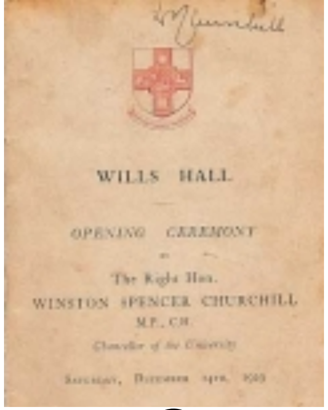
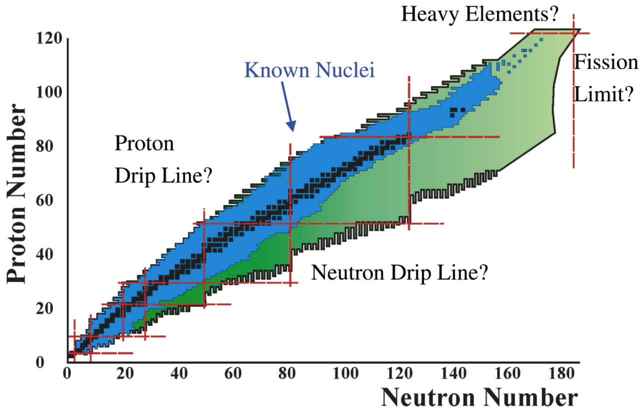
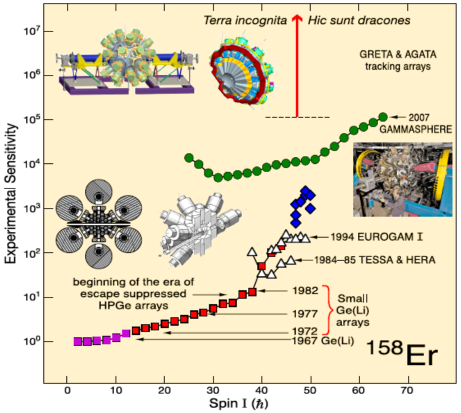
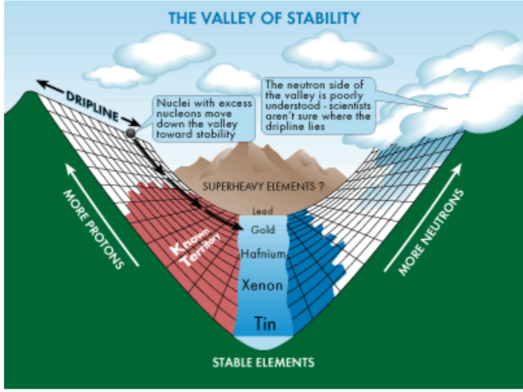
17th UK Nuclear Physics
Postgraduate Summer School
University of Bristol
27th August and 6th September 2013



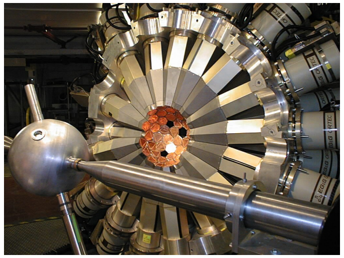
Episode 2. Gamma-Ray Spectroscopy: Selected Exotic Phenomena in Nuclei

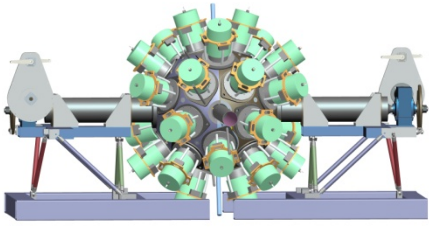






Mark Riley (Florida State University)





Selected Exotic Phenomena in Nuclei:

- I will outline selected physics highlights from of the glorious past…. With a UK emphasis of course!
- In order to move forward with new facilities etc it is important to understand what has gone before…"*The further back you can look, the further forward you are likely to see*." (W. Churchill)

- Nature holds many fascinating secrets!

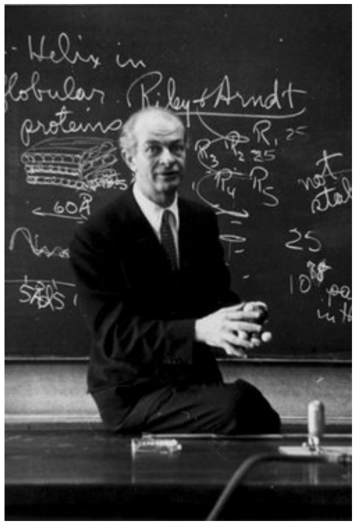
The nucleus is always full of surprises!

Exptal + Theoretical advances ⇔ New Science

What a time we have had! And the fun continues…..

Linus Pauling

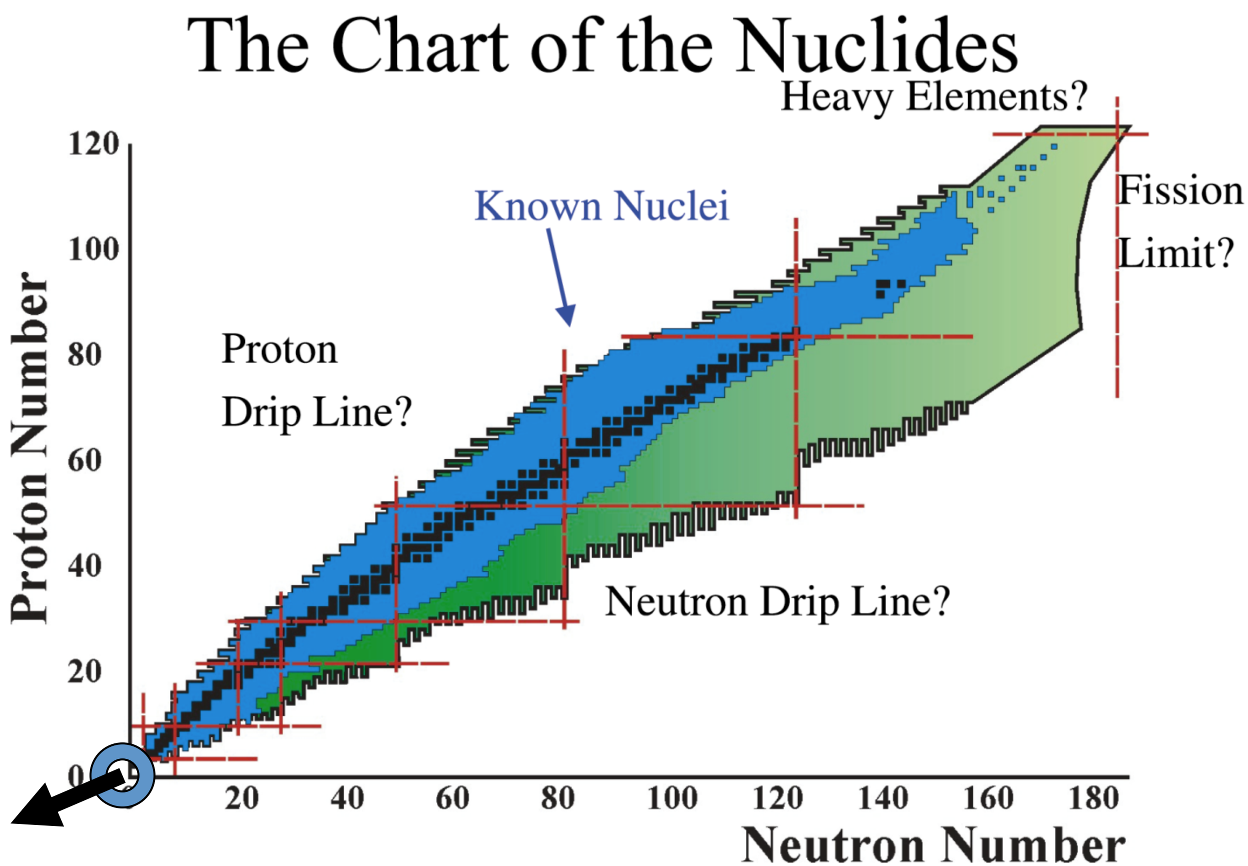
"Satisfaction of one's curiosity is one of the greatest sources of happiness in life."



Albert Einstein

"Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning."

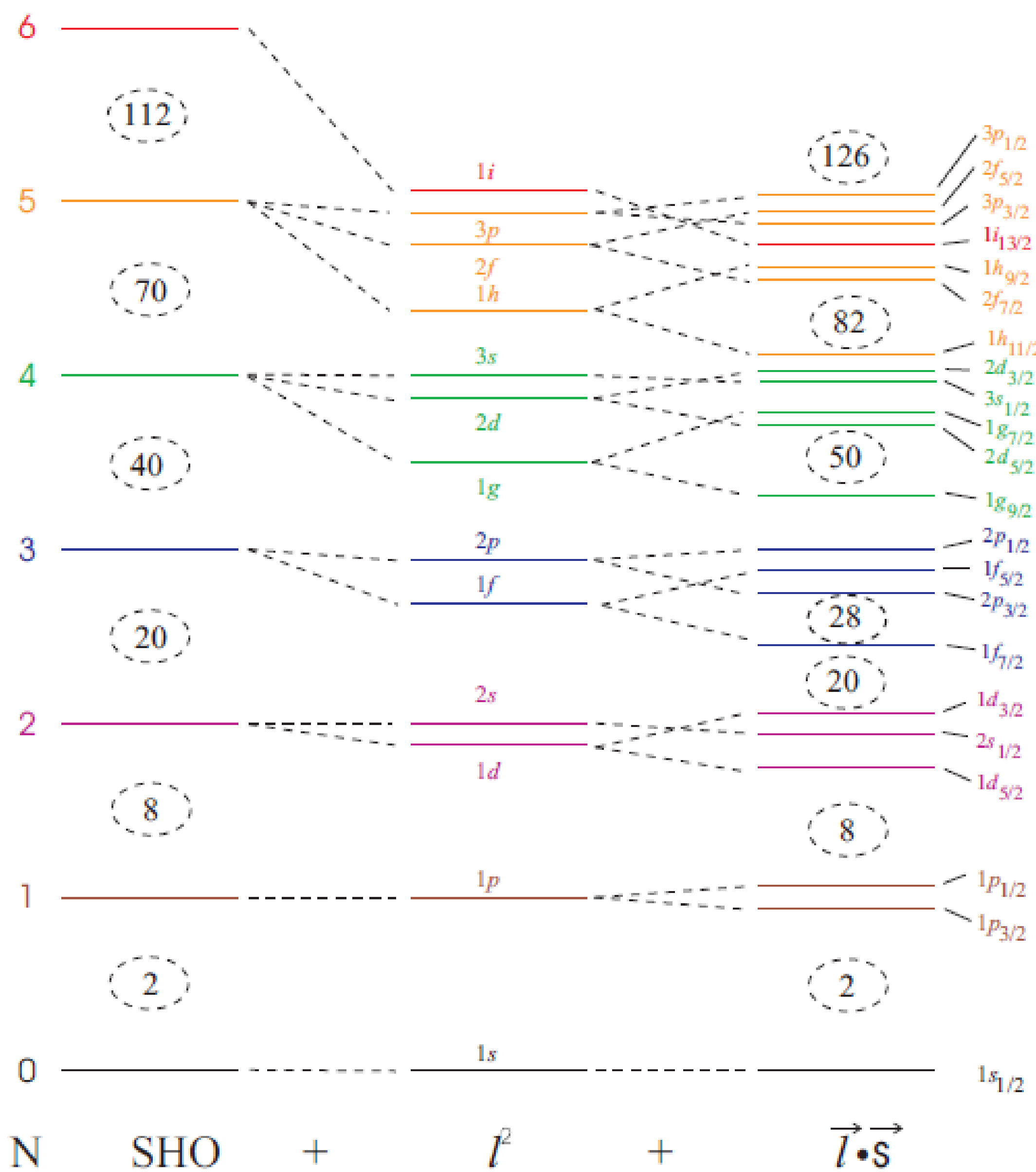
Pushing to the limits allows us also to look in more detail at excited states in nuclei in from the experimental edge … it is all important!



Increasing Angular Momentum and Excitation Energy:

A most excellent way to investigate nuclear structure, especially to see what the intruder orbitals are doing.

