Nuclear Spectroscopy II

Augusto O. Macchiavelli

Nuclear Science Division
Lawrence Berkeley National Laboratory

2015 TRIUMF Summer Institute (TSI)

Theory for exploring experiments in light and medium-mass nuclei

Many thanks to
Dirk Weisshaar

BERKELEY LAB
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

Work supported under contract number DE-AC02-05CH11231.

Outline

γ-ray Spectroscopy

- Interactions of gamma-rays with matter
- Scintillators
- Ge –detectors
- Compton-suppression
- Resolving power

Some examples of quadrupole collectivity

- Cranking analysis
- Superdeformation
- Wobbling
- Tidal waves

Gamma-ray Spectroscopy and Nuclear Physics

Gamma-ray spectroscopy has played a major role in the study of the atomic nucleus.

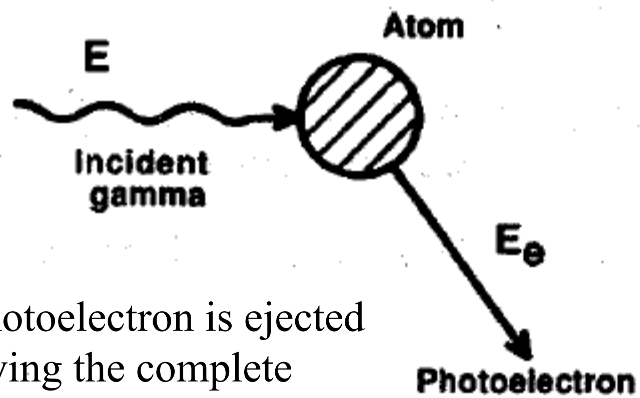
• Coincidence relations	→	Level/decay scheme
• Angular distributions /correlations	→	Multipolarity, spins
• Linear polarization	→	E/M, parity
• Doppler shifts	→	Lifetimes, B(E/M λ)

"Effective" Energy resolution (δE), Efficiency (ε), Peak-to-Background (P/T)

Resolving Power

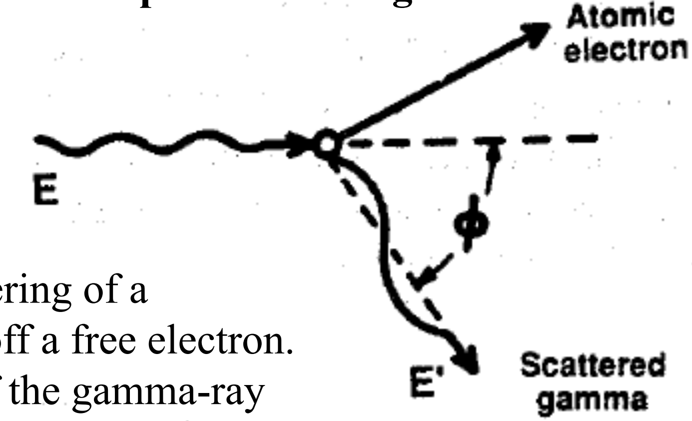
Interaction of gamma-rays with matter

Photo effect



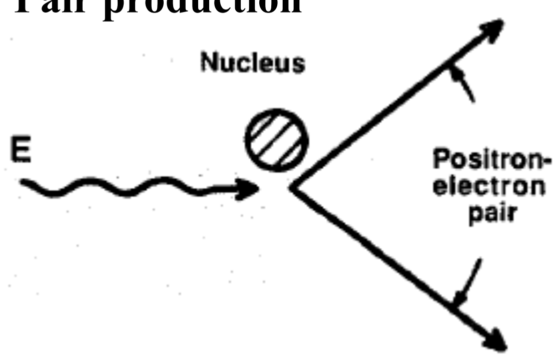
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering

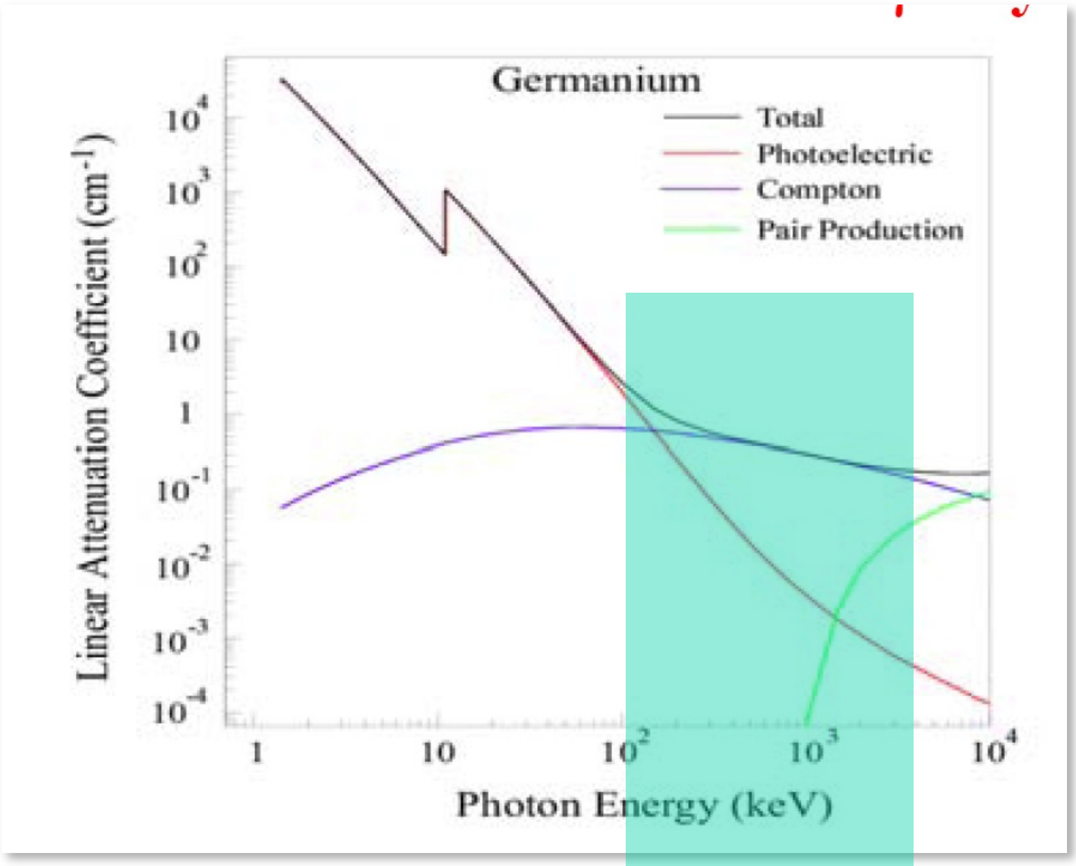


Elastic scattering of a gamma ray off a free electron. A fraction of the gamma-ray energy is transferred to the Compton electron

Pair production



If gamma-ray energy is >> 2 $m_o c^2$ (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus. This pair carries the gamma-ray energy minus 2 $m_o c^2$.



Photoelectric:

~ Z^{4-5}, $E_g^{-3.5}$

Compton:

~ Z, E_g^{-1}

Pair production:

~ Z^2, increase with E_g

Example; 1.33 MeV
5 interactions: 4 Compton, 1 photo
Separation of interactions: 0.5 – 5 cm

Scintillators

Scintillators are materials that produce 'small flashes of light' when struck by ionizing radiation (e.g. particle, gamma, neutron). This process is called '**Scintillation**'.

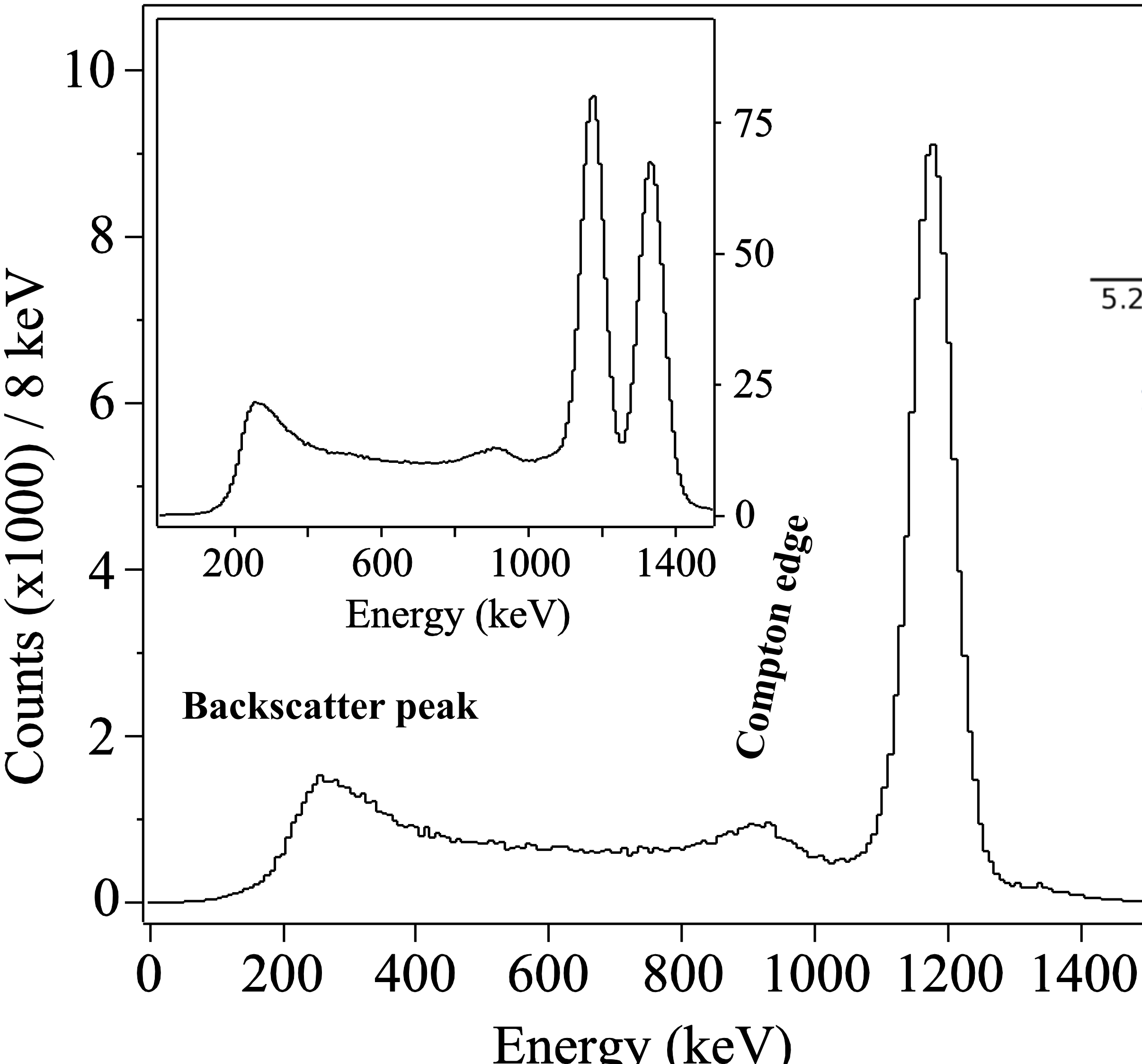
Scintillators may appear as solids, liquids, or gases.

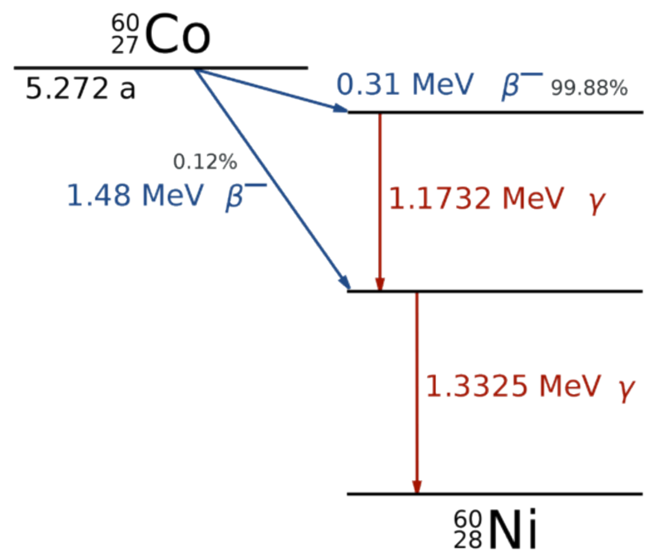
Major properties for different scintillating materials are:

- Light yield and linearity **(energy resolution)**
- How fast the light is produced **(timing)**
- Detection efficiency

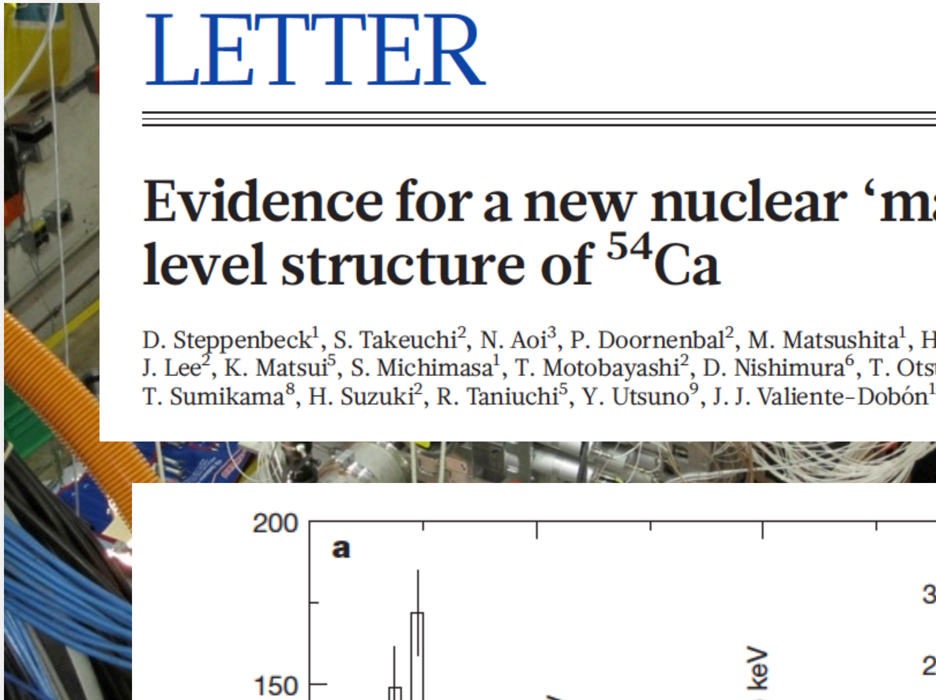
Organic Scintillators ("plastics"):
Light is generated by fluorescence of molecules; usually fast, but low light yield
Inorganic Scintillators:
Light generated by electron transitions within the crystalline structure of detector; usually good light yield, but slow

Scintillator spectrum (here CsI(Na))





CAESAR at NSCL

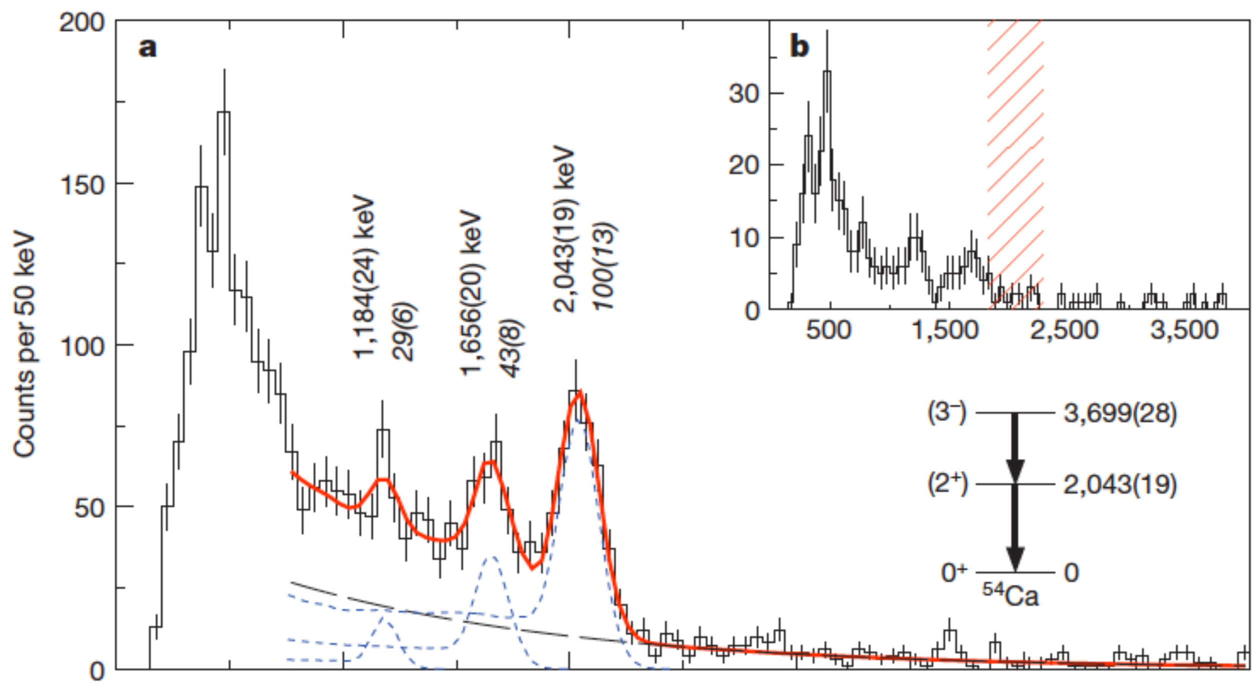


LETTER

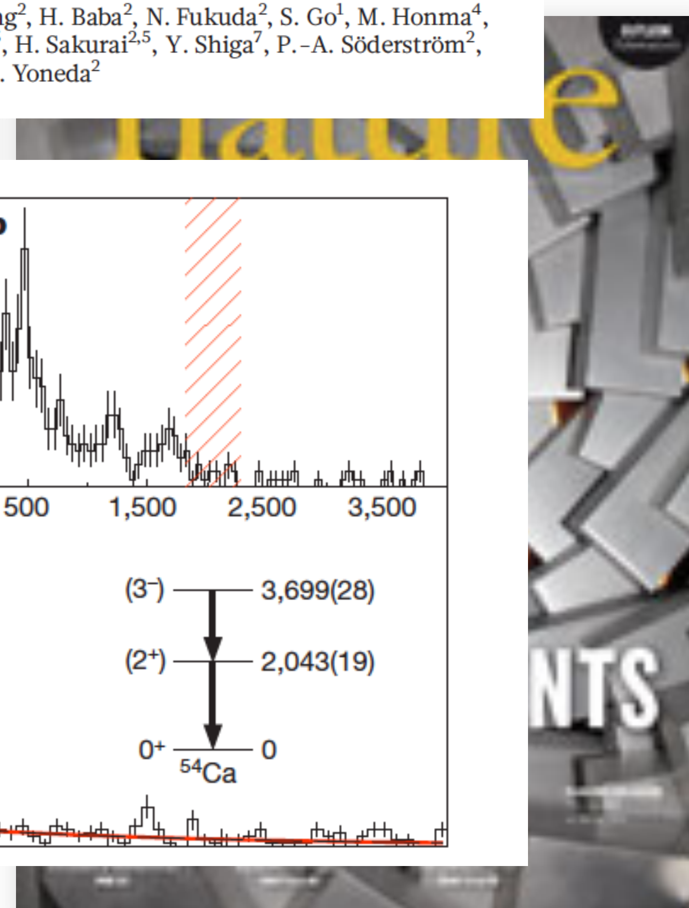
doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

