ANL-4626
Physics & Mathematics

ARGONNE NATIONAL LABORATORY
P. O. Box 5207
Chicago 80, Ill.

NUCLEAR SHELL STRUCTURE AND β-DECAY

I. ODD A NUCLEI

by

M. G. Mayer and S. A. Moszkowski
Argonne National Laboratory
Chicago, Illinois

L. W. Nordheim
Duke University
Durham, North Carolina
(At present on leave at the
Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

II. EVEN A NUCLEI

by

L. W. Nordheim

This document is
PUBLICLY RELEASABLE
Hugh Kinser H. Kinser
Authorizing Official
Date 1/12/04

May 1951

The study reported in Part I was started independently by the Chicago and Duke authors. The results and conclusions from the two studies were practically the same. For that reason these are reported in one paper.

Operated by The University of Chicago
under
Contract W-31-109-eng-38

ANL-4626
Physics & Mathematics

Distribution	No. of Copies
Argonne National Laboratory	189
American Cyanamid Company	1
Armed Forces Special Weapons Project	1
Atomic Energy Commission - Washington	6
Battelle Memorial Institute	1
Brush Beryllium Company	1
Brookhaven National Laboratory	4
Bureau of Medicine and Surgery	1
Bureau of Ships	1
Carbide and Carbon Chemicals Company (C-31), Paducah	2
Carbide and Carbon Chemicals Company (K-25)	4
Carbide and Carbon Chemicals Company (Y-12)	4
Columbia University (Failla)	1
Columbia University (Havens)	1
du Pont de Nemours and Company	5
Eldorado Mining and Refining Ltd.	2
General Electric Company, Richland	3
Idaho Operations Office	4
Iowa State College	2
Kansas City Operations Branch	1
Kellex Corporation	2
Kirtland Air Force Base	2
Knolls Atomic Power Laboratory	4
Los Alamos Scientific Laboratory	3
Mallinckrodt Chemical Works	1
Massachusetts Institute of Technology (Kaufmann)	1
Mound Laboratory	3
National Advisory Committee for Aeronautics	1
National Bureau of Standards (Taylor)	1
Naval Medical Research Institute	1
Naval Radiological Defense Laboratory	2
New Brunswick Laboratory	1
New York Operations Office	3
North American Aviation, Inc.	1
Oak Ridge National Laboratory (X-10)	8
Patent Branch, Washington	1
Rand Corporation	1
Sandia Corporation	1
Savannah River Operations Office	1
Technical Information Service, Oak Ridge	75
USAF, Major James L. Steele	6
U. S. Geological Survey	2
U. S. Public Health Service	2
University of California at Los Angeles	1
University of California Radiation Laboratory	5
University of Rochester	2
University of Washington	1
Western Reserve University	1
Westinghouse Electric Corporation	4

ANL-4626
Physics & Mathematics

Supplementary Distribution	No. of Copies
Atomic Energy Project, Chalk River (The Library)	4
Dr. Gregory Breit (Sloane Physics Laboratory)	1
Carnegie Institute of Technology (Dr. E. Creutz)	1
Chief of Naval Research	1
H. K. Ferguson Company (Miss Dorothy M. Lasky)	1
Harshaw Chemical Company (Mr. K. E. Long)	1
Isotopes Division (Mr. J. A. McCormick)	1
Library of Congress (Alton H. Keller)	2
National Bureau of Standards (The Library)	1
National Research Council, Ottawa (Mr. J. M. Manson)	1
Naval Research Laboratory (Code 2028)	15
Nevis Cyclotron Laboratories (Mr. M. W. Johnson)	2
Oak Ridge Institute of Nuclear Studies (Mr. R. A. Schleuter)	2
United Kingdom Scientific Mission	10
USAF, Central Air Documents Office (CADO-E)	5
USAF, Director of Research & Development (Research Division)	1
USAF, Wright-Patterson Air Force Base (Colonel Leo V. Harman)	1
U. S. Army, Army Field Forces (CWO Edwin H. Hoffman)	1
U. S. Army, Army Medical Service Graduate School (Col. W. S. Stone)	1
U. S. Army, Chemical and Radiological Laboratories (Miss Amoss)	3
U. S. Army, Director of Operations Research Office (Dr. E. Johnson)	1
U. S. Army, Office, Chief of Ordnance (Col. A. R. Del Campo)	1
U. S. Army, Office of the Chief Signal Officer (Mr. N. Stulman thru Lt. Col. G. C. Hunt)	2
U. S. Army, Special Weapons Branch (Lt. Col. A. W. Betts)	1
UT-AEC Agricultural Research Program (C. L. Comar)	1
Total	432

NUCLEAR SHELL STRUCTURE AND β-DECAY

4

I. ODD A NUCLEI

by

M. G. Mayer and S. A. Moszkowski
Argonne National Laboratory
Chicago, Illinois

L. W. Nordheim
Duke University
Durham, North Carolina
(At present on leave at the
Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

ABSTRACT

A systematics is given of all transitions for odd A nuclei for which sufficiently reliable data are available. The allowed or forbidden characters of the transitions are correlated with the positions of the initial and final odd nucleon groups in the nuclear shell scheme. The nuclear shells show definite characteristics with respect to parity of the ground states. The latter is the same as the one obtained from known spins and magnetic moments in a one-particle interpretation.

A. INTRODUCTION

The correlation between nuclear shell structure and β-decay characteristics had been noticed in early discussions on shell models.[1),2)] It is already quite customary to refer to shell considerations in the discussion of decay schemes. The present paper, together with the immediately following companion paper[3)] on even A nuclei, is intended to give a comprehensive review and interpretation of β-decay data based on all available information.[4)]

An excellent compilation of all nuclear data has recently been issued by the National Bureau of Standards.[5)] Tabulations of f factors and ft values have been compiled by S. A. Moszkowski,[6)] and by Feenberg and Trigg.[7)]

In the present paper we confine our attention to the ground states and isomeric states of nuclei. It is possible in many cases to interpret also known excited states. However, the uncertainties are here much greater, and the application of shell considerations are more uncertain.

The approach of this paper is essentially an empirical one. It would seem that there are a number of results of significance for the general theory of β-decay. However, the chief interest here is in a clarification of facts.

---

1) L. W. Nordheim, Phys. Rev. 75, 1894 (1949)

2) E. Feenberg and K. C. Hammack, Phys. Rev. 75, 1877 (1949)

3) L. W. Nordheim, Rev. Mod. Phys., 24,000, (1952), quoted henceforth as II.

4) The results of this work have already been summarized by L. W. Nordheim, Phys. Rev. 78, 294 (1950); the basic material has been presented by L. W. Nordheim, Tables for β-decay Systematics, informal distribution, 1950.

5) NBS Circular 499: Nuclear Data, K. Way, L. Fano, M.R. Scott, & K. Thew, 1950.

6) S. A. Moszkowski, A Summary of β-decay Theory, Chicago, Institute for Nuclear Studies, ONR Progress Report, 1949.

7) E. Feenberg and G. Trigg, Tables of Comparative Halflives of Radioactive Transitions, O.N.R. and A.E.C. report, 1949, also Rev. Mod. Phys. 22, 399 (1950).

In view of the rapidly growing information on decay schemes, it is obvious that many of the given interpretations will have to be changed in course of time. It has, however, been our experience that a clarification of facts generally tended to remove difficulties and did not add to them.

B. APPLICATION OF SHELL CONSIDERATIONS TO β-DECAY

The selection rules[8] for β-decay involve primarily the changes of spin and parity; an interpretation of the character of a given decay demands thus an assignment of these quantum numbers.

It is known (e.g. compare Reference 1) that the values of the magnetic moments of odd A isotopes fall definitely into two groups, which in a fashion may be interpreted as arising from parallel or anti-parallel coupling of intrinsic spin and orbital angular momentum of the last odd nucleon. These groups will be referred to as Schmidt groups because of their original discoverer. A measurement of spin and magnetic moment for a nucleus thus gives formally an angular momentum quantum number. We will call this the "orbital" for the nucleus in question, without implying that a one particle wave function gives a close approximation to its actual wave function. The fundamental hypothesis underlying this investigation is that the parity of the ground state of the nucleus is the same as the one for a single particle with this orbital.

It is further known that there are marked regularities in the occurrence of definite spin values and associated magnetic moments, which are associated with the shell numbers 8, 20, (28), 50, 82, 126. Thus for a given number of protons or neutrons, only one or a very few orbitals, in the sense of the previous paragraph, are known to occur. In particular, parity is

---

8) For a comprehensive review of the theory of β-decay, see E. J. Konopinski, Rev. Mod. Phys. 15, 209 (1943).

definitely connected with position in the shells. The second assumption made is that the state of a nucleus, whose spin and moment has not been measured, must correspond to one of the observed orbitals in an appropriate range.

The procedure to be followed then is that for each transition possible orbitals for the initial and final nucleus are selected which give a coherent scheme of ft values with proper selection rules. The validity of this procedure is strongly supported by our main result, that it is indeed possible to set up such a scheme with a high degree of internal consistency.

In general, nothing more than the above assumptions will be implied about nuclear structure and our results are thus independent of any detailed model except in showing a perfect correlation with a general shell scheme. They will give information about spins and parities of radioactive nuclei, but do not do much to prove or disprove particular models. On the other hand, it is much easier to speak in terms of a definite picture. The spin orbit coupling model proposed by Haxel, Jensen, and Suess9) and by M. G. Mayer10)11), particularly with the rules formulated by the latter, gives an almost perfect description of the empirical spins and moments. It will, therefore, be used to help in the discussion.

There are a small number of anomalies in spins and moments. In Na^{23} and Mn^{55} the spin differs by 1 from the expected values. The allowed character of the β-transition of Ne^{23} proves that the parity of Na^{23} corresponds to the shell scheme. It supports, therefore, the customary explanation that in these cases the odd particles outside a closed shell couple to a different configuration from those in the neighboring nuclei but with preservation of the parity. This assumption is made here throughout. The evidence from β-decay data makes it likely that the spins of such configurations

---

9) O. Haxel, J. Jensen and H. Suess, Phys. Rev. 75, 1766 (1949)
10) Maria G. Mayer, Phys. Rev. 75, 1969 (1949)
11) Maria G. Mayer, Phys. Rev. 78, 16, 22, (1950)

differ from those of the single particle orbitals by not more than one unit, in which case the characters of the transitions are in general not affected.

In the two cases of anomalous magnetic moments, Eu^{153} and Yb^{173}, no β -decay data are available to decide whether the shell-parity correlation is violated. In view of such anomalies one would expect occasional discrepancies between shell scheme and characteristics. It is only surprising that there seem to be so few of them.

TABLE I

Table I gives the observed orbitals12), 13) for odd A nuclei as functions of the number of particles (Z = number of protons, N = number of neutrons). The usual spectroscopic notation for single particle orbits is used. The already mentioned cases with anomalous spins are distinguished by capital letters, indicating a configuration which cannot result from a single particle model. The values in brackets are those which were inferred from β-decay data though they have not been directly observed. Not listed are $g_{9/2}$ for 39 and $h_{11/2}$ for 63 to 81, which may occur in isomeric states.

The alternatives are few below 50 and one can make assignments with considerable confidence. The selection becomes more and more ambiguous at higher numbers, particularly for $N > 82$, where only a few spins have been measured.

The parities can be predicted with considerably more confidence than the spins. In the oxygen shell, 3 to 7 particles, the parity is odd; for 9 to 19 it is even. From 21 to 49 the parity is odd except for $g_{9/2}$ orbits, which compete with $p_{1/2}$ orbits between 41 and 49 and which seem to occur for 39 in isomeric states. From 51 to 81 the parity is even, except again for $h_{11/2}$ orbits which are inferred from isomeric states above 63. The

---

12) H. L. Poss, Brookhaven National Laboratory 26 (T-10)(1949)

13) J. E. Mack, Rev. Mod. Phys. 22, 64 (1950)

states of 83 to 125 neutrons should again be odd. This alternating behavior excludes, in general, the occurrence of allowed transitions when the odd proton and neutron involved in it belong to different shells.