Importance of Intruder Orbitals



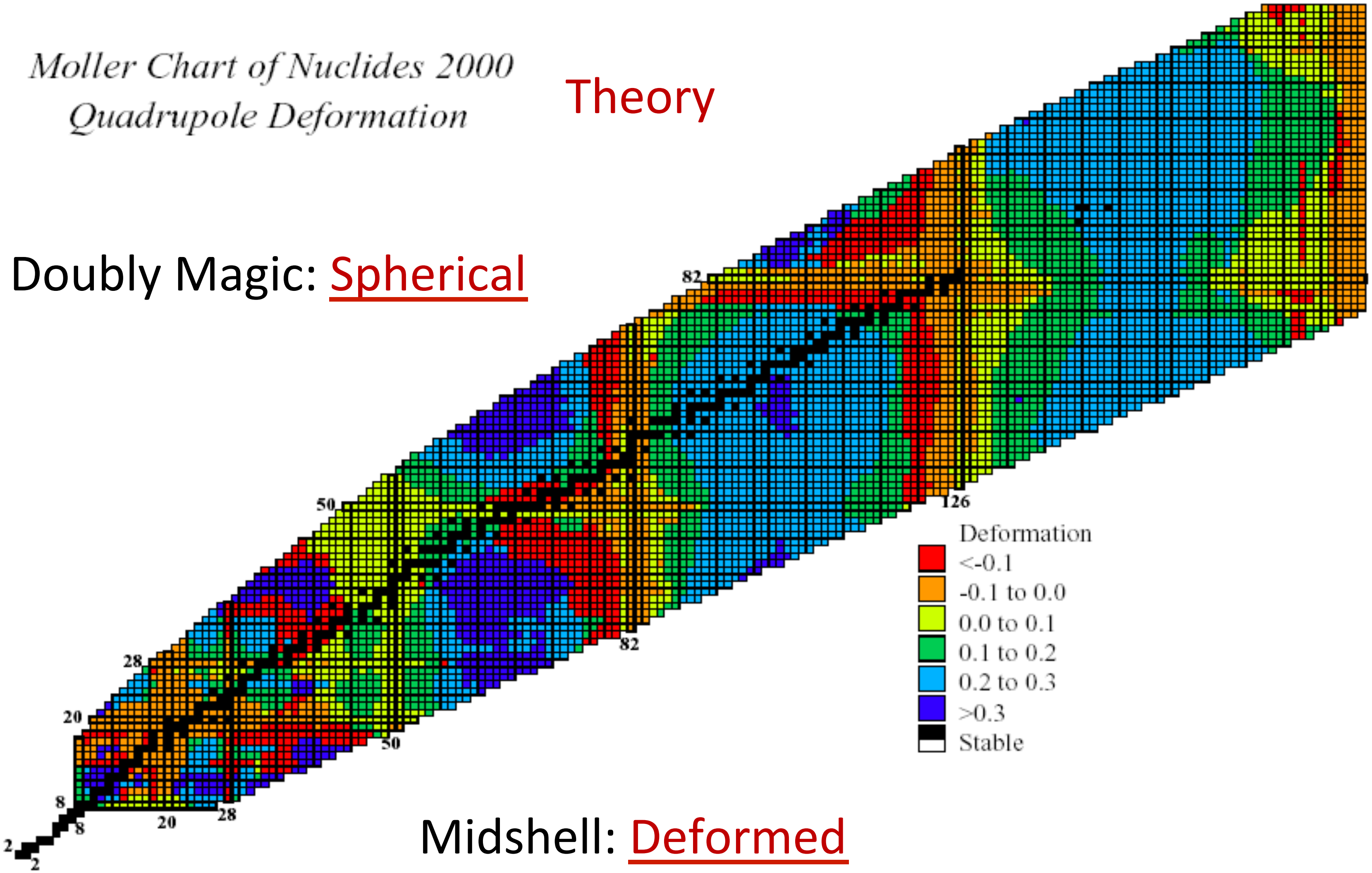
Eddie Paul's Lecture Notes: A Must Download

- ***Liverpool*: Nuclear Structure - *Nuclear Physics***
- *ns.ph.liv.ac.uk/**PHYS490/Phys490**_revision.pdf*
- File Format: PDF/Adobe Acrobat - Quick View
10/05/2010. E.S. *Paul*: *PHYS490* Advanced *Nuclear Physics* Revision. 1. Revision: *PHYS490*. Advanced *Nuclear Physics* **...**

Deformation Systematics

Theory

Doubly Magic: Spherical



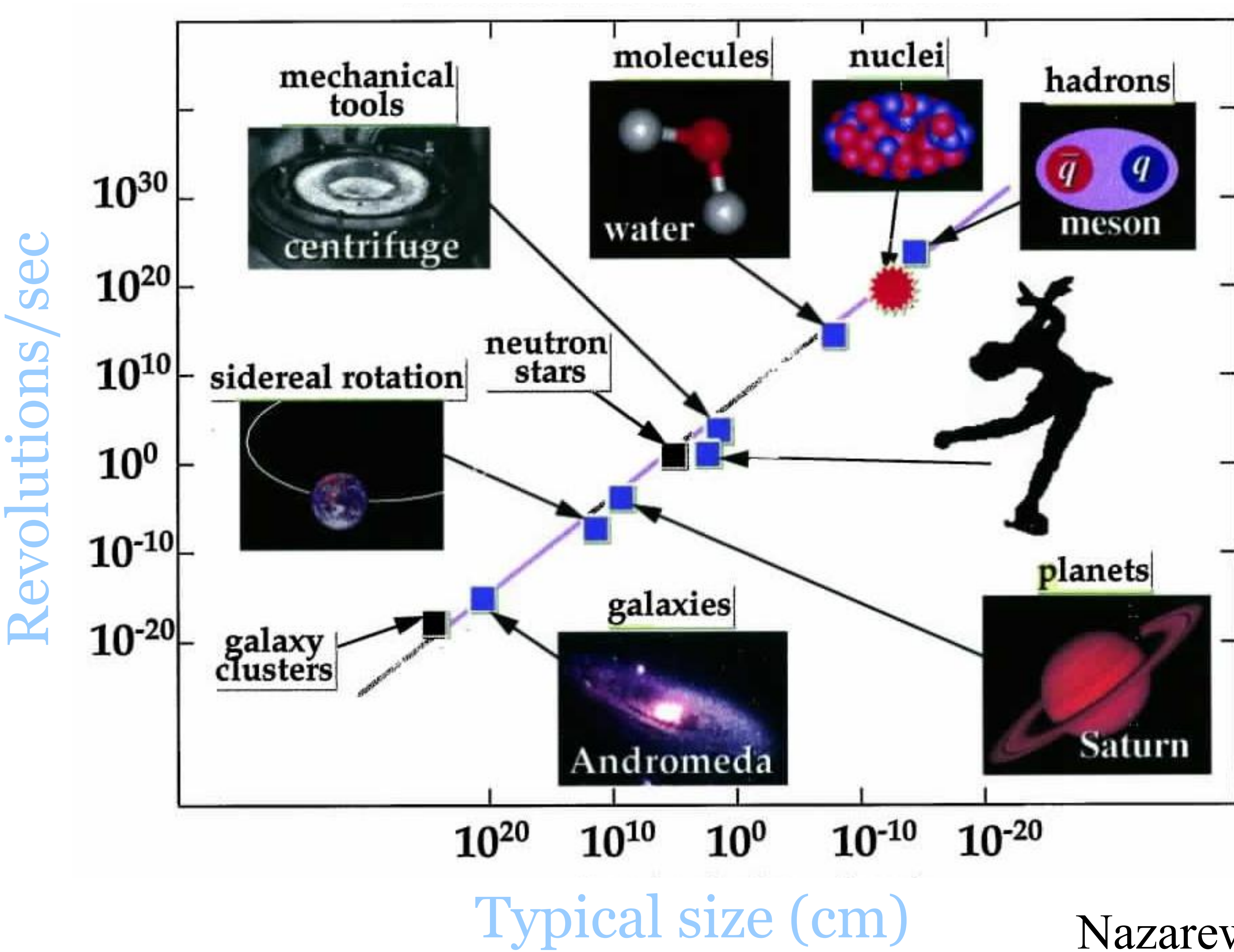
Midshell: Deformed

Deformation allows Rotation! Rotation can reveal information about the internal structure!

- Hard boiled and soft boiled egg experiment.

Spinning objects are fun!

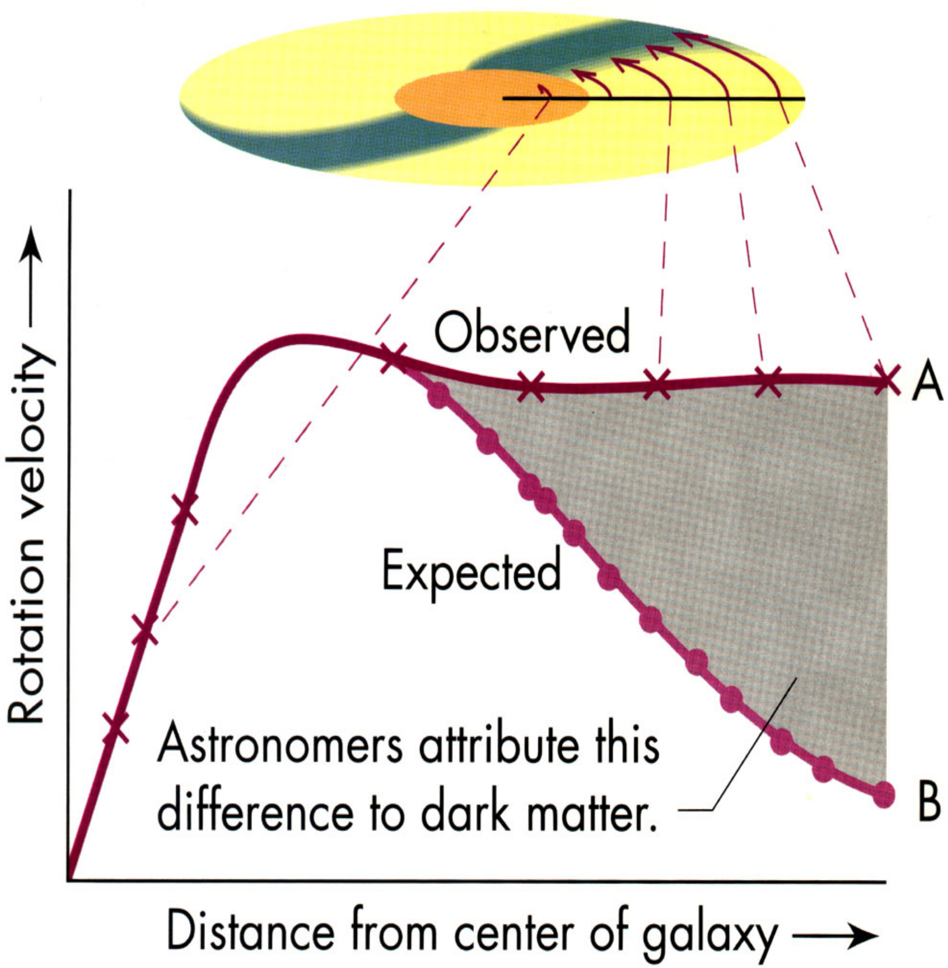
Rotations in the Universe

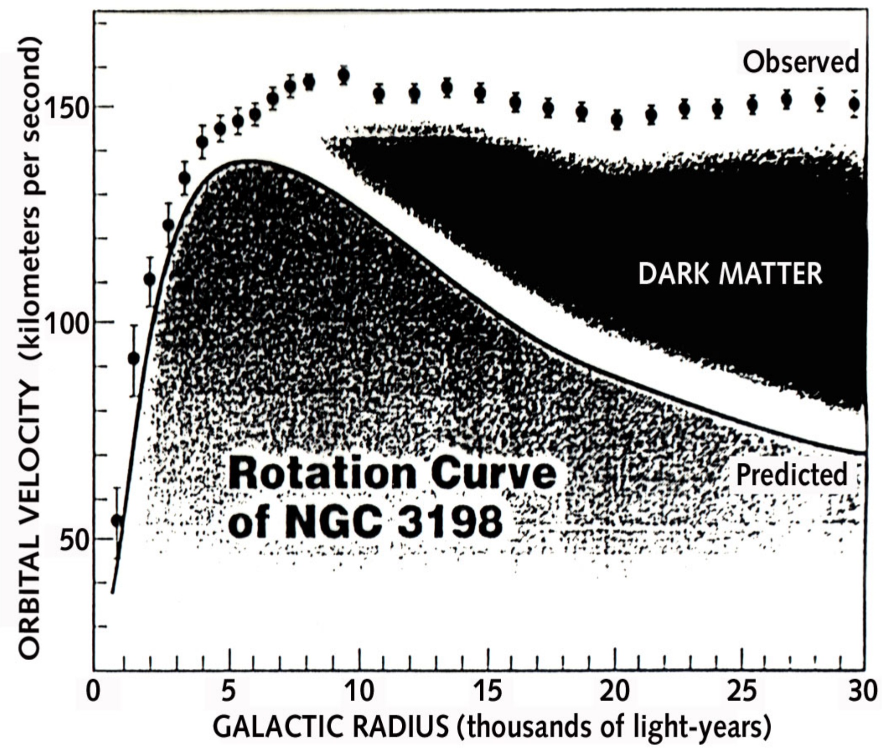


Nazarewicz

Large Rotating Body

Dark Matter in a Spiral Galaxy





Quantized angular momentum and rotations in nuclei

ON THE
TRANSMUTATION OF ATOMIC NUCLEI BY IMPACT OF MATERIAL PARTICLES

I. GENERAL THEORETICAL REMARKS

BY

N. BOHR AND F. KALCKAR

Mathematisk-fysiske Meddelelser XIV, 10 1937

We must in fact assume that any orbital momentum is shared by all the constituent particles of the nucleus in a wav which resembles that of the rotation of a solid body. Denoting by J the moment of inertia, we obtain

