Physics Opportunities of Gamma-ray Tracking Detector

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Outline

- Principle of gamma-ray tracking
- Status of GRETINA and other arrays
- Physics opportunities of gamma-ray tracking
- Nuclear data implication
- Summary

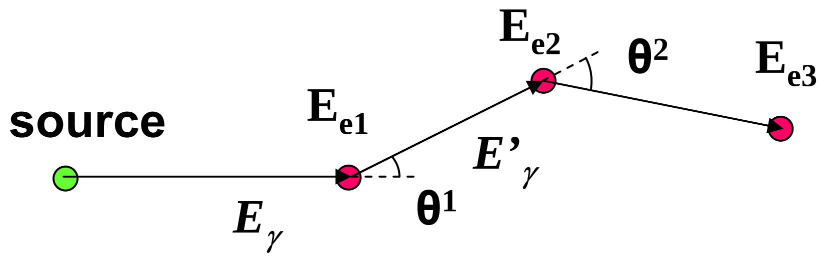
Compton Tracking Principle

source location and interaction points are known

1) Assume full energy is deposited

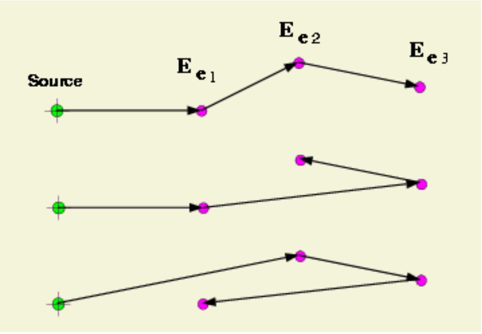
$$E_\gamma = E_{e1} + E_{e2} + E_{e3}$$

2) Start tracking from the source

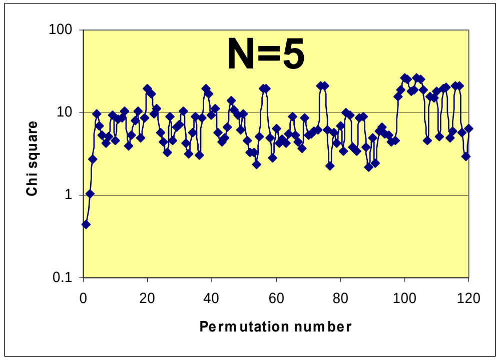


For N! possible permutations, check each interaction point for Compton scattering conditions

$$\cos\theta_C = 1 + \frac{0.511}{E_\gamma} - \frac{0.511}{E'_\gamma}$$



$$\chi^2 = \frac{1}{N-1}\sum_{i=1}^{N-1}\left(\frac{\theta^i - \theta^i_C}{\sigma^i_\theta}\right)^2$$



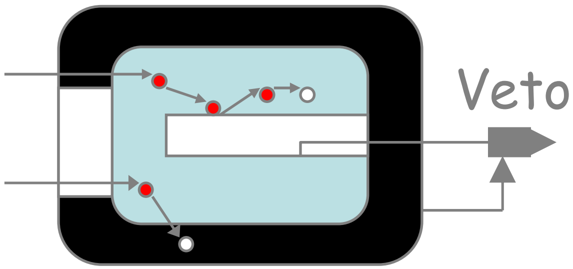
Select the sequence with the minimum $\chi^2 < \chi^2_{max}$

➔ **correct scattering sequence**

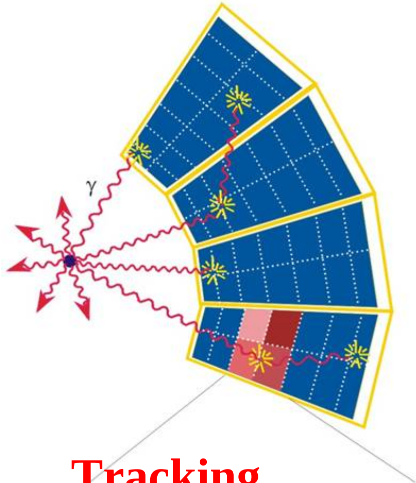
➔ **rejects partial energy event**

➔ **reject gamma rays with wrong direction**

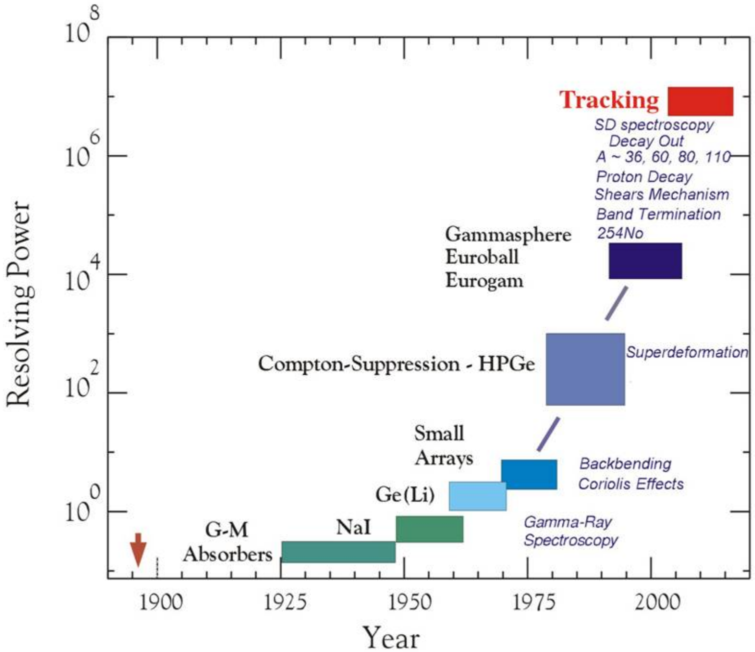
Advantages of γ-ray tracking



Compton suppression



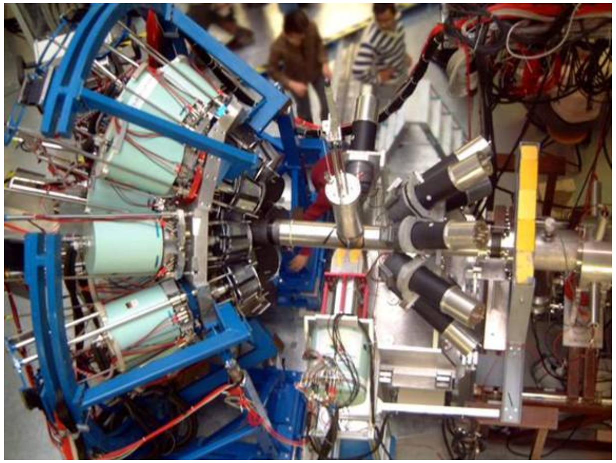
Tracking



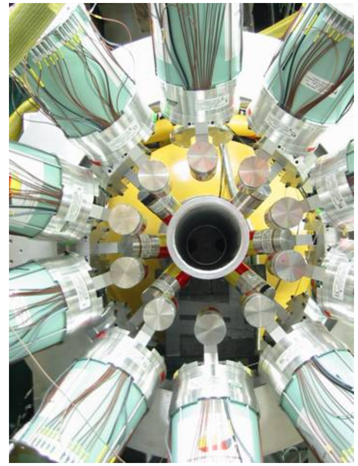
- **Efficiency –** proper summing of scattered gamma rays
- **Peak-to-background –** reject Compton events
- **Doppler correction -** Position of 1st interaction
- **Polarization –** angular distribution of the 1st scattering
- **Counting rate -** many segments