TABLE I. NUCLEAR ORBITALS AS FUNCTIONS OF N AND Z

N or Z	Orbital	N	Orbital	Z	Orbital
3, 5	$p_{3/2}$	51–55	$d_{5/2}(g_{7/2})$	51,53	$g_{7/2}$, $d_{5/2}$
7	$p_{1/2}$	57–61	$(d_{5/2},g_{7/2},s_{1/2})$	55,57	$g_{7/2}(d_{5/2})$
9	$s_{1/2}$	63–75	$s_{1/2}(d_{3/2},g_{7/2})$	59	$d_{5/2}$
11	$D_{3/2}(d_{5/2})$	77–81	$d_{3/2}$	61	$(d_{5/2})$
13	$d_{5/2}$	83–99	$(f_{7/2},h_{9/2})$	63	$d_{5/2}$
15	$s_{1/2}$	101	$p_{1/2}$	65	$d_{3/2}$
17, 19	$d_{3/2}$	103	$f_{5/2}$	67	$g_{7/2}$
21, 23	$f_{7/2}$	105,107	$p_{1/2},p_{3/2}(f_{5/2},h_{9/2})$	69	$s_{1/2}(d_{5/2})$
25	$F_{5/2}(f_{7/2})$	109,111	$(p_{1/2},p_{3/2},h_{9/2})$	71,73	$g_{7/2}$
27	$f_{7/2}$	113,115	$p_{1/2}(p_{3/2})$	75	$d_{5/2}$
29, 31	$p_{3/2}$	117,119	$p_{1/2}$	77,79	$d_{3/2}$
33, 35	$p_{3/2}(f_{5/2})$	121	$p_{3/2}$	81	$s_{1/2}$
37	$p_{3/2}$, $f_{5/2}$	123	$(p_{3/2},f_{5/2})$	83	$h_{9/2}$
39	$p_{1/2}$	125	$p_{1/2}$		
41, 43	$g_{9/2}(p_{1/2})$	127,129	$(g_{9/2},d_{5/2})$		
45	$(g_{9/2}, p_{1/2})$				
47	$g_{9/2}$, $p_{1/2}$				
49	$g_{9/2}(p_{1/2})$				

C. INTERPRETATION

The entire material on β-decay data for odd A nuclei is given in Table III, Section D. It contains all isotopes (except the mirror nuclei) for which we believe our knowledge is sufficient to obtain an ft value and to decide whether the transition (or part of it) goes to the ground state or an excited state.

The mirror nuclei in which the number of initial protons are equal with those of final neutrons are omitted for shortness since we have nothing new to add to their discussions. As is well known, they form a very distinct group of superallowed transitions with log ft values in the narrow range from 3.3 to 3.7 and with no over-all trend from H^3 to Ti^{43}.

While the master Table III, Section D, contains all available material, it is instructive to group the transitions according to type. This is done in Table II for all those decays which go at least partially to the ground state of the final nucleus and where the empirical evidence seems to be sufficiently clear. The table gives the isotope as identified by its charge, chemical symbol and mass number, the type and energy of its transition, the number of the initial and final odd nucleons in this order (the larger numbers refer always to the neutron), the assignment of orbitals, and the value of log ft. Further details can be obtained by reference to the master Table III, Section D.

TABLE II

The main result of an inspection of Table II is the close correlation of type of transition and shell structure and comparatively small amount of straggling of log ft values within each group.

The members of the allowed group with the assignments $\Delta \ell = 0$, $\Delta I = 0,1$ have, without exception, the initial and final odd nucleon group in the same shell. There is no trend in ft values with atomic number up to Nd^{141} (which occurs at the highest place where allowed transitions to the ground state can be expected). This absence of a trend, which will be found also in all other groups, is in marked contrast to previous expectations. The largest log ft value found is 6 with a few examples near this number. The majority, however, is contained in the band 5.0 ± 0.3. There is no recognizable distinction between transitions with $\Delta I = 0$ and $\Delta I = 1$; that is, one has to postulate Gamow-Teller selection rules.

The members of the group with the assignment $\Delta \ell = 1$, $\Delta I = 0, 1$ (first forbidden) leave without exception initial and final odd nucleon group in a different shell. No log ft value below*6 or above 8 is found with a clustering around about 6.2 and 7.2 (compare Feenberg and Trigg, Reference 7). The distinction between the allowed and first forbidden groups, which formerly seemed to be somewhat vague, has now become quite clear. The dividing line at log ft 6 seems never to be violated by either group, but a more reliable criterion is given by the numbers of the odd nucleon groups in relation to shell structure.

There is again no clear distinction between transitions with $\Delta I = 0$ and $\Delta I = 1$. In this connection it should be pointed out that inferences from transitions with $N > 83$ have to be taken with caution, owing to the ambiguities in interpretation in this range.

TABLE II. CLASSIFICATION OF β-DECAYS TO GROUND STATE OF ODD A NUCLEI ACCORDING TO CHANGES IN SPIN (Δ I) AND PARITY (NO,YES)

Column 1: Initial isotope Z-Element-A.

Column 2: Sign of emitted charge, maximum energy in Mev.

Column 3: Initial and final odd nucleon number in this order.

Column 4: Assignment of orbitals to initial and final odd nucleon group in this order.

Column 5: Log ft.

Column 6: Log (W_o^2-1)ft for $\Delta I = 2$, Yes. W_o = energy of β transition in units mc^2.

---

*Exceptions are the two very heavy nuclei Hg^{205} and Pb^{209} where Z-dependent factors in the matrix elements may have become of importance. (Compare the discussion by Konopinski, Ref. 8).

TABLE II (cont.)

a) $\Delta I = 0, 1.$ No (Allowed)

1	2	3	4	5
10 Ne 23	- 4.1	13-11	$d_{5/2}-D_{\underline{3/2}}$	4.9
11 Na 25	- 3.7	11-13	$D_{3/2}-d_{\underline{5/2}}$	5.2
16 S 35	- 0.17	19-17	$d_{3/2}-d_{\underline{3/2}}$	5.0
20 Ca 45	- 0.22	25-21	$f_{7/2}-f_{\underline{7/2}}$	5.6
21 Sc 43	+ 1.13	21-23	$f_{7/2}-f_{7/2}$	4.8+
21 Sc 47	- 0.61	21-25	$f_{7/2}-f_{7/2}$	5.6+
21 Sc 49	- 1.8	21-27	$f_{7/2}-f_{7/2}$	5.5
22 Ti 45	+ 1.2	23-21	$f_{7/2}-f_{7/2}$	4.7+
23 V 47	+ 1.65	23-25	$f_{7/2}-f_{7/2}$	4.7+
24 Cr 49	+ 1.45	25-23	$f_{7/2}-f_{7/2}$	4.5+
25 Mn 51	+ 2.0	25-27	$F_{5/2}-f_{7/2}$	5.1+
26 Fe 53	+ 2.8	27-25	$f_{7/2}-F_{5/2}$	5.0+
27 Co 61	- 1.3	27-33	$f_{7/2}-f_{5/2}$	5.2
30 Zn 63	+ 2.36	33-29	$P_{3/2}-P_{\underline{3/2}}$	5.4
30 Zn 69	- 1.0	39-31	$P_{1/2}-P_{\underline{3/2}}$	4.6
30 Zn 71	- 2.1	41-31	$P_{1/2}-P_{\underline{3/2}}$	4.5+
31 Ga 73	- 1.4	31-41	$P_{3/2}-P_{1/2}$	5.9
32 Ge 75	- 1.1	43-33	$P_{1/2}-P_{\underline{3/2}}$	5.0
32 Ge^m 77	- 2.8	45-33	$P_{1/2}-P_{3/2}$	4.8+
33 As 71	+ 0.6	33-39	$P_{3/2}-P_{1/2}$	5.1
33 As 77	- 0.7	33-43	$P_{3/2}-P_{1/2}$	5.7
34 Se 73	+ 1.29	39-33	$P_{1/2}-P_{3/2}$	5.3
34 Se 81	- 1.5	47-35	$P_{1/2}-P_{\underline{3/2}}$	4.8

TABLE II (cont.)

a) Δ I = 0, 1. No (Allowed)

1	2	3	4	5
34 Se^{m} 83	- 3.4	49-35	$p_{1/2}-p_{3/2}$	5.2+
35 Br 75	+ 1.6	35-41	$p_{3/2}-p_{1/2}$	5.6
35 Br 77	+0.36	35-43	$p_{3/2}-p_{1/2}$	5.0
35 Br 83	- 1.05	35-47	$p_{3/2}-p_{1/2}$	5.3
35 Br 85	- 2.5	35-49	$p_{3/2}-p_{1/2}$	5.1
36 Kr 77	+ 1.7	41-35	$p_{1/2}-p_{3/2}$	5.4 +
40 Zr^{m} 89	+ 1.07	49-39	$p_{1/2}-p_{\underline{1/2}}$	5.8 +
42 Mo 91	+ 3.7	49-41	$g_{9/2}-g_{9/2}$	5.8 +
45 Rh 105	- 0.57	45-59	$g_{9/2}-g_{7/2}$	5.5
48 Cd 107	+ 0.32	59-47	$g_{7/2}-G_{7/2}$	4.9
50 Sn 121	-0.38	71-51	$d_{3/2}-d_{\underline{5/2}}$	5.0
52 Te 127	- 0.76	75-53	$d_{3/2}-d_{\underline{5/2}}$	5.6
55 Cs 127	+ 1.2	55-73	$d_{5/2}-d_{3/2}$	4.7 +
60 Nd 141	+ 0.7	81-59	$d_{3/2}-d_{\underline{5/2}}$	5.2

b) Δ I = 0, 1. Yes (first forbidden)

1	2	3	4	5
35 Br 87	- 8.0	35-51	$p_{3/2}-d_{5/2}$	7.3
36 Kr 87	- 3.2	51-37	$d_{5/2}-p_{\underline{3/2}}$	7.0
37 Rb 89	- 3.8	37-51	$p_{3/2}-d_{5/2}$	6.6
46 Pd 111	- 3.5	65-47	$s_{1/2}-p_{1/2}$	6.8
47 Ag 111	- 1.0	47-63	$p_{1/2}-s_{\underline{1/2}}$	7.2
47 Ag 113	- 2.2	47-65	$p_{1/2}-s_{\underline{1/2}}$	7.0
47 Ag 115	- 3.0	47-67	$p_{1/2}-s_{1/2}$	6.4
48 Cd 115	- 1.13	67-49	$s_{1/2}-p_{1/2}$	6.8 +
48 Cd 117	- 1.5	69-49	$s_{1/2}-p_{1/2}$	6.1

TABLE II (cont.)

b) ΔI = 0, 1. Yes(first forbidden)

1	2	3	4	5	
49 In^m 115	- 0.83	49-65	$p_{1/2}-s_{\underline{1/2}}$	6.6	
49 In 117	- 1.73	49-67	$p_{1/2}-s_{\underline{1/2}}$	6.2	
49 In 119	- 2.7	49-69	$p_{1/2}-s_{\underline{1/2}}$	6.2	
54 Xe 137	- 4.0	83-55	$f_{7/2}-g_{\underline{7/2}}$	6.3	
56 Ba 139	- 2.27	83-57	$f_{7/2}-g_{\underline{7/2}}$	6.7 +	
57 La 141	- 2.9	57-83	$g_{7/2}-f_{7/2}$	7.6	
58 Ce 141	- 0.56	83-59	$f_{7/2}-d_{\underline{5/2}}$	7.7	
59 Pr 143	- 0.93	59-83	$d_{5/2}-f_{7/2}$	7.6	
60 Nd 147	- 0.7	87-61	$f_{7/2}-d_{\underline{5/2}}$	7.0 +	
61 Pm 147	- 0.23	61-85	$d_{5/2}-f_{7/2}$	7.6	
62 Sm 151	- 0.076	89-63	$f_{7/2}-d_{\underline{5/2}}$	6.9	
66 Dy 165	- 1.28	99-67	$f_{7/2}-g_{\underline{7/2}}$	6.1 +	
67 Er 169	- 0.33	101-69	$p_{1/2}-s_{\underline{1/2}}$	6.1	
68 Er 171	- 1.49	103-69	$f_{5/2}-d_{5/2}$	7.0	
71 Lu 177	- 0.49	71-105	$g_{7/2}-f_{5/2}$	6.8	
72 Hf 181	- 0.40	109-73	$p_{1/2}-s_{1/2}$	7.2	
74 W 185	- 0.43	111-75	$p_{3/2}-d_{\underline{5/2}}$	7.5	
74 W 187	- 1.33	113-75	$p_{3/2}-d_{5/2}$	7.8	
78 Pt 199	- 1.8	121-79	$p_{1/2}-d_{3/2}$	6.3	
80 Hg 205	- 1.6	125-81	$p_{1/2}-s_{1/2}$	5.4	
82 Pb 209	- 0.68	127-83	$g_{9/2}-h_{\underline{9/2}}$	5.6	
83 Bi 213	- 1.3	83-129	$h_{9/2}-g_{9/2}$	6.0	
		c) ΔI = 2. Yes (first forbidden)			
16 S 37	- 4.3	21-17	$f_{7/2}-d_{\underline{3/2}}$	7.1	9.1
18 A 41	- 2.55	23-19	$f_{7/2}-d_{\underline{3/2}}$	8.6	10.1