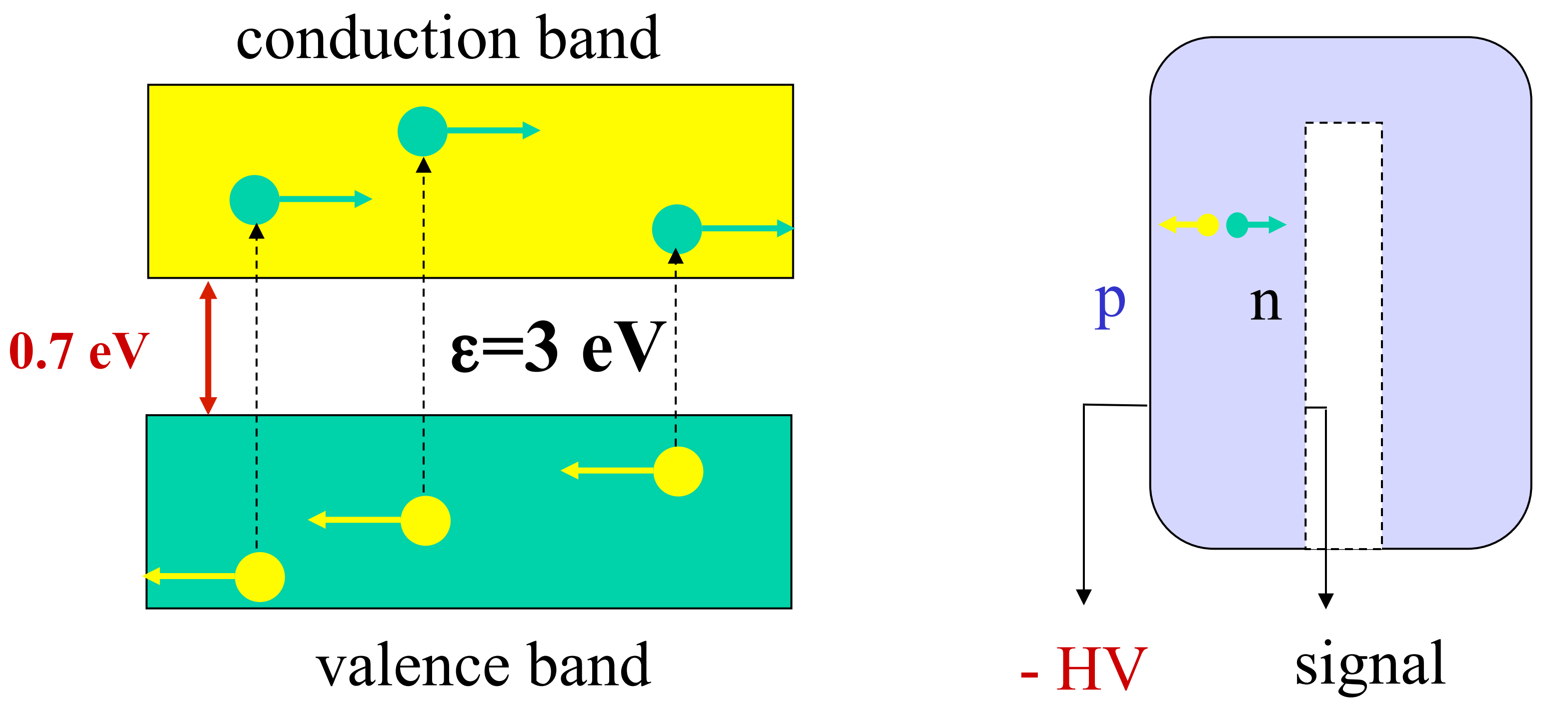


RIBF



Germanium Semi-conductor Detectors

Energy resolution !



Intrinsic energy resolution determined by statistics of charge carriers ~

$$\sqrt{N} \rightarrow FWHM = 2.35\sqrt{\mathrm{F\ \ E}\gamma / \varepsilon}$$

Compton Suppression

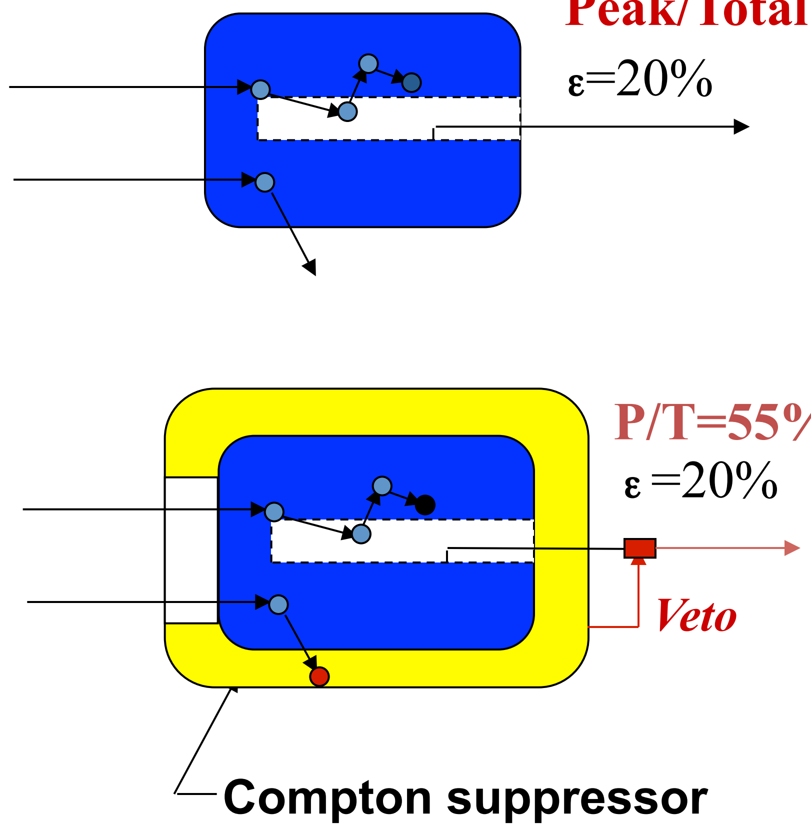
Improve peak-to-total ratio

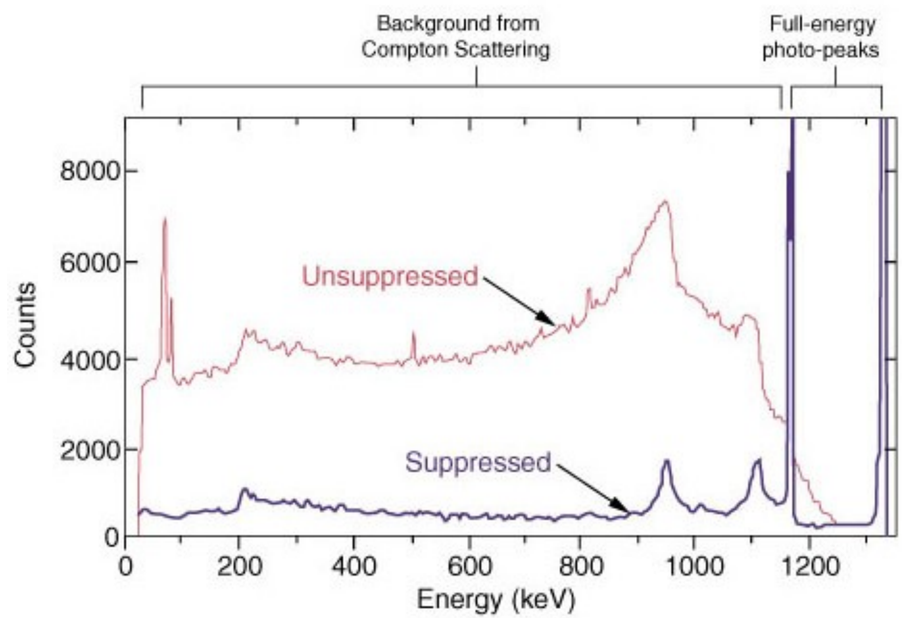
Peak/Total = 20%

ε=20%

P/T=55%

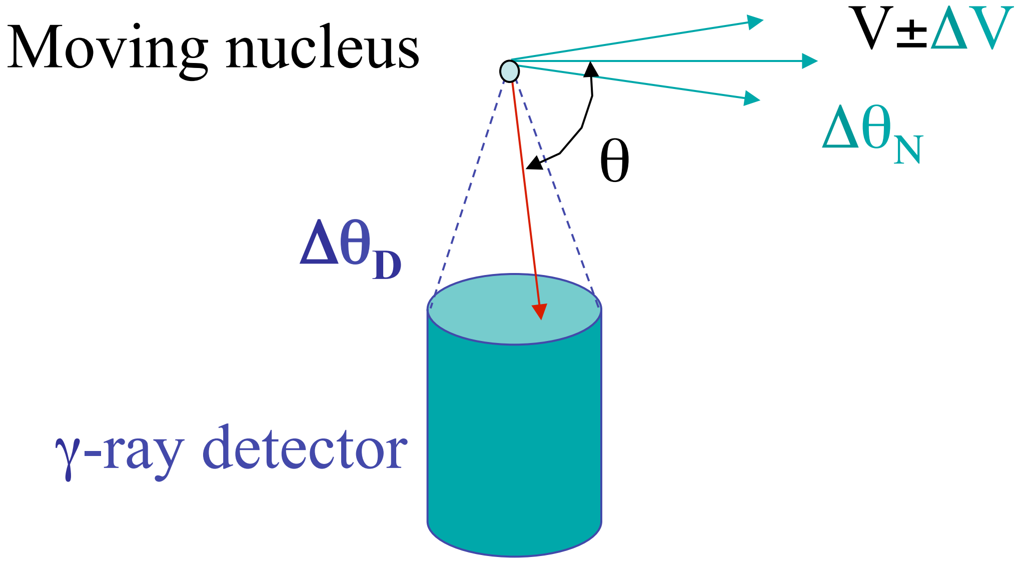
ε =20%





CAESAR, EUROBALL, GAMMASPHERE

Effective Resolution: Doppler Broadening



Doppler shift

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

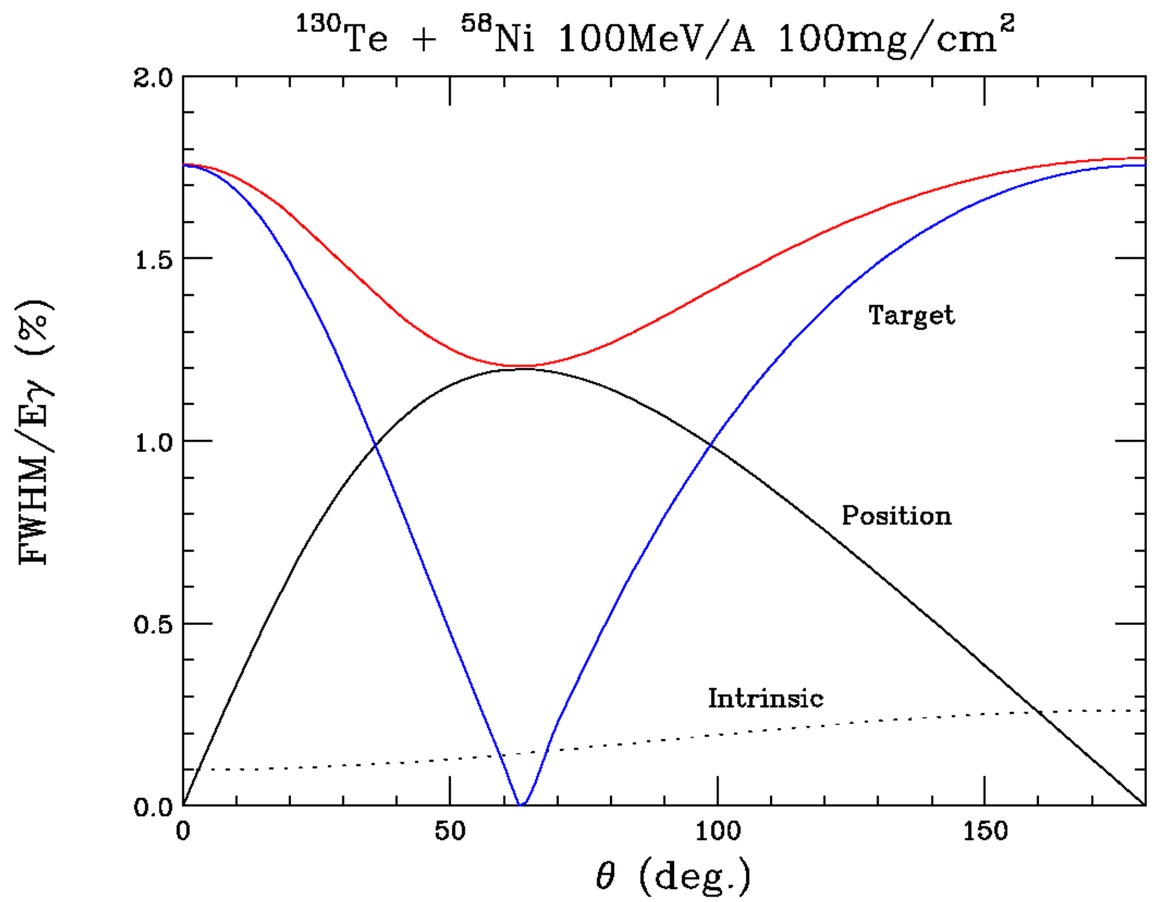
Broadening of detected gamma ray energy due to:

- 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.**

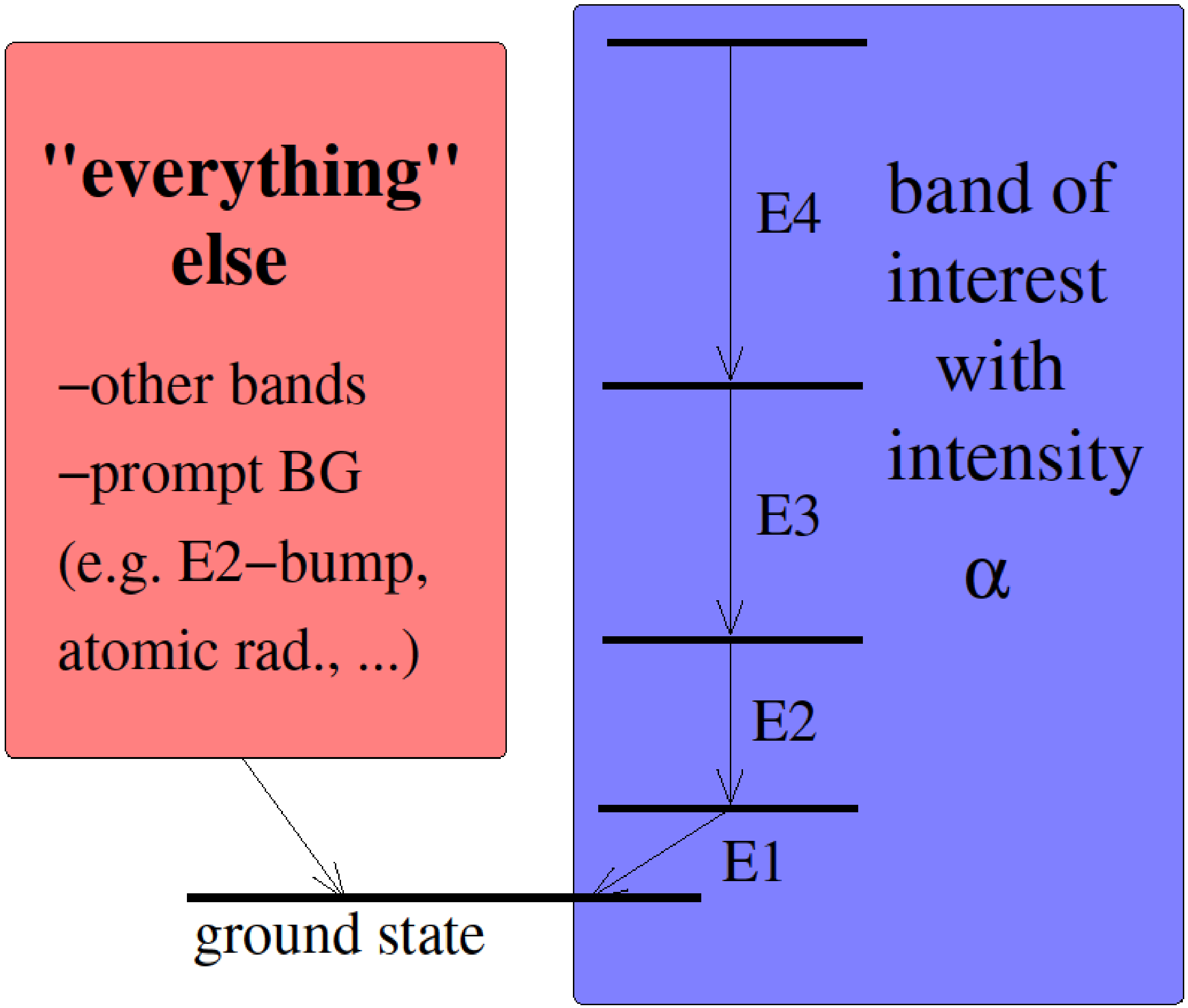
➔ Minimize opening angle and particle detector