Examples of detector array

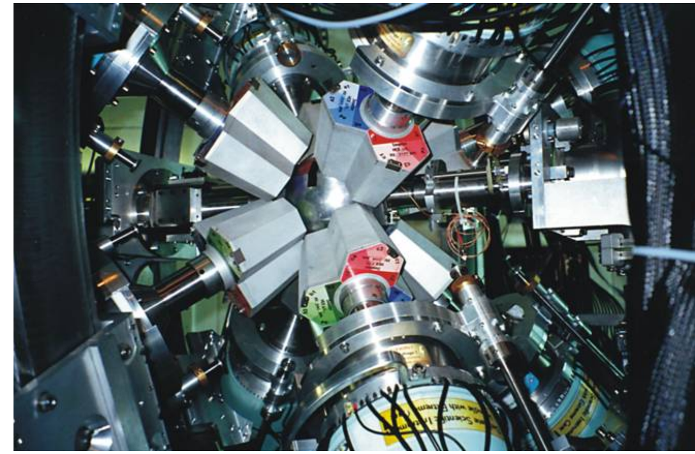
currently operational



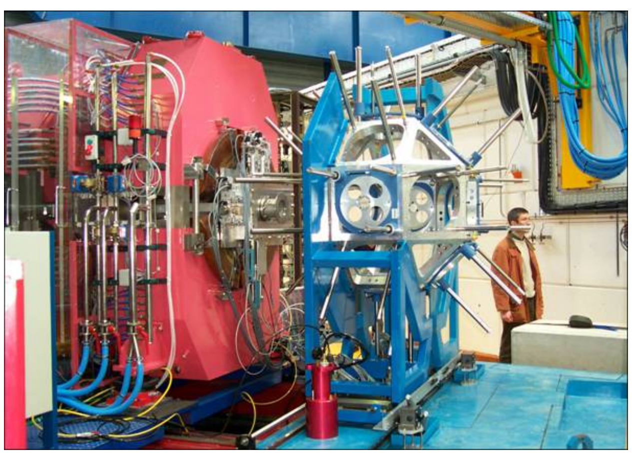
RISING



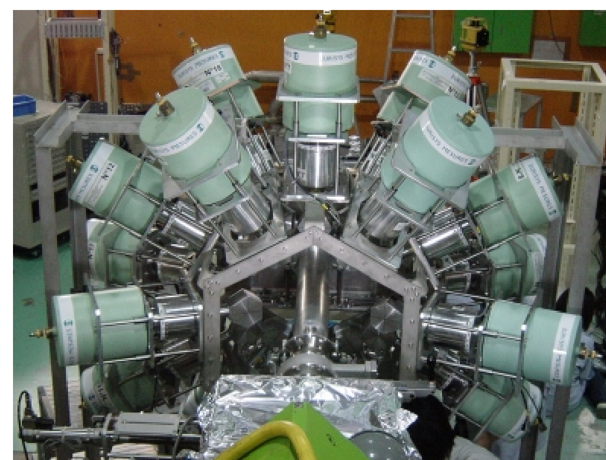
SeGA



MINIBALL

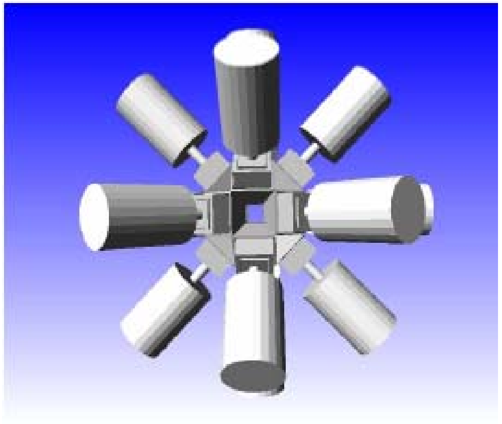


EXOGAM

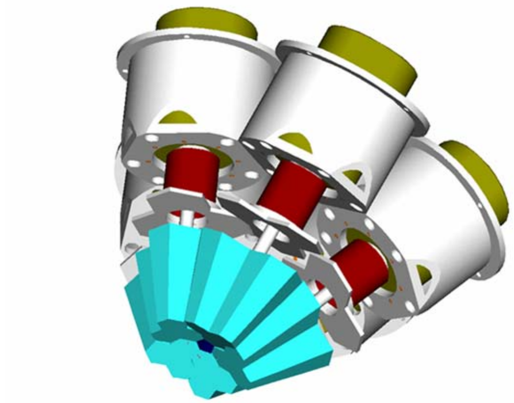


GRAPE

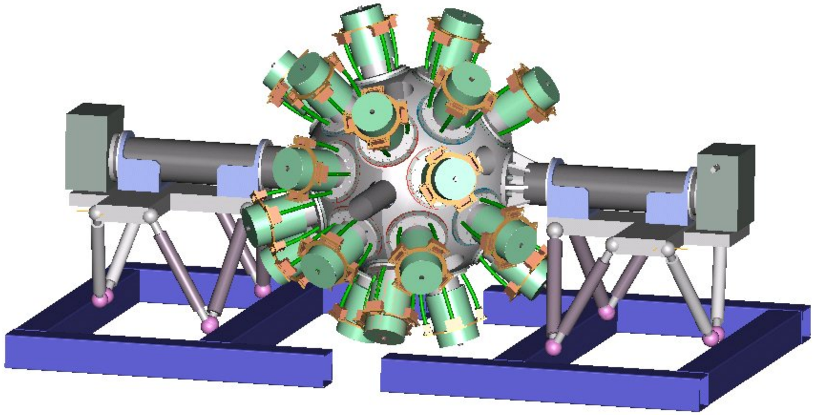
Examples of detector array
under construction



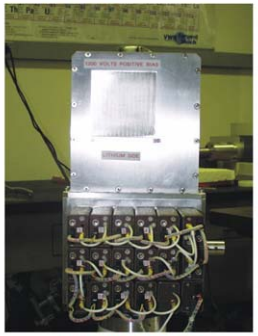
TIGRESS (2009)



AGATA Demo



GRETINA (2010)

