduction, programme description, activities and staff
Nuclear data information brochure - the IAEA nuclear and atomic data programme
Nuclear data newsletters - from 1995 to now
Subscribe to our mailing list - get the latest newsletter and other information

Datalinks

Atomic and molecular data - AMBDAS, ALADDIN, GENIE, etc.
List of available CD-ROMs - nuclear data and utility codes on CD-ROM
Nuclear data links for medical applications - relevant sites at the IAEA and worldwide

Other useful links

IAEA home page
IAEA - Department of Nuclear Sciences and Applications
International network of Nuclear Structure and Decay Data evaluators - the NSDD network
Nuclear Reaction Data Centre network - the NRDC network, contacts, webpages, etc.
Other information resources - collection of links to other nuclear information resources

Register with NDS

Old NDS main page

Nuclear Data Section

IAEA Nuclear Data Section

More on Coordinated Research Projects, Technical Cooperation, Nuclear Data Section - people and activities

NDS Partners

NNDC

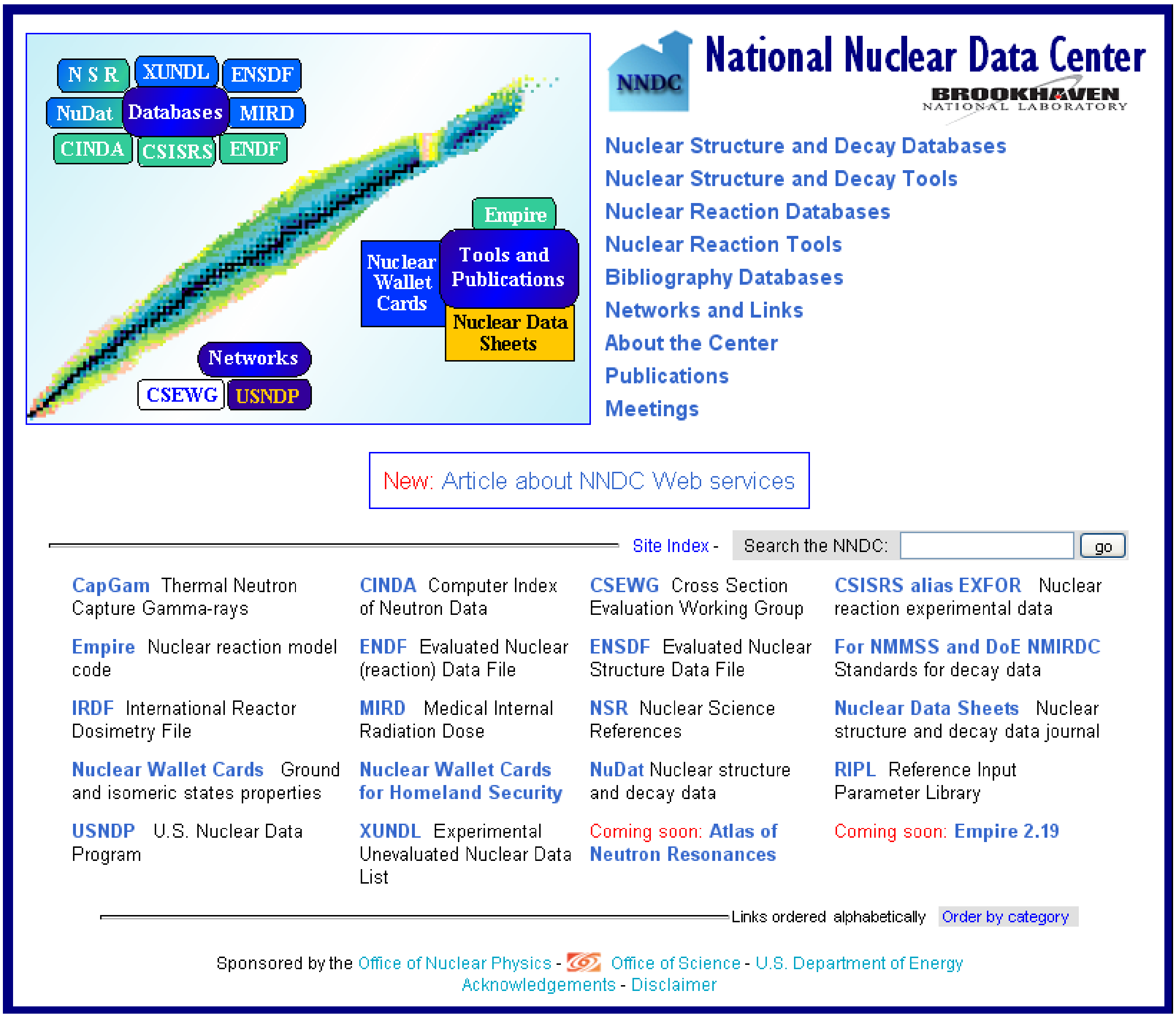
National Nuclear Data Center, Brookhaven, USA

OECD NEA

OECD Nuclear Energy Agency, Nuclear Data Services, France

IPPE

Institute of Physics and Power Engineering, Obninsk, Russia


N S R
XUNDL
ENSDF
NuDat
Databases
MIRD
CINDA
CSISRS
ENDF
Empire
Nuclear Wallet Cards
Tools and Publications
Nuclear Data Sheets
Networks
CSEWG
USNDP
NNDC
National Nuclear Data Center
BROOKHAVEN NATIONAL LABORATORY
Nuclear Structure and Decay Databases
Nuclear Structure and Decay Tools
Nuclear Reaction Databases
Nuclear Reaction Tools
Bibliography Databases
Networks and Links
About the Center
Publications
Meetings
New: Article about NNDC Web services
Site Index - Search the NNDC: go
CapGam Thermal Neutron Capture Gamma-rays
CINDA Computer Index of Neutron Data
CSEWG Cross Section Evaluation Working Group
CSISRS alias EXFOR Nuclear reaction experimental data
Empire Nuclear reaction model code
ENDF Evaluated Nuclear (reaction) Data File
ENSDF Evaluated Nuclear Structure Data File
For NMMSS and DoE NMIRDC Standards for decay data
IRDF International Reactor Dosimetry File
MIRD Medical Internal Radiation Dose
NSR Nuclear Science References
Nuclear Data Sheets Nuclear structure and decay data journal
Nuclear Wallet Cards Ground and isomeric states properties
Nuclear Wallet Cards for Homeland Security
NuDat Nuclear structure and decay data
RIPL Reference Input Parameter Library
USNDP U.S. Nuclear Data Program
XUNDL Experimental Unevaluated Nuclear Data List
Coming soon: Atlas of Neutron Resonances
Coming soon: Empire 2.19
Links ordered alphabetically Order by category
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Acknowledgements - Disclaimer

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