TABLE II (cont.)

c) Δ I = 2, Yes (first forbidden)

1	2	3	4	5	6
36 Kr 85	-0.74	49–37	$g_{9/2}-f_{\underline{5/2}}$	9.2	9.9
38 Sr 89	-1.46	51–39	$d_{5/2}-p_{\underline{1/2}}$	8.5	9.7
38 Sr 91	-3.2	53–39	$d_{5/2}-p_{1/2}$	8.0	9.7
39 Y 91	-1.56	39–51	$p_{1/2}-d_{\underline{5/2}}$	8.7	9.9
40 Zr 95	-1.0	55–41	$d_{5/2}-p_{1/2}$	9.8	10.7
43 Tc^m95	$+0.4$	43–53	$p_{1/2}-d_{\underline{5/2}}$	8.3	8.6
44 Ru 103	-0.8	59–45	$d_{5/2}-p_{1/2}$	8.5	9.3
50 Sn^m123	-1.42	73–51	$h_{11/2}-g_{\underline{7/2}}$	9.1	10.3
51 Sb 123	-0.62	51–73	$g_{7/2}-h_{11/2}$	9.4	10.0
55 Cs 137	-0.53	55–81	$g_{\underline{7/2}}-h_{11/2}$	9.6	10.1
69 Tm 171	-1.0	69–101	$d_{5/2}-p_{\underline{1/2}}$	9.5	10.4

d) Δ I = 1. No $\Delta \ell = 2$(ℓ -forbidden)

8 O 19	-4.5	11–9	$D_{3/2}-s_{\underline{1/2}}$	5.5	
14 Si 31	-1.8	17–15	$d_{3/2}-s_{\underline{1/2}}$	5.9	
28 Ni 63	-0.05	35–29	$f_{5/2}-p_{\underline{3/2}}$	6.8	
28 Ni 65	-2.10	37–29	$f_{5/2}-p_{\underline{3/2}}$	6.6	
29 Cu 61	$+1.22$	29–33	$p_{3/2}-f_{5/2}$	4.9	
29 Cu 67	-0.65	29–37	$p_{3/2}-f_{\underline{5/2}}$	5.5	
30 Zn 65	$+0.32$	35–29	$f_{5/2}-p_{\underline{3/2}}$	7.0	
32 Ge 69	$+1.0$	37–31	$f_{5/2}-p_{\underline{3/2}}$	6.0	
46 Pd 109	-1.0	63–47	$d_{5/2}-G_{7/2}$	6.2	

e) Δ I = 2. No and Δ I > 2 (second and higher forbidden)

37 Rb 87	-0.13	37–49	$p_{\underline{3/2}}-g_{\underline{9/2}}$	16.5	
43 Tc 99	-0.30	43–55	$g_{\underline{9/2}}-d_{5/2}$	13.0	

TABLE II (cont.)

e) $\Delta I = 2$. No and $\Delta I >= 2$ (second and higher forbidden)

1	2	3	4	5
49 In 115	- 0.63	49-65	$g_{\underline{9/2}}-s_{\underline{1/2}}$	23.2
53 I 129	- 0.12	53-75	$g_{\underline{7/2}}-s_{\underline{1/2}}$	13.5
55 Cs 135	- 0.21	55-79	$g_{\underline{7/2}}-d_{\underline{3/2}}$	13.1
55 Cs 137	- 1.19	55-81	$g_{\underline{7/2}}-d_{\underline{3/2}}$	12.2
75 Re 187	- 0.043	75-111	$d_{\underline{5/2}}-h_{9/2}$	17.7

The next group with the assignments $\Delta \ell = 1$, $\Delta I = 2$(also first forbidden) was first recognized by Feenberg.7), 14) It is of particular interest since its spectra show a uniquely defined shape different from the allowed type.15) Since the f factors for such transitions should also be different from that of allowed transitions approximately by a factor $(W^2 - 1)$, we have added in Table II values of $\log(W_o^2 - 1)$ ft, where W_o is the energy of the transition inclusive of the rest of the mass of the electron in units mc^2. The resultant values are remarkably homogeneous except for the very light and energetic nucleus S^{37} and for the positron decay of the Tc^{95} isomeric state. Again the initial and final odd nucleon configurations belong always to different shells except those involving the orbital $h_{11/2}$ of isomeric states. The occurrence of this well defined and easily recognized group constitutes a very valuable check on spins and parity assignments in the shell scheme.

There is a small and perhaps not too well defined group for which the formal assignment of orbitals gives $\Delta \ell = 2$ and $\Delta I = 1$. According to

---

14) F. B. Shull and E. Feenberg, Phys. Rev. 75, 1768 (1949)

15) Compare the recent review by Chien Shiung Wu, Rev. Mod. Phys. 22, 386 (1950)

the formal selection rules these transitions should be allowed since there is no change of parity. The ft values for these transitions, however, seem to be larger than expected, and there may be the remnant of a selection rule pertaining to orbital angular momentum. The discussion of this group will be deferred to Paper II, where a few more examples will be available.

The last group contains the second and higher forbidden transitions which involve spin changes of at least 2. The most important remark is that there is no example with a log ft value** below 12. This is true for even the second forbidden ones (Δ I = 2,3, no change in parity) as shown most clearly by the two Cs isotopes, where the spins in both the initial and the final state have been measured. The ratio of the probabilities of allowed to second forbidden transition seems to be thus at least of the order of 10^6, if not higher, in place of 10^4 as has been frequently assumed. This low probability of high forbidden transitions explains the small number of examples found and the failure to find many spectral shapes different from the allowed or unique first forbidden forms.

There is a considerable number of transitions which go to an excited state with subsequent γ-radiation in series. The validity of an interpretation demands then that the ft value for the observed β-ray be much lower than that for a transition between the expected ground states. This is fulfilled in all cases listed in Table III of Section D. The actual ft values observed classify most of these transitions as allowed or first forbidden with Δ I = 0, 1, while most of the assignments predict an at least second forbidden transition between the ground states. This gives a margin in the square of the matrix elements of order 10^5-10^7 which is ample to explain the absence of observation of high-energy β -rays.

**Again the f function for these transitions will show a different energy dependence from that for allowed ones, but a qualitative comparison remains useful.

There are still quite a few ambiguities in the interpretation as noted in the footnotes in Table III. There are also a considerable number of cases where the facts are not well known. However, no outstanding difficulties occur whenever the characteristics of the transitions are definitely established. There can thus be little doubt as to the correctness of the scheme presented here.

As the main results we may summarize: The Schmidt groups give definite indication of the parities of the nuclear states which in turn are closely correlated with the shell numbers. The character of the ground states of a nucleus with one odd nucleon group is essentially determined by the number of nucleons in this group in formal agreement with the rules of the spin-orbit coupling model.

The success of the scheme, however, does not give support to an extreme one particle model. On the contrary, the clear distinction between the super-allowed transitions of the mirror nuclei and the normal allowed group (unfavored allowed in Wigner's terminology) shows clearly the inadequacy of the one particle model. The difference in ft values for these two groups is of the order of 30 to 40, that is, a difference in the matrix elements of the order of 5 to 6. It will be the task of future theories of nuclear structure and β-decay, especially the establishing of the form of the interaction hamiltonian, to explain this ratio and other ratios between the probabilities of the various types of transitions.

The authors wish to thank Dr. Henry Brysk for his valuable assistance in preparing the tables.

D. TABLES FOR β -DECAY SYSTEMATICS: ODD A

TABLE III. β -DECAY DATA AND ORBITAL ASSIGNMENTS FOR ODD-A NUCLEI

Legend to table:

1. Class of transition

   A. isotope certain

   B. isotope probable

   C. isotope doubtful

   Class C. nuclei are only included if the β -decay data contribute to the identification.

   a. decay data well established

   b. decay data probably correct

   c. decay data uncertain and possibly incorrect

   α. configuration assignment well established

   β. configuration assignment probable

   γ. configuration assignment uncertain and possibly incorrect

2. Initial isotope: Z-Element-A. The m denotes a metastable state.

3. Sign of emitted charge, maximum energy in m.e.v. of the most energetic observed β -ray. The energy is given in brackets, if the transition is believed to go to an excited state.

4. Halflife

5. g,e,m, mean, respectively, transition is believed to go to the ground, an excited or a metastable state of the final nucleus. The figure following gives the branching percentage to the specified state when known. The 100 means that there is a branching, but of unknown percentage. Omission of a figure means that most of the transitions go to the specified state.

6. Initial and final odd nucleon number in this order. The larger number is always the odd neutron.

7. Assignment of orbitals to initial and final nucleon in this order.

Capitalized letters signify that a configuration has to be invoked. The $D_{3/2}$ for 11 nucleons means, for instance, a configuration with orbital angular momentum 2 which results from d 5/2 orbits of the last 3 nucleons. Underlining signifies that the spin has been measured.

8. Log ft value calculated with the f function for allowed transitions. The values are given in brackets if the transition goes to an excited state. A plus sign is added if branching of unknown percentage is known to occur.

9. Reference to bibliography. No authors are quoted if all references are given in the compilations by Seaborg and Perlman (S1), Mitchell (M1), or Nat. Bur. Stand. (N1).

10. References to footnotes for table.

Class		Sign	Halflife		Numbers		log ft		Footnotes
	Z-Element-A	Energy		Final	State	Configuration		Ref.	
1	2	3	4	5	6	7	8	9	10
Abβ	6-C-15	-(8.8)	2.4s	e	9-7	s1/2-p1/2	(5.3)	H1	
Aaβ	7-N-17	-(3.7)	4.2s	e	7-9	p1/2-s1/2	(3.8)	A1	
Aaβ	8-0-19	-4.5	27.0s	g 30	11-9	D3/2-s1/2	5.5	S1	
Abα	10-Ne-23	- 4.1	40.7s	g	13-11	d5/2-D3/2	4.9	S1	
Baα	11-Na-25	- 3.7	61s	g 55	11-13	D3/2-d5/2	5.2	B1	1
Aaα	12-Mg-27	-(1.8)	10m	e 80	15-13	s1/2-d5/2	(4.7)	M1	
Aaα	13-Al-29	-(2.5)	6.6m	e 70	13-15	d5/2-s1/2	(5.2)	S2	
Aaα	14-Si-31	- 1.8	170m	g	17-15	d3/2-s1/2	5.9	S1	
Abα	16-S-35	- 0.17	87.1d	g	19-17	d3/2-d3/2	5.0	S1	
Aaα	16-S-37	- 4.3	5.0m	g 10	21-17	f7/2-d3/2	7.1	N1	
Aaα	18-A-41	- 2.55	109m	g0.7	23-19	f7/2-d3/2	8.6	S1	
Aaβ	20-Ca-45	- 0.22	152d	g	25-21	f7/2-f7/2	5.6	M2	2
Abβ	21-Sc-43	+ 1.13	3.92h	g<80	21-23	f7/2-f7/2	4.8+	H2	
Bbβ	21-Sc-47	- 0.61	3.43d	g<100	21-25	f7/2-f7/2	5.6+	K1	2,3