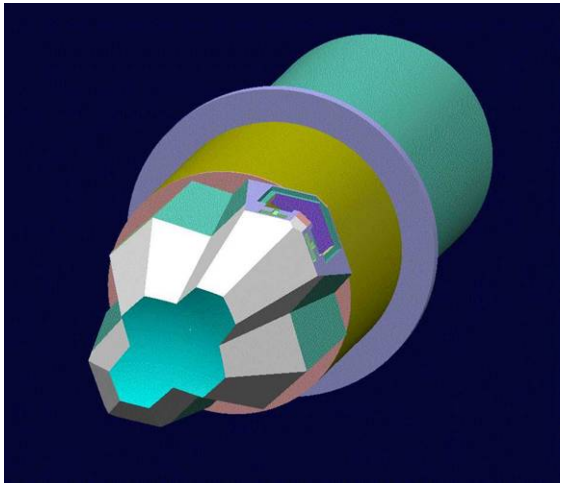


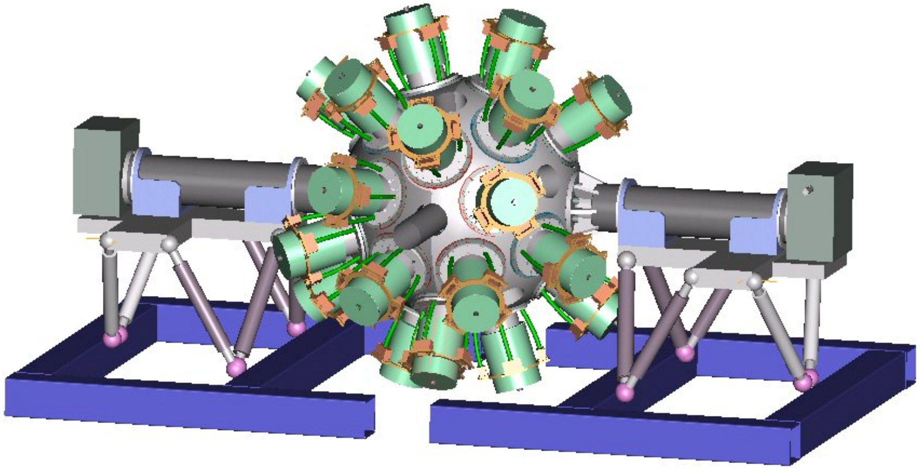
The ANL HpGeDSSD
Planar Detector

ANL

GRETINA Design

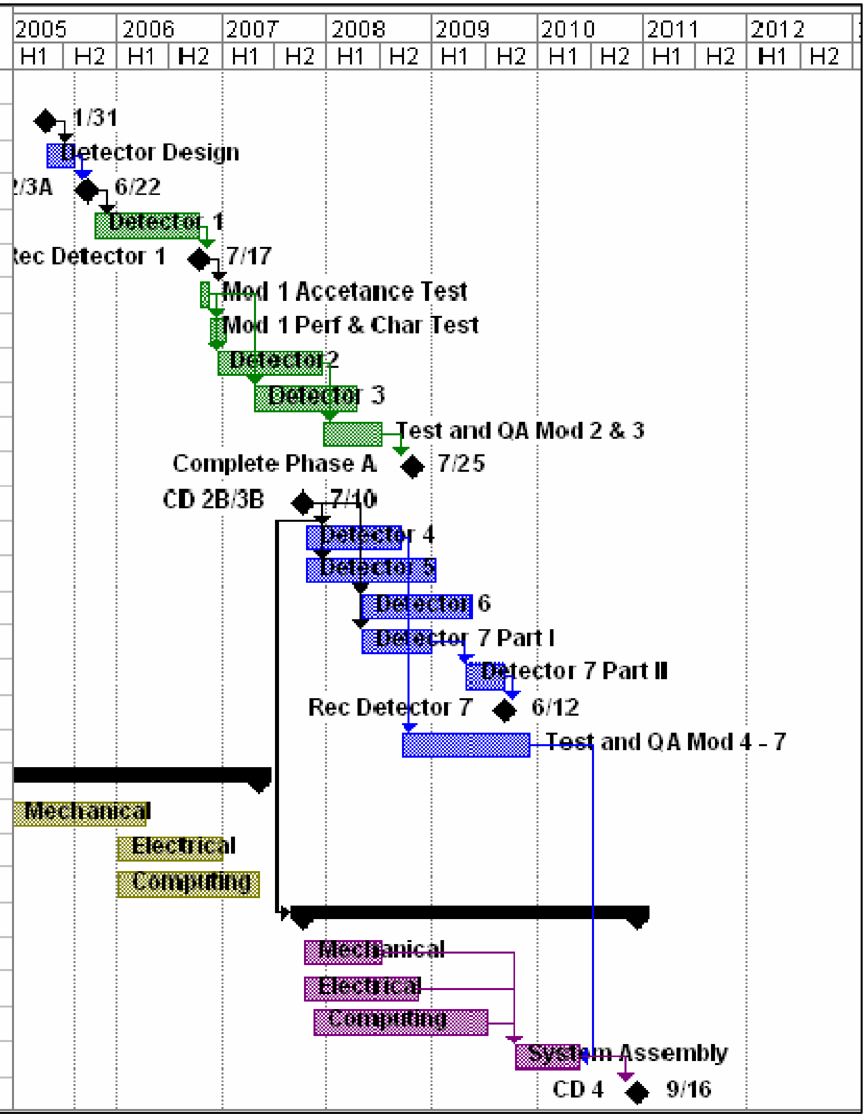
- 7 modules with 4 crystals each – cover $\approx 1\pi$ solid angle (cover 4π will take 30 modules).
- Modules can be placed at 31.7º (5 positions), 58.3º (4), and 90º (8).
- On-line processing gives gamma-ray energy and position.





GRETINA Schedule (fiscal year)

ID	Task Name	Start	Finish
1	Detector Deliviery Schedule	1/31/05	9/8/09
2	Start Detector Design	1/31/05	1/31/05
3	Detector Design	1/31/05	5/9/05
4	CD 2/3A	6/22/05	6/22/05
5	Detector 1	7/13/05	7/17/06
6	Rec Detector 1	7/17/06	7/17/06
7	Mod 1 Accetance Test	7/18/06	8/14/06
8	Mod 1 Perf & Char Test	8/15/06	10/18/06
9	Detector2	9/13/06	9/14/07
10	Detector 3	1/26/07	1/15/08
11	Test and QA Mod 2 & 3	9/17/07	4/2/08
12	Complete Phase A	7/25/08	7/25/08
13	CD 2B/3B	7/10/07	7/10/07
14	Detector 4	7/18/07	6/16/08
15	Detector 5	7/18/07	10/16/08
16	Detector 6	1/31/08	2/13/09
17	Detector 7 Part I	1/31/08	9/30/08
18	Detector 7 Part II	1/29/09	6/12/09
19	Rec Detector 7	6/12/09	6/12/09
20	Test and QA Mod 4 - 7	6/17/08	9/8/09
21	GRETINA Design/Prototype	10/1/04	2/7/07
22	Mechanical	10/1/04	1/9/06
23	Electrical	10/3/05	10/5/06
24	Computing	10/3/05	2/7/07
25	GRETINA Production	7/11/07	9/16/10
26	Mechanical	7/11/07	4/3/08
27	Electrical	7/11/07	8/13/08
28	Computing	8/13/07	4/7/09
29	System Assembly	7/14/09	2/23/10
30	CD 4	9/16/10	9/16/10