MAY 15, 1938 PHYSICAL REVIEW VOLUME 53

On the Rotation of the Atomic Nucleus

E. TELLER, *George Washington University, Washington, D. C.*

AND

J. A. WHEELER, *University of North Carolina, Chapel Hill, N. C.*

(Received March 23, 1938)

Physical Review 90 (1953) 717 - Letters to Editor

Rotational States in Even-Even Nuclei

AAGE BOHR AND BEN R. MOTTELSON*
Institute for Theoretical Physics, Copenhagen, Denmark

$$E_I = \frac{\hbar^2}{2\mathcal{J}} I(I+1), \quad I = 0, 2, 4, 6, \text{ even parity} \qquad (1)$$

Bohr and Mottelson (with Rainwater) were awarded the 1975 Nobel Prize for connecting the single-particle and collective aspects of nuclear behavior into a consistent framework.

Physical Review online PROLA system is now complete back to 1893 with linked references. Fantastic step forward. Thanks APS!

PHYSICAL REVIEW VOLUME 81, NUMBER 1 JANUARY 1, 1951

On the Quantization of Angular Momenta in Heavy Nuclei

AAGE BOHR
*Department of Physics, Columbia University, New York, New York**

(Received May 31, 1950)

The individual particle model of nuclear structure fails to account for the observed large nuclear quadrupole moments. It is possible, however, to allow for the existence of the quadrupole moments, and still retain the essential features of the individual particle model, by assuming the average field in which the nucleons move to deviate from spherical symmetry. The assumptions underlying such an asymmetric nuclear model are discussed; this model implies, in particular, a quantization of angular momenta in analogy with molecular structure. The asymmetric model appears to account better than the extreme single particle model for empirical data regarding nuclear magnetic moments.

I. INTRODUCTION

THE individual particle model, which describes the stationary state of a nucleus in terms of the motion of the individual nucleons in an average nuclear field, has accounted successfully for a large number of nuclear properties.[1] In the simplest form of this model the nucleons are assumed to move in a field of spherical symmetry and the quantization of angular momenta is similar as in atomic structures.

A model of this type has recently been considered independently by J. Rainwater,[3] who found it possible to account for the order of magnitude of the quadrupole moments by estimating the nuclear deformation produced by the centrifugal pressure of the odd particle. The following considerations, however, are largely independent of the origin of the nuclear deformations responsible for the large quadrupole moments.

II. THE ASYMMETRIC NUCLEAR MODEL

The Angular Momentum World of the Nucleus according to Bohr & Mottelson circa mid-70's

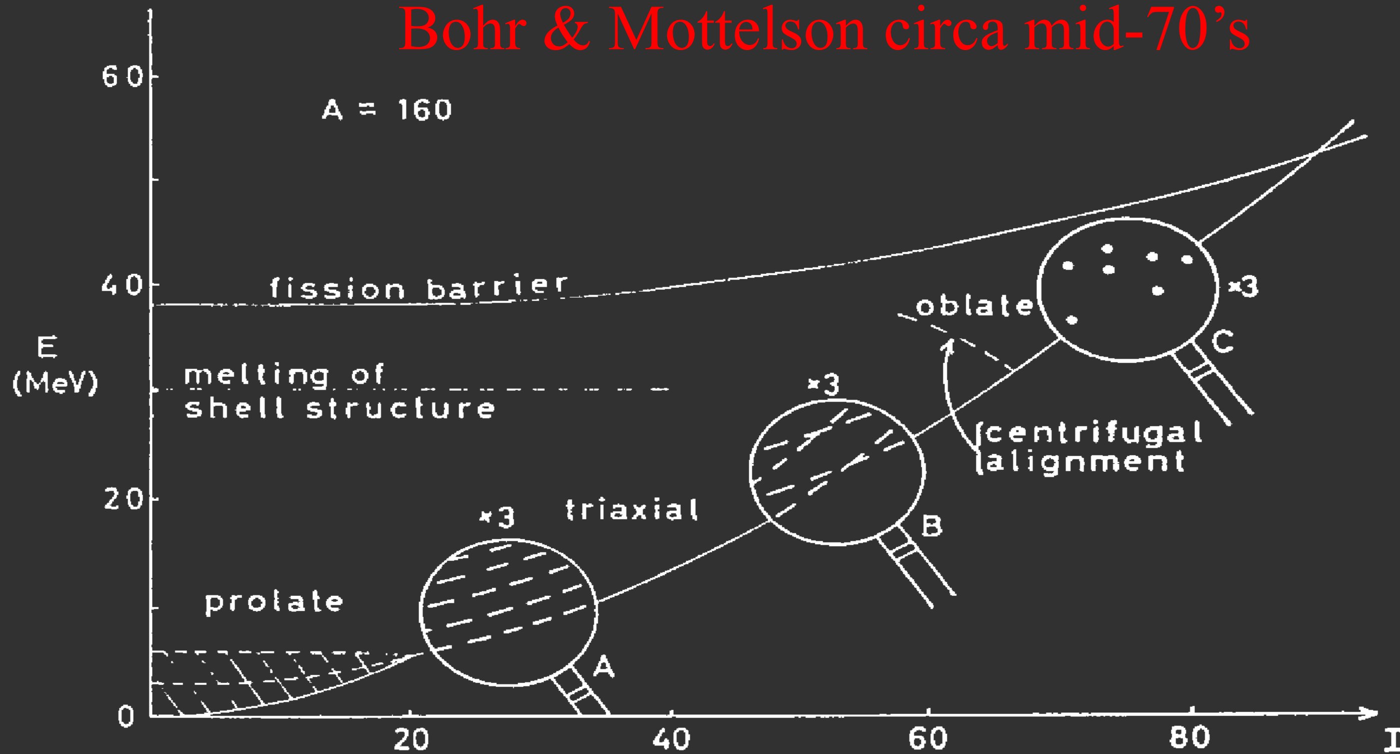
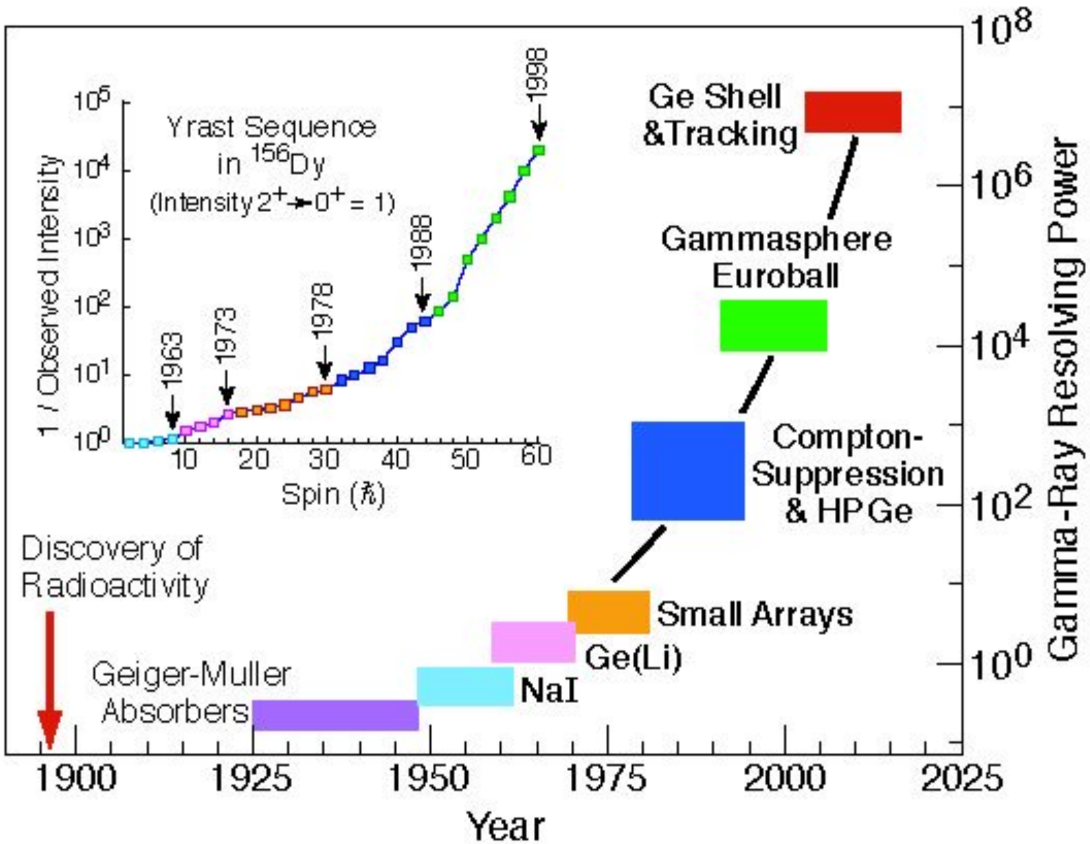


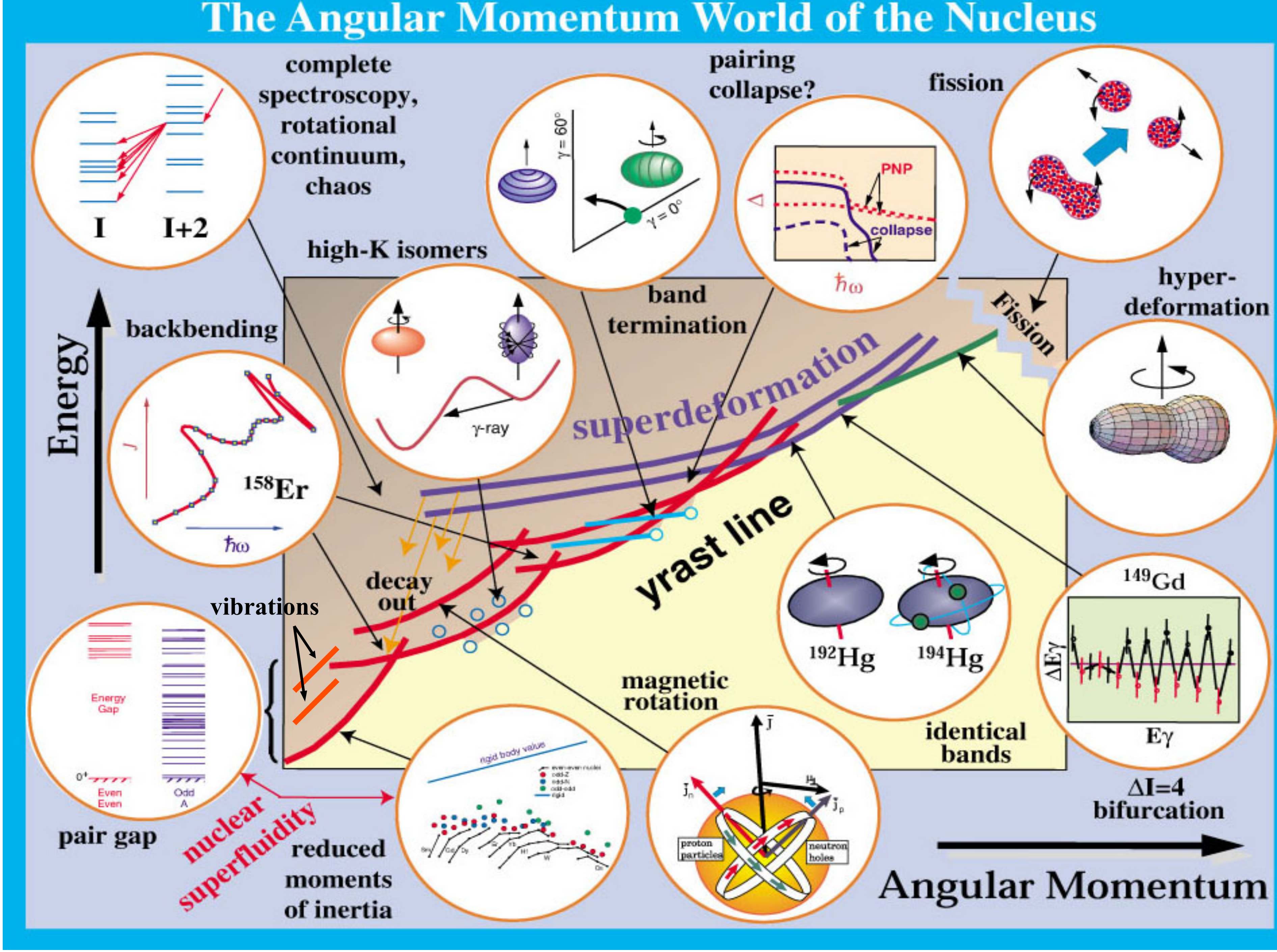
Fig. 11. Nuclear phases a a function of angular momentum and excitation energy (schematic).