TABLE III (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 log ft	9 Ref.	10 Footnotes
Aa α	21-Sc-49	- 1.8	57m	g	21-27	f7/2-f7/2	5.5	S1	
Ab β	22-Ti-45	+ 1.2	3.08h	g<100	23-21	f7/2-f7/2	4.7 +	S1	
Bb β	23-V -47	+ 1.65	33m	g<100	23-25	f7/2-f7/2	4.7 +	K1	2,3
Ac β	24-Cr-49	+ 1.45	41.9m	g<100	25-23	f7/2-f7/2	4.5 +	S1	2,3
Ab β	25-Mn-51	+ 2.0	46m	g<100	25-27	F5/2-f7/2	5.1 +	S1	2
Aa α	26-Fe-53	+ 2.8	8.9m	g<100	27-25	f7/2-F5/2	5.0 +	N2	2
Aa α	26-Fe-59	-(0.46)	47d	e 50	33-27	p3/2-f7/2	(6.7)	M1	
Aa α	27-Co-55	+(1.5)	18.2h	e<50	27-29	f7/2-p3/2	(6.2)	D1	
Ab α	27-Co-57	+(0.26)	270d	e<100	27-31	f7/2-p3/2	(5.3)	S1	
Ab γ	27-Co-61	- 1.3	1.75h	g	27-33	f7/2-f5/2	5.2	P1	4
Aa α	28-Ni-57	+(0.73)	35.7h	e<100	29-27	p3/2-f7/2	(5.0+)	M3	
Ba β	28-Ni-63	- 0.05	300y	g	35-29	f5/2-P3/2	6.8	S1	
Aa β	28-Ni-65	- 2.10	2.6h	g 57	37-29	f5/2-p3/2	6.6	M1	
Bb β	29-Cu-61	+ 1.22	3.4h	g 65	29-33	p3/2-f5/2	4.9	B2	4
Ab β	29-Cu-67	- 0.65	61h	g	29-37	p3/2-f5/2	5.5	S1	
Aa α	30-Zn-63	+ 2.36	38m	g 85	33-29	p3/2-p3/2	5.4	S1	
Ab β	30-Zn-65	+ 0.32	250d	g 3	35-29	f5/2-p3/2	7.0	N1	5
Aa α	30-Zn-69	- 1.0	57m	g	39-31	p1/2-p3/2	4.6	S1	
Bb α	30-Zn-71	- 2.1	2.2m	g<100	41-31	p1/2-p3/2	4.5+	S1	
Bb α	31-Ga-73	- 1.4	5h	m	31-41	p3/2-p1/2	5.9	S1	6
Ab α	32-Ge-69	+ 1.0	1.65d	g 33	37-31	f5/2-p3/2	6.0	M4	
Aa α	32-Ge-75	- 1.1	1.37h	g	43-33	p1/2-p3/2	5.0	M4	
Aa β	32-Ge-77	-(1.74)	12h	e	45-33	g9/2-p3/2	(6.8)	M5	
Aa β	32-$\overset{m}{\text{Ge}}$-77	- 2.8	59s	g<100	45-33	p1/2-p3/2	4.8 +	S1	
Ab α	33-As-71	+ 0.6	55h	g 33	33-39	p3/2-p1/2	5.1	N1	
Ab β	33-As-77	- 0.7	40h	m	33-43	p3/2-p1/2	5.7	N1	7

TABLE III (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 log ft	9 Ref.	10 Footnotes
Bbα	34-Se-73	+ 1.29	7.1h	g 50	39-33	p1/2-p3/2	5.3	C1	
Baα	34-Se-81	- 1.5	17m	g	47-35	p1/2-p3/2	4.8	S1	
Abβ	34-Se-83	-(1.5)	25m	e	49-35	g9/2-p3/2	(5.0)	S1	
Abβ	34-$\overset{m}{\text{Se}}$-83	- 3.4	67s	g<100	49-35	p1/2-p3/2	5.2+	S1	
Abβ	35-Br-75	+ 1.6	1.7m	m 18	35-41	P3/2-P1/2	5.6	W1	8
Bbα	35-Br-77	+ 0.36	2.4d	m 5	35-43	P3/2-P1/2	5.0	W1	7
Aaα	35-Br-83	- 1.05	2.4h	m	35-47	P3/2-P1/2	5.3	S1	
Abα	35-Br-85	- 2.5	3.0m	m	35-49	P3/2-P1/2	5.1	S1	
Bbβ	35-Br-87	- 8.0	55.6s	g	35-51	p3/2-d5/2	7.3	S3	
Baα	36-Kr-77	+ 1.7	1.1h	g<30	41-35	p1/2-p3/2	5.4+	S1	
Abα	36-Kr-79	+(0.9)	34h	e 0.6	43-35	g9/2-p3/2	(7.5)	S1	
Aaα	36-Kr-85	- 0.74	9.4y	g	49-37	g9/2-f5/2	9.2	S1	
Acβ	36-$\overset{m}{\text{Kr}}$-85	-(0.75)	4.36m	e<100	49-37	p1/2-f5/2	(5.1+)	K2	
Abα	36-Kr-87	- 3.2	1.3h	g	51-37	d5/2-p3/2	7.0	K2	
Abα	37-Rb-87	- 0.13	$6\text{x}10^{10}$ y	g	37-49	p3/2-g9/2	16.5	S1	
Abβ	37-Rb-89	- 3.8	15m	g	37-51	p3/2-d5/2	6.6	S1	
Aaα	38-Sr-89	- 1.46	53d	g	51-39	d5/2-p1/2	8.5	L1	
Aaα	38-Sr-91	- 3.2	9.7h	g 60	53-39	d5/2-p1/2	8.0	S1	
Aaβ	38-Sr-91	-(1.3)	9.7h	e 40	53-39	d5/2-g9/2	(6.6)	N1	9
Aaα	39-Y -91	- 1.56	61d	g	39-51	p1/2-d5/2	8.7	A2	
Abβ	40-$\overset{m}{\text{Zr}}$-89	+ 1.07	78h	g<100	49-39	p1/2-p1/2	5.8+	S1	10
Acβ	40-Zr-95	- 1.0	65d	m 2	55-41	d5/2-p1/2	9.8	S1	11
Abβ	41-Nb-95	-(0.15)	37d	e	41-53	g9/2-d5/2	(5.0)	S1	11
Bcβ	41-Nb-97	-(1.4)	68m	e	41-55	g/9/2-d5/2	(5.4)	S1	11
Aaβ	42-Mo-91	+ 3.7	15.5m	g	49.41	g9/2-g9/2	5.8+	D2	
Acβ	42-Mo-99	-(1.03)	67h	e	57-43	d5/2-g9/2	(6.8+)	M6	

TABLE III (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 log ft	9 Ref.	10 Footnotes
Ab β	42-Mo-101	-(2.2)	14.6m	e	59-43	d5/2-g9/2	(5.6+)	S1	12
Ab β	43-Tc-93	+(0.83)	2.7h	e 7	43-51	g9/2-d5/2	(7.5+)	K3	12
Bb β	43-Tc^{m}-95	+0.4	62d	g 0.4	43-53	p1/2-$\underline{d5/2}$	8.3	M7	13
Aa α	43-Tc-99	- 0.30	10^{6} y	g	43-55	$\underline{g9/2}$-d5/2	13.0	K4	
Ab γ	43-Tc-101	-(1.3)	16m	e	43-57	g9/2-d5/2	(4.7)	S1	12
Ab β	44-Ru-95	+(1.1)	1.65h	e<100	51-43	d5/2-g9/2	(4.1+)	S1	12
Ab α	44-Ru-103	- 0.8	42d	m 3	59-45	d5/2-p1/2	8.5	N1	
Ab β	44-Ru-105	-(1.15)	4.5h	e<100	61-45	d5/2-g9/2	(5.6)	D3	
Ab β	45-Rh-105	- 0.57	36h	g	45-59	g9/2-g7/2	5.5	D3	14
Bc γ	46-Pd-101	-(0.53)	9h	e	55-45	d5/2-g9/2	(5.2)	S1	15
Ab γ	46-Pd-109	- 1.0	14h	m	63-47	d5/2-G7/2	6.2	S1	16
Ab α	46-Pd-111	- 3.5	26m	g	65-47	s1/2-p1/2	6.8	S1	
Aa α	47-Ag-111	- 1.0	7.5d	g	47-63	p1/2-$\underline{s1/2}$	7.2	S1	
Aa α	47-Ag-113	- 2.2	5.3h	g	47-65	p1/2-$\underline{s1/2}$	6.0	S1	
Ab α	47-Ag-115	- 3.0	20m	g	47-67	p1/2-s1/2	6.4	D4	
Aa γ	48-Cd-107	0.32	6.7h	m0.31	59-47	g7/2-G7/2	4.9	N1	16
Ab β	48-Cd-115	- 1.13	56h	m<100	67-49	s1/2-p1/2	6.8+	M1	
Ab β	48-Cd-117	- 1.5	170m	g	69-49	s1/2-p1/2	6.1	S1	
Aa α	49-In-115	- 0.63	6×10^{14} y	g	49-65	$\underline{g9/2}$-$\underline{s1/2}$	23.2	M8	
Aa α	49-In^{m}-115	- 0.83	4.5h	g 6	49-65	p1/2-$\underline{s1/2}$	6.6	B3	
Aa α	49-In-117	- 1.73	117m	g	49-67	p1/2-$\underline{s1/2}$	6.2	S1	
Aa α	49-In-119	- 2.7	17.5m	g	49-69	p1/2-$\underline{s1/2}$	5.2	D5	
Aa α	50-Sn-121	- 0.38	28h	g	71-51	d3/2-$\underline{d5/2}$	5.0	D6	
Ab β	50-Sn-123	-(1.26)	39.5m	e	73-51	d3/2-$\underline{g7/2}$	(5.2)	D6	
Ab β	50-Sn^{m}-123	-1.42	136d	g	73-51	h11/2-$\underline{g7/2}$	9.1	N1	
Aa α	51-Sb-125	- 0.62	2.7y	m 18	51-73	g7/2-h11/2	9.4	M1	

TABLE III (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 log ft	9 Ref.	10 Footnotes
Aa α	52-Te-127	- 0.76	9.3h	g	75-53	d3/2-d5/2	5.6	S1	
Ac β	52-Te-129	-(1.8)	70m	e	77-53	d3/2-g7/2	(6.1)	S1	
Ab α	53-I -129	- 0.12	3x10^{7}y	g	53-75	g7/2-s1/2	13.5	N1	
Aa α	53-I -131	-(0.61)	8.0d	e 86	53-77	g7/2-d3/2	(6.6)	S1	
Ac β	53-I -133	-(1.4)	22h	e	53-79	g7/2-d3/2	(6.9)	S1	
Ab β	53-I -135	-(1.40)	6.7h	e 25	53-81	g7/2-d3/2	(7.0)	S1	
Ac β	54-Xe-133	-(0.42)	5.3d	e	79-55	d3/2-g7/2	(5.9)	S1	
Ab β	54-Xe-135	-(0.93)	9.2h	e	81-55	d3/2-g7/2	(5.0)	S1	
Ab β	54-Xe-137	- 4.0	3.8m	g	83-55	f7/2-g7/2	6.3	S1	17
Ab β	55-Cs-127	+ 1.2	5.5h	g<100	55-73	d5/2-d3/2	4.7 +	F1	18
Aa α	55-Cs-135	- 0.21	2.1x10^{6} y	g	55-79	g7/2-d3/2	13.1	S4	
Aa α	55-Cs-137	- 0.53	33y	m 95	55-81	g7/2-h11/2	9.6	M1	
Aa α	55-Cs-137	- 1.19	33y	g 5	55-81	g7/2-d3/2	12.2	M1	
Ab β	56-Ba-139	- 2.27	84m	g<100	83-57	f7/2-g7/2	6.7 +	N1	17
Ab β	57-La-141	- 2.9	3.7h	g	57-83	g7/2-f7/2	7.6	S1	17
Aa β	58-Ce-141	- 0.56	28d	g 30	83-59	f7/2-d5/2	7.7	N1	17
Aa β	59-Pr-143	- 0.93	13.7d	g	59-83	d5/2-f7/2	7.6	F2	19
Bb α	60-Nd-141	+ 0.7	145m	g 2	81-59	d3/2-d5/2	5.2	W2	
Ab β	60-Nd-147	- 0.7	11d	g<100	87-61	f7/2-d5/2	7.0 +	M9	19
Aa β	61-Pm-147	- 0.23	3.7y	g	61-85	d5/2-f7/2	7.6	A2	19
Aa β	62-Sm-151	- 0.076	20y	g	89-63	f7/2-d5/2	6.9	A2	20
Ab β	66-Dy-165	- 1.28	2.5h	g<100	99-67	f7/2-g7/2	6.1+	M1	21
Bb β	68-Er-169	- 0.33	9.4d	g	101-69	p1/2-s1/2	5.1	S1	
Ba γ	68-Er-171	- 1.49	7.5h	g 6	103-69	f5/2-d5/2	8.1	S1	22
Bb β	69-Tm-171	- 1.0	500d	g	69-101	d5/2-p1/2	9.5	S1	
Ab γ	71-Lu-177	- 0.49	7.0d	g 65	71-105	g7/2-f5/2	6.8	D7	22

TABLE III (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 log ft	9 Ref.	10 Footnotes
Ab β	72-Hf-181	- 0.40	47d	m	109-73	p1/2-s1/2	7.2	M1	23
Aa β	74-W -185	- 0.43	73.2d	g	111-75	p3/2-d5/2	7.5	S1	24
Ab β	74-W -187	- 1.33	24.1h	g	30113-75	p3/2-d5/2	7.8	M1	24
Aa γ	75-Re-187	- 0.043	$4x10^{12}$ y	g	75-111	d5/2-h9/2	17.7	S1	25
Ab γ	78-Pt-199	- 1.8	31m	g	121-79	p3/2-d3/2	6.3	S1	
Aa β	79-Au-199	-(0.32)	3.3d	e	79-119	d3/2-p1/2	(5.8)	M1	
Aa γ	80-Hg-203	-(0.21)	43.5d	e	123-81	f5/2-s1/2	(6.4)	M1	26
Ab β	80-Hg-205	- 1.62	55m	g	125-81	p1/2-s1/2	5.4	S1	27
Aa β	82-Pb-209	- 0.68	3.32h	g	127-83	g9/2-h9/2	5.6	S1	27
Ab β	83-Bi-213	- 1.3	46m	g	96 83-129	h9/2-g9/2	6.0	S1	27

Footnotes to Table III

1. It cannot be decided, whether the 11 protons in Na^{25} are in a D3/2 or d5/2 configuration.
2. It cannot be decided whether the 25 nucleon configurations in Ca^{45}, Ti^{47}, Cr^{49}, Mn^{51}, Mn^{53} are of the type F 5/2 or f 7/2.
3. There is no experimental evidence that the γ-rays in Sc^{47}, V^{47} and Cr^{49} are in series with the β-rays.
4. Co^{61} and Cu^{61} both go to Ni^{61} with no γ-rays reported and with ft values corresponding to allowed transitions. It is suggested that the facts are not completely known in this case. The table assigns an f5/2 orbit to the 33 neutrons in Ni^{61} so as to make the Co^{61} transition an allowed one; Cu^{61} would then be ℓ-forbidden with abnormally low ft value.
5. The series γ-ray reported for Zn^{65} does not fit with the shell scheme. If it really exists it would constitute a serious difficulty.
6. The transition goes to the meta state of Ge^{73}. The spin of the ground state

is measured to be 9/2.