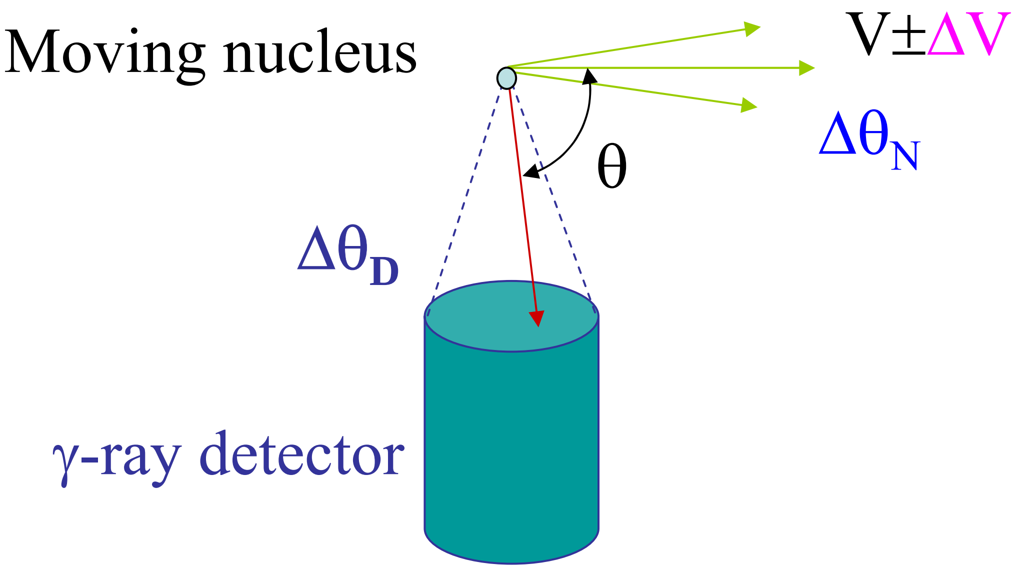


Physics opportunities with a 4π array

(e.g. GRETA)

- Resolving power: 10^7 vs. 10^4
  - Cross sections down to ~1 nb
    - Most exotic nuclei
    - Heavy elements (e.g. ^{253,254}No)
    - Drip-line physics
    - High level densities (e.g. chaos)
- Efficiency (high energy) (5% vs. 0.5% at E_γ=10 MeV)
  - Shape of GDR
  - Studies of hypernuclei
- Efficiency (slow beams) (43% vs. 8% at E_γ =1.3 MeV)
  - Fusion evaporation reactions
- Efficiency (fast beams) (43% vs. 0.5% at E_γ =1.3 MeV)
  - Fast-beam spectroscopy with low rates -> RIA
- Angular resolution (0.2° vs. 8°)
  - N-rich exotic beams
    - Coulomb excitation
  - Fragmentation-beam spectroscopy
    - Halos
    - Evolution of shell structure
    - Transfer reactions
- Count rate per crystal (100 kHz vs. 10 kHz)
  - More efficient use of available beam intensity
- Linear polarization
- Background rejection by direction

Doppler Broadening

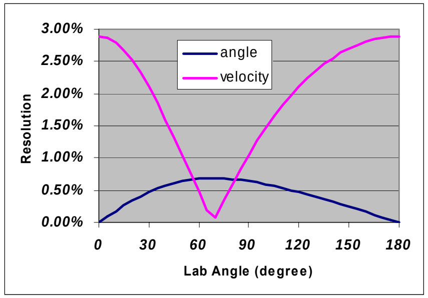


Doppler shift

$$E_\gamma = E_\gamma^0 \frac{\sqrt{1-\frac{V^2}{c^2}}}{1-\frac{V}{c}\cos\theta}$$

Broadening of detected gamma ray energy due to:

- Spread in speed ΔV
- Distribution in the direction of velocity $\Delta\theta_N$
- Detector opening angle $\Delta\theta_D$



➔ **Need accurate determination of V and θ.**

➔ Position sensitive γ-ray detector and particle detector

Challenges of radioactive beams

- Beams are **radioactive**
  - Stopped/scattered beam can give huge background
  - Good beam quality & careful tuning essential
  - ➔ Need high *peak-to-total* ratio
  - ➔ Need information on gamma ray *direction*
- Beams are generally **contaminated with isobars**
  - High background rate
  - ➔ Need good γ-ray *energy resolution*
  - ➔ Need high *counting rate* capability
- Beams are **weak** (or the *interesting part* is)
  - γ, $\gamma\gamma$ rates of interest generally $\leq$ 1 /s
  - Background rate from stopped beam may be $\geq \sim 10^4$ /s
  - ➔ Need best possible *efficiency*
  - ➔ Need *clean trigger* and *good timing* (to reduce random)
- Usually require light targets, **inverse kinematics**
  - Large recoil velocity, Doppler broadening
  - ➔ Need excellent *angular (position) resolution*

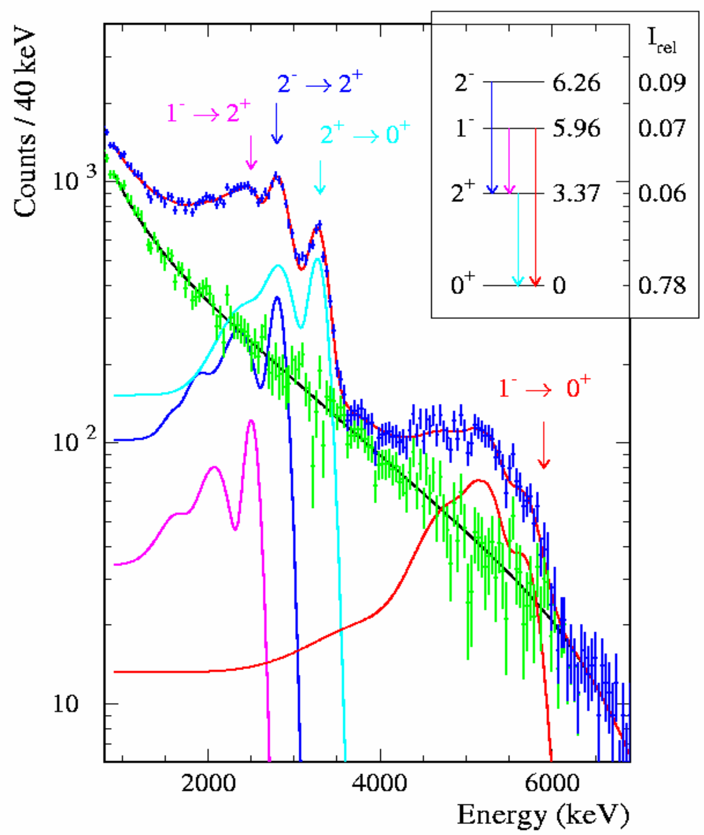
Discovery potential in many areas of nuclear structure physics

Goal: Gain a quantitative understanding of the atomic nucleus

- What are the properties of the heaviest nuclei?
- How deformed can a nucleus become and how fast can a nucleus rotate before it breaks up?
- Does the atomic nucleus display new symmetries?
- What are the properties of atomic nuclei with extreme neutron-proton ratios?
- How does the structure of nuclei change towards the limits of stability when binding becomes weak?
- What are the wave functions of spatially very extended halo nuclei?