The picture sketched in Fig. 11 is admittedly highly conjectural; however, with the ingenious experimental approaches that are being developed, we may look forward with excitement to the detailed spectroscopic studies that will illuminate the behavior of the spinning quantized nucleus.

Evolution of γ-ray detector technology



The calculated resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states.


The Angular Momentum World of the Nucleus
complete spectroscopy, rotational continuum, chaos
I
I+2
pairing collapse?
PNP
Δ
collapse
ħω
fission
$\gamma = 60°$
$\gamma = 0°$
high-K isomers
γ-ray
band termination
Fission
hyper-deformation
Energy
backbending
J
^{158}Er
ħω
superdeformation
yrast line
decay out
vibrations
^{192}Hg
^{194}Hg
^{149}Gd
ΔEγ
Eγ
Energy Gap
0+
Even Even
Odd A
pair gap
nuclear superfluidity
rigid body value
reduced moments of inertia
magnetic rotation
proton particles
neutron holes
identical bands
ΔI=4 bifurcation
Angular Momentum

VOLUME 83, NUMBER 14 PHYSICAL REVIEW LETTERS 4 OCTOBER 1999

Yrast Spectra of Weakly Interacting Bose-Einstein Condensates

B. Mottelson

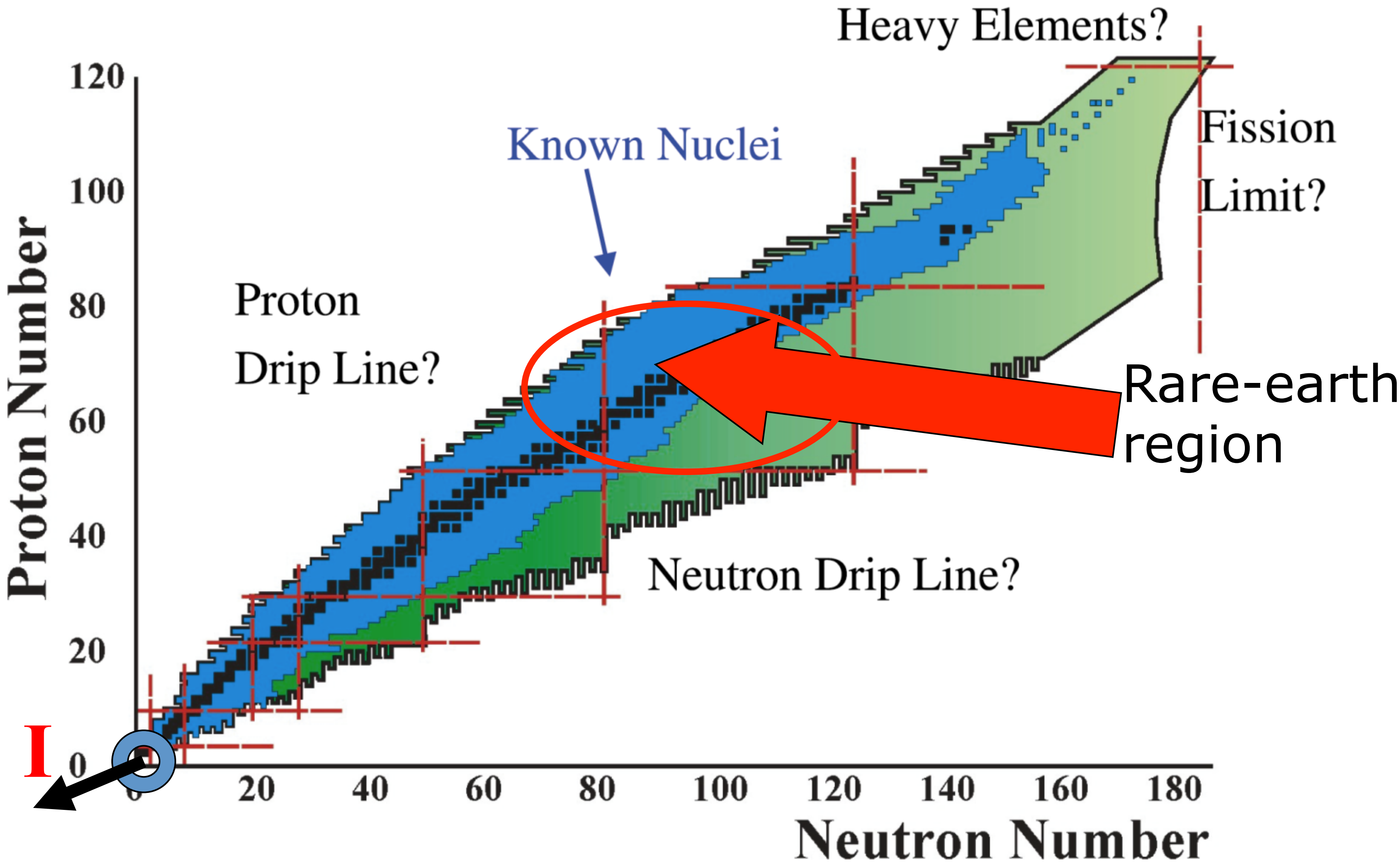
Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

(Received 23 December 1998)

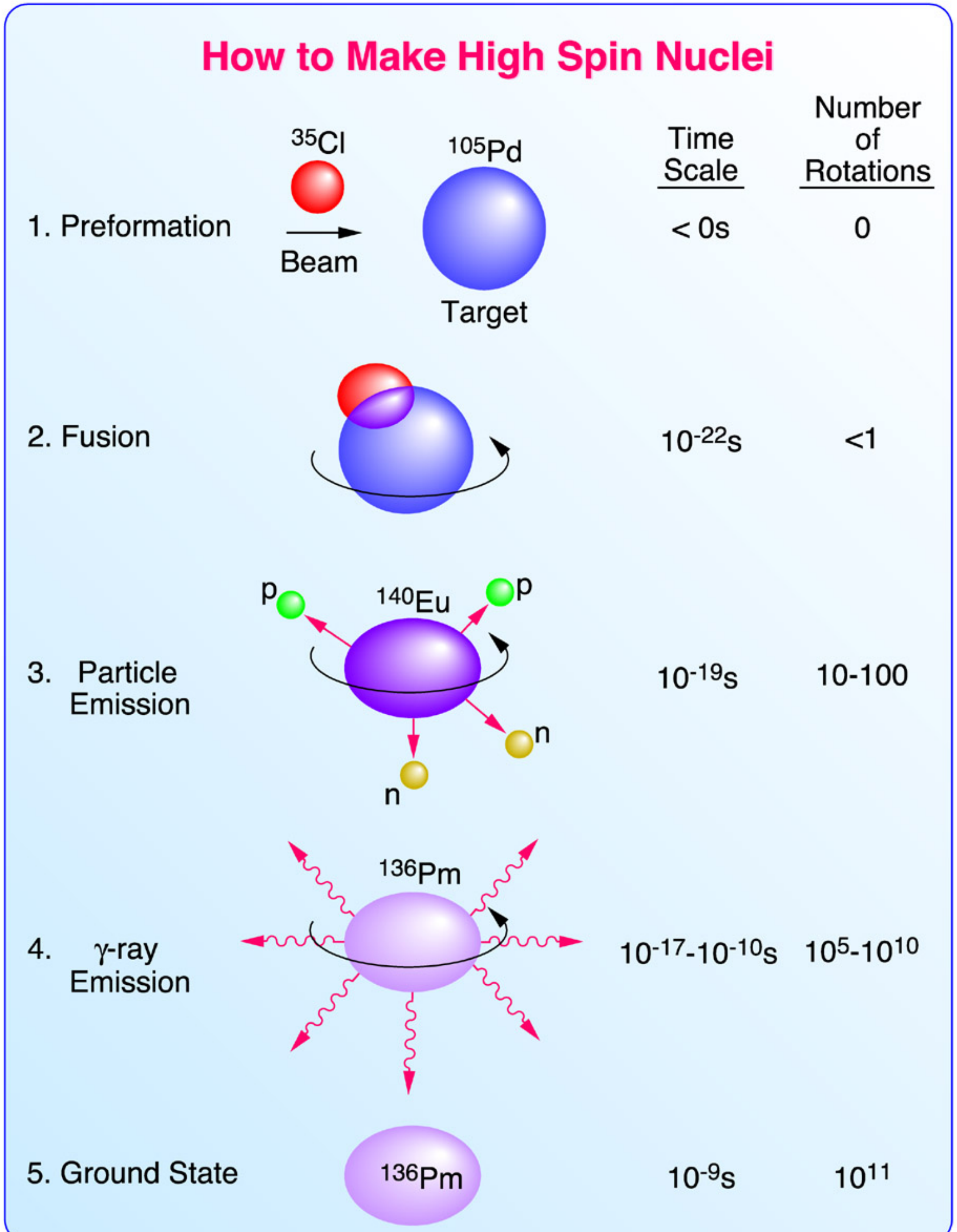
Lessons learned in nuclei being used to understand BECs

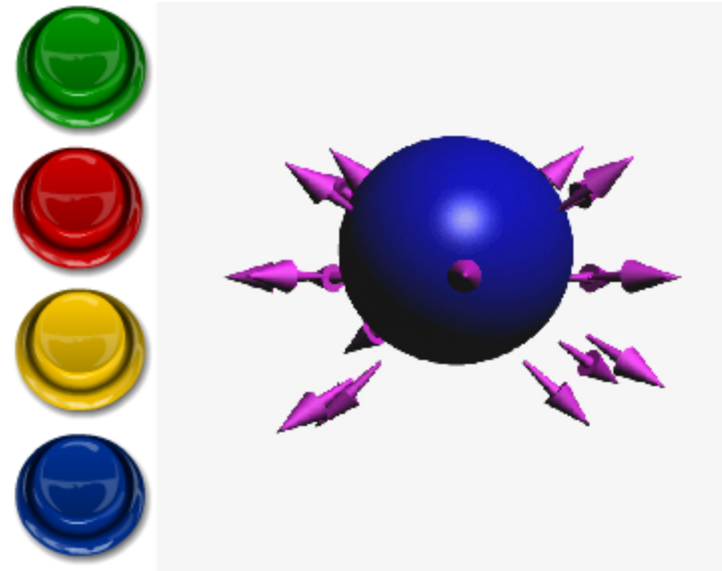
Other mesoscopic systems have benefited also!

Where are the limits and what happens on the way?



Increasing Angular Momentum and Excitation Energy: An excellent way to investigate nuclear structure, especially to see what the critically important intruder orbitals are doing.