7. The transition goes to the meta state of Se^{77}, the ground state of which is reported to have a spin 7/2±1(J. E. Mack, Rev. Mod. Phys. 22, 64(1950).)
8. The ground state of Se^{75} is likely to be g 9/2 since it exhibits a very complex γ-spectrum.
9. This is the transition to the meta state of Y^{91}, which goes over an excited state with series γ-ray.
10. This transition could also go from the ground state of Zr^{89} to a meta state of Y^{89} in which case the interpretation would be g9/2-g9/2. The ft value is high for an allowed transition, but no other assignments seem possible.
11. The experimental evidence on Zr^{95} and the Nb isotopes is not clear enough to prove the given assignments.
12. The interpretation of this transition is not unique owing to lack of sufficient evidence.
13. The ft value is rather low for this type of transition. An alternative would be to ascribe to the 43 protons of Tc^{95} a g7/2 configuration, which would make the transition an ℓ-forbidden one.
14. g7/2 for 59 neutrons gives the only possibility for an allowed transition for the Rh^{105} decay.
15. Experimental evidence on decay data conflicting.
16. The lifetimes of the isomeric states of Ag^{107} and Ag^{109} make it likely that their configuration is G7/2 in place of g9/2.
17. An alternative for the f7/2 configuration of the 83 neutrons is h9/2.
18. The expected configuration for 73 neutrons is s1/2. In this case a series γ-ray has to be assumed.
19. In place of d5/2 also g7/2 is possible, while there may be an h9/2 configuration instead of f7/2.
20. In place of f7/2 also p3/2 is possible.

21. f5/2 is possible in place of f7/2.

22. The interpretation of this transition is highly ambiguous, and several alternatives are possible.

23. The ground state of Ta^{181} is g7/2.

24. In place of p3/2 also f5/2 is possible.

25. To explain the high forbiddenness of this transition a spin of at least 9/2 has to be assumed for Os^{187}. The assumption of the table makes it third order ℓ-forbidden. Another possibility is i13/2, which would make it fourth forbidden.

26. p3/2 in place of f5/2 would not exclude the direct transition to the ground state.

27. There is no possibility for an allowed transition for these nucleon numbers. The low ft value for these first forbidden transitions may be due to the importance of the Z-dependent factors in the matrix elements, which reduce the ratio of the transition probabilities of allowed to forbidden transitions at high Z values; compare Konopinski, Rev. Mod. Phys. 15, 209 (1943).

Bibliography

A 1 L. W. Alvarez, Phys. Rev. 75, 1127 (1949).

A 2 H. M. Agnew, Phys. Rev. 77, 655 (1950).

B 1 E. Bleuler and W. Zunti, Helv. Phys. Acta 20, 195 (1947).

B 2 R. Bouchez and G. Kayas, J. Phys. et le Rad. (Ser. 8) 10, 110 (1949).

B 3 P. R. Bell, B. H. Ketelle and J. M. Cassidy, Phys. Rev. 76, 574 (1949).

C 1 W. S. Cowart, M. L. Pool, D. A. McCown, and L. L. Woodward, Phys. Rev. 73, 1454 (1948).

D 1 M. Deutsch and A. Hedgran, Phys. Rev. 75, 1443 (1949).

D 2 R. B. Duffield and J. D. Knight, Phys. Rev. 76, 573, (1949).

D 3 R. B. Duffield and L. M. Langer, Phys. Rev. 81, 203 (1951).

D 4 R. B. Duffield and J. D. Knight, Phys. Rev. 75, 1613 (1949).

D 5 R. B. Duffield and J. D. Knight, Phys. Rev. 75, 1967 (1949).

D 6 R. B. Duffield and L. M. Langer, Phys. Rev. 76, 1272, (1949).

D 7 D. G. Douglas, Phys. Rev. 75, 1960 (1949).

F 1 R. W. Fink, F. L. Reynolds, and D. H. Templeton, Phys. Rev. 77, 614 (1950).

F 2 L. Feldman, L. Lidofsky, P. Macklin, and C. S. Wu, Phys. Rev. 76, 1888 (1949).

H 1 E. L. Hudspeth, C. W. Swann, and N. P. Heydenberg, Phys. Rev. 77, 736 (1950).

H 2 C. T. Hibdon, M. L. Pool, and J. D. Kurbatov, Phys. Rev. 67, 289 (1945).

K 1 N. L. Krisberg and M. L. Pool, Phys. Rev. 75, 1693 (1949).

K 2 J. Koch, O. Kofoed-Hansen, P. Kristensen, and W. Drost-Hansen, Phys. Rev. 76, 279 (1949).

K 3 D. N. Kundu and M. L. Pool, Phys. Rev. 74, 1775 (1948).

K 4 B. H. Ketelle and J. W. Ruch, Phys. Rev. 77, 565 (1950).

Bibliography (cont.)

L 1 L. M. Langer and H. C. Price, Phys. Rev. 76, 641 (1949).

M 1 A. C. G. Mitchell, Rev. Mod. Phys. 22, 36 (1950).

M 2 P. Macklin, L. Feldman, L. Lidofsky, and C. S. Wu, Phys. Rev. 77, 137 (1950).

M 3 F. Maienscheim and J. L. Meem, Phys. Rev. 76, 899 (1949).

M 4 D. A. McCown, L. L. Woodward and M. L. Pool, Phys. Rev. 74, 1311 (1948).

M 5 C. E. Mandeville, Y. H. Woo, M. V. Scherb, W. B. Keighton, and E. Shapiro, Phys. Rev. 75, 1528 (1949).

M 6 C. E. Mandeville and M. V. Scherb, Phys. Rev. 73, 848 (1948).

M 7 H. Medicus, P. Preiswerk, P. S. Scherrer, Helv. Phys. Acta, 23, 299 (1950).

M 8 E. A. Martell and W. F. Libby, Phys. Rev. 80, 977 (1950).

M 9 C. E. Mandeville and M. V. Scherb, Phys. Rev. 76, 186 (1949).

N 1 Natl. Bur. Stand. Cir. 499: Nuclear Data 1950.

N 2 M. E. Nelson and M. L. Pool, Phys. 77, 682 (1950).

P 1 T. J. Parmley, B. J. Moyer and R. C. Lilly, Phys. Rev. 75, 619 (1949).

S 1 G. T. Seaborg and I. Perlman, Rev. Mod. Phys. 20, 585 (1948).

S 2 L. Seidlitz, E. Bleuler, and D. J. Tendam, Phys. Rev. 76, 861 (1949).

S 3 A. Stechney, Private communication.

S 4 N. Sugarman, Phys. Rev. 75, 1473 (1949).

W 1 L. L. Woodward, D. A. McCown and M. L. Pool, Phys. Rev. 74, 870 (1948).

W 2 G. Wilkinson and H. G. Hicks, Phys. Rev. 75, 1687 (1949).

NUCLEAR SHELL STRUCTURE AND β-DECAY

II. EVEN A NUCLEI

L. W. Nordheim
Duke University
Durham, North Carolina
(At present on leave at the
Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

ABSTRACT

A systematics of the β transitions of even A nuclei is given. An interpretation of the character of the transitions in terms of nuclear shell structure is achieved on the hypothesis that the odd nucleon groups have the same structure as in odd A nuclei, together with a simple coupling rule between the neutron and proton groups in odd-odd nuclei.

A. The coupling of odd proton and neutron groups.

In the preceding paper(1) the β-decay properties of nuclei with odd mass number were discussed on the basis of our present knowledge of nuclear shell structure. In the present paper the discussion is extended to cover nuclei with even A. The general background, arguments, and references are the same as in I and need not be repeated here.

The situation is somewhat more complex than for odd A nuclei. A β transition for an even A nucleus demands at one end point an even-even nucleus, which, in so far as we know, has zero spin. The other end point, mostly the initial nucleus, is of odd-odd type, in which there will be a coupling of neutron and proton groups, each of which will contribute to the resultant spin. Unfortunately only a very few spings of odd-odd nuclei have been measured so far, among these are several very high ones (Be^{10}, Na^{22}, K^{40}, Lu^{176}). The frequent occurrence of highly complex β spectra with series γ-rays is also an indication that the spins of odd-odd nuclei are often quite large.

Of course, not much can be said a priori about the coupling between the proton and neutron groups. The persistence of the islands of isomerism (I, ref. 1), leads to the suspicion that their configurations are largely independent of each other, and that their structure must in the main be preserved. More definite information can be obtained from the study of those β transitions which connect the ground states of the initial and final nucleon.

The resultant pattern, which will be discussed in greater detail later, resembles closely the pattern of the odd A nuclei. Of particular interest are the groups of allowed transitions with neutron and proton

---

(1) M. G. Mayer, S. Moszkowski, and L. W. Nordheim, part I of this paper, pg. 1-29, and Rev. Mod. Phys., 24,000, 1952, quoted henceforth as I.

numbers below 50 and of the first forbidden transitions with $\Delta I = 2$, which can be recognized by a value of $\log (W_0^2 - 1)$ ft of about 10 and by the shape of their spectra, if observed. These transitions can be interpreted in an entirely unforced manner by assuming that the respective odd proton and neutron groups have the same Schmidt orbitals as occur for the same nucleon numbers in odd A nuclei and that the spins of the neutron and proton groups are antiparallel, that is, couple to a minimum resultant. An inspection of the orbitals involved reveals further that they belong in these cases always to opposite Schmidt groups. Conversely, in light nuclei for which the expected orbitals for the neutron and proton groups are identical, the indications are always for a high resultant spin. We are thus led to the following hypotheses (2):

(1) The individual configurations of neutrons and protons in odd-odd nuclei are the same as in odd A nuclei with the same number of nucleons in the odd particle group.

(2) If the odd neutron and proton groups belong to different Schmidt groups, then their resultant spins will subtract.

(3) If the odd neutron and proton groups belong to the same Schmidt group, their spins will couple to a larger than minimum resultant.

In terms of the notation for orbitals (2) and (3) can be expressed as follows: If the spins of the odd particle groups are $j_1 = \ell_1 \pm 1/2$ and $j_2 = \ell 2 \mp 1/2$ then the resultant spin is $I = |j_1 - j_2|$. If $j_1 = \ell 1 \pm 1/2$, $j_2 = \ell 2 \pm 1/2$ then $I > |j_1 - j_2|$.

The magnitude of the resultant spins in case (3) will be discussed later. In many, but not all cases, they seem to be near the possible maximum $j_1 + j_2$.

---

(2) L. W. Nordheim, Phys. Rev. 78, 294 (1950)

The subsequent discussion is based on the above rules. They restrict greatly the choice of possible assignments, and the fact that it is possible to carry through the scheme on this basis gives strong support for its validity.