Mapping wave functions of exotic nuclei

■ What are the spectroscopic factors in the wave function of exotic nuclei?



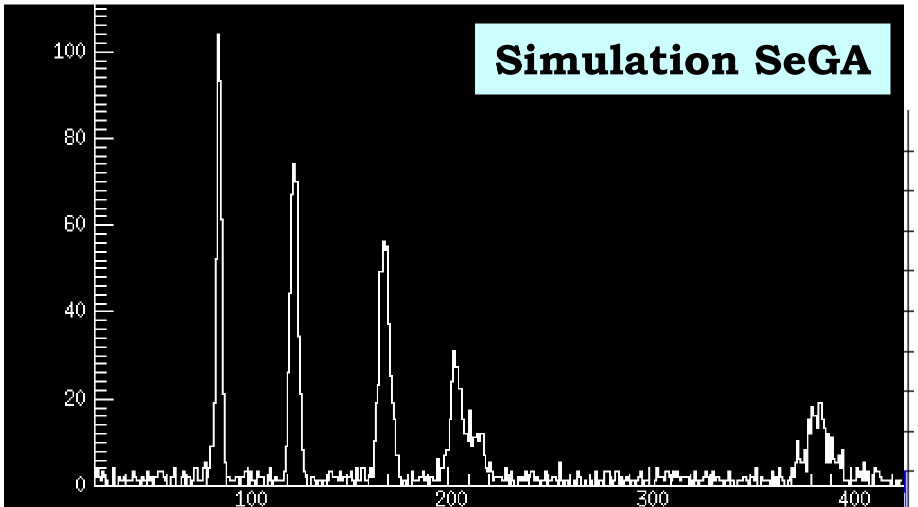
T. Aumann *et al.*, Phys. Rev. Lett. **84** (2000) 35.

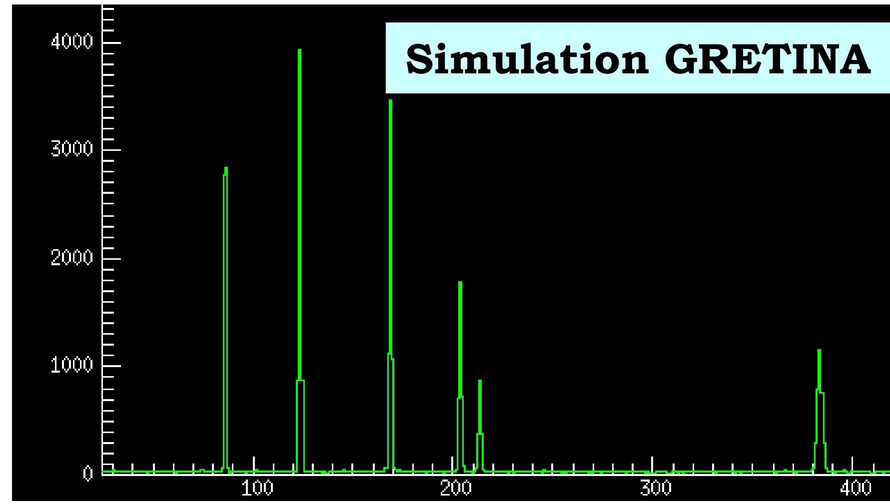
Experiment
- Intermediate-energy nucleon knockout
- Thick secondary targets require γ-ray detection to indicate inelastic scattering

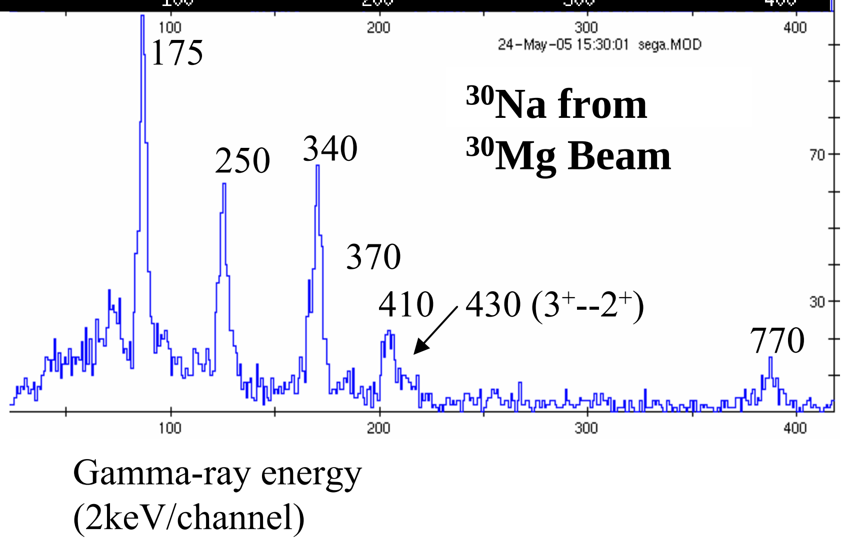
Challenges
- Need γ-ray emission angle for Doppler-shift reconstruction
- Low beam rate (0.1/s)

The gamma-ray tracking advantage
- Efficiency
- Angular resolution
- Extends reach of NSCL CCF and RIA two neutrons further from stability

n-rich nuclei from fragmentation reactions





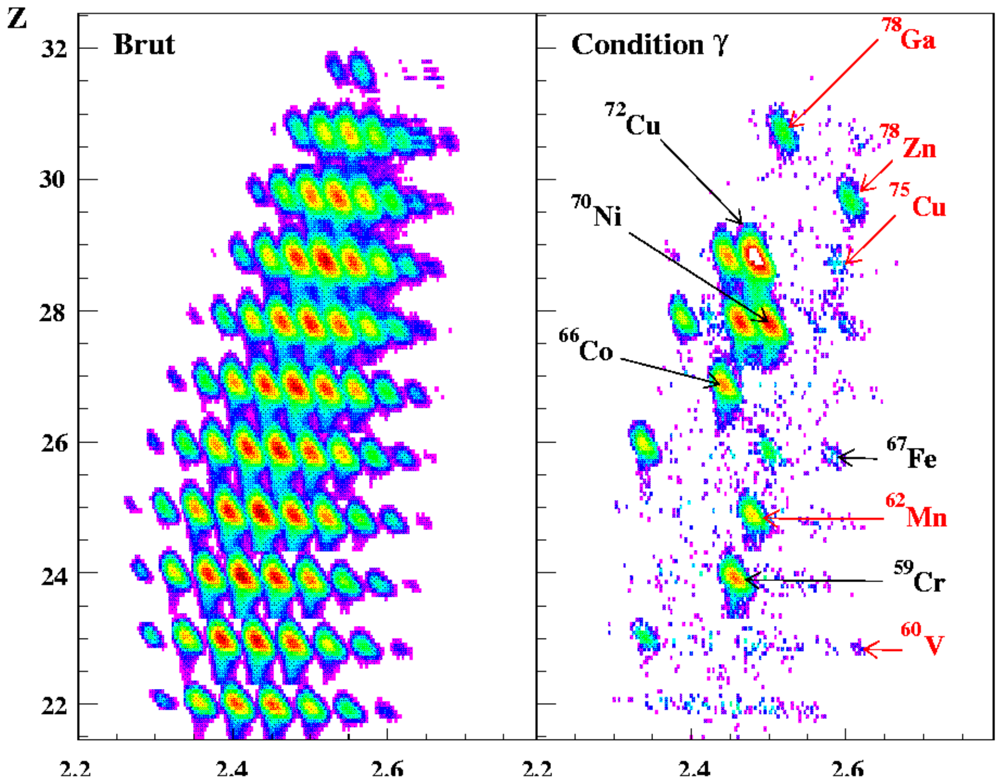


^{30}Mg (pn) → ^{30}Na (100 MeV/u)
v/c=0.43
charge exchange reaction
Gamma-gamma coincidence

NSCL data SeGA
(E. Rodriguez-Vieitez et al.)