Doppler Broadening



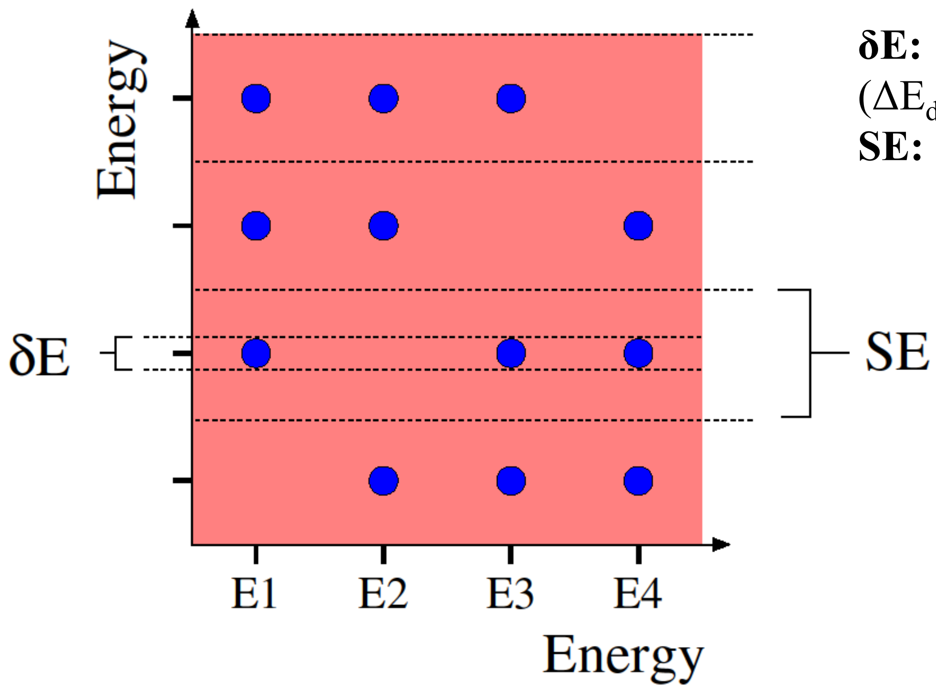
Resolving Power…

A figure of merit (resolving power) could be measured by the ability to observe weak branches from rare and exotic nuclear states.



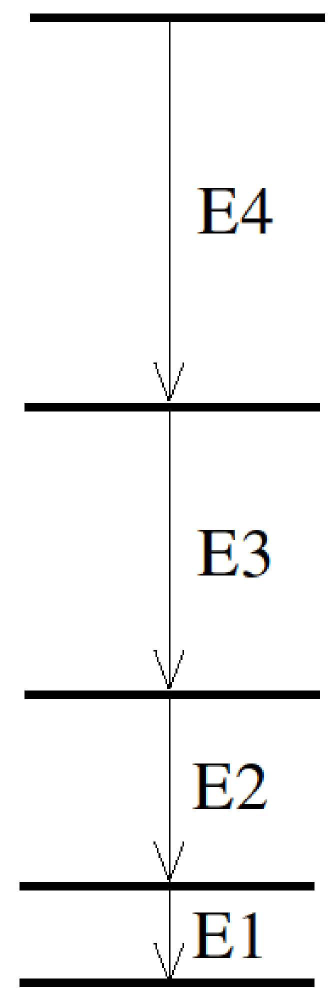
Improving Peak-to-Background…

…using F-fold coincidences (here 'matrix': F=2)



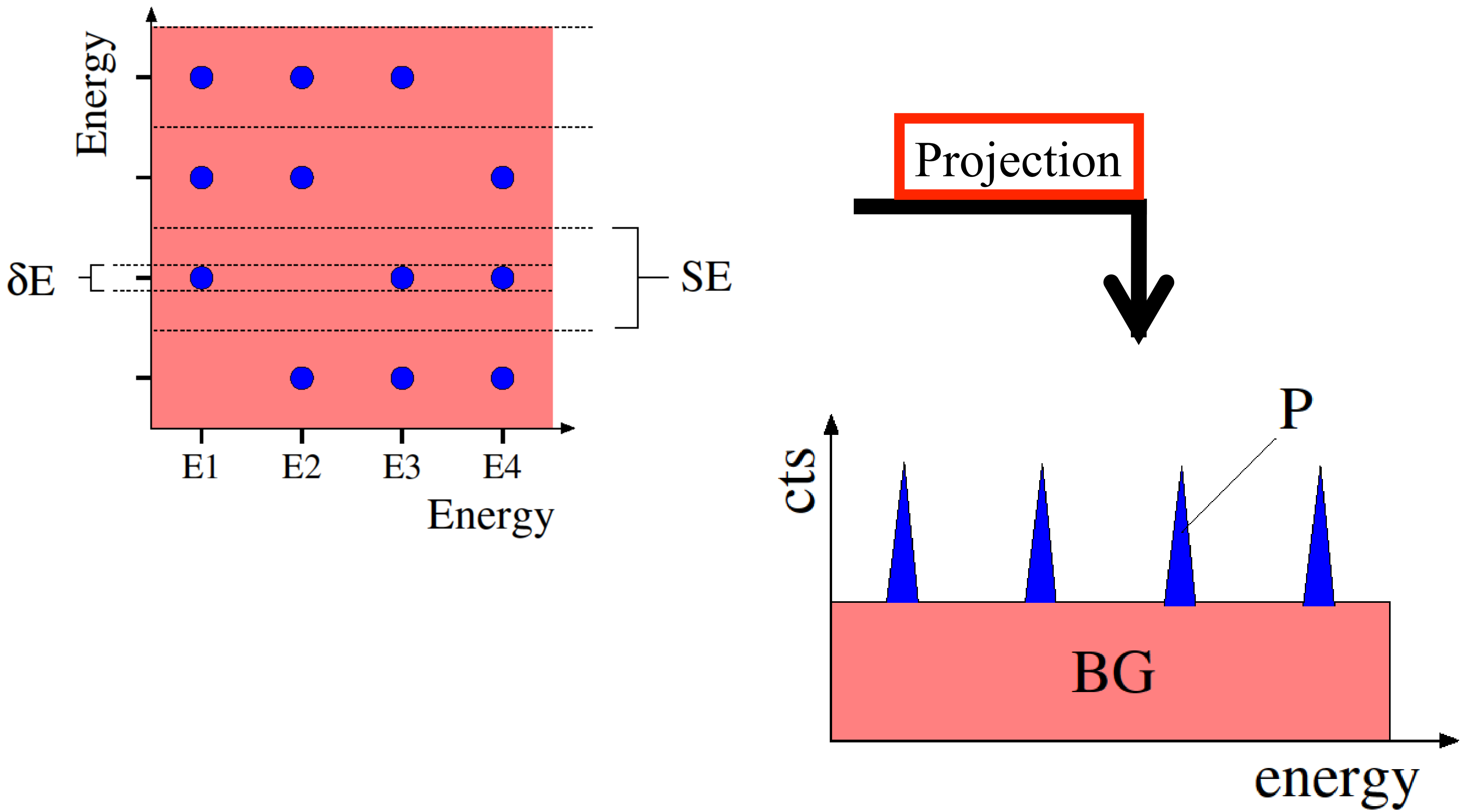
δE: 'effective' E-resolution (ΔE_{det} and $\Delta E_{Doppler}$)
SE: average energy spacing

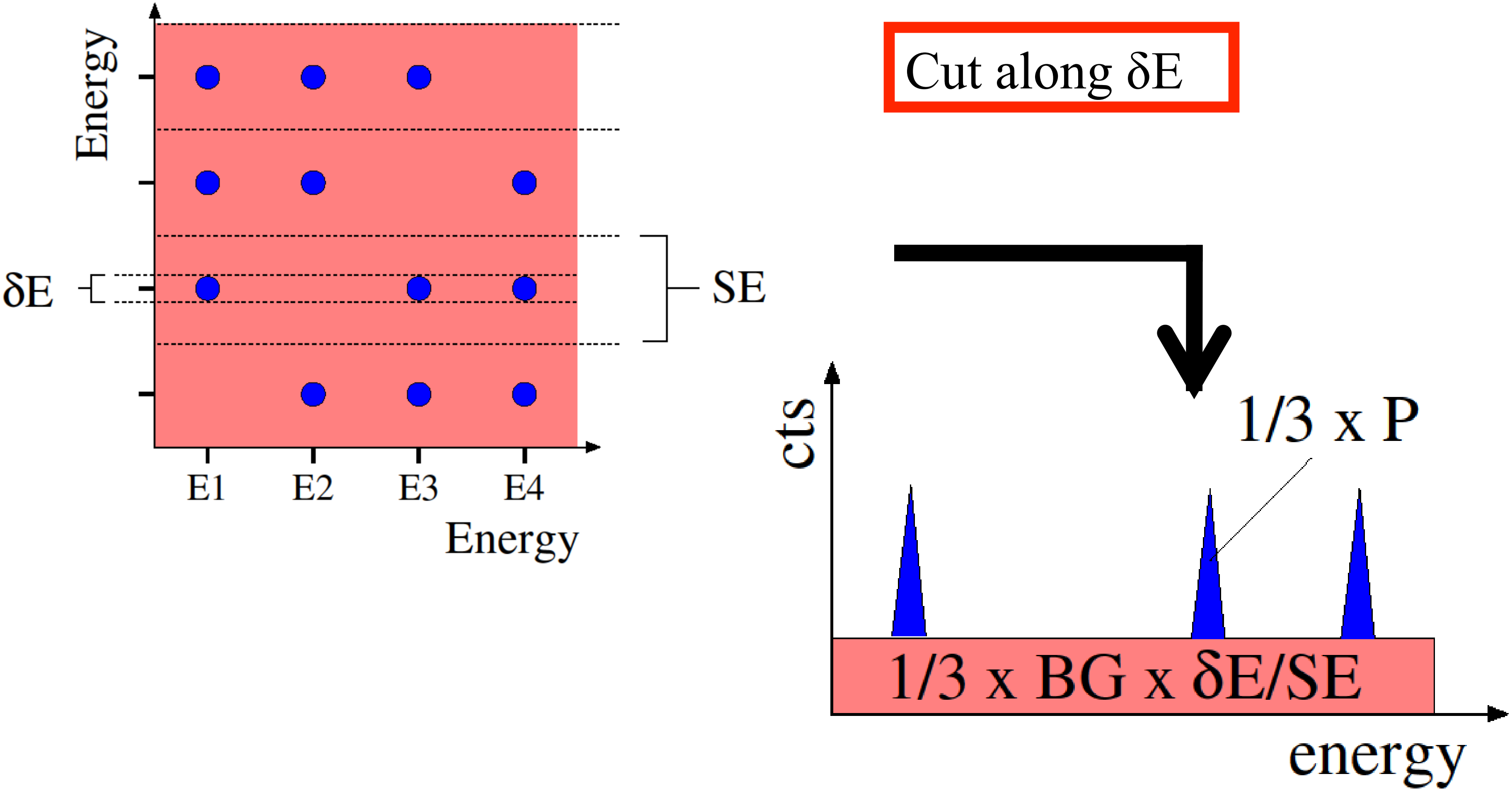
→ E_x-E_y coincidences go into peak (blue)
→ "everything else" spread over red area, as it isn't coincident with any E_x



Improving Peak-to-Background…

…using F-fold coincidences (here 'matrix' : F=2)



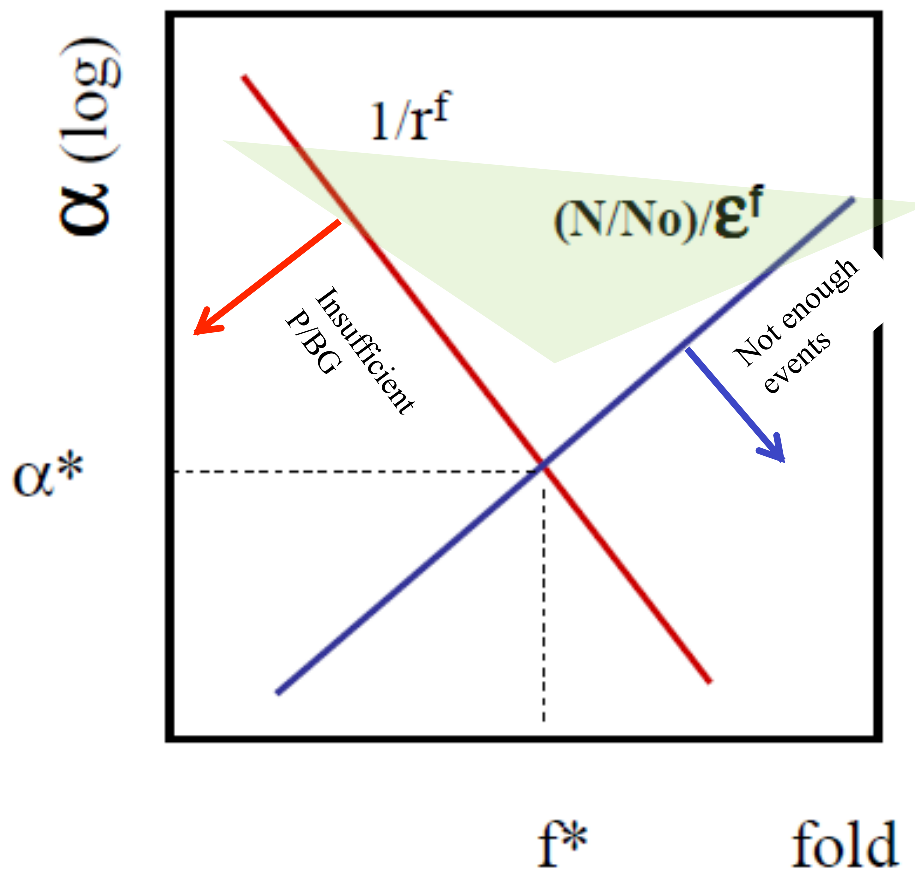


Improvement of P/BG by factor **SE/δE** !!!