B. Discussion

The complete material on even A nuclei is collected in Table V, Section C. Here we discuss as in I the transitions which go to the ground state ordered according to type. They are given in Table IV. It is to be noted that the nucleon numbers refer to the odd-odd nucleons involved in these transitions, and that the assignments refer to the neutron and proton configurations in this same nucleus. The even-even nuclei are assumed throughout to have spin zero and even parity.

TABLE IV

CLASSIFICATION OF β-DECAYS TO GROUND STATE OF EVEN A NUCLEI ACCORDING TO CHANGES IN SPIN (Δ I) AND PARITY (NO, YES)

Column 1: Initial isotope Z-Element-A.

2: Sign of emitted charge, and maximum energy in Mev.

3: Initial and final nucleon number in this order.

4: Assignment of orbitals to the proton and neutron groups in the odd-odd nucleus.

5: log ft

6: log $(W_o^2 - 1)$ ft for $\Delta I = 2$, yes. W_o energy of β transition in units mc^2.

7: Observed spin of odd-odd nucleus.

TABLE IV (cont.)

a) $\Delta I = 1$. No (Allowed)

1	2	3	4	5	6
5 B 12	-13.4	5-7	p3/2-p1/2	4.2	
7 N 12	+16.6	7-5	p1/2-p3/2	4.1	
15 P 30	+ 3.5	15-15	s1/2-s1/2	5.0	
15 P 34	- 5.1	15-19	d5/2-d3/2	4.7	
31 Ga 70	- 1.65	31-39	p3/2-p1/2	5.0	
35 Br 78	+ 2.3	35-43	p3/2-p1/2	4.4 +	
35 Br 80	+ 0.7	35-45	p3/2-p1/2	4.3 +	
	2.0			5.4 +	
44 Ru 106	- 0.039	45-61	g9/2-g7/2	4.3	
45 Rh 104	- 2.6	45-59	g9/2-g7/2	4.7 +	
45 Rh 106	- 3.55	45-61	g9/2-g7/2	5.2	
46 Pd 112	- 0.2	47-65	g9/2-g7/2	4.0	
47 Ag 106	+ 2.04	47-59	g9/2-g7/2	4.7 +	
47 Ag 108	- 2.8	47-61	g9/2-g7/2	5.3	
47 Ag 110	- 2.86	47-63	g9/2-g7/2	4.7 +	
49 In 110	+ 1.6	49-61	g9/2-g7/2	4.7 +	
49 In 114	- 1.98	49-65	g9/2-g7/2	4.4	
49 In 116	- 2.8	49-67	g9/2-g7/2	4.4	
49 In 118	- 1.5	49-69	g9/2-g7/2	4.7 +	
53 I 128	- 2.02	53-75	d5/2-d3/2	5.7	
57 La 136	+ 2.1	57-79	d5/2-d3/2	4.8	
59 Pr 140	+ 2.4	59-81	d5/2-d3/2	4.2+	

TABLE IV (cont.)

b) Δ I = 0, Yes (First Forbidden)

1	2	3	4	5	6
7 N 16	-10.3	7-9	pl/2-sl/2	6.9	
36 Kr 88	- 2.4	37-51	f5/2-d5/2	6.8	
37 Rb 88	- 4.6	37-51	f5/2-d5/2	7.0	
54 Xe 138	- 2.68	55-83	g7/2-f7/2	6.5	
58 Ce 144	- 0.30	59-85	g7/2-f7/2	7.2	
59 Pr 142	- 2.22	59-83	g7/2-f7/2	7.8	
81 RaE" 206	- 1.70	81-125	sl/2-pl/2	5.5	

c) Δ I = 2, Yes (First Forbidden)

17 Cl 38	- 4.81	17-21	d3/2-f7/2	7.4	9.6
19 K 42	- 3.58	19-23	d3/2-f7/2	8.0	9.8
33 As 76	- 3.04	33-43	f5/2-g9/2	8.3	10.0
37 Rb 86	- 1.82	37-49	f5/2-g9/2	8.3	9.5
38 Sr 90	- 0.53	39-51	pl/2-d5/2	9.2	9.7
39 Y 90	- 2.18	39-51	pl/2-d5/2	8.0	9.5
39 Y 92	- 3.5	39-53	pl/2-d5/2	7.9+	9.7
41 Nb 94m	- 1.3	41-53	Pl/2-d5/2	7.4	8.5
45 Rh 102	+ 1.13	45-57	pl/2-d5/2	7.7+	8.6
	- 1.04			8.7+	9.6
59 Pr 142	- 2.22	59-83	g7/2-f7/2	7.8	8.1
69 Tm 170	- 0.97	69-101	sl/2-f5/2	8.9	9.8
81 Tl 204	- 0.78	81-123	sl/2-p3/2	9.6	10.4
83 RaE 210	- 1.17	83-127	h9/2-d5/2	8.0	9.0

TABLE IV (cont.)

d) Δ I = 1; No, $\Delta \ell = 2$ (ℓ- Forbidden)

1	2	3	4	5	6
6 C 14	- 0.156	7-7	p1/2-p1/2	9.0	
15 P 32	- 1.71	15-17	s1/2-d3/2	7.9	
29 Cu 60	+ 3.3	29-31	p3/2-f5/2	7.1+	
29 Cu 64	- 0.66	29-35	p3/2-f5/2	5.0	
	+ 0.57			5.4	
31 Ga 68	+ 1.9	31-37	p3/2-f5/2	5.1	
51 Sb 122	- 1.94	51-71	d5/2-g7/2	7.9+	
53 I 126	- 1.27	53-73	d5/2-g7/2	7.6	
e) Δ I = 2; No, or Δ I > 2 (Second and Higher Forbidden)					
4 Be 10	- 0.56	5-5	p3/2-p3/2	13.7	3
11 Na 22	+ 1.86	11-11	D3/2-D3/2	14.0	3
17 Cl 36	- 0.71	17-19	d3/2-d3/2	13.5	2
19 K 40	- 1.36	19-21	d3/2-f7/2	17.6	4

The composition rules introduced in Section A exclude the occurrence of allowed transitions with spin change 0 and of first forbidden transitions with spin change 1.

A very numberous group in the allowed class is formed by nuclei with Z = 45 to 49 and N from 59 to 69. There is no analogue to this group among the odd A nuclei. The only possibility to account for the absence of parity change in the shell scheme is with the help of the g9/2 orbitals for Z < 50. This demands the assignment of the orbital g7/2 to the neutrons, which is not observed in this range in odd A nuclei. However the situation is here somewhat different. In odd A nuclei there is a definite discrimination against high spins for odd neutron numbers above 50. The assignment g9/2-g7/2 proposed for the group under discussion gives a total spin of only 1, so that a mechanism working against high spins may not be operative here, and a small coupling energy between the neutron and proton groups may produce a change in the preference of orbitals.

The presence of a first forbidden group with $\Delta I = 2$, of course, does not in itself prove rule (2) since a resultant spin 1 in place of 0 would not show up in the ft values. The latter fall within the same limits as given in I for odd A nuclei. Feen berg and Trigg(3) have remarked that for even A ft values for allowed transitions are somewhat lower and for first forbidden transitions with $\Delta I = 2$ somewhat higher than for odd A nuclei, and such a tendency is indeed reflected in the figures given here. The ft values for first forbidden transitions with $\Delta I = 2$ are, however, strictly comparable in the two cases.

The conclusion of I of the smallness of the matrix elements for second forbidden transitions is borne out by the high log ft values for Be^{10}, Na^{22}, and Cl^{36}, which lie all in the neighborhood of 14.

A special discussion is required for the cases where the orbital assignments lead to a change of the Schmidt angular momentum by 2 units, that is, no change in parity, while the spin change is 1. According to the formal selection rules such transitions should be allowed. In case the orbital angular momentum were a good quantum number, these transitions would be second forbidden. Among the cases for odd A nuclei (I, Table 2) O^{19}, Si^{31}, and Ge^{69} show log ft values, respectively, of 5.5, 5.9, 6.0, which are somewhat high for allowed transitions but fall just within the limits of the group. Zn^{65} with log ft = 7.4 falls definitely out of line, while no first forbidden interpretation is compatible with the shell model.

---

(3) E. Feenberg and G. Trigg, Rev. Mod. Phys. 22, 399 (1950)

Pd^{109} with 6.2 is again a borderline case. The evidence from this transition is, however, not conclusive since it goes to the metastate of Ag^{107}, whose spin and parity are subject to doubt.

For even A there is the puzzling case of C^{14}, where the spin change is measured to be 1 while log ft = 9. The next case is P^{32} with 7.9. No first forbidden interpretation (i.e., change in parity) is possible for this nucleus, while a spin change of 2 with no parity change would lead to the expectation of a much higher ft value. An experimental determination of the spin of P^{32} would thus be particularly interesting. Cu^{60}, Sb^{122}, and I^{126} have ft values compatible with first forbidden transitions but with neutron and proton configuration in the same shell, which should exclude a change in parity. Cu^{64} and Ga^{68} have ft values which classify their decays as allowed. However, it cannot be ruled out that their configuration is $p_{3/2}$-$p_{3/2}$ under violation of rule (3).

The data on these nuclei, in which the transition occurs within the same shell, suggest strongly that they form a distinct group which is neither allowed nor second forbidden. An appropriate name for this class may be "L-forbidden." The log ft values of these nuclei fluctuate widely from seemingly allowed values in the neighborhood of 5 to 9 for C^{14}. It seems thus that a remnant of our selection rule is operative and that it is very much a matter of chance, how far it is violated. We are thus inclined to consider the long life time of C^{14} as an accident.

The nuclei with series γ-rays find in most cases an unforced interpretation by rule (3). An outstanding group of this type is that with Z between 21 and 27 which have the interpretation $f_{7/2}$-$f_{7/2}$ or $f_{7/2}$-$p_{3/2}$ and which go without exception to excited states. It is unfortunately not possible to obtain reliable information about the actual spins of nuclei which fall under rule (3). In B^{10}, N^{14}, Na^{22} the spins of the neutron and proton groups are known to be parallel. For Cl^{36} a spin of 2 has been reported(4). The evidence seems, however, not to be absolutely forcing, and the shape of the β-spectrum(5)(6) is in doubt.

For many other nuclei the decay schemes indicate high values of the spin in view of the presence of more than one γ-ray in series. Examples are Na^{24}, Sc^{48}, Ti^{48}, Mn^{52}, Co^{60}, Br^{82}, I^{130}, Cs^{134}. We believe, therefore, that in general the spins in this group are quite high and may result from a parallel coupling of neutron and proton spins, though this is probably not true in all cases.

There are some exceptions or difficulties to the scheme, which require special mention.

Li^6 has the observed spin 1, while a parallel coupling would lead to spin 3 as in B^{10}. This is not a direct contradiction to rule (3), but it seems that so low a spin in such a case is rather an exception.

Al^{26}: The decay of this nucleus belongs to Wigner's family of super-allowed transitions* with even A which is characterized by an odd-odd nucleus which could be composed by α-particles plus a deuteron. There is evidence (7) that the mass difference to Mg^{26} is higher than corresponding to the energy of the observed β-ray, so that there should be a series γ-ray. Otherwise it would have to be assumed that the two $d_{5/2}$ configurations couple to an abnormally low total spin of 1 or 0.

---

(4) C. H. Townes and L. G. Aamodt, Phys. Rev. 76, 691 (1949).

(5) C. S. Wu and L. Feldman, Phys. Rev. 76, 693 (1949).

(6) H. W. Fulbright and J. C. D. Milton, Phys. Rev. 82, 274 (1949).

* The other members of this group are He^6, F^{18}, which go to the ground state, and C^{10} and O^{14}, which go to excited states of the daughter nuclei.

(7) K. Way, private communication.

K^{40}: This nucleus constitutes the one definite exception to rule (2). The assignment of orbitals $d_{3/2}$ - $f_{7/2}$ in this case is particularly free from ambiguity, and the magnetic moment fits well with it. Rule (2) would lead to a spin 2, while 4 is observed.

Cu^{64} and Ga^{68} have already been mentioned as possible exceptions to rule (3). There are further a number of problems arising from an incomplete knowledge of the facts. These cases are pointed out in the notes of table 5, section C.

Summing up, one may say that the rules (1) to (3) seem to hold for the great majority of cases, but not without exception. This is not surprising in view of the great complexity of the situation. Nevertheless, they provide apparently an excellent key to the understanding of the β-transitions of even A nuclei.