Properties of the most exotic nuclei

■ What are the properties of the most exotic nuclei?



Experiment

- Beta-decay after implantation
- Bound excited states of daughter
- Clean beta trigger, beta detection >98% efficient

Major challenge

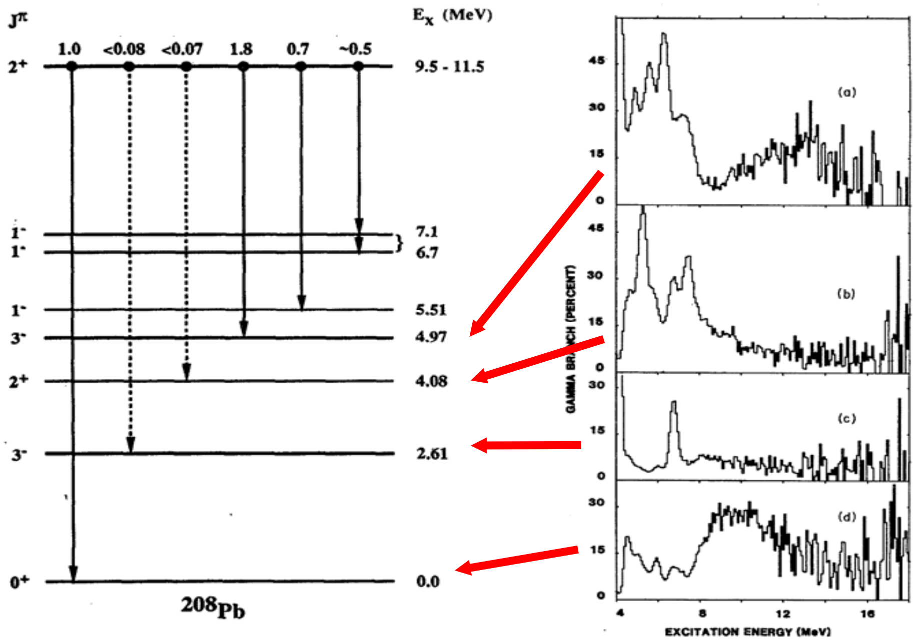
- Minute cross section: 1 atom/week (fb)

The gamma-ray tracking advantage

- Efficiency
- Background rejection by photon direction

Giant resonances built on excited states

■ What is the angular momentum dependence of the giant resonance width?



J.R. Beene et al., Phys. Rev. C ***39*** *(1989) 1307.*

Experiment

- Virtual photon scattering
- Tag on low-energy transitions
- Simultaneously detect high-energy γ-rays

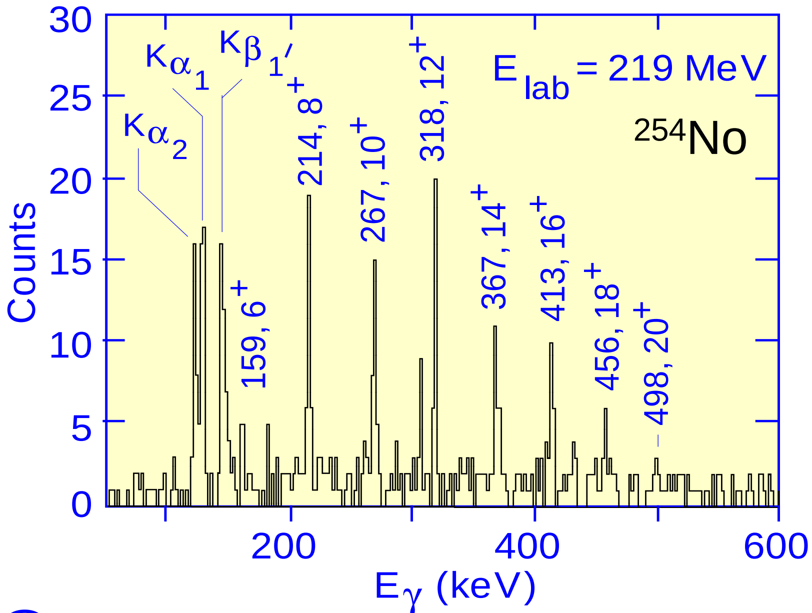
Challenges

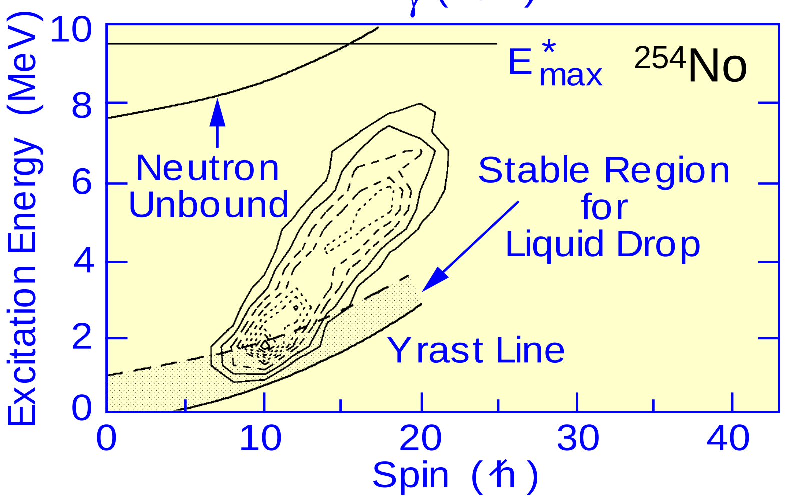
- Need γ-ray emission angle for Doppler-shift reconstruction