Note: r >1, ε<1

With $r \approx (\frac{SE}{\delta E})(\frac{P}{T})$

$$\alpha = 1/r^f$$

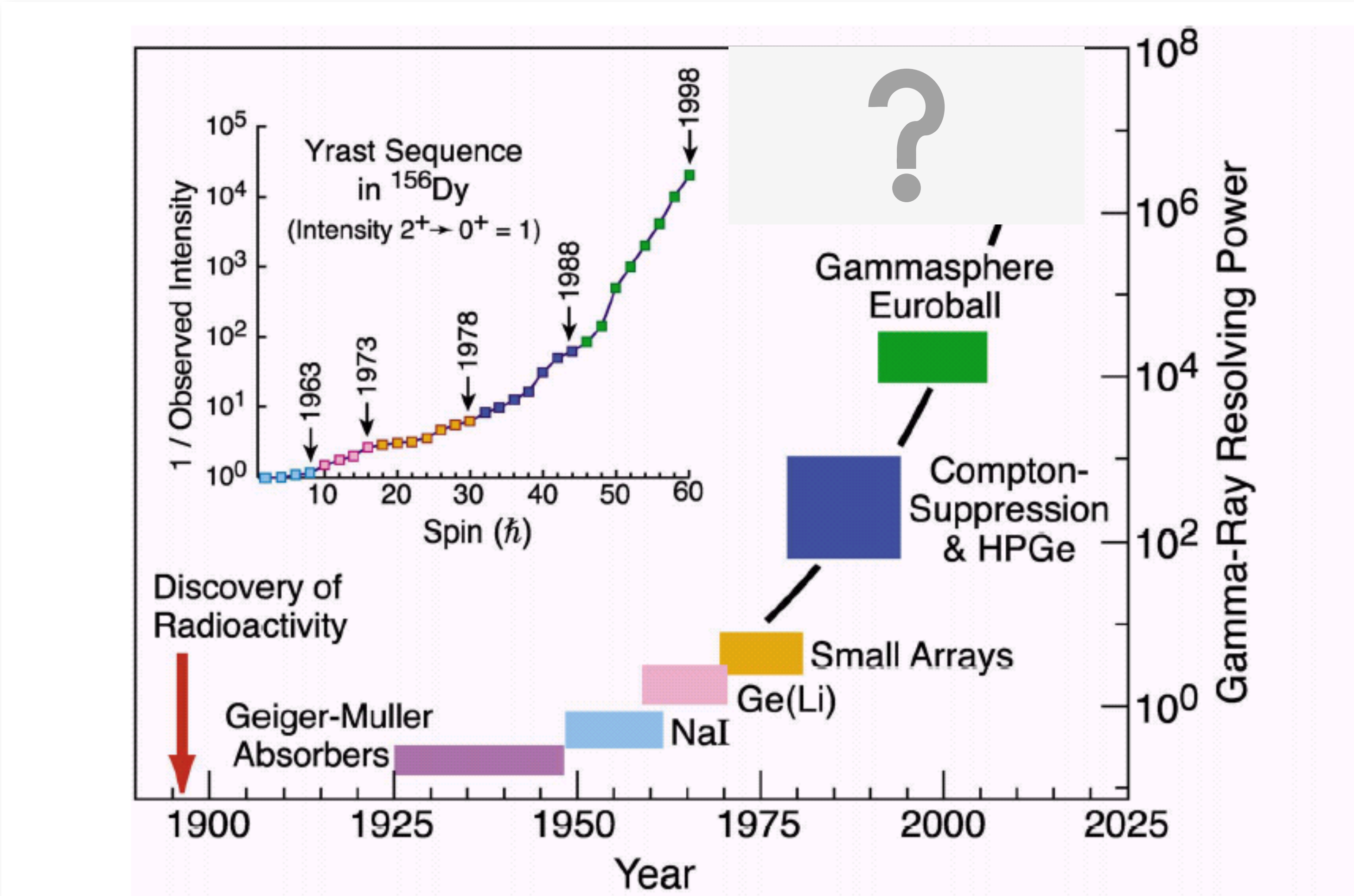


The counts in the peak of interest

$$N = \alpha N_o \varepsilon^f$$

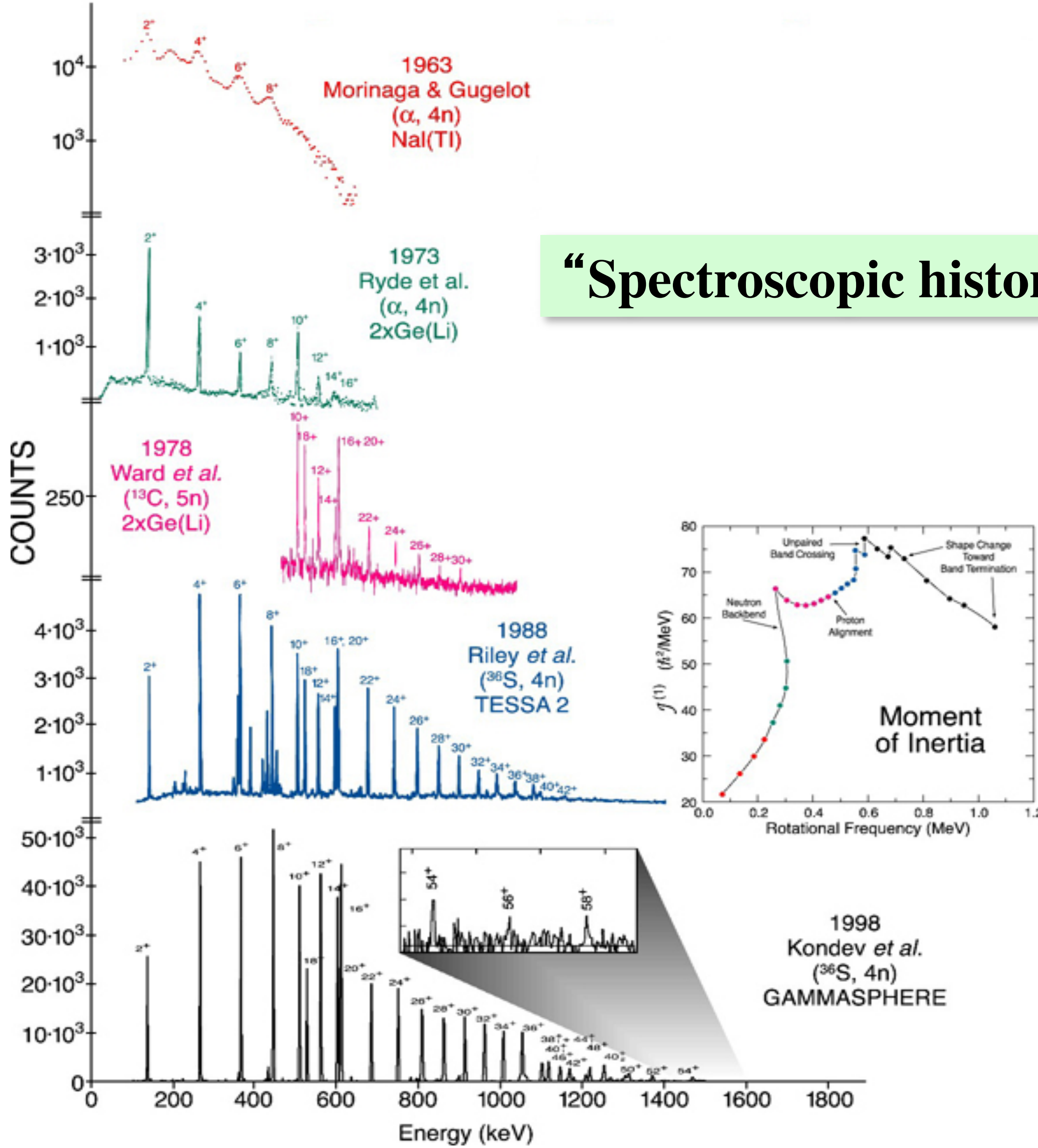
The resolving power is $RP = \frac{1}{\alpha^*} = r^{f^*}$

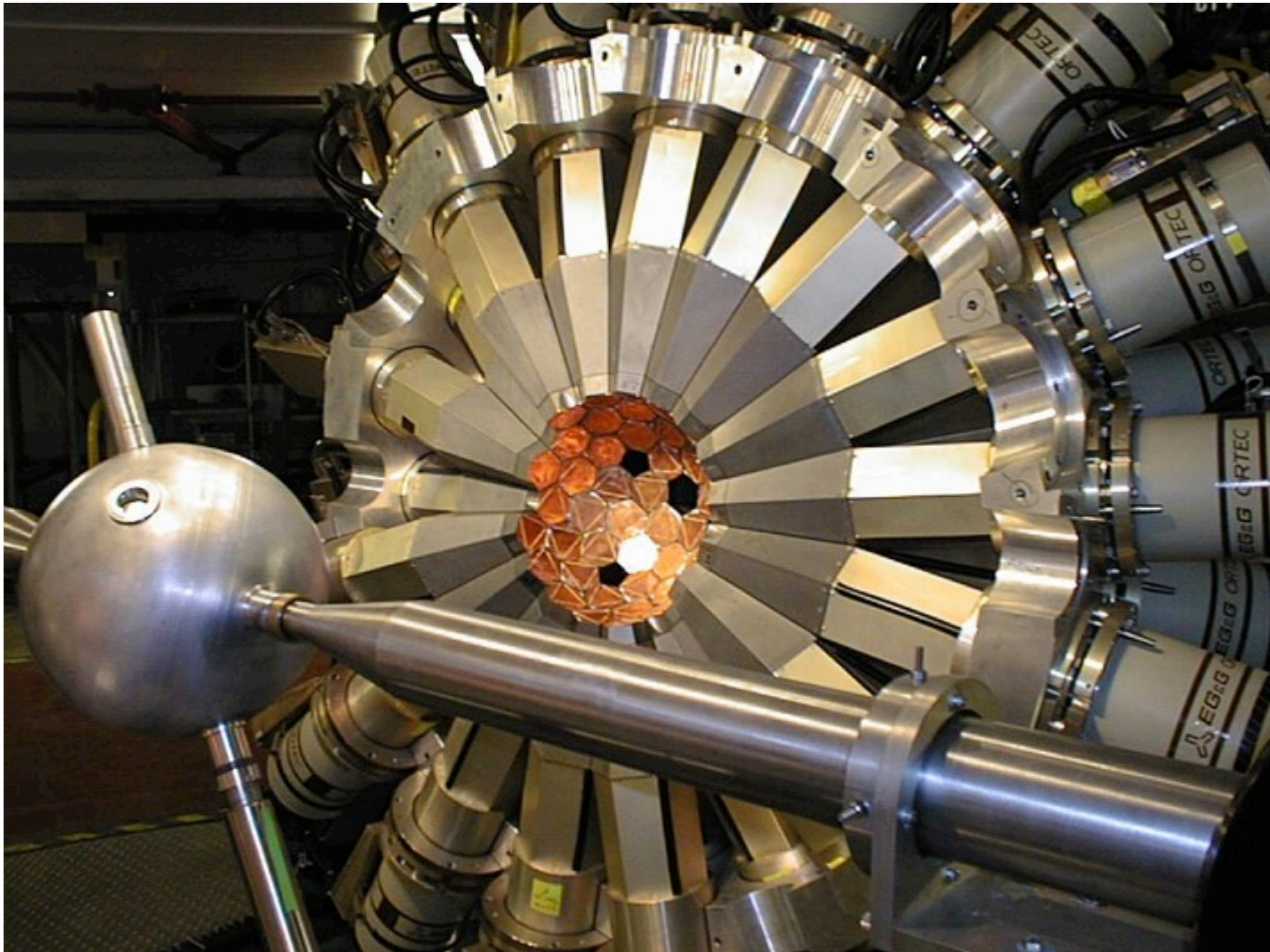
Evolution of Gamma-ray Spectroscopy Resolving Power



Development of new detectors and techniques have always led to discoveries of new and unexpected phenomena.

"Spectroscopic history" of ^{156}Dy





Number of modules	110
Ge Size	7cm (D) × 7.5cm (L)
Distance to Ge	25 cm

Peak efficiency	9% (1.33 MeV)
Peak/Total	55% (1.33 MeV)
Resolving power	10,000

ATLAS
Argonne Tandem Linear Accelerator System

Argonne NATIONAL LABORATORY

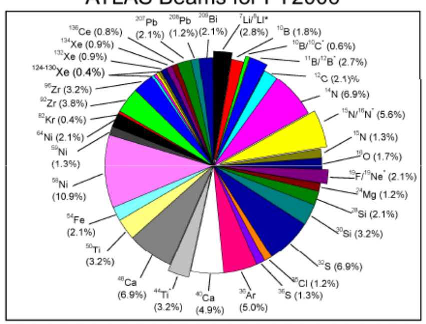
The prime national facility for nuclear structure research

The ATLAS facility is a leading facility for nuclear structure research in the United States. It provides a wide range of beams for nuclear reaction and structure research to a large community of users from the US and abroad. The full range of all stable ions can be produced in ECR ion sources, accelerated in the world's first superconducting linear accelerator for ions to energies of 7-17 MeV per nucleon and delivered to one of several target stations. About 20% of the beam-time is used to generate secondary radioactive beams. These beams are used mostly to study nuclear reactions of astrophysical interest and for nuclear structure investigations.

User community

ATLAS provides beams and experimental instruments for a large community of nuclear scientists. In 2006, there were 436 active users, including 75 graduate students. Typically, research at ATLAS results in 10 Ph.D. theses and 60 publications in peer reviewed scientific journals every year. Beam time is allocated based on the recommendations of a Program Advisory Committee which meets twice a year.

ATLAS Beams for FY2006



* Radioactive Beams comprised 17% of running time

Distribution of ATLAS beams in FY2006

Research programs

The ATLAS research programs focus on the key questions that are central to our understanding of baryonic matter and on the description of the astrophysical processes that generate energy and produce elements in the stars. These areas of research have been endorsed in several major reviews of the science. Specific issues being addressed are 1) the quantum structure of nuclei, 2) nuclear shapes,

GAMMASPHERE is one of the forefront instruments available for experiments at ATLAS. It consists of 110 Compton-suppressed Ge detectors used to detect gamma rays emitted from compound nuclei formed by fusion of accelerated heavy ions and target nuclei.

3) exotic decay modes, 4) masses of exotic nuclei, 5) fundamental interactions, 6) nuclear reactions of astrophysical importance, 7) properties of the heaviest nuclei and 8) accelerator mass spectrometry.

Future developments

Since its inception in 1985, the ATLAS facility has continually been upgraded in order to be at the forefront of nuclear research. At present, the Californium Rare Ion Breeder Upgrade, CARIBU, is being built. This facility will provide for the acceleration of neutron-rich fission fragments from a one Curie ^{252}Cf source to study neutron-rich nuclei, particularly those of relevance for the astrophysical rapid neutron capture process responsible for the production of a large fraction of the heavy elements in the Universe. A novel superconducting solenoid spectrometer, HELIOS, which is ideal for the study of the structure of these neutron-rich species, is under construction and an energy upgrade of ATLAS is also under way. In order to fully explore neutron-rich nuclei, a current frontier in nuclear physics research, a major new facility for beams of radioactive ions is in the planning stages.

Contact

Robert V. F. Janssens, Scientific Director, Janssens@anl.gov
December 2006

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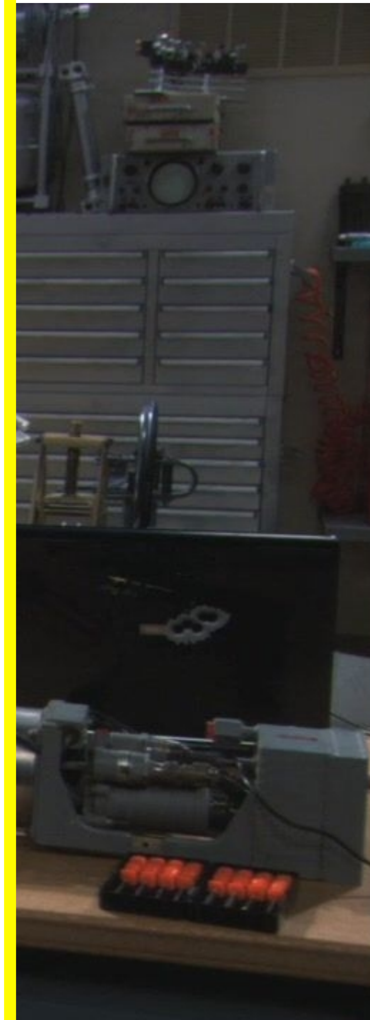