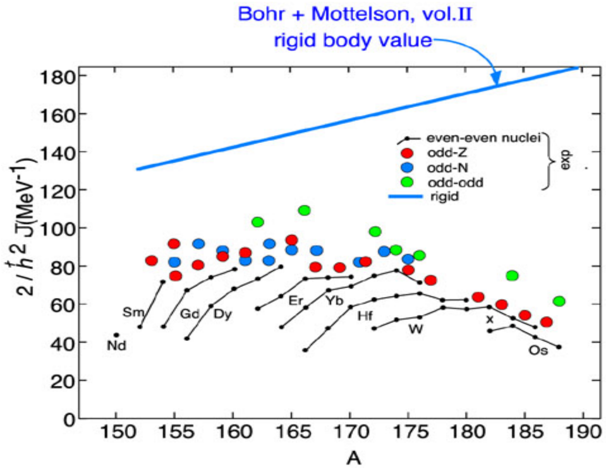
- **Need to catch as many of the γ rays in each cascade as possible.**

- **Need efficient detector systems!**

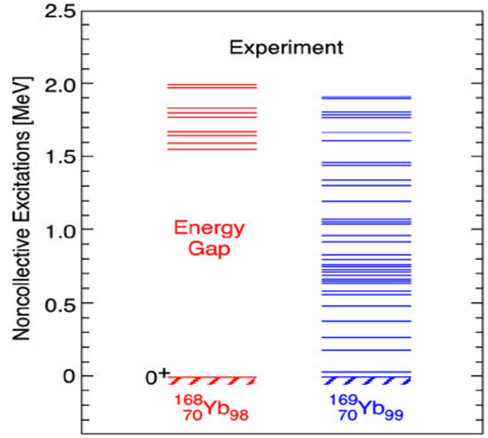
Backbending

Nuclear Superfluidity and Rotation

The unique laboratory of the nucleus is found to display superfluid properties.

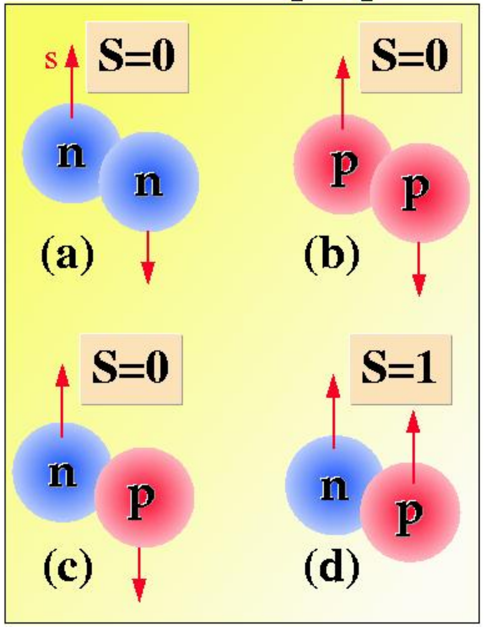


For deformed nuclei
$\mathcal{J} \approx 30\% \, \mathcal{J}_{rigid}$

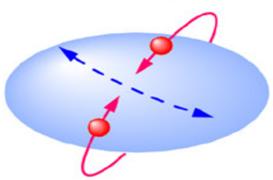


For even-even nuclei $I^{\pi}_{g.s.}=0^+$ and show a large energy gap as compared to odd-nuclei.

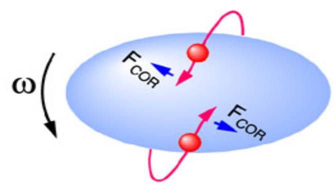
nucleonic Cooper pairs

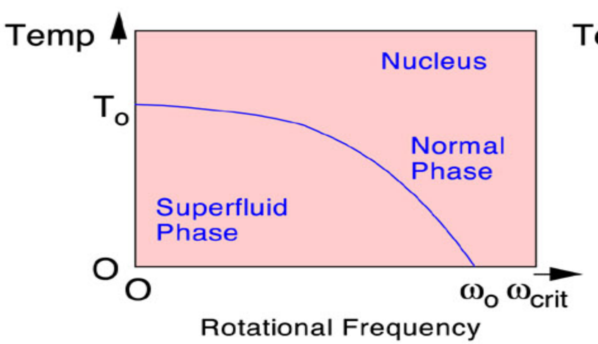


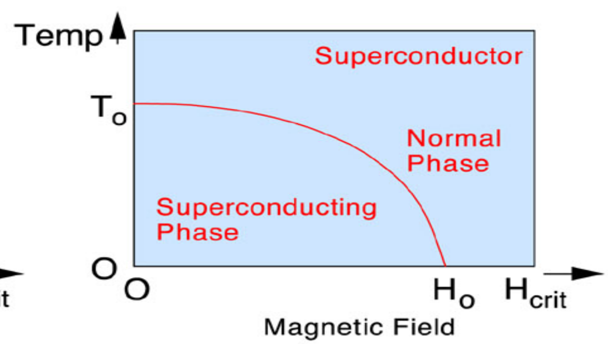
The superfluid condensate arises from nucleons teaming up in time-reversed "Cooper" pairs and scattering coherently.

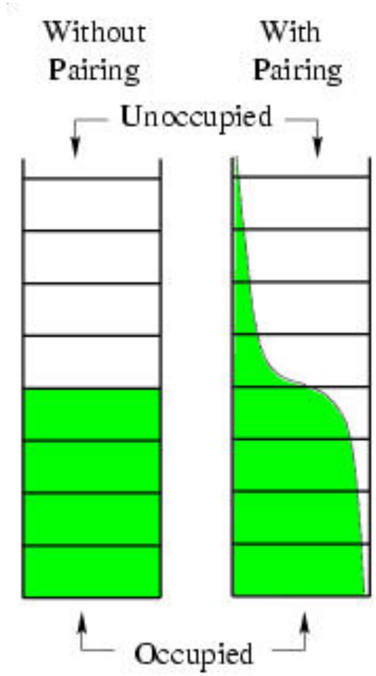


But collective rotation of the nucleus tries to break these correlated fermions apart (The Mottelson-Valatin Effect).

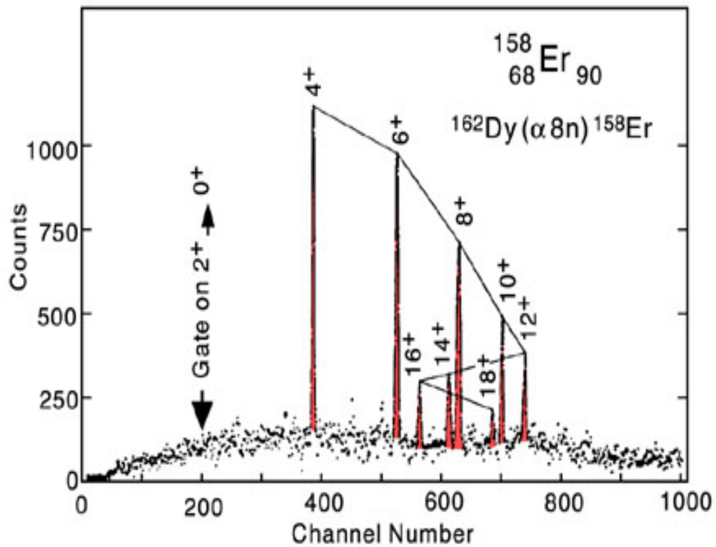


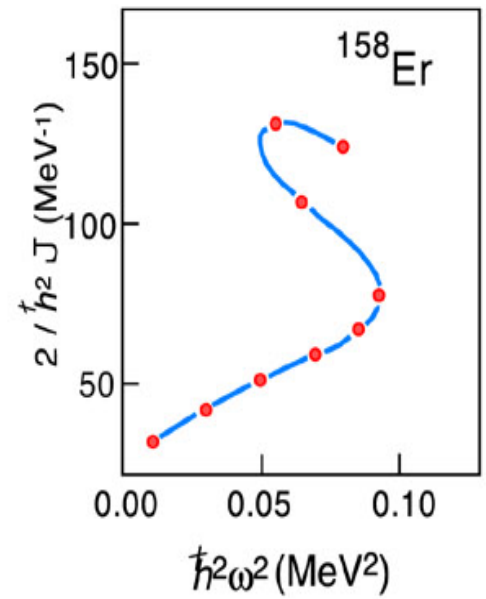






In the 1970's it was thought that this "phase transition" had been discovered with the observation of "backbending".

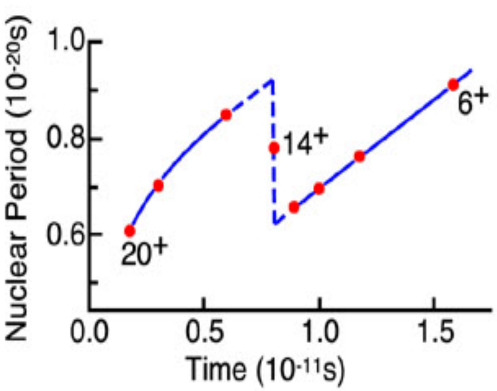


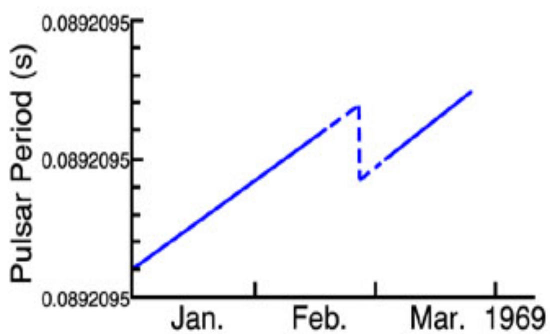


>700 backbends now observed. Lots of important theory work,

eg, Lund, Warsaw + many others

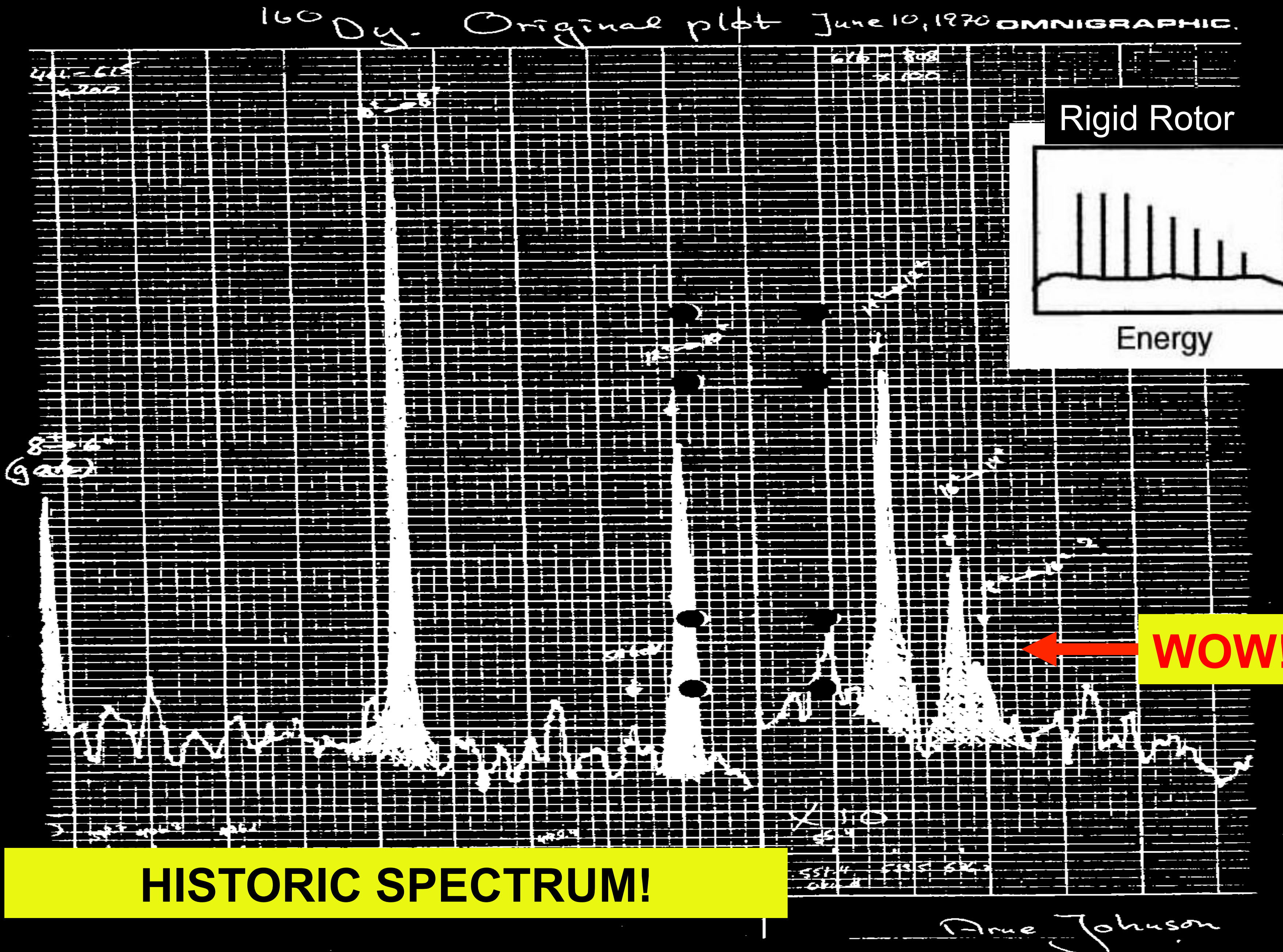
But this turned out not to be the case. Backbending is now understood as the rotational alignment of a specific pair of high-j nucleons.