The gamma-ray tracking advantage

- Efficiency at low and high photon energies
- Angular resolution

Properties of super-heavy nuclei





P. Reiter *et al.*, Phys. Rev. Lett. **82** (1999) 509; **84** (2000) 3542.

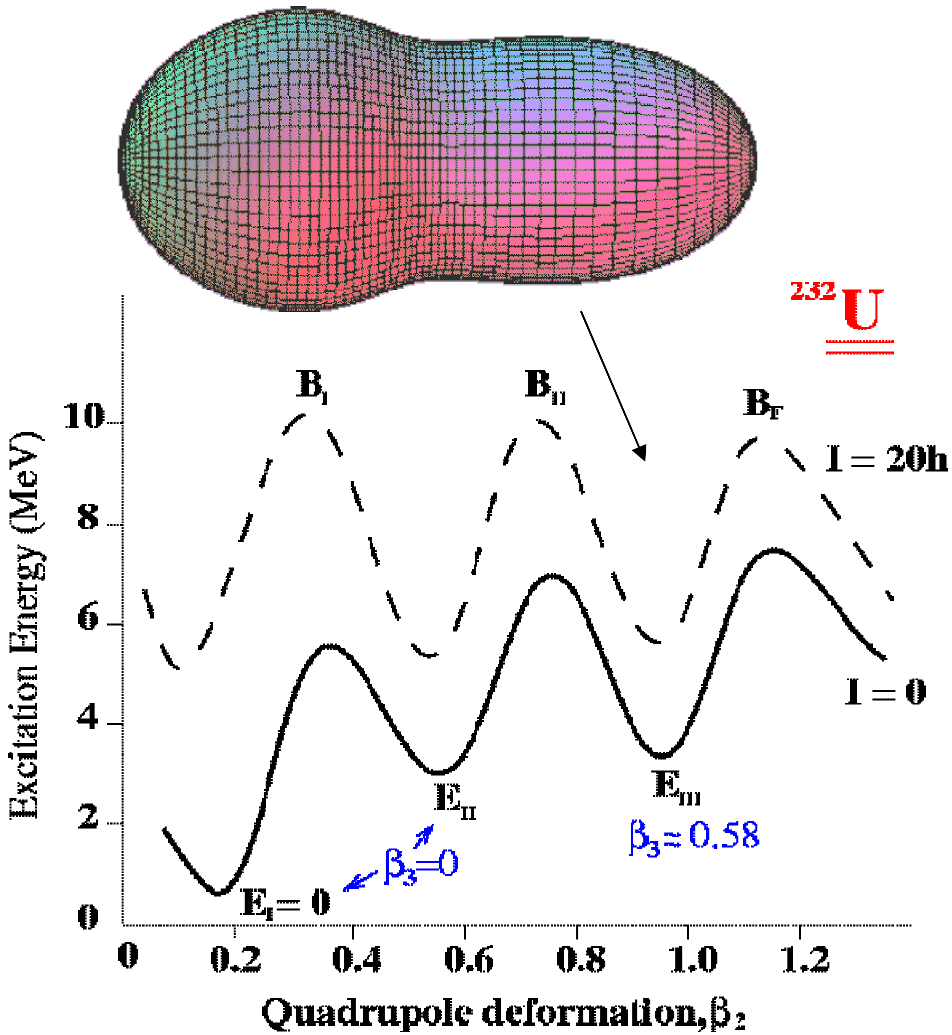
- What are the properties of super-heavy nuclei?
- Why does a super-heavy nucleus not explode from Coulomb repulsion?

Experiment
- Fusion-evaporation with recoil-decay tagging trigger

Challenges
- Small cross section (1 μb – 10 nb)
- Fission background

The gamma-ray tracking advantage
- Resolving power
- Efficiency
- Count rate capability
- Linear polarization

Nuclei with extremely deformed shapes



- How deformed can a nucleus become and what is its structure?

- Exotic shapes with 3:1 axis ratio
- Predicted to exist near fission limit: Very heavy nuclei
  or at high angular momentum

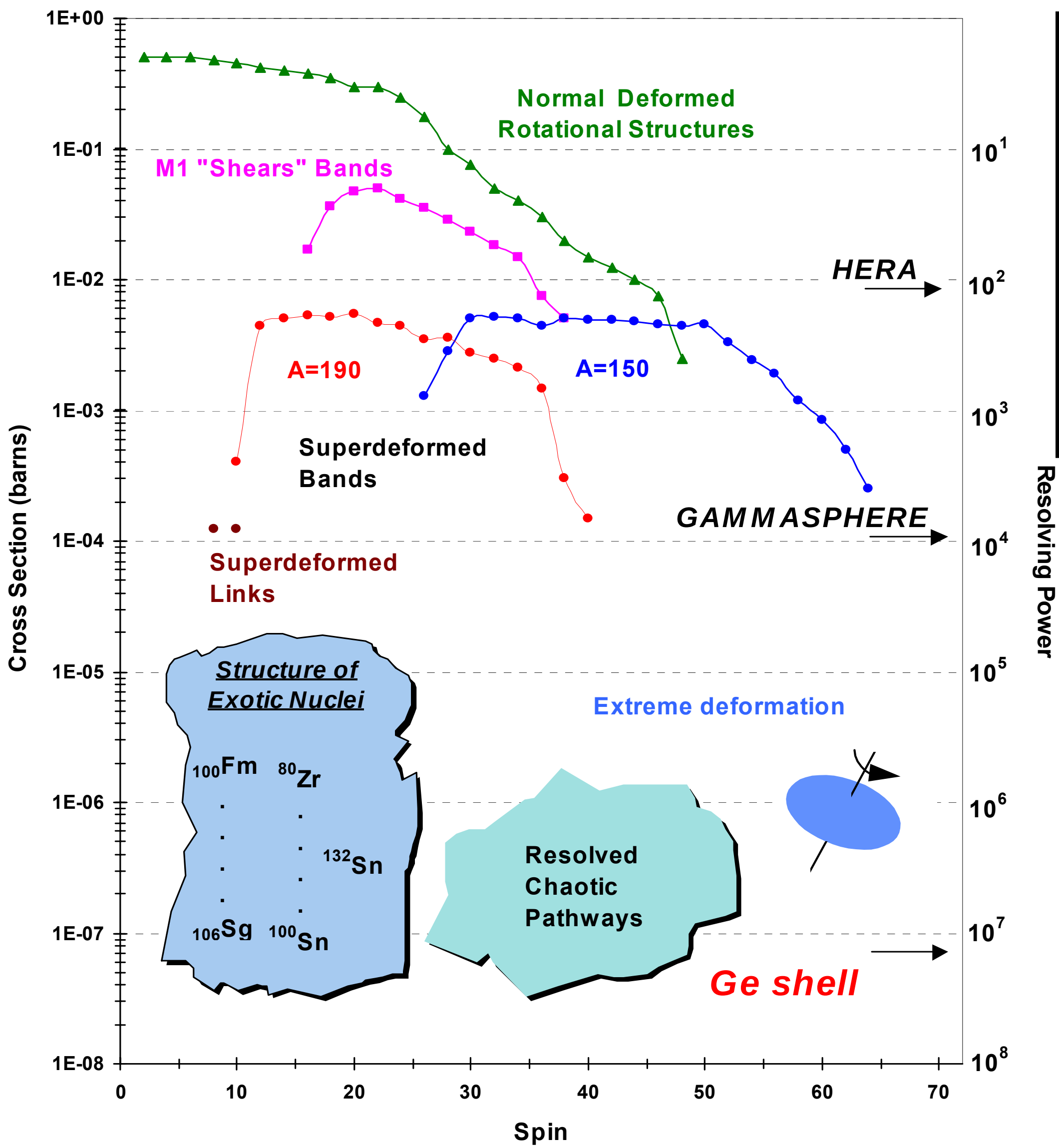
Challenges

- Small cross section
- Weak channel
- Fission background

The gamma-ray tracking advantage

- Resolving power
- Efficiency
- Count rate capability
- Linear polarization

Nuclei with large angular momentum



- How much angular momentum can a nucleus sustain?
- Are there new symmetry effects?
- What are the roles of pairing and the proximity to the continuum?