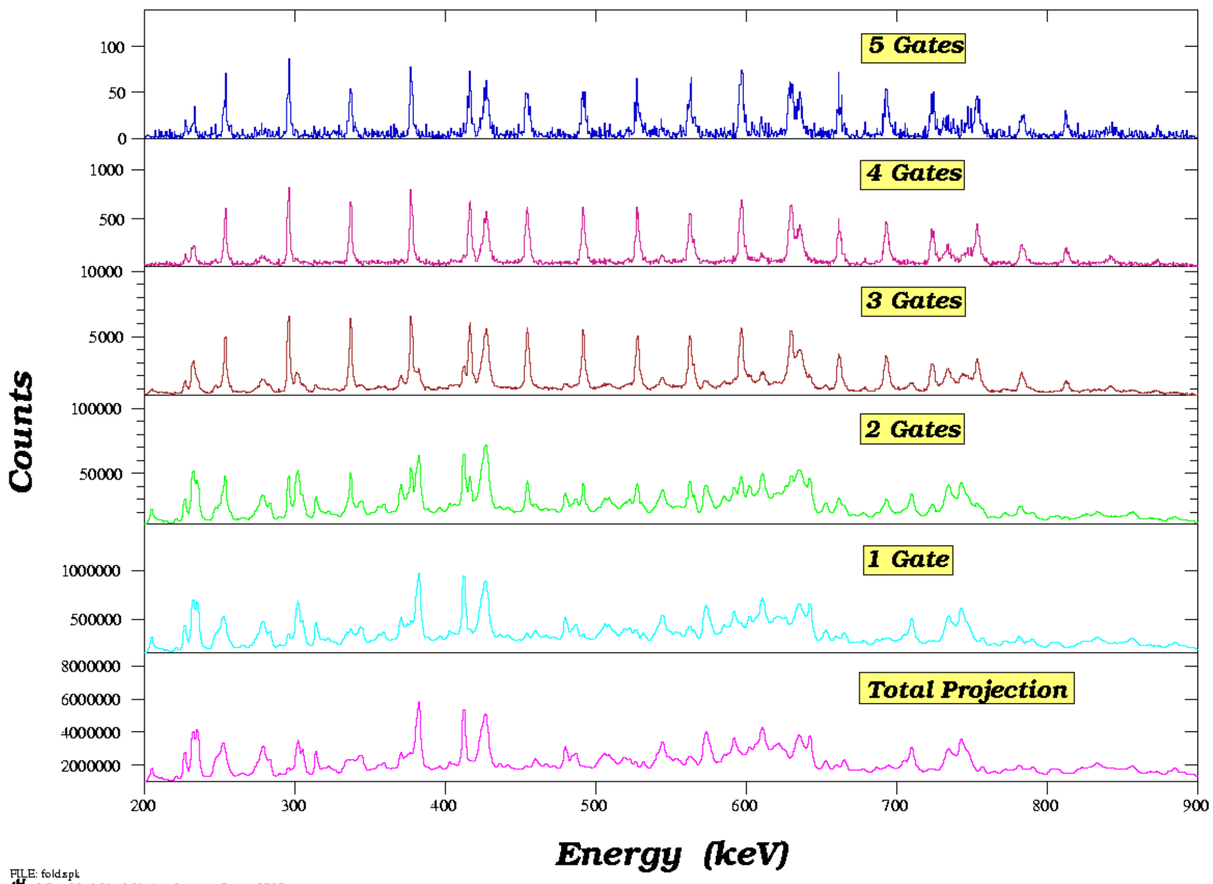
Courtesy of Robert Janssens

PHYSICAL REVIEW C VOLUME 54, NUMBER 5 NOVEMBER 1996

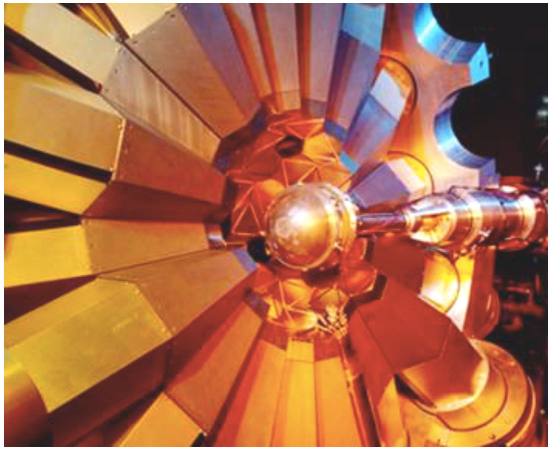
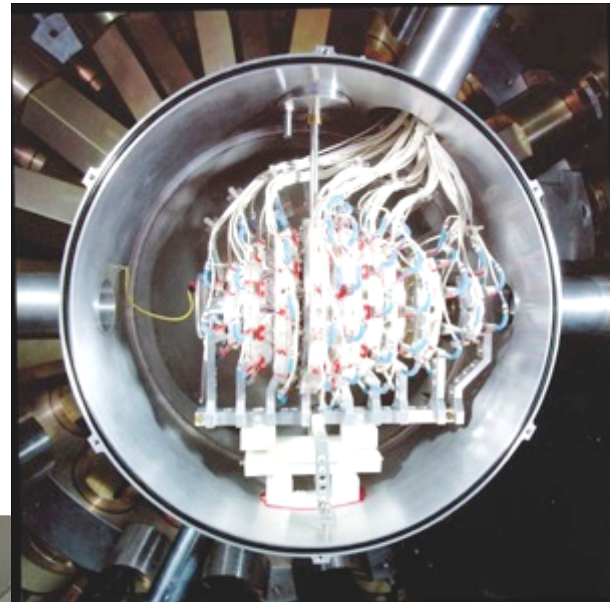
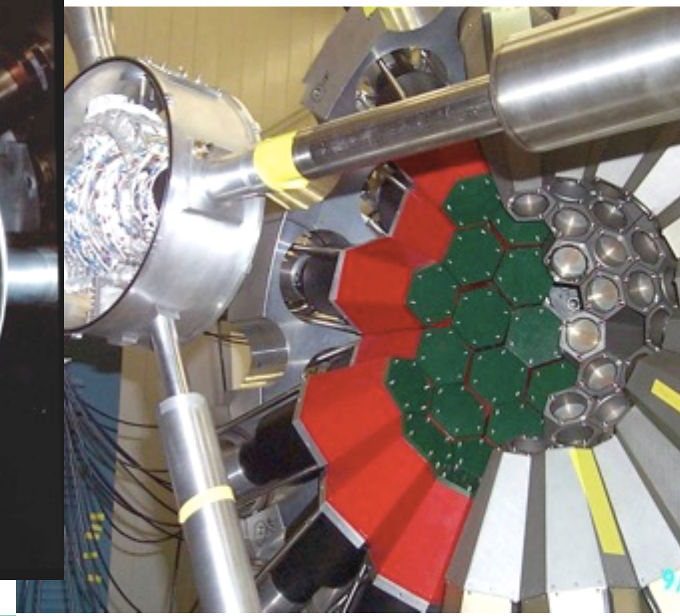
Test of $\Delta I = 2$ staggering in the superdeformed bands of ^{194}Hg

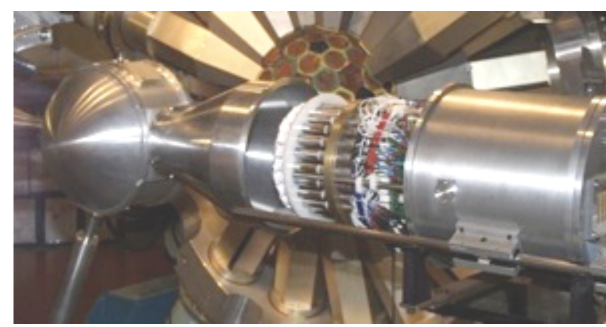
R. Krücken,[1] G. Hackman,[2] M. A. Deleplanque,[1] R. V. F. Janssens,[2] I. Y. Lee,[1] D. Ackermann,[2] I. Ahmad,[2] H. Amro,[2] S. Asztalos,[1] D. J. Blumenthal,[2] M. P. Carpenter,[2] R. M. Clark,[1] R. M. Diamond,[1] P. Fallon,[1] S. M. Fischer,[2] B. Herskind,[3] T. L. Khoo,[2] T. Lauritsen,[2] A. O. Macchiavelli,[1] R. W. MacLeod,[1] D. Nisius,[2] G. J. Schmid,[1] F. S. Stephens,[1] and K. Vetter[1]

^{150}Nd(^{48}Ca,4n) at 201 MeV



Auxiliary Devices



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Nuclear Instruments and Methods in Physics Research A 381 (1996) 418–432

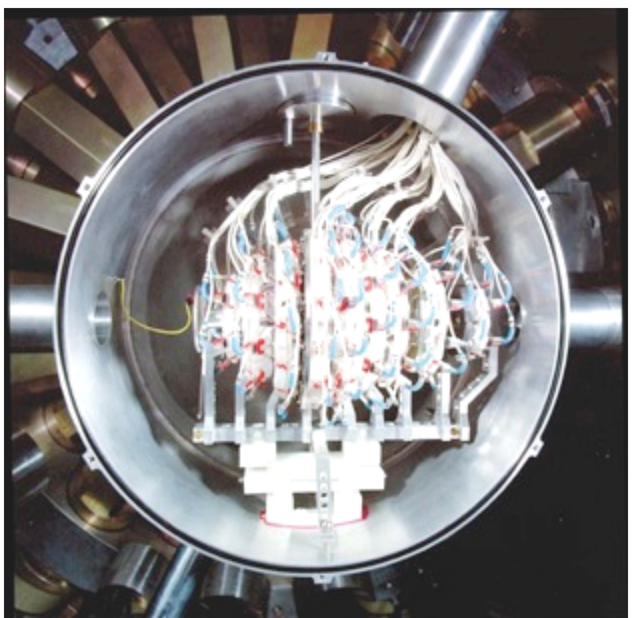
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

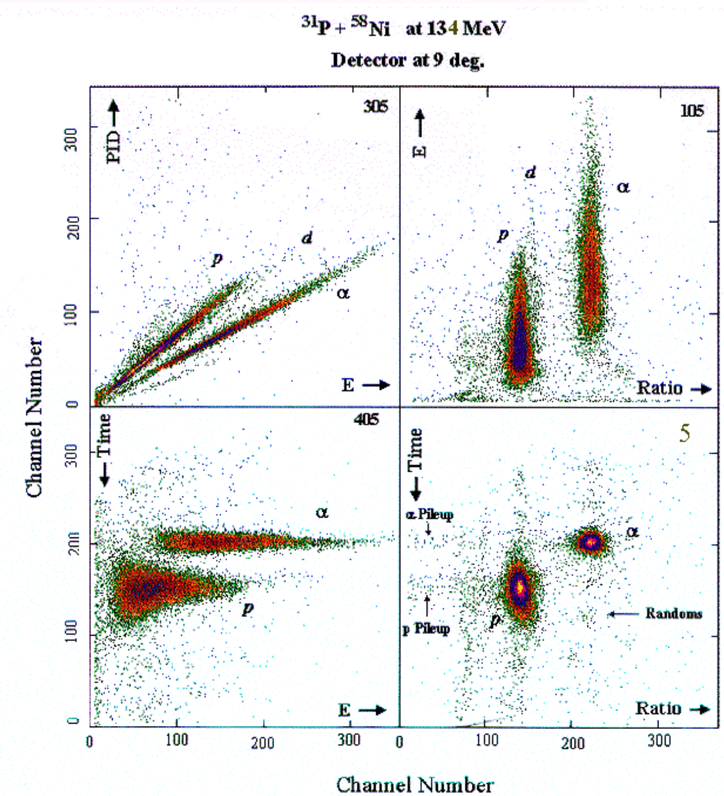
"The Microball"
Design, instrumentation and response characteristics of a 4π-multidetector exit channel-selection device for spectroscopic and reaction mechanism studies with Gammasphere

D.G. Sarantites[a,*], P.-F. Hua[a], M. Devlin[a], L.G. Sobotka[a], J. Elson[a], J.T. Hood[a], D.R. LaFosse[a], J.E. Sarantites[a] M.R. Maier[b]

[a] *Department of Chemistry, Washington University, St. Louis, MO 63130, USA*

[b] *Engineering Division Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA*

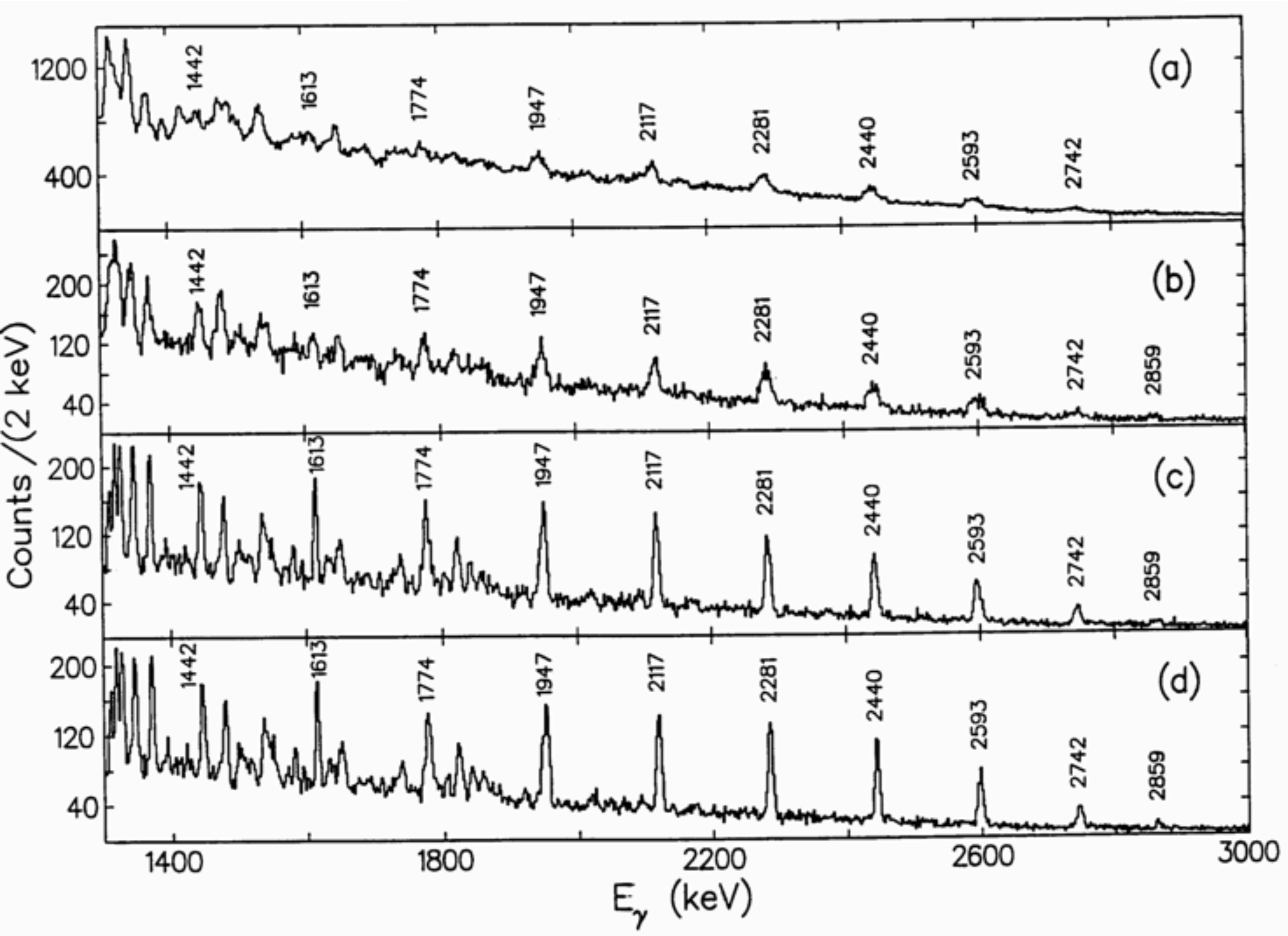




- Channel selection - lower background
- Recoil correction - better Resolution

$^{28}Si + ^{58}Ni \Rightarrow ^{80}Sr + \alpha 2p$ Yrast SD band

No Background subtraction



GS alone γγ

MB + GS γγ, no Recoil C.

MB + GS γγ + RC (const β)

MB+GS γγ + RC-β(E_π)

N·H
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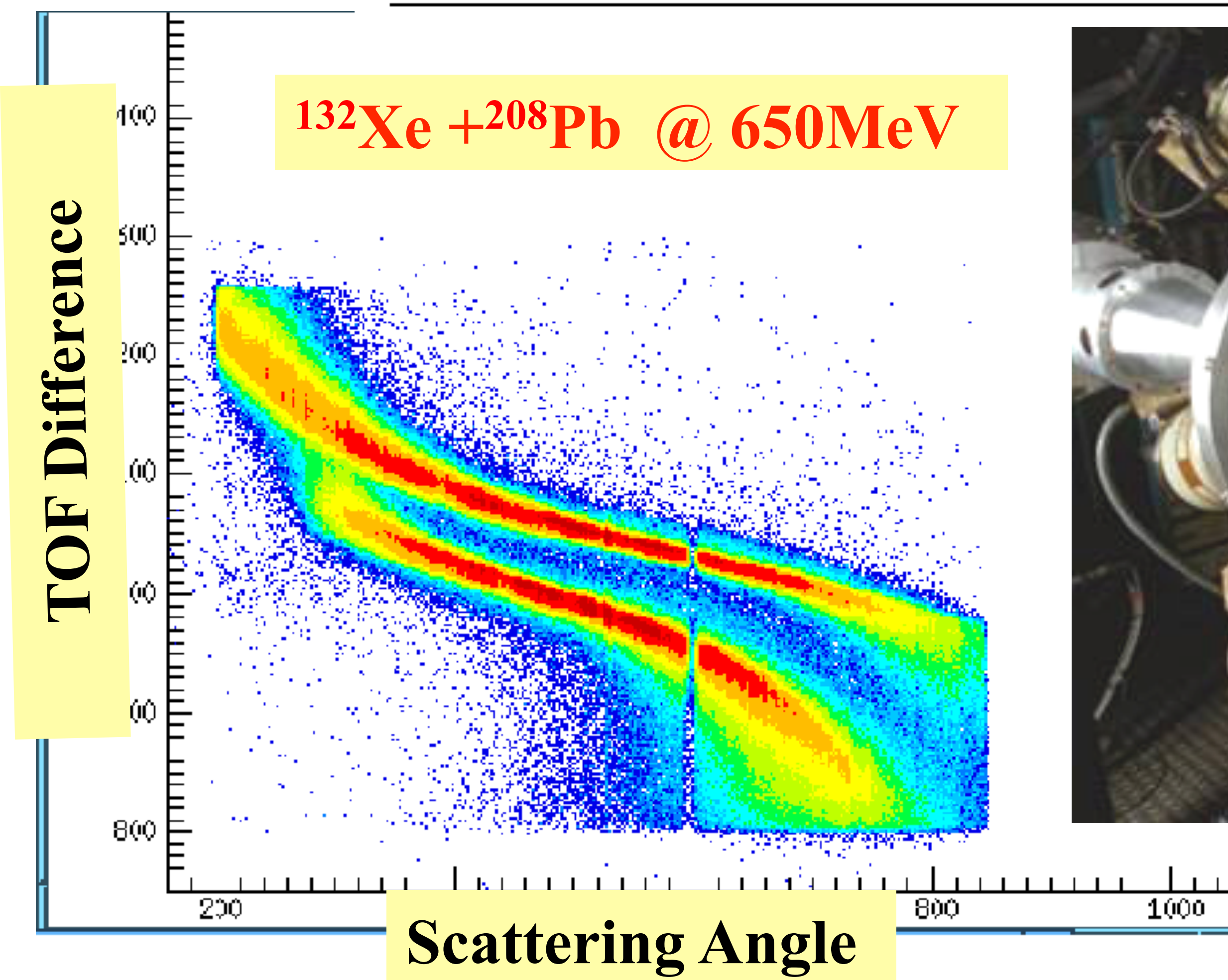
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
www.elsevier.nl/locate/nima