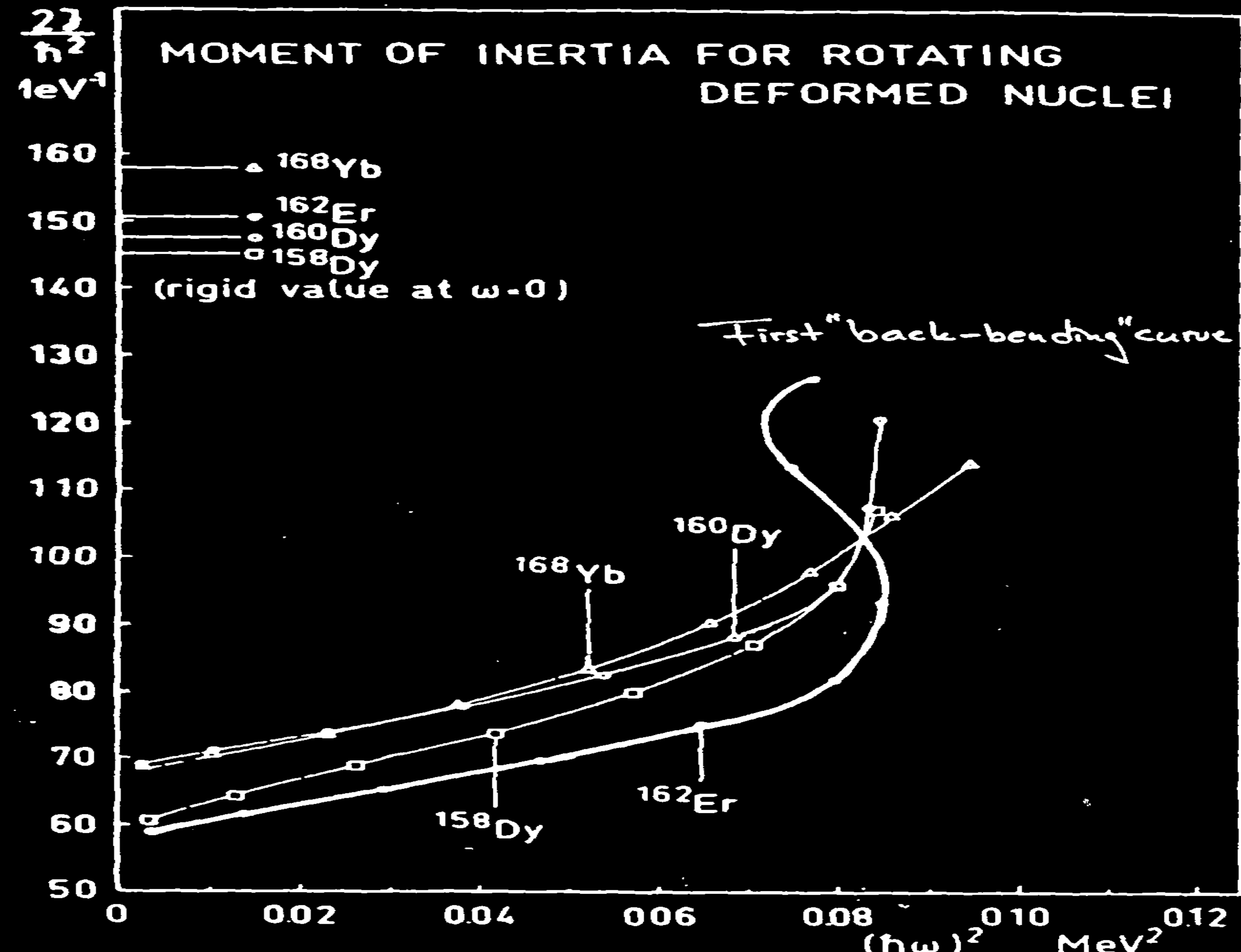
Note the analogy of rotating nuclei and pulsars when comparing plots of the rotation period versus time.

Glendenning, Pei & Weber PRL 79 (1997) 1603



WOW!!

HISTORIC SPECTRUM!



A. Johnson, H. Ryde and S.A. Hjorth
Nuc. Phys. A179 (1972) 753

CORIOLIS EFFECTS IN THE YRAST STATES

Stephens and Simon

Nuc. Phys. A183 (72) 257

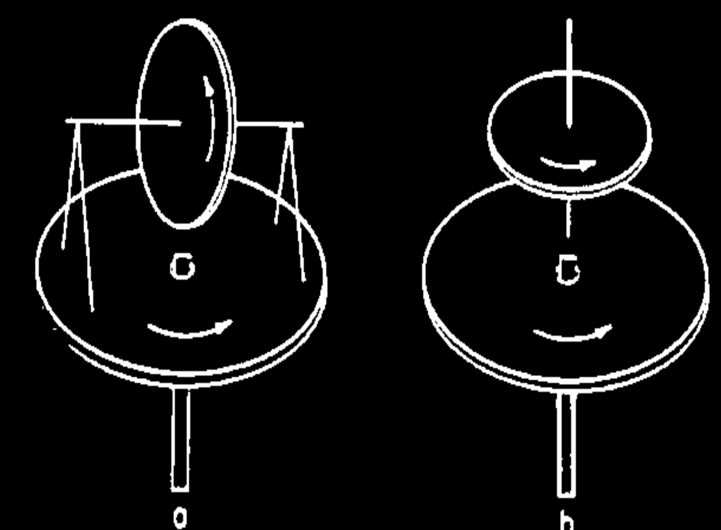
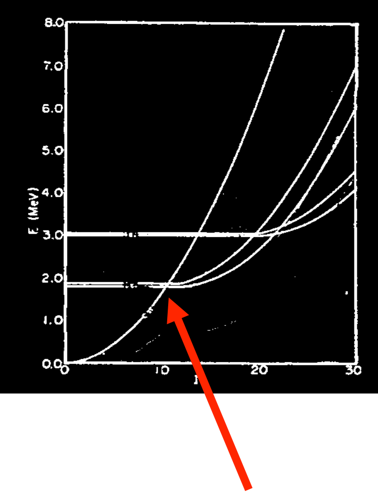


Fig. 4. The Coriolis effects on a spinning wheel constrained to turn with a turntable (a) tend to produce the configuration shown in (b).

Energy vs Spin plot



Backbend!

Gamma Ray Energies and Rotational Frequency

- The energy of a rotational band for $K = 0$ is:

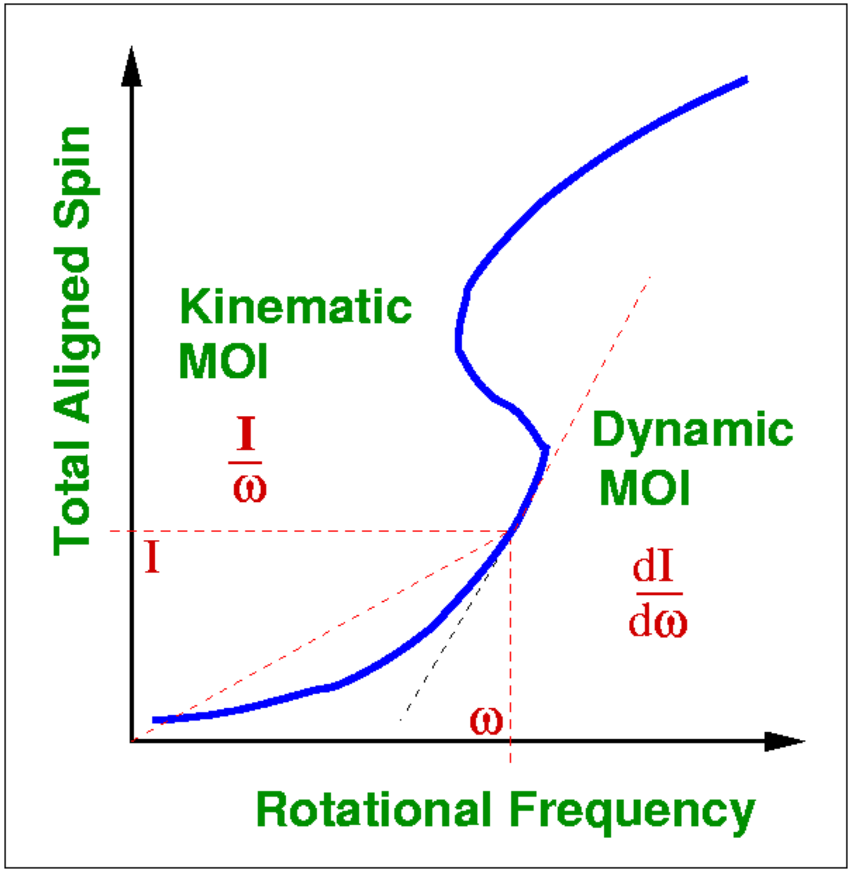
  $E = E_0 + (\hbar^2/2\Im)\, I(I + 1)$, $I = 0, 2, 4\ldots$

- The energy difference between consecutive levels ΔE represents the gamma-ray energy
- The spin difference between consecutive levels is $\Delta I = 2$
- The rotational frequency ω is defined as:

  $\omega\hbar = dE/dI = \Delta E/\Delta I = E_\gamma/2$

  i.e. the frequency is just half the gamma-ray energy

Kinematic and Dynamic MoI's



Rigid body: $\mathfrak{I}^{(1)} = \mathfrak{I}^{(2)}$

High spin: $\mathfrak{I}^{(1)} \approx \mathfrak{I}^{(2)}$

- Assuming maximum alignment on the x-axis ($I_x \sim I$), the kinematic moment of inertia is defined:

  $\mathfrak{I}^{(1)} = [(2/\hbar^2)\, dE(I)/d(I^2)]^{-1}$

  $= \hbar\, I/\omega$

- The dynamic moment of inertia (response of the system to a force) is:

  $\mathfrak{I}^{(2)} = [(1/\hbar^2)\, d^2E(I)/dI^2]^{-1}$

  $= \hbar\, dI/d\omega$

- And $\mathfrak{I}^{(2)} = \mathfrak{I}^{(1)} + \omega\, d\mathfrak{I}^{(1)}/d\omega$