C. TABLES FOR β-DECAY SYSTEMATICS: EVEN A (Table 5)

Legend to Table:

Column 1: Column 2: Column 3: Column 4: Column 5:	See items 1 thru 5 for table III, page 19.
Column 6:	Proton and neutron numbers in this order for the odd-odd nucleus involved in the transition.
Column 7:	Assignment of orbitals to the odd proton and the odd neutron in the odd-odd nucleus.
Column 8:	Predicted spin for the odd-odd nucleus. h means that the spin is higher than the difference between proton and neutron spins. Underlining signifies that the spin has been measured.
Column 9:	Log ft value calculated with the f function for allowed transitions. The values are given in brackets if the transition goes to an excited state. A plus sign is

added if branching of unknown percentage is known to occur.

Column 10: Reference to bibliography. No authors are quoted if all references are given in the compilations by Seaborg(S1), Mitchell(M1) or Nat. Bur. Stand.(N1).

Column 11: Reference to footnotes for table.

TABLE V

Beta-Decay Data and Orbital Assignments for Even-A Nuclei

Class 1	Z-Element-A 2	Sign Energy 3	Halflife 4	Final State 5	Numbers 6	Configuration 7	Spin 8	log ft 9	Ref. 10	Footnotes 11
Aa γ	2-He -6	- 3.22	0.82s	g	3-3	p3/2-p3/2	$\underline{1}$	2.8	P 1	
Aa α	3-Li -8	-(13)	0.89s	e<100	3-5	p3/2-p3/2	h	(5.6+)	H 1	1
Aa α	4-Be -10	- 0.56	2.7×10^{6} y	g	5-5	p3/2-p3/2	$\underline{3}$	13.7	H 2	
Aa α	5-B -12	-13.4	0.027s	g	5-7	p3/2-p1/2	1	4.2	H 1	
Ab α	6-C -10	+(2.2)	19.1s	e	5-5	p3/2-p3/2	$\underline{3}$	3.3	S 1	2
Aa β	6-C -14	- 0.156	5720y	g	7-7	p1/2-p1/2	$\underline{1}$	9.0	E 1	3
Bb α	7-N -12	+16.6	0.0125s	g	7-5	p1/2-p3/2	1	4.1	A 1	
Aa α	7-N -16	-10.3	7.35s	g18	7-9	p1/2-s1/2	0	6.9	B 1	
Ba β	8-O -14	+(1.8)	76s	e	7-7	p1/2-p1/2	$\underline{1}$	(3.5)	S 1	2
Ab α	9-F -18	+ 0.63	112m	g<100	9-9	s1/2-s1/2	1	3.6+	B 2	4
Ab β	9-F -20	-(5.01)	12s	e	9-11	s1/2-D3/2	1	(4.9)	S 1	5
Ab β	11-Na -22	+ 1.86	30y	g 0.005	11-11	D3/2-D3/2	$\underline{3}$	14.0	M 2	5
Aa β	11-Na -24	-(1.39)	14.9h	e	11-13	d5/2-d5/2	h	(6.1)	M 1	6
Ac γ	13-Al -26	-(2.99)	6.3s	e	13-13	d5/2-d5/2	h	(3.3)	S 1	7
Aa β	13-Al -28	-(3.01)	2.3m	e	13-15	d5/2-s1/2	h	(5.0)	M 1	
Ab α	15-P -30	+ 3.5	2.55m	g	15-15	s1/2-s1/2	1	5.0	S 1	8
Aa β	15-P -32	- 1.71	14.1d	g	15-17	s1/2-d3/2	1	7.9	S 1	8
Bb β	15-P -34	- 5.1	12.4s	g75	15-19	d5/2-d3/2	1	4.7	S 1	8
Ac α	17-Cl -34	+(5.1)	33m	e80	17-17	d3/2-d3/2	h	(7.0)	H 3	9
Aa α	17-Cl -36	- 0.71	4.4×10^{5} y	g	17-19	d3/2-d3/2	$\underline{2}$?	13.5	W 1	10
Aa α	17-Cl -38	- 4.81	38m	g53	17-21	d3/2-f7/2	2	7.4	L 1	

TABLE V (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 Spin	9 log ft	10 Ref.	11 Footnotes
Ab α	19-K-38	+(2.53)	7.5m	e	19-19	d3/2-d3/2	h	(4.8)	S 1	
Aa γ	19-K-40	- 1.36	4×10^{8} y	g	19-21	d3/2-f7/2	4	17.6	A2, B3	11
Aa α	19-K-42	- 3.58	12.4h	g75	19-23	d3/2-f7/2	2	8.0	M 1	
Ac β	21-Sc-44	+(1.33)	3.92h	e<33	21-23	f7/2-f7/2	h	(5.5)	H 4	
Aa β	21-Sc-46	-(1.49)	85d	e2	21-25	f7/2-f7/2	h	(10.2)	M 1	12
Ab α	21-Sc-48	-(0.64)	44h	e	21-27	f7/2-f7/2	h	(5.4)	M 1	
Ab β	23-V-48	+(0.72)	16d	e58	23-25	f7/2-f7/2	h	(6.2)	M 1	12
Ab β	23-V-52	-(2.05)	3.9m	e<100	23-29	f7/2-p3/2	h	(4.4)	M 1	
Aa β	25-Mn-52	+(0.58)	6.5d	e50	25-27	f7/2-f7/2	h	(5.1)	M 1	12
Aa β	25-Mn-56	-(2.81)	2.5h	e50	25-31	f7/2-p3/2	h	(7.1)	M 1	12
Ac β	26-Fe-52	+(0.55)	7.8h	e<100	25-27	f7/2-f7/2	h	(3.7+)	S 1	13
Ab α	27-Co-56	+(1.48)	80d	e<100	27-29	f7/2-p3/2	h	(8.1+)	M 1	
Ab α	27-Co-58	+(0.47)	72d	e15	27-31	f7/2-p3/2	h	(6.6)	M 1	
Aa α	27-Co-60	-(0.31)	5.3y	e	27-33	f7/2-p3/2	h	(7.5)	M 1	
Bb β	27-Co-62	-(2.3)	13.9m	e	27-35	f7/2-p3/2	h	(5.4)	P 2	
Ab α	29-Cu-60	+ 3.3	24.6m	g5	29-31	p3/2-f5/2	1	7.1	S 1	14
Ac β	29-Cu-62	+(2.83)	10.1m	e	29-33	p3/2-p3/2	h	(5.1)	B 5	
Aa γ	29-Cu-64	- 0.66	13h	g18	29-35	p3/2-f5/2	1	5.0	B 6	15
		+ 0.57		g35				5.4		
Ab β	29-Cu-66	-(2.58)	5m	e	29-37	p3/2-f5/2	1	(5.2)	N 1	
Ab β	30-Zn-62	+(0.665)	9.2h	e10	29-33	p3/2-p3/2	h	(5.1)	H 5	
Ac β	30-Zn-72	-(1.6)	49h	e5	31-41	p3/2-g9/2	h	(8.5)	S 1	16
Ab β	31-Ga-66	+(4.14)	9.4h	e29	31-35	p3/2-p3/2	h	(8.0)	M 3	
Ab γ	31-Ga-68	+ 1.9	68m	g<100	31-37	p3/2-f5/2	1	5.1+	S 1	17
Ab α	31-Ga-70	- 1.65	20m	g	31-39	p3/2-p1/2	1	5.0	S 1	
Aa α	31-Ga-72	-(3.17)	14.3d	e8	31-41	p3/2-g9/2	h	(9.0)	M 1	

TABLE V (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 Spin	9 log ft	10 Ref.	11 Footnotes
Bb β	33-As -72	+(2.78)	26h	e33	33-39	f5/2-p1/2	h	(7.3)	M 4	18
Aa α	33-As -76	- 3.04	26.8h	g60	33-43	f5/2-g9/2	2	8.3	M 1	19
Ac β	35-Br -78	+ 2.3	6.4m	g<100	35-43	p3/2-p1/2	1	4.4+	S 1	20
Ab α	35-Br -80	+ 0.7	18m	g<3	35-45	p3/2-p1/2	1	4.3+	N 1	
		- 2.0		g97				5.4	N 1	
Ab β	35-Br -82	-(0.447)	36h	e<100	35-47	p3/2-g9/2	h	(5.1)	M 1	
Ab α	36-Kr -88	- 2.4	2.8h	g	37-51	f5/2-d5/2	0	6.8	K 1	
Aa α	37-Rb -86	- 1.82	19.5d	g80	37-49	f5/2-g9/2	2	8.3	M 1	
Ab α	37-Rb -88	- 4.6	17.5m	g	37-51	f5/2-d5/2	0	7.0	S 1	
Aa α	38-Sr -90	- 0.53	25y	g	39-51	p1/2-d5/2	2	9.2	J 1	
Aa β	39-Y -88	+(0.83)	105d	e 0.2	39-49	p1/2-g9/2	4	(9.6)	M 1	
Aa α	39-Y -90	- 2.18	65h	g	39-51	p1/2-d5/2	2	8.0	L 2	
Ac α	39-Y -92	- 3.5	3.5h	g<100	39-53	p1/2-d5/2	2	7.9+	S 1	21
Ab β	41-Nb -92	-(1.38)	10.1d	e	41-51	g9/2-d5/2	h	(7.7)	S 1	22
Ab β	41-Nb^m -94	- 1.3	6.6m	g 0.1	41-53	p1/2-d5/2	2	7.4	S 1	
Bb β	41-Nb -96	-(0.67)	23.3h	e	41-55	g9/2-d5/2	h	(5.6)	K 2	23
Ab α	44-Ru -106	- 0.039	1.0y	g	45-61	g9/2-g7/2	1	4.3	A 3	
Ab α	45-Rh -102	+ 1.13	210d	g<100	45-57	p1/2-d5/2	2	7.7+	S 1	
		- 1.04		g<100				8.7+	S 1	
Ab β	45-Rh -104	- 2.6	44s	g<100	45-59	g9/2-g7/2	1	4.7+	N 1	24
Aa α	45-Rh -106	- 3.55	30s	g82	45-61	g9/2-g7/2	1	5.2	M 1	
Aa α	46-Pd -112	- 0.2	21h	g	47-65	g9/2-g7/2	1	4.0	S 1	25
Aa α	47-Ag -106	+ 2.04	24.5m	g<100	47-59	g9/2-g7/2	1	4.7+	S 1	
Ab α	47-Ag -108	- 2.8	2.3m	g	47-61	g7/2-g7/2	1	5.3	S 1	
Aa α	47-Ag -110	- 2.86	24s	g<100	47-63	g9/2-g7/2	1	4.7+	S 2	
Aa β	47-Ag^m -110	-(0.53)	225d	e	47-63	p1/2-g7/2	h	(7.6)	S 2	

TABLE V (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 Spin	9 log ft	10 Ref.	11 Footnotes
Ab α	49-In -110	+1.6	65m	g<100	49-61	g9/2-g7/2	1	4.7+	S1	
Aa α	49-In -114	- 1.98	72s	g96	49-65	g9/2-g7/2	1	4.4	M 5	
Aa α	49-In 116	- 2.8	13s	g	49-67	g9/2-g7/2	1	4.4	S 1	
Ab β	49-In^m -116	-(0.85)	54m	e	49-67	p1/2-g7/2	h	(4.7+)	S 1	
Bb β	49-In -118	- 1.5	4.5m	g<100	49-69	g9/2-g7/2	1	4.7 +	D 1	26
Ab β	51-Sb -122	- 1.94	2.6d	g<100	51-71	d5/2-g7/2	1	7.9 +	M 1	27
Aa β	51-Sb -124	-(2.37)	60d	e21	51-73	g7/2-s1/2	3	(10.3)	M 1	28
Bb β	52-Te -132	-(0.36)	77h	e	53-79	g7/2-d3/2	h	(5.4)	S 1	29
Aa β	53-I -124	+(2.20)	4d	e<50	53-71	d5/2-s1/2	h	(7.6+)	M 1	30
Aa β	53-I -126	- 1.27	13d	g27	53-73	d5/2-g7/2	1	7.6	M 1	31
Aa α	53-I -128	- 2.02	25m	g93	53-75	d5/2-d3/2	1	5.7	M 1	
Aa β	53-I -130	-(1.03)	12.6h	e60	53-77	g7/2-d3/2	h	(6.4)	M 1	
Bb β	54-Xe -138	- 2.68	30m	g	55-83	g7/2-f7/2	0	6.5	T 1	
Aa β	55-Cs -134	-(0.66)	2.3y	e75	55-79	g7/2-d3/2	h	(8.9)	M 1	
Ab β	55-Cs -136	-(0.28)	13d	e	55-81	g7/2-d3/2	h	(5.8)	S 1	
Ac γ	56-Ba -140	- 1.02	12.8d	g 60?	57-83	d5/2-f7/2	h	7.9	M 1	32
Ab α	57-La -136	+ 2.1	9.5m	g33	57-79	d5/2-d3/2	1	4.8	N 2	
Aa β	57-La -140	-(2.26)	40h	e10	57-83	d5/2-f7/2	h	(9.1)	M 1	32
Aa β	58-Ce -144	- 0.30	275d	g	59-85	g7/2-g7/2	0	7.2	S 1	
Ab γ	59-Pr -140	+ 2.4	3.5m	g<100	59-81	d5/2-d3/2	1	4.2 +	S 1	
Ab γ	59-Pr -142	- 2.22	19.3h	g98	59-83	g7/2-f7/2	0	7.8	M 6	33
Aa γ	65-Tb -160	-(0.86)	71d	e42	65-95	d5/2-f7/2	h	(8.6)	B 7	34
Ab γ	69-Tm -170	- 0.97	127d	g90	69-101	s1/2-f5/2	2	8.9	M 1	
Ab β	71-Lu -176	-(0.4)	2.4x10^{10} y	e33	71-105	g7/2-h9/2	≥7	(18.9)	S 1	35
Ab γ	73-Ta -182	-(0.53)	113d	e	73-109	g7/2-p3/2	2	(8.0)	B 4	36
Ab γ	75-Re -186	-(1.07)	90h	e	75-111	d3/2-p1/2	h	(7.5)	M 1	

TABLE V (cont.)