CHICO, a heavy ion detector for Gammasphere☆

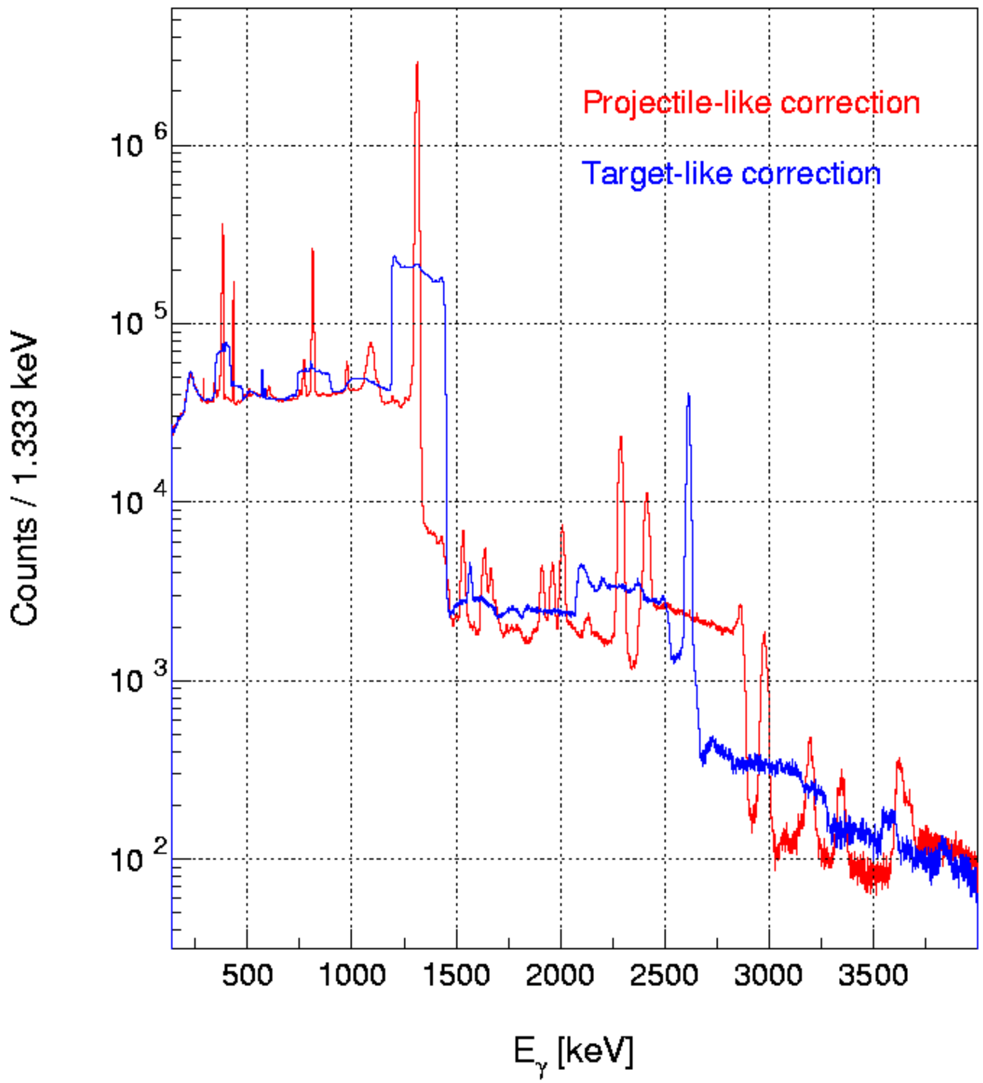
M.W. Simon*, D. Cline, C.Y. Wu, R.W. Gray, R. Teng, C. Long[1]

Nuclear Structure Research Laboratory, University of Rochester, 271 East River Road, Rochester, NY 14623, USA

Received 19 January 2000; accepted 7 March 2000



$^{136}Xe + ^{208}Pb$ at 650 MeV



SOME EXAMPLES

Cranking analysis:

Angular momentum and moments of inertia as functions of the rotational frequency

$$\omega = \frac{\partial E}{\partial I}$$ rotational frequency

$$I(\omega)$$ angular momentum

$$\Im^{(1)}(\omega) = \frac{I}{\omega}$$ kinematical moment of inertia

$$\Im^{(2)}(\omega) = \frac{dI}{d\omega}$$ dynamical moment of inertia

$$p = m^{(1)} v$$

$$f = dp / dt = (dp / dv) a \qquad f = m^{(2)} a$$

Cranking analysis: Experimental formulae

$\Delta I = 1$ -transitions:

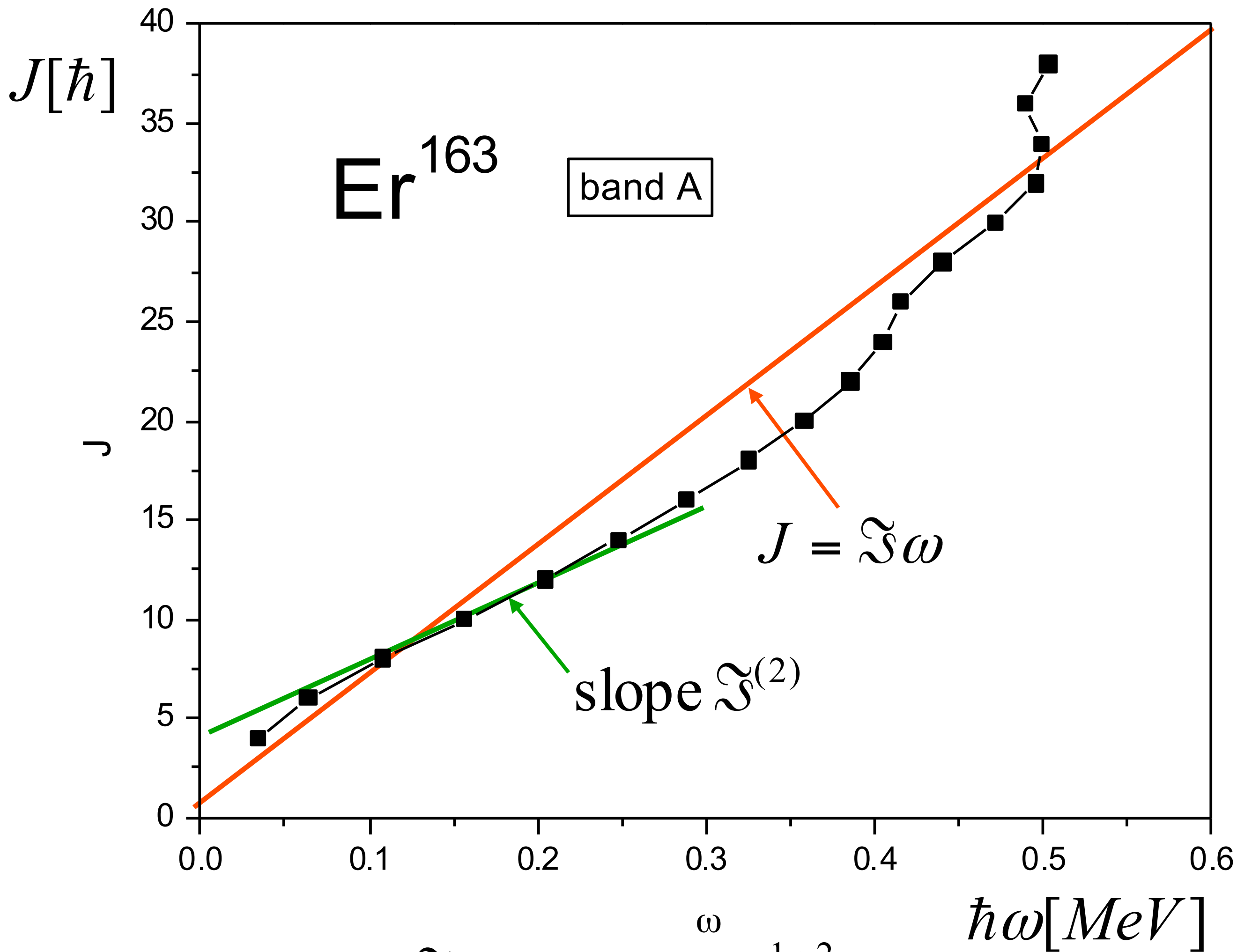
$$\hbar\omega(I) = E(I) - E(I-1)$$

$$E'(I) = \frac{1}{2}\big(E(I) + E(I-1)\big) - \hbar\omega(I)I$$

$\Delta I = 2$ -transitions:

$$\hbar\omega(I) = \frac{E(I) - E(I-2)}{2}$$

$$E'(I) = \frac{1}{2}\big(E(I) + E(I-2)\big) - \hbar\omega(I)I$$



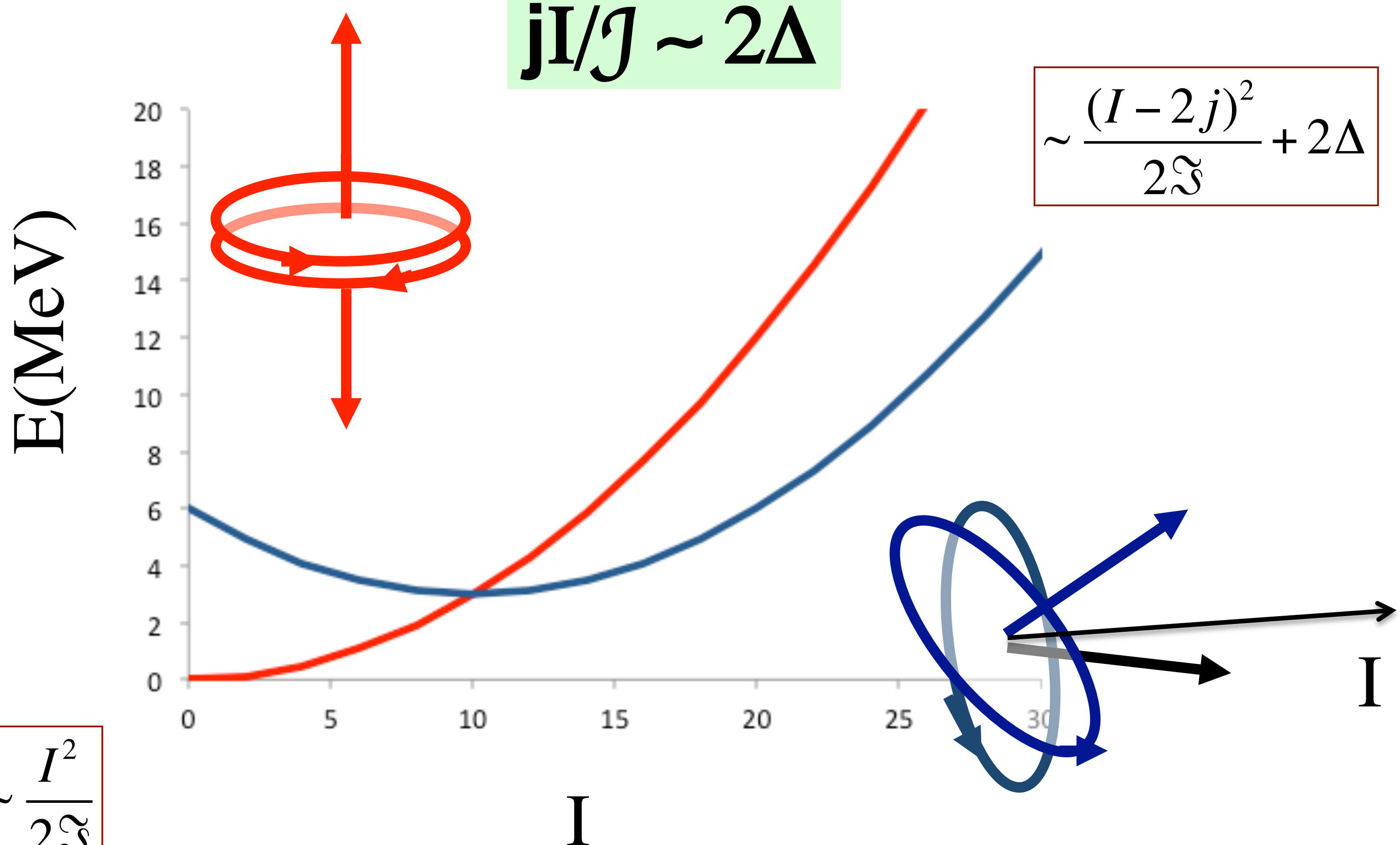
$$\Im = 63.4\,MeV^{-1}\hbar^{2}$$

Coriolis effects

Problem #5

$$jI/\mathcal{J} \sim 2\Delta$$

$$\sim \frac{(I-2j)^2}{2\Im} + 2\Delta$$



$$\sim \frac{I^2}{2\Im}$$

Stephens and Simon

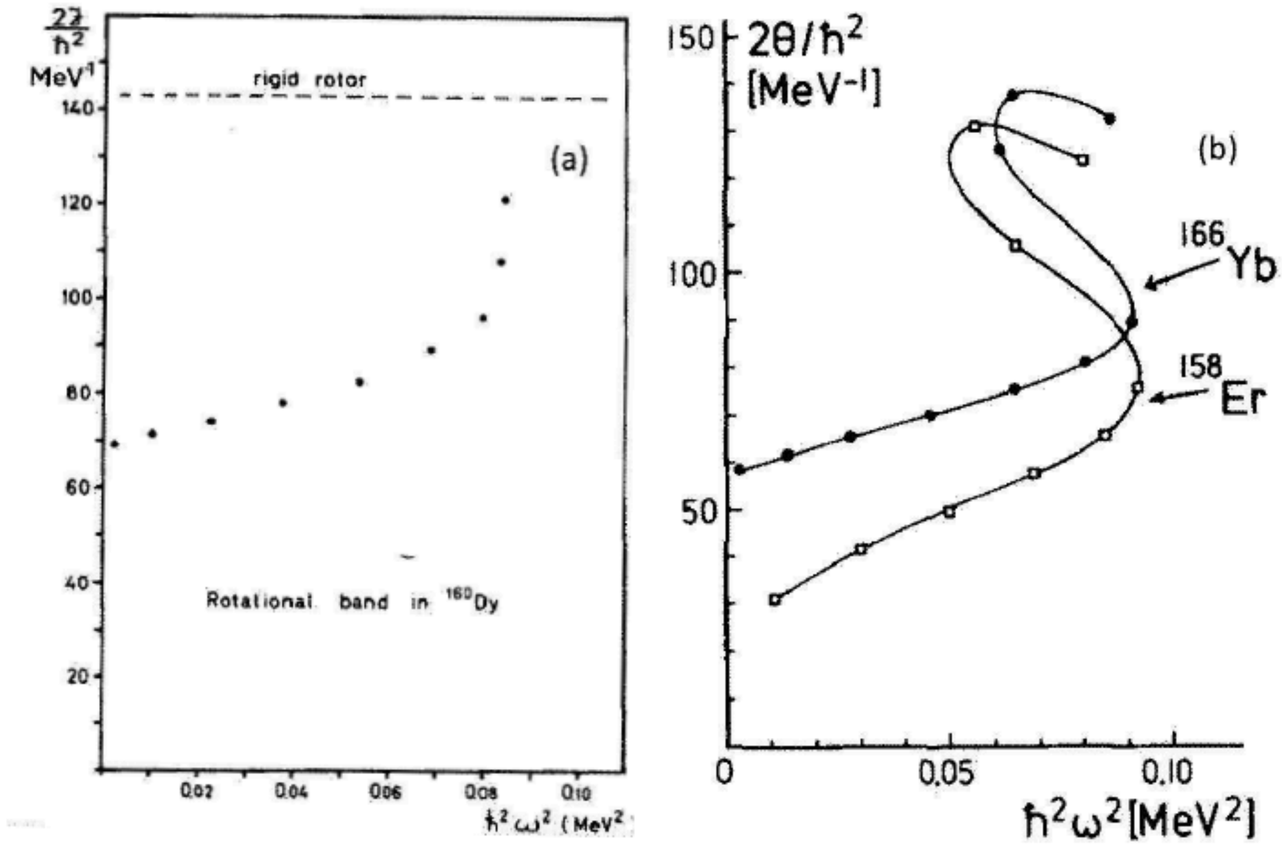
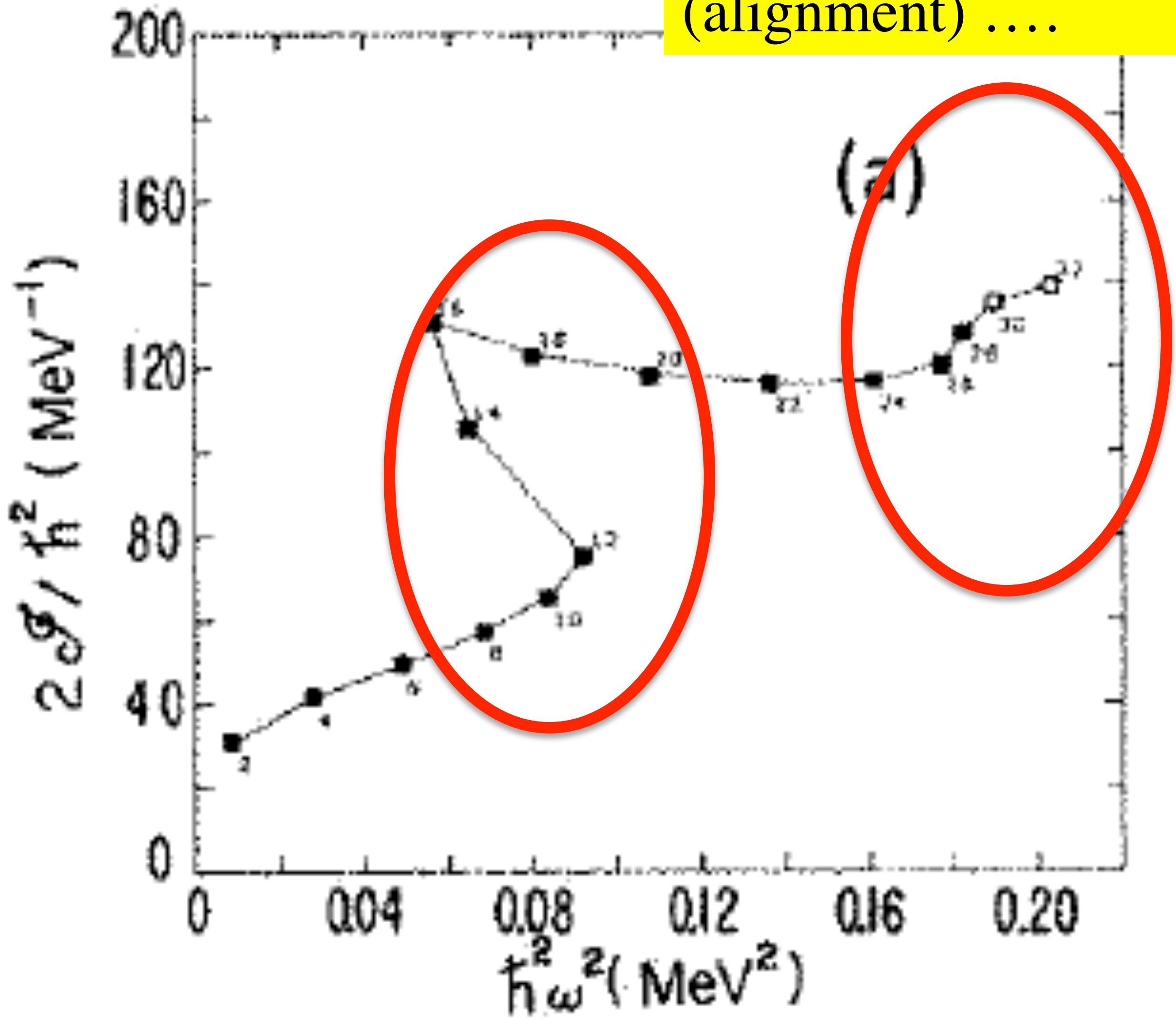
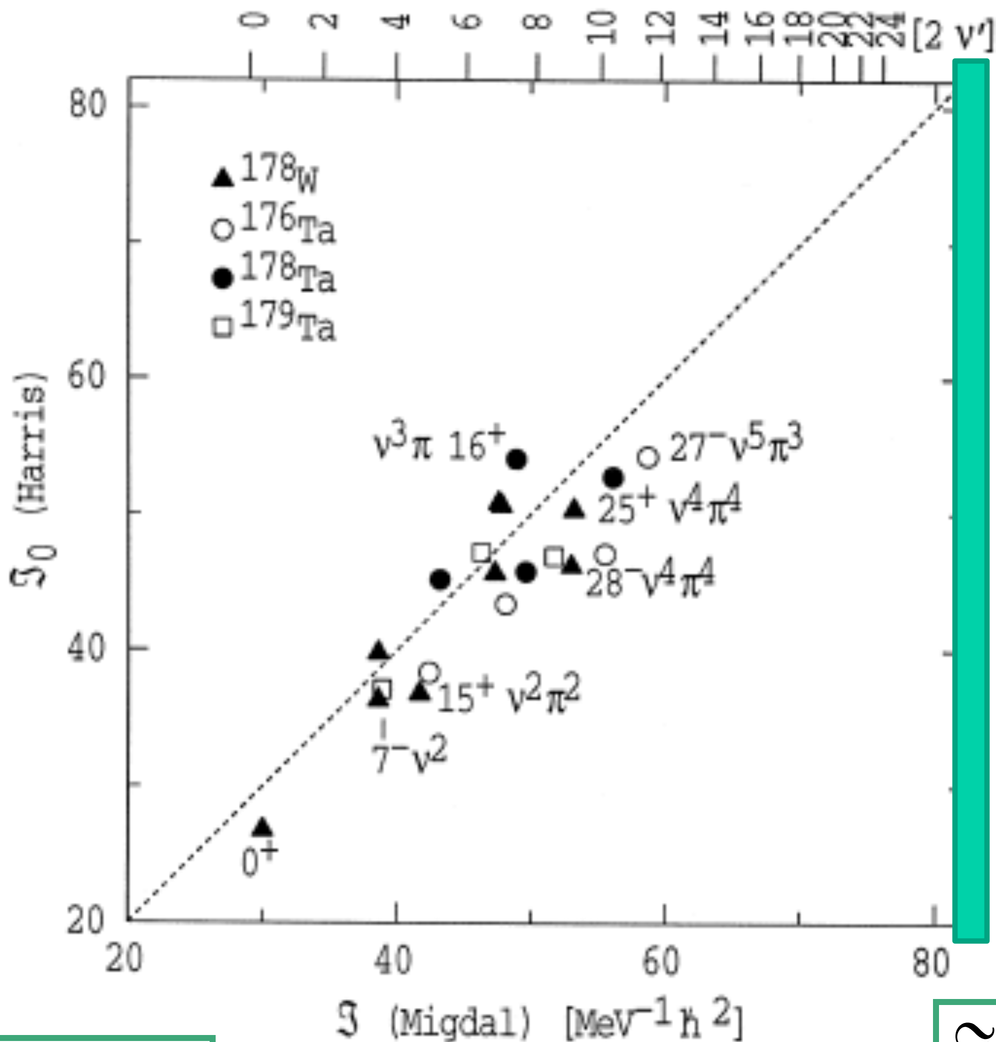