- Yrast banc in ^{158}Er

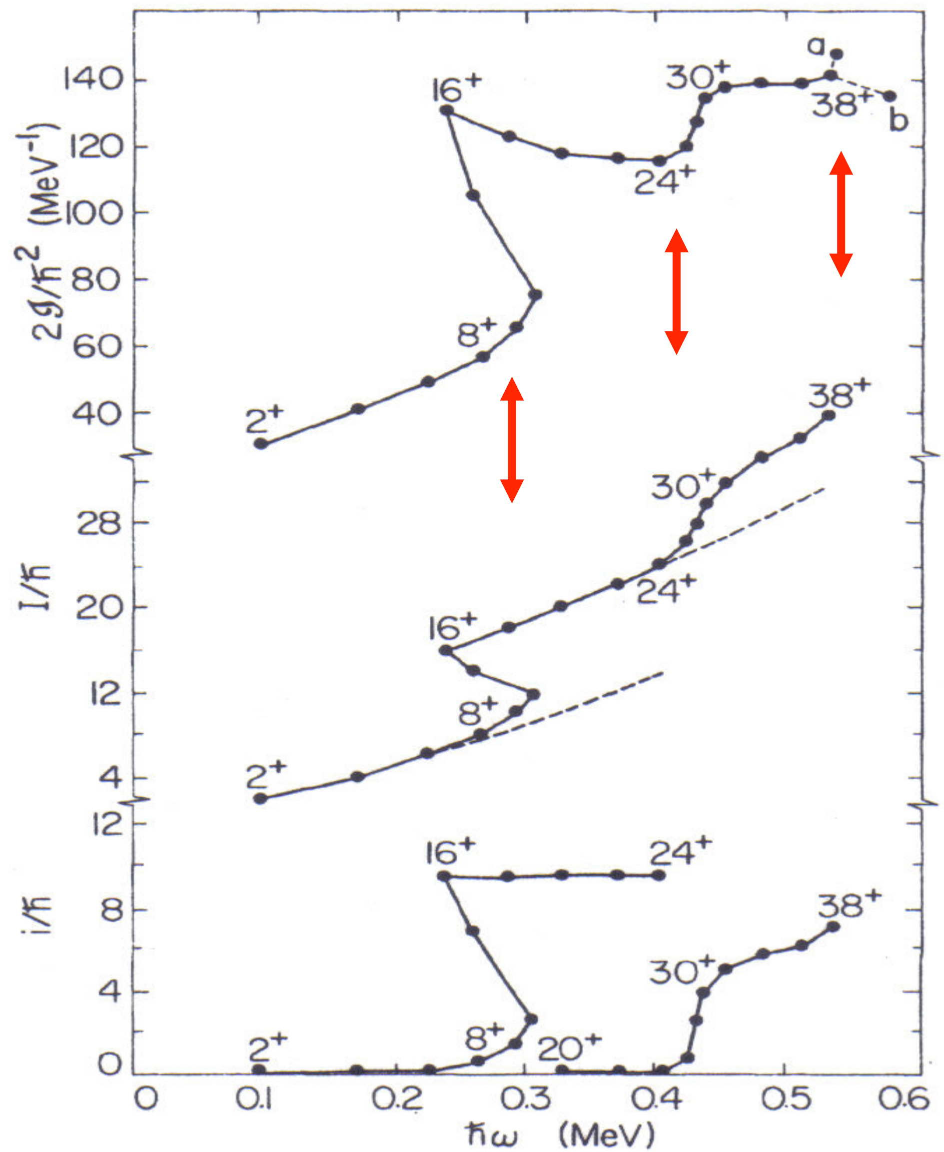
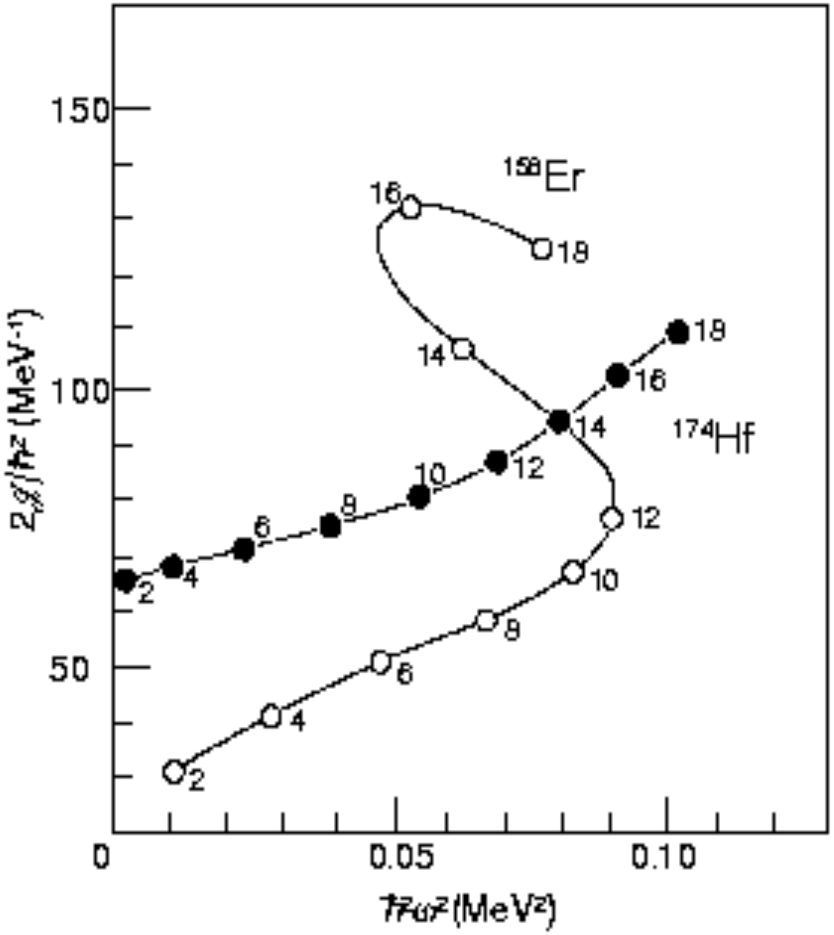


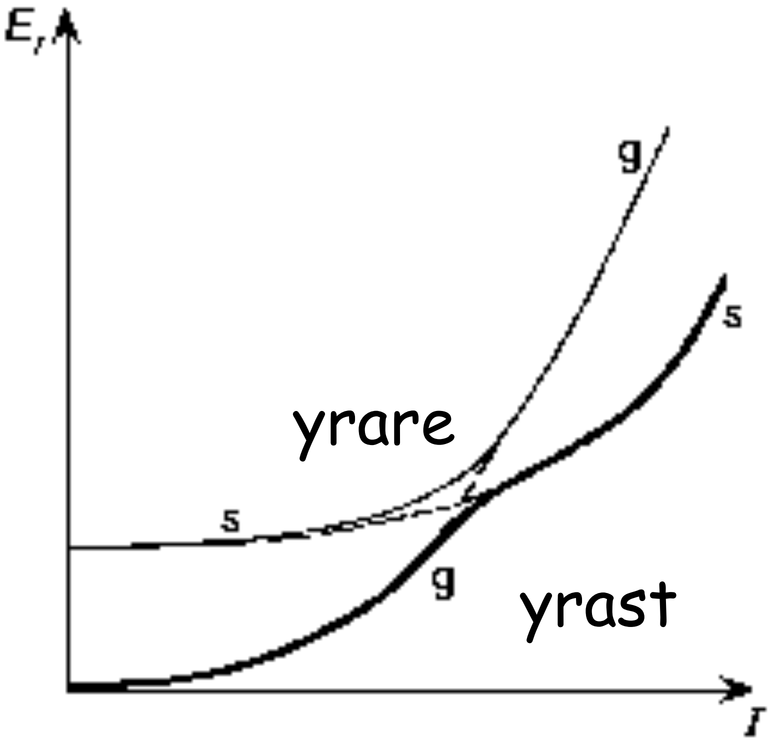
FIG. 2. Plots of the moment of inertia (top), yrast spin (middle), and spin alignment (bottom) vs the rotational frequency.

Backbending



- The moment of inertia increases with increasing rotational frequency
- Around spin 10ħ a dramatic rise occurs
- The characteristic 'S' shape is called a <u>backbend</u> (^{158}Er)
- A more gradual increase is called an <u>upbend</u> (^{174}Hf)

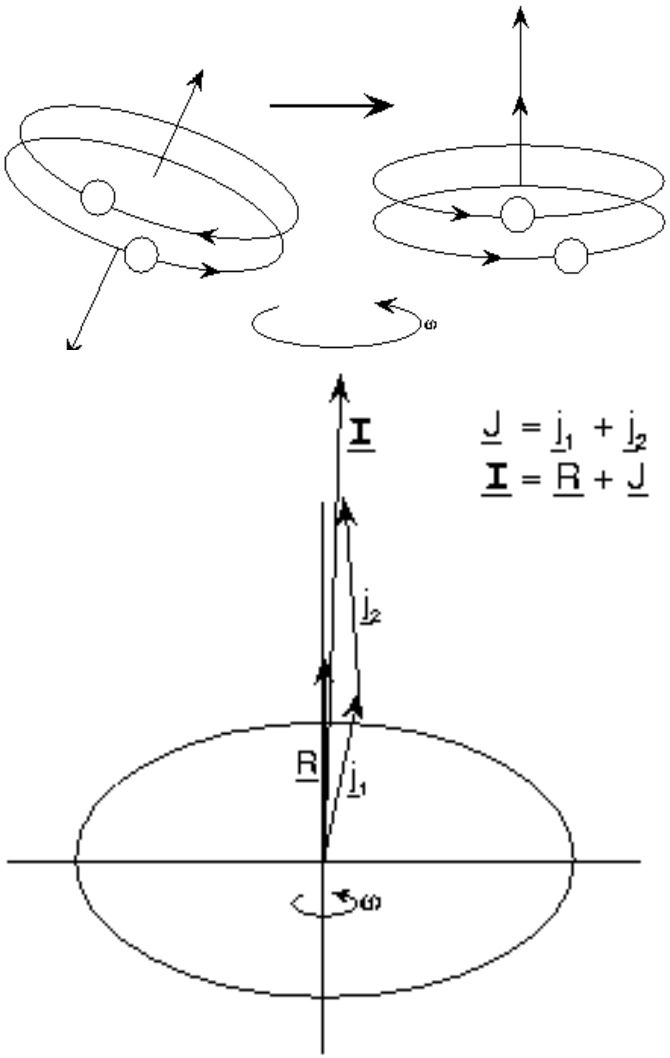
Crossing Bands



Yrast and **yrare** states: **dizziest** and **dizzier** in the Swedish language

- A backbend corresponds to the crossing of two bands ('g' and 's' configurations)
- The states we observe are called yrast states (thick line) which have the lowest energy for a given spin
- The s-band, where s stands for 'Stockholm' or 'super', arises from the breaking of a pair of nucleons. Their angular momenta j_1 and j_2 align with the rotation axis

Pair Breaking



- For the ground state band:

  $E_g = (\hbar^2/2\Im_g)\ I(I + 1)$

- For the s-band:

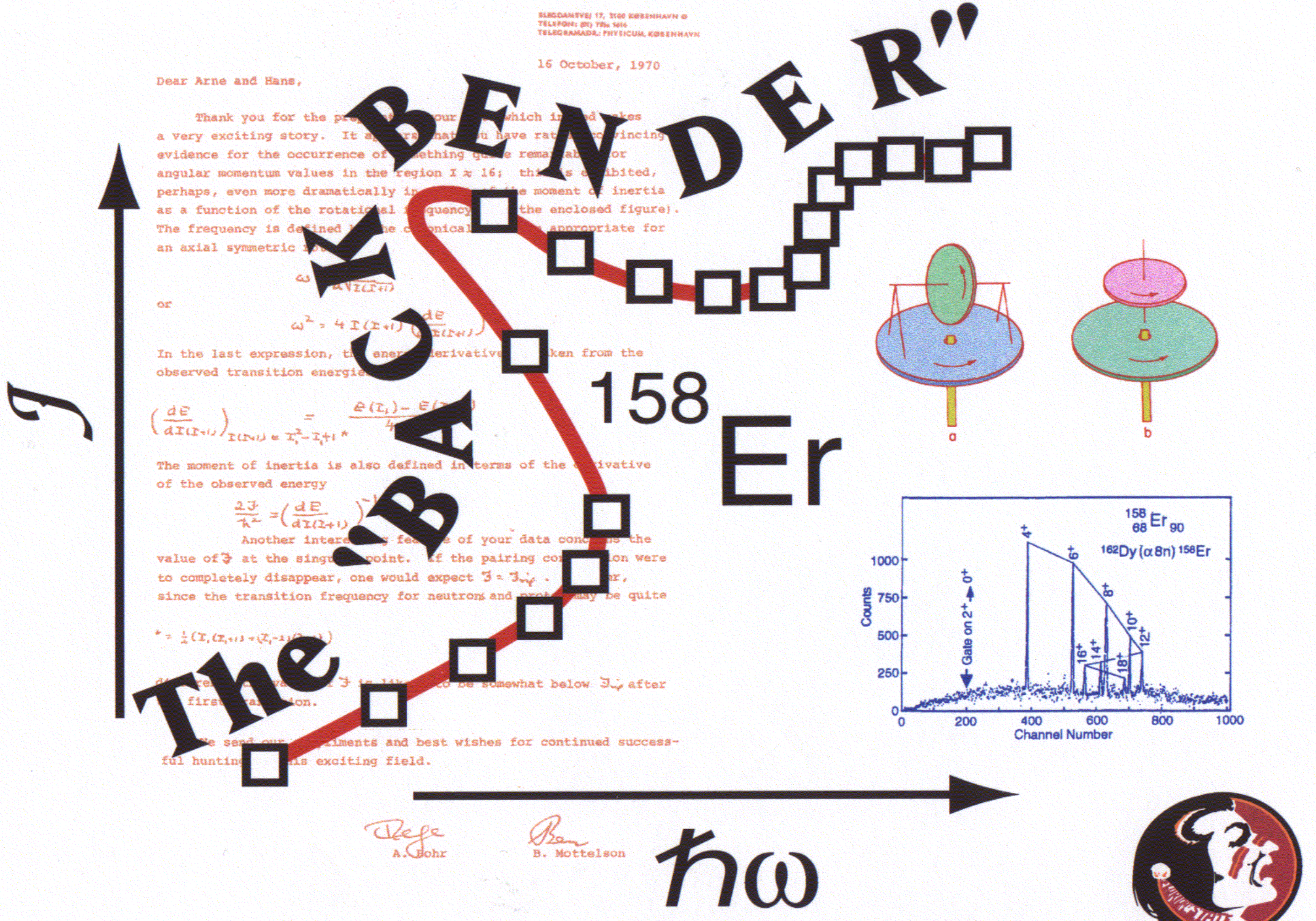
  $E_s = (\hbar^2/2\Im_s)\ (\underline{I} - \underline{J}\ )^2 + E_J$

  where $J = \underline{j_1} + \underline{j_2}$ and E_J is the energy required to break a pair of nucleons:

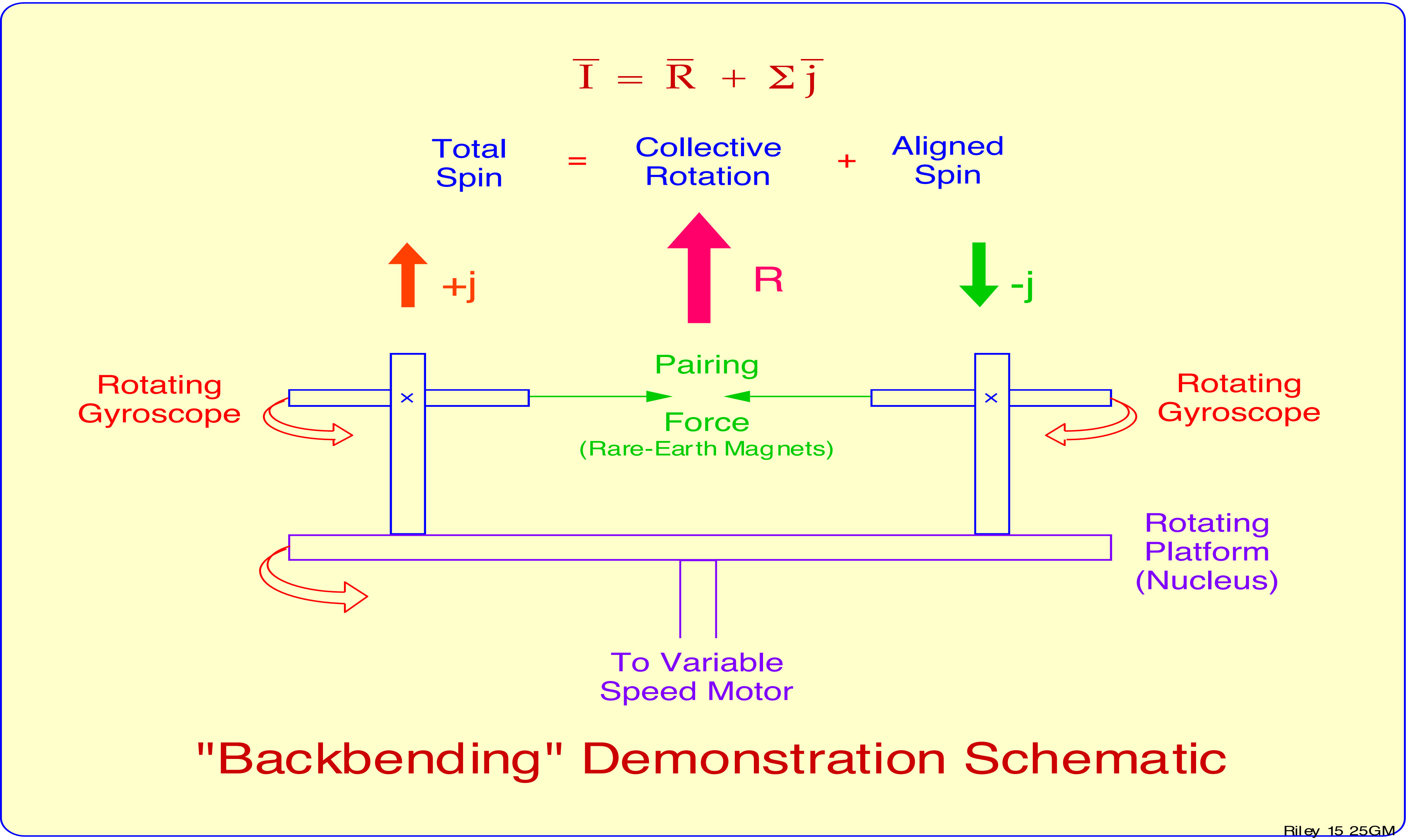
  $E_J \sim 2\Delta \sim 24\ A^{-1/2}$ MeV

- The aligned angular momentum of the s-band increases by approximately:

  $j_1 + j_2 - 1$ (~ $12\hbar$ for ^{158}Er)



Built by Ray Willis
Nuclear Research Workshop, FSU, 1997



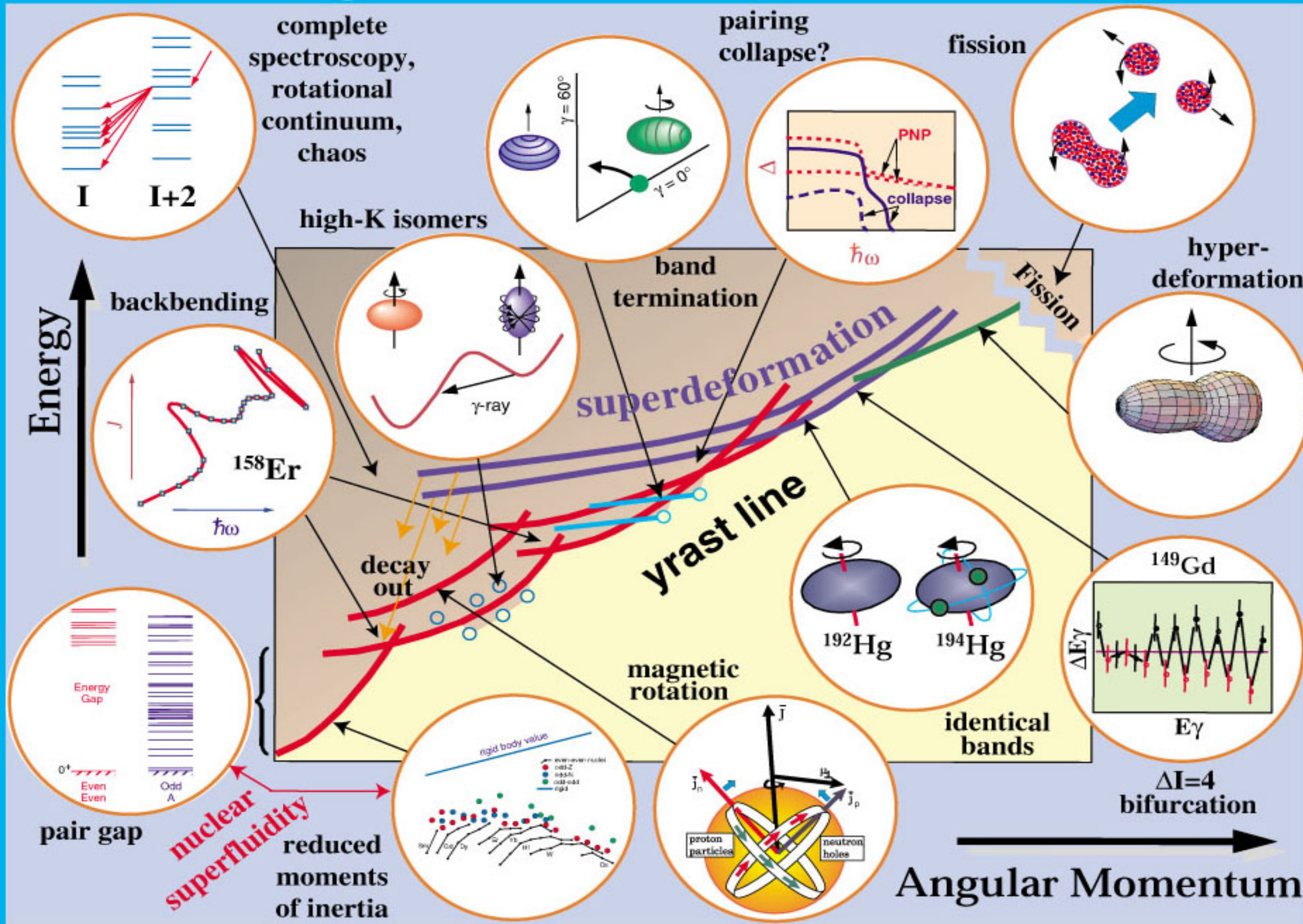
Much longer and more detailed video available. Email me for it.

SHOW MOVIE

Backbending today

- What was once a surprise and a mystery is now a beautiful diagnostic instrument!
- Very sensitive to changes in pairing, deformation and what the intruder orbitals are doing.
- We have super systematics on the p-rich side and a good understanding ….. Or so we think.
- Is the n-rich side the same where pairing may be very different?

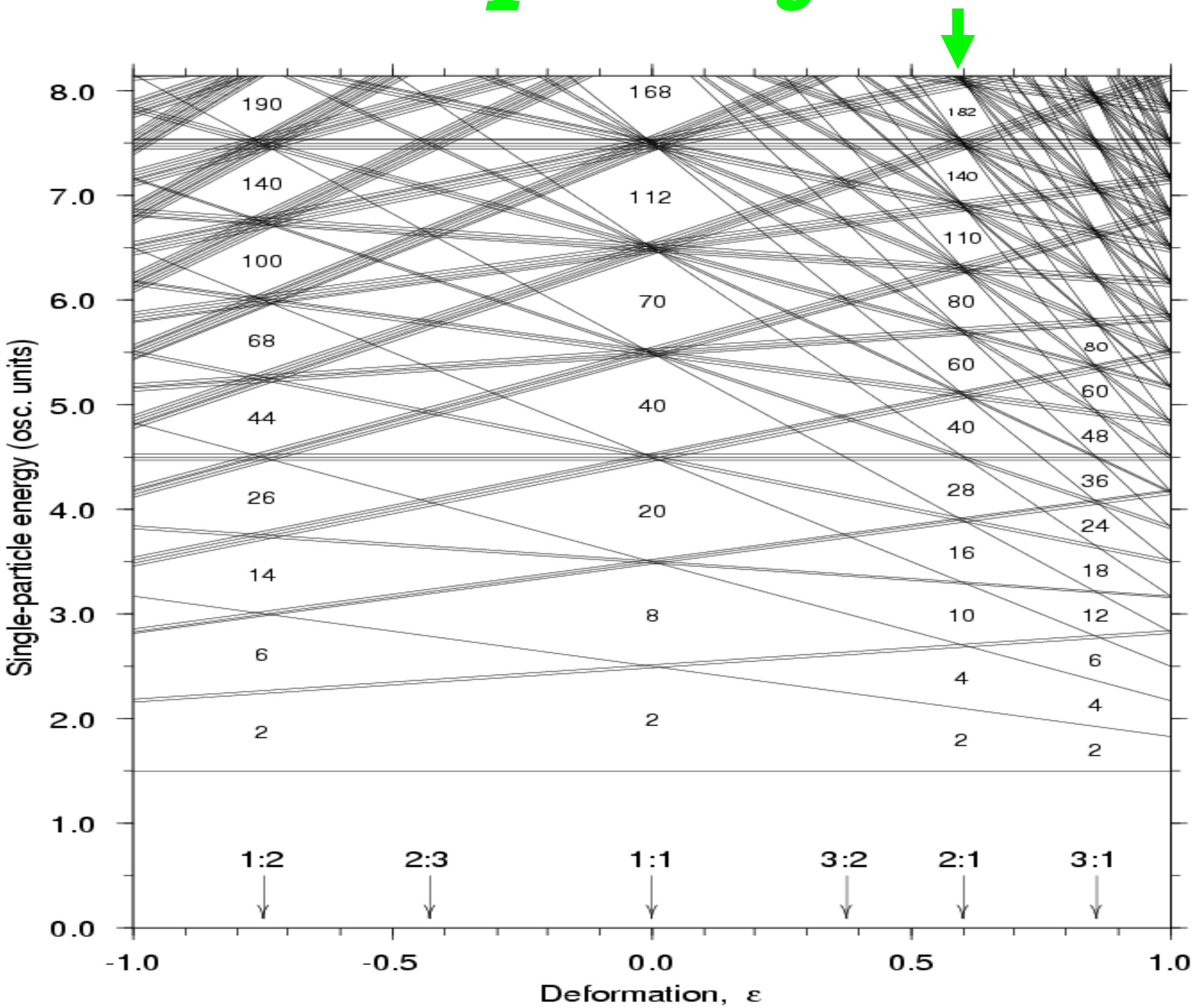
The Angular Momentum World of the Nucleus



Superdeformation