1 Class	2 Z-Element-A	3 Sign Energy	4 Halflife	5 Final State	6 Numbers	7 Configuration	8 Spin	9 log ft	10 Ref.	11 Footnotes
Ab γ	79-Au -192	+(1.9)	4.0h	e1	79-113	d3/2-p1/2	2	(7.4)	W 2	36
Bb γ	79-Au -194	+(1.8)	39.5h	e3	79-115	d3/2-p1/2	2	(7.9)	W 2	36
Aa γ	79-Au -196	-(0.30)	5.6d	e5	79-117	d3/2-p1/2	2	(7.3)	S 3	36
Aa γ	79-Au -198	-(0.97)	2.8d	e	79-119	d3/2-p1/2	2	(7.3)	M 1	
Aa β	81-Tl -204	- 0.78	3y	g	81-123	s1/2-p3/2	2	9.6	S 4	37
Aa β	81-RaE"-206	- 1.70	4.25m	g	81-125	s1/2-p1/2	0	5.5	F 1	38
Ab γ	81-ThC"-208	-(1.79)	3.1m	e33	81-127	s1/2-g9/2	h	(5.8)	F 1	
Ab γ	81-RaC"-210	-(1.88)	1.32m	e	81-129	s1/2-g9/2	h	(5.1)	F 1	
Ab γ	82-RaD -210	-(0.029)	22y	e	83-127	h9/2-d5/2	2	(6.1)	C 1	
Aa γ	83-RaE -210	- 1.17	5.0d	g	83-127	h9/2-d5/2	2	8.0	S 1	

Even A: Notes

1. The transition goes preferentially to an excited state of Be^{8} which decays directly into two He^{4} nuclei.

2. Superallowed into an excited state.

3. C^{14} represents an extreme ℓ-forbidden case. O^{14}, which goes into the same product nucleus N^{14} has a superallowed transition via an excited state.

4. Superallowed.

5. It cannot be decided, whether the configurations for 11 nucleons are D3/2 or d5/2.

6. This transition is certainly high forbidden since there are two γ-rays in cascade. It cannot be decided, whether in this case a D3/2 configuration for the 11 protons couples with the d3/2 neutrons to a high spin, or whether the protons also have a d5/2 configuration.

7. The empirical data for Al^{26} suggest a series γ-ray and thus a superallowed transition to an excited state.

8. The three P isotopes furnish an instructive example for the working of the shell scheme. All three must be assumed to have spin 1. P^{32} is ℓ-forbidden. The orbital for the 15 protons in P^{34} has to be assumed to be d5/2 to explain the allowed character of its decay. An alternative interpretation is s1/2-s1/2.

9. The shell scheme suggests strongly a series γ-ray for this transition, which is by no means excluded by the experimental evidence. The coupling rule in its narrower form demands, of course, only that the spin is 0.

10. Lifetime and shape of specturm both suggest a spin 3 for Cl^{36}, while the reported evidence for spin 2 does not seem to be forcing.

11. K^{40} constitutes the most notable exception to the spin rule, which would predict a spin of 2 in place of the observed 4. The alternative possible configuration s1/2-f7/2 would give a spin 4, but would make it difficult to explain the observed magnetic moment.

12. It cannot be decided whether the configurations of 25 nucleons are $F_{5/2}$ or $f_{7/2}$. They couple with $f_{7/2}$ and $p_{3/2}$ opposites always to a high resultant spin.

13. Insufficient experimental evidence.

14. Experimental evidence insufficient. However, f5/2 orbits for the odd neutrons seem to occur in other Ni isotopes.

15. Cu^{64} presents a definite difficulty for the shell scheme. The interpretation of the table (p3/2 - f5/2) makes its transition ℓ-forbidden with an abnormally low ft value. The natural p3/2-p3/2 combination should lead to a high resultant spin according to the composition rule.

16. This transition should be highly forbidden since this is also the case for the odd-odd product nucleus Ga^{72}.

17. This not too well investigated isotope poses a difficulty. The transition

either shows an abnormally low ft value for its ℓ-forbidden character or would involve the anomolous occurrence of a pl/2 orbit in place of f5/2. A series γ-ray would eliminate the problem.

18. A series γ-ray is reported for this transition, which is thus empirically high forbidden. The f5/2 orbit for the 33 protons is somewhat uncomfortable, but so would be the alternative p3/2-g9/2.
19. This assignment is strongly supported by the shape of the β-spectrum.
20. Evidence not sufficient to decide whether the γ-rays of this transition are in parallel or in series. The interpretation in the latter case would be p3/2-g9/2 with probable spin 3.
21. γ-ray probably not in series.
22. pl/2-d5/2 is an alternative, which would also be possible if the γ-ray should not be in series as assumed.
23. pl/2-d5/2 is another possible assignment.
24. This interpretation assumes the γ-rays to be in parallel. Several alternatives are possible if they are in series.
25. The g9/2-g7/2 configurations show particularly low ft values. In the case of Pd^{112} the energy is not too accurately known.
26. Insufficient evidence about the occurring γ-radiation.
27. The more natural d5/2-sl/2 combination would give a too highly forbidden transition. A possible alternative is g7/2-hll/2 with spin 2.
28. The assignment of the ground state of Sb^{124} is made on basis of spin 7/2 for Sb^{123} and spin 1/2 for Te^{123}. An attempt to interpret the complex situation presented by the two metastable states of Sb^{124} would seem to be premature.
29. The interpretation would be d5/2-d3/2 if the γ-ray is not in series.
30. In place of d5/2 also g7/2 is possible.
31. The g7/2 configuration for 73 neutrons is somewhat unusual but not too

strange since 73 protons in Ta^{181} show a spin 7/2.

32. In the chain Ba^{140} - La - Ce the odd-odd nucleus is the middle one. The transition of La is certainly highly forbidden, indicating a high spin. It is then very difficult to understand why Ba^{140} is much less strongly forbidden, unless its spin is different from zero. The other alternative is that the 1.02-Mev β-ray does not go to the ground state.

33. According to a recent private communication by E. Jensen Pr^{142} shows the form of the β spectrum typical for transition with change of parity and spin change 2. This poses a somewhat difficult problem. A possibility suggested by Jensen is d5/2-h9/2. However, this means a change of orbital momentum by 3, which one would expect to lead to considerably higher ft values.

34. Most interpretations from here on are very tentative, owing to the absence of spin data for high neutron numbers.

35. The combination given is the only one which gives a high enough spin. The ft value for this β-decay, although very large, is considerably less than expected for the transition to the Hf^{176} ground state involving a spin change of 7.

36. The γ-rays in these transitions are all assumed to be in series.

37. Alternatives are d3/2-p1/2 and s1/2-f5/2.

38. The low ft value for a first forbidden transition may be explained on the basis of the high Z value; compare Konopinski, Rev. Mod. Phys. <u>15</u>, 209 (1943).

Bibliography

A 1 L. W. Alvarez, Phys. Rev. 75, 1815 (1949)

A 2 D. E. Alburger, Phys. Rev. 75, 1442 (1949)

A 3 H. M. Agnew, Phys. Rev. 77, 655 (1950)

B 1 E. Bleuler, P. Scherrer, M. Walter, and W. Zunti, Helv. Phys. Acta 20, 96 (1947)

B 2 J. P. Blaser, F. Boehm, and P. Marmier, Phys. Rev. 75, 1953 (1949)

B 3 P. R. Bell, B. Weaver, and J. M. Cassidy, Phys. Rev. 77, 399 (1950)

B 4 L. A. Beach, C. L. Peacock, and R. G. Wilkinson, Phys. Rev. 76, 1585 (1949)

B 5 R. A. Becker, F. S. Kirn, and W. L. Buck, Phys. Rev. 76, 1406 (1949)

B 6 R. Bouchez and G. Kayas, J. phys. et Le rad. (Ser. 8) 10, 110 (1949)

B 7 S. B. Burson, K. W. Blair, and D. Saxon, Phys. Rev. 77, 403 (1950)

C 1 L. Cranberg, Phys. Rev. 77, 155 (1950)

D 1 R. B. Duffield and J. D. Knight, Phys. Rev. 75, 1967 (1949)

E 1 A. G. Engelkemeir, W. H. Hamill, M. G. Inghram, and W. F. Libby, Phys. Rev. 75, 1825 (1949)

F 1 N. Feather, Nucleonics 5 (No. 1), 22 (1949)

H 1 W. F. Hornyak and T. Lauritsen, Phys. Rev. 77, 160 (1950)

H 2 D. J. Hughes, C. Eggler, and D. E. Alburger, Phys. Rev. 77, 726 (1950)

H 3 Zah-Wei Ho, Phys. Rev. 70, 782 (1946)

H 4 C. T. Hibdon, M. L. Pool, and J. D. Kurbatov, Phys. Rev. 67, 289 (1945)

H 5 R. W. Hayward, Phys. Rev. 78, 87 (1950)

J 1 E. N. Jensen and L. J. Laslett, Phys. Rev. 75, 1949 (1949)

K 1 J. Koch, O. Kofoed-Hansen, P. Kristensen, and W. Drost-Hansen, Phys Rev. 76, 279 (1949)

K 2 D. N. Kundu and M. L. Pool, Phys. Rev. 75, 1690 (1949)

L 1 L. M. Langer, Phys. Rev. 77, 50 (1950)

Bibliography (contd.)

L 2 L. M. Langer and H. C. Price, Phys. Rev. 76, 641 (1949)

M 1 A. C. G. Mitchell, Rev. Mod. Phys. 22, 36 (1950)

M 2 K. H. Morganstern and K. P. W. Wolf, Phys. Rev. 76, 1261 (1949)

M 3 R. D. Moffat and L. M. Langer, Phys. Rev. 79, 237, (1950)

M 4 A. C. G. Mitchell, E. T. Jurney, and M. Ramsey, Phys. Rev. 71, 825 (1947)

M 5 J. T. Mei, A. C. G. Mitchell and D. J. Zaffarano, Phys. Rev. 76, 1883 (1949)

M 6 C. E. Mandeville, Phys. Rev. 75, 1017 (1949)

N 1 Natl. Bur. Stand. Circular 499, Nuclear Data, 1950

N 2 R. A. Naumann, F. L. Reynolds, and I. Perlman, Phys. Rev. 77, 398 (1950)

P 1 B. Perez-Mendez and H. Brown, Phys. Rev. 77, 404 (1950)

P 2 T. J. Parmley, B. J. Moyer, and R. C. Lilly, Phys. Rev. 75, 619 (1949)

S 1 G. T. Seaborg and I. Perlman, Rev. Mod. Phys. 20, 585 (1948)

S 2 K. Siegbahn, Phys. Rev. 77, 233 (1950)

S 3 R. M. Steffens, O. Huber, and F. Humbel, Helv. Phys. Acta 22, 167 (1949)

S 4 D. Saxon and J. Richards, Phys. Rev. 76, 982 (1949)

T 1 S. Thulin, I. Bergstrom, and A. Hedgran, Phys. Rev. 76, 871 (1949)

W 1 C. S. Wu and L. Feldman, Phys. Rev. 76, 693 (1949)

W 2 G. Wilkinson, Phys. Rev. 75, 1019 (1949)