Fig. 3. The Plots of $2\Im/\hbar^2$ against $(\hbar\omega)^2$. (a) The discovery[7] of backbending (upbending) in ^{160}Dy. (b) Plots for the two nuclei reported by Beuscher *et al.*[8]

2nd Backbending (alignment) ….



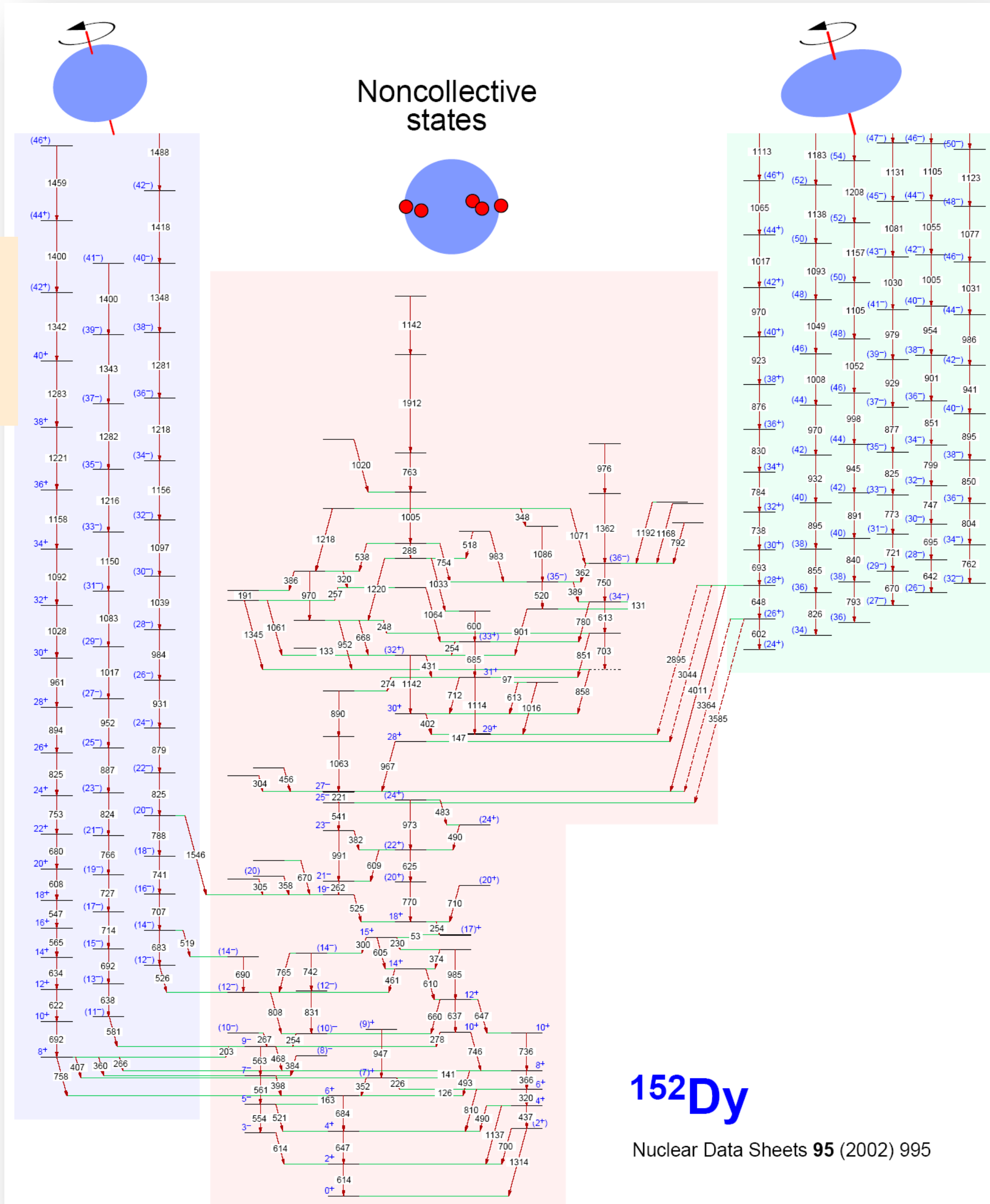


$\mathfrak{I}_{rigid}$

$$\Delta_\nu \approx 0.75\Delta_{\nu-2}$$

Coexistence of Excitations

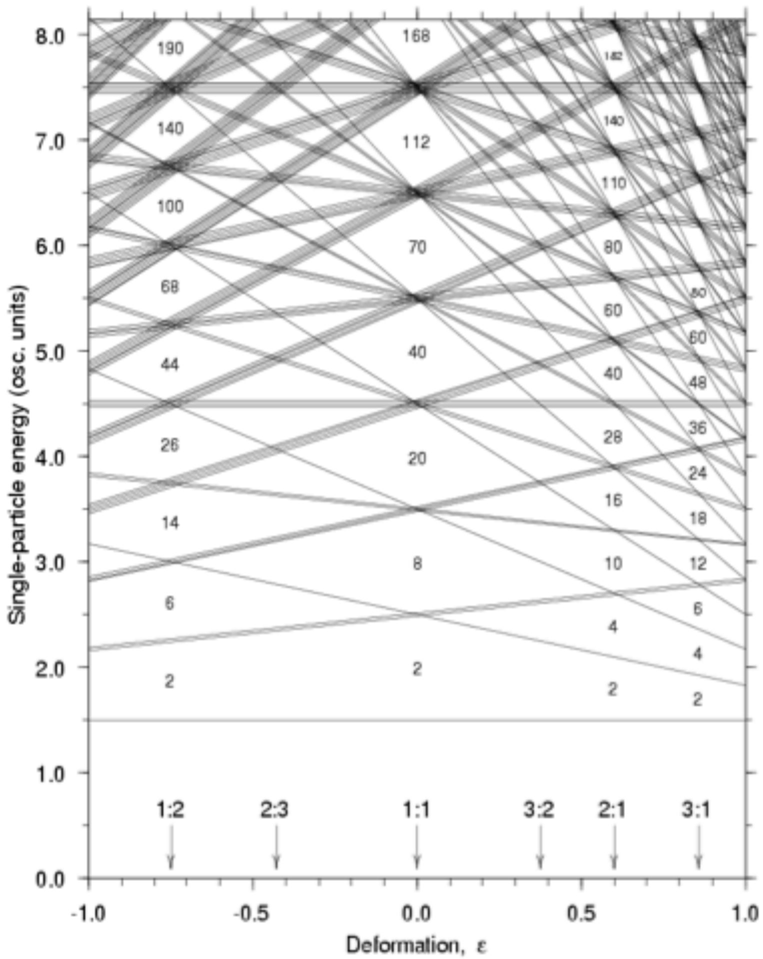
Normal-Deformed Rotational Bands (β~0.3)



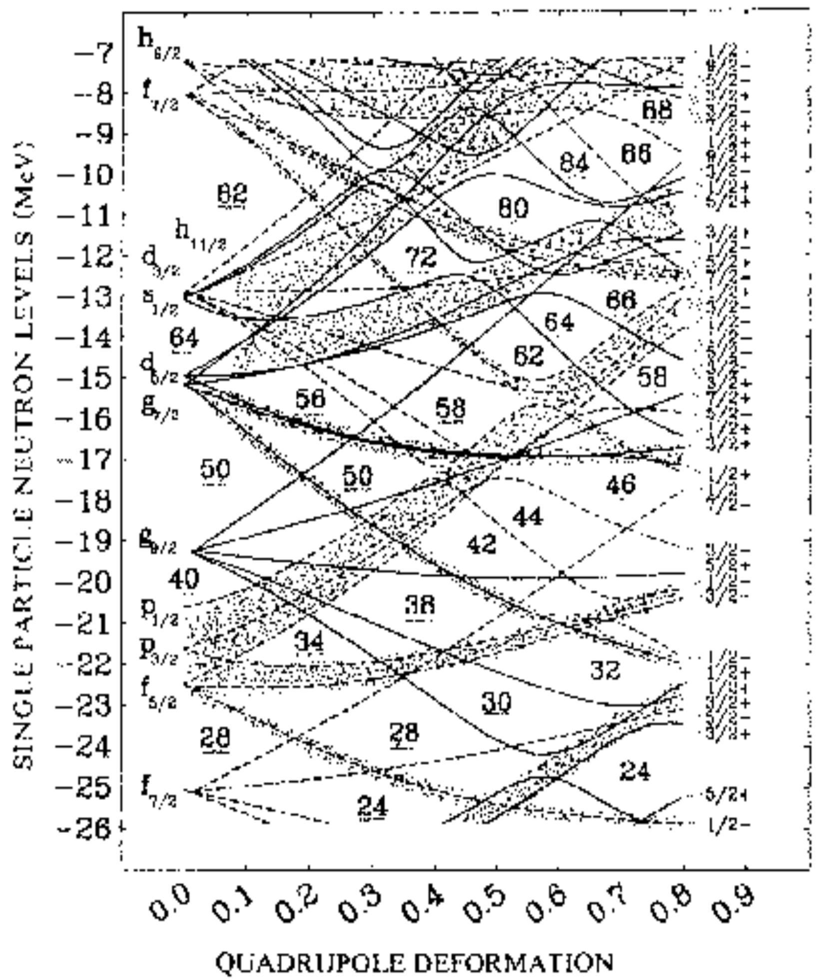
Super-Deformed Rotational Bands (β~0.6)

Superdeformation

shell structure



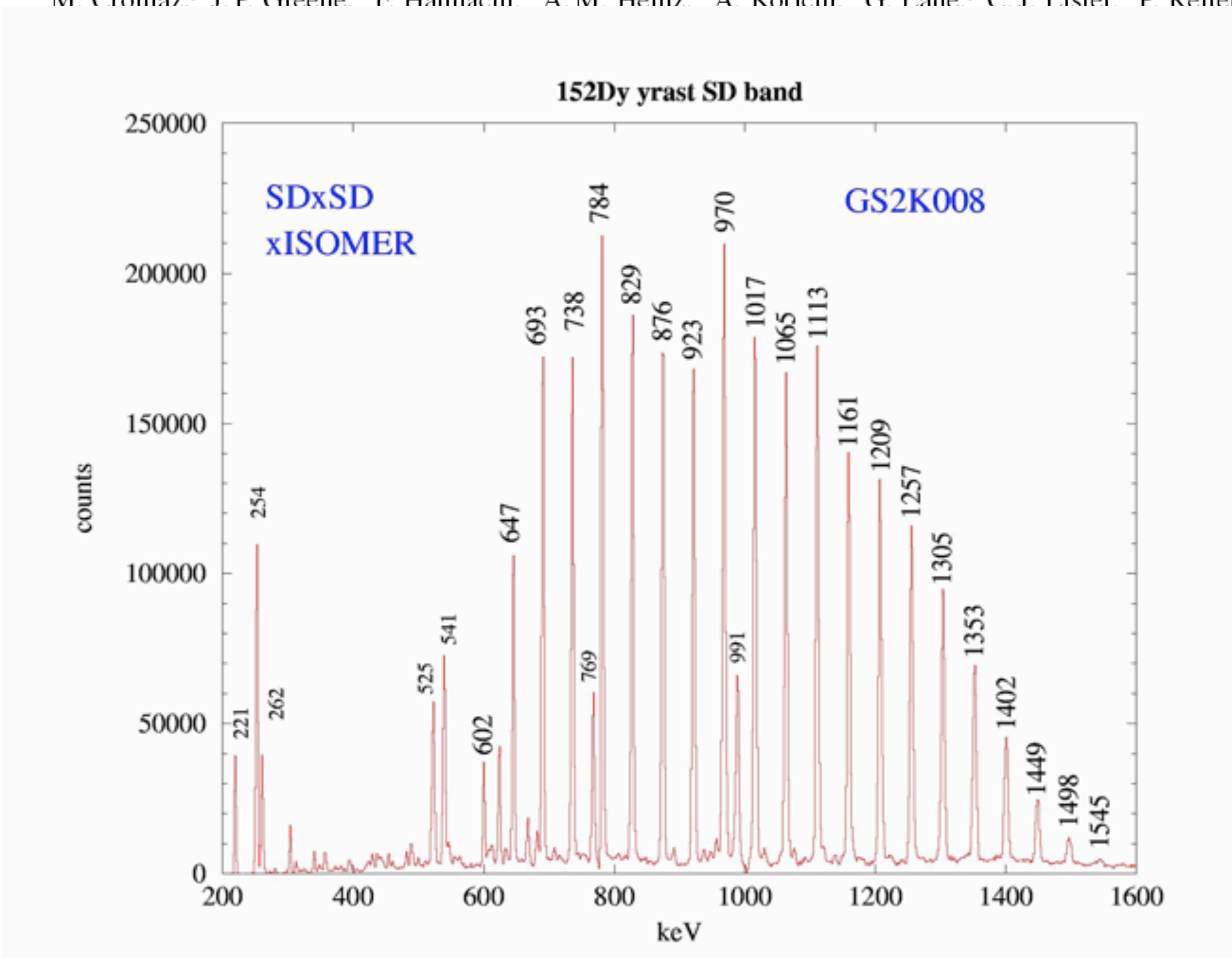
Harmonic oscillator



Wood Saxon potential

Direct Decay from the Superdeformed Band to the Yrast Line in $^{152}_{66}Dy_{86}$