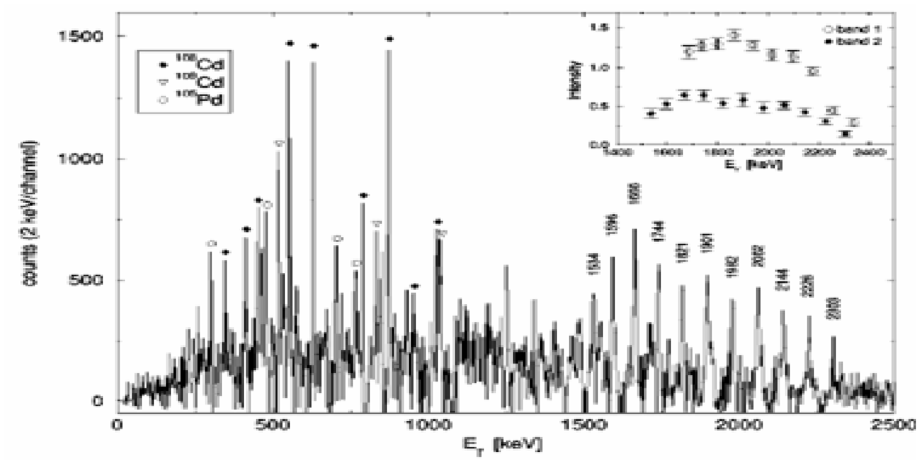
Experiment
- Fusion-evaporation

Challenges
- Small cross section
- Weak channel

The gamma-ray tracking advantage
- Resolving power
- Efficiency
- Count rate capability
- Linear polarization

High spin state from fusion reactions

^{64}Ni (^{48}Ca, 4n) ^{108}Cd, Gammasphere



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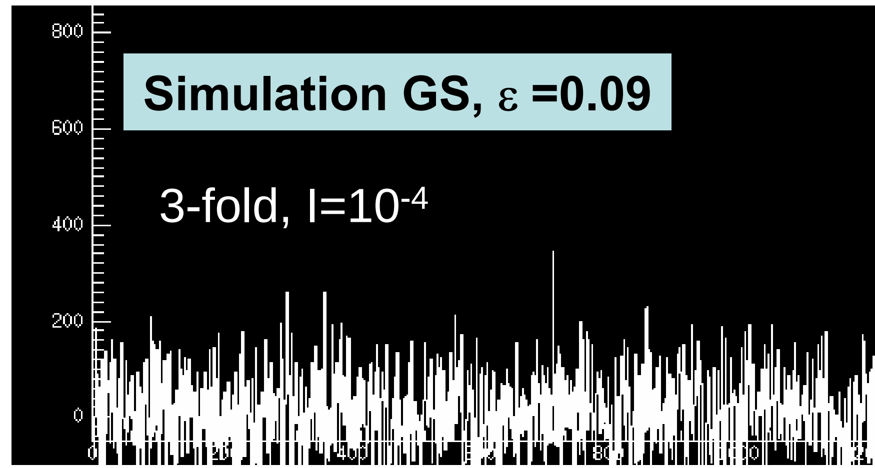

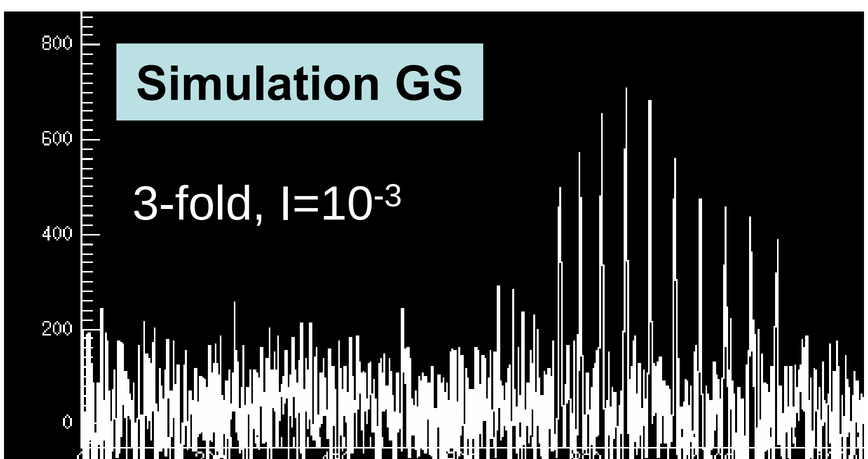

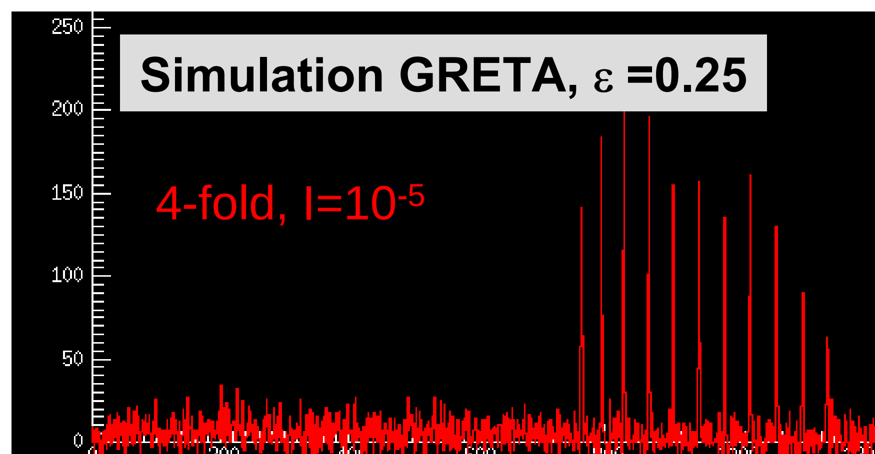

Nuclear data are used extensively

- Planning experiments
- Comparing new results with existing data
- Systematic studies of nuclear properties
- Communicating with colleagues

Nuclear data is an integral part of nuclear structure research programs

- Users of nuclear data and services
  - Data bases
    - ENSDF, Superdeformation, XUNDL, NDS, ToI, ToRI.
  - Tools
    - NSR, Isotope Explorer, NUDAT2.
  - Utility computer codes
    - Conversion coefficients, angular distributions.
- Suppliers of nuclear data
  - Publication
  - Unpublished data

Acknowledgement

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N. Aoi

and

GRETINA Advisory Committee

Summary

- Gamma ray tracking provides new capabilities in nuclear science and applications
- Considerable advances have been made in all technical areas
- A number of detector systems are being constructed
- USNDP products and services are an integral and important part of the research programs

End