T. Lauritsen,[1] M. P. Carpenter,[1] T. Døssing,[2] P. Fallon,[3] B. Herskind,[2] R. V. F. Janssens,[1] D. G. Jenkins,[1] T. L. Khoo,[1]
F. G. Kondev,[1] A. Lopez-Martens,[4] A. O. Macchiavelli,[3] D. Ward,[3] K. S. Abu Saleem,[1] I. Ahmad,[1] R. Clark,[3]
M. Cromaz,[3] J. P. Greene,[1] F. Hannachi,[4] A. M. Heinz,[1] A. Korichi,[4] G. Lane,[3] C. J. Lister,[1] P. Reiter,[1,5]



^{80}Se + ^{76}Ge @ 311MeV and ^{108}Pd + ^{48}Ca @ 191MeV

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Superdeformation in the $N = Z$ Nucleus ^{36}Ar: Experimental, Deformed Mean Field, and Spherical Shell Model Descriptions

C. E. Svensson,[1] A. O. Macchiavelli,[1] A. Juodagalvis,[2] A. Poves,[3] I. Ragnarsson,[2] S. Åberg,[2] D. E. Appelbe,[4] R. A. E. Austin,[4] C. Baktash,[5] G. C. Ball,[6] M. P. Carpenter,[7] E. Caurier,[8] R. M. Clark,[1] M. Cromaz,[1] M. A. Deleplanque,[1] R. M. Diamond,[1] P. Fallon,[1] M. Furlotti,[9] A. Galindo-Uribarri,[5] R. V. F. Janssens,[7] G. J. Lane,[1] I. Y. Lee,[1] M. Lipoglavsek,[5] F. Nowacki,[10] S. D. Paul,[5] D. C. Radford,[5] D. G. Sarantites,[9] D. Seweryniak,[7] F. S. Stephens,[1] V. Tomov,[9] K. Vetter,[1] D. Ward,[1] and C. H. Yu[5]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

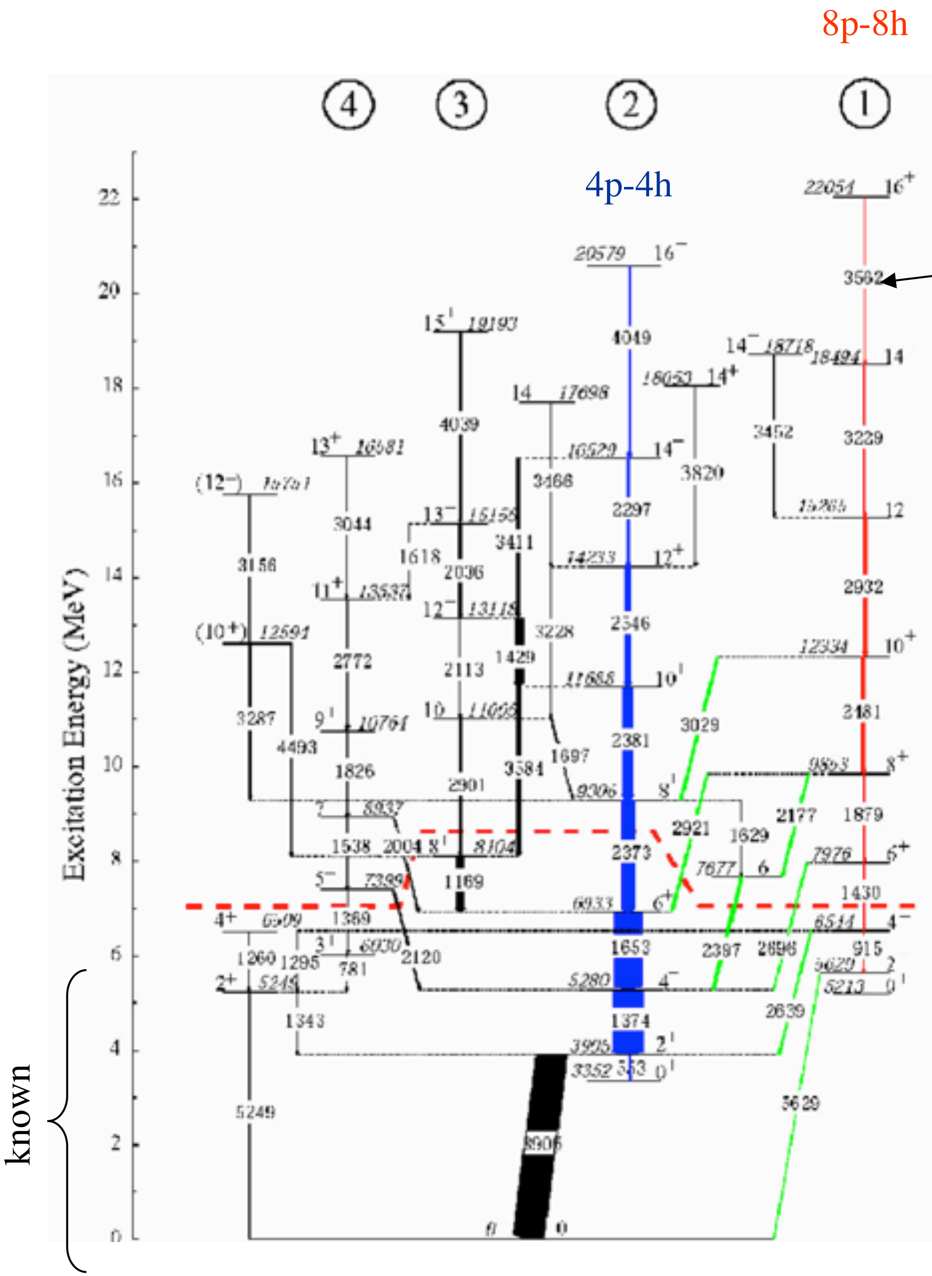
VOLUME 87, NUMBER 22 PHYSICAL REVIEW LETTERS 26 NOVEMBER 2001

Superdeformation in the Doubly Magic Nucleus $^{40}_{20}Ca_{20}$

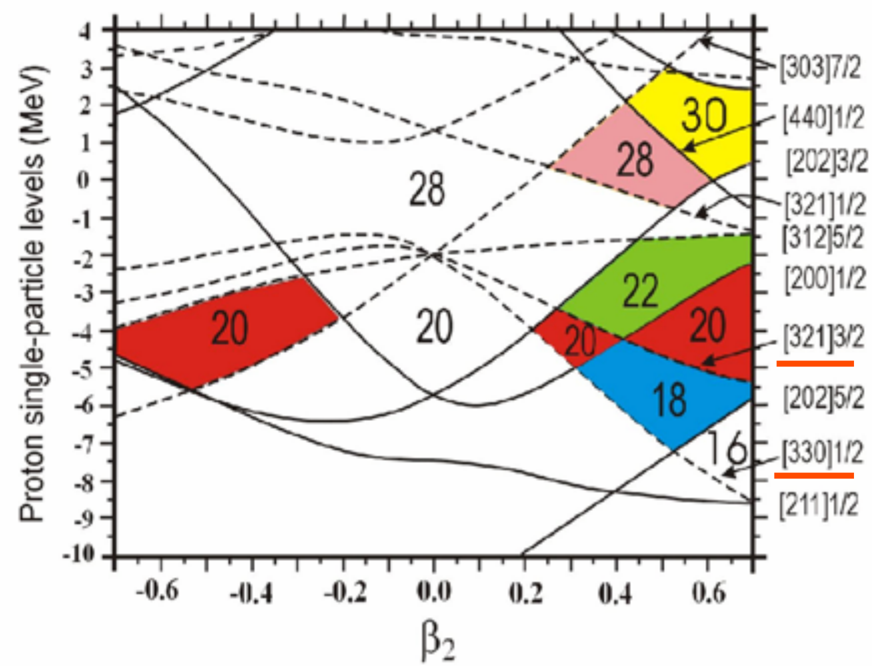
E. Ideguchi,[1] D. G. Sarantites,[1] W. Reviol,[1] A. V. Afanasjev,[2,3,4] M. Devlin,[1,*] C. Baktash,[5] R. V. F. Janssens,[2] D. Rudolph,[6] A. Axelsson,[7] M. P. Carpenter,[2] A. Galindo-Uribarri,[5] D. R. LaFosse,[8] T. Lauritsen,[2] F. Lerma,[1] C. J. Lister,[2] P. Reiter,[2] D. Seweryniak,[2] M. Weiszflog,[7] and J. N. Wilson,[1,†]

[1]*Chemistry Department, Washington University, St. Louis, Missouri 63130*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Physics Department, University of Notre Dame, Indiana 46556-5670*
[4]*Laboratory of Radiation Physics, University of Latvia, LV2169, Miera str. 31, Latvia*
[5]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 37831-6371*
[6]*Department of Physics, Lund University, S-22100 Lund, Sweden*
[7]*The Svedberg Laboratory and Department of Radiation Science, Uppsala University, S-75121 Uppsala, Sweden*
[8]*Department of Physics and Astronomy, SUNY-Stony Brook, New York 11794*
(Received 23 July 2001; published 8 November 2001)

Extend our microscopic understanding of collective rotations in a "complex rotor"

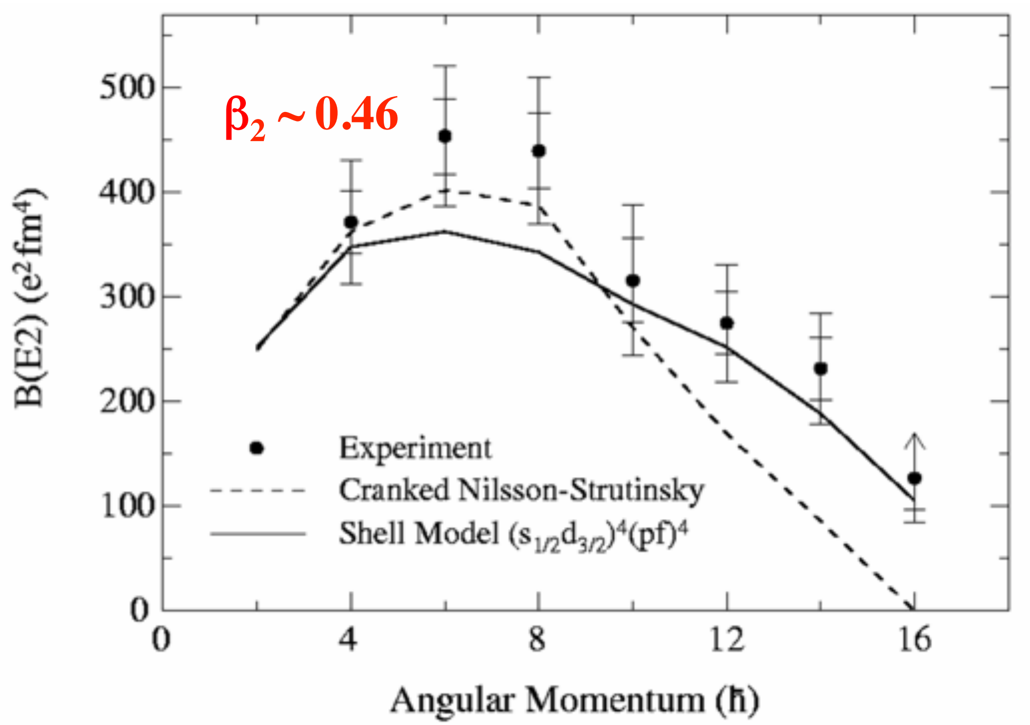


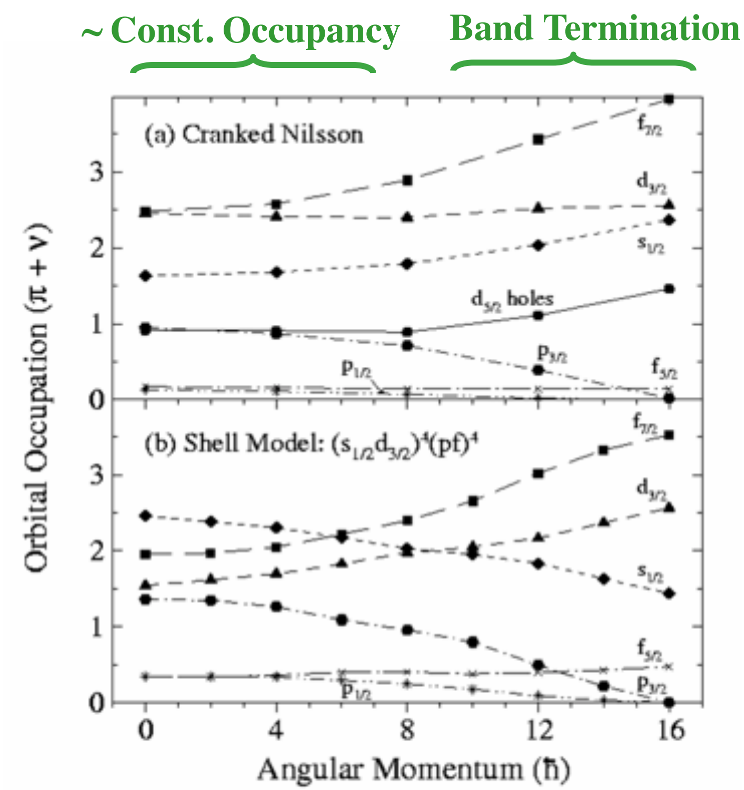
- $^{28}Si(^{20}Ne,2\alpha)^{40}Ca$
- $^{24}Mg(^{24}Mg,2\alpha)^{40}Ca$
- 8p-8h structure identified as $\pi 3^4$, $\nu 3^4$



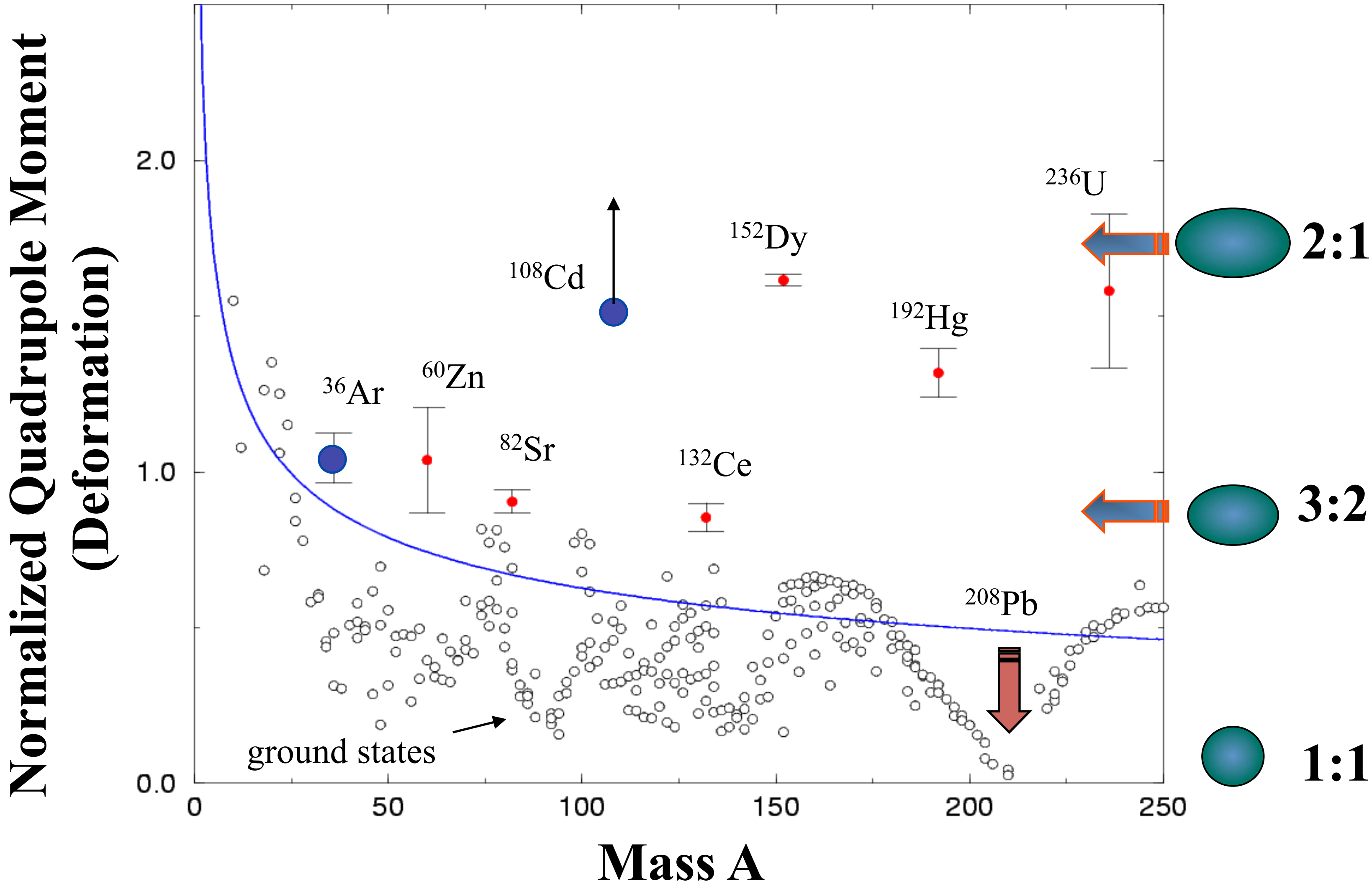
β_2 (high) ~ 0.59
β_2 (low) ~ 0.4

^{36}Ar : Comparison with Theory





- Configurations dominated by core excitations from *sd* to *pf* shell ($\pi 3^2$, $\nu 3^2$)



Normalized Quadrupole Moment
(Deformation)
Mass A
0
50
100
150
200
250
0.0
1.0
2.0
^{36}Ar
^{60}Zn
^{82}Sr
^{108}Cd
^{132}Ce
^{152}Dy
^{192}Hg
^{236}U
^{208}Pb
ground states
2:1
3:2
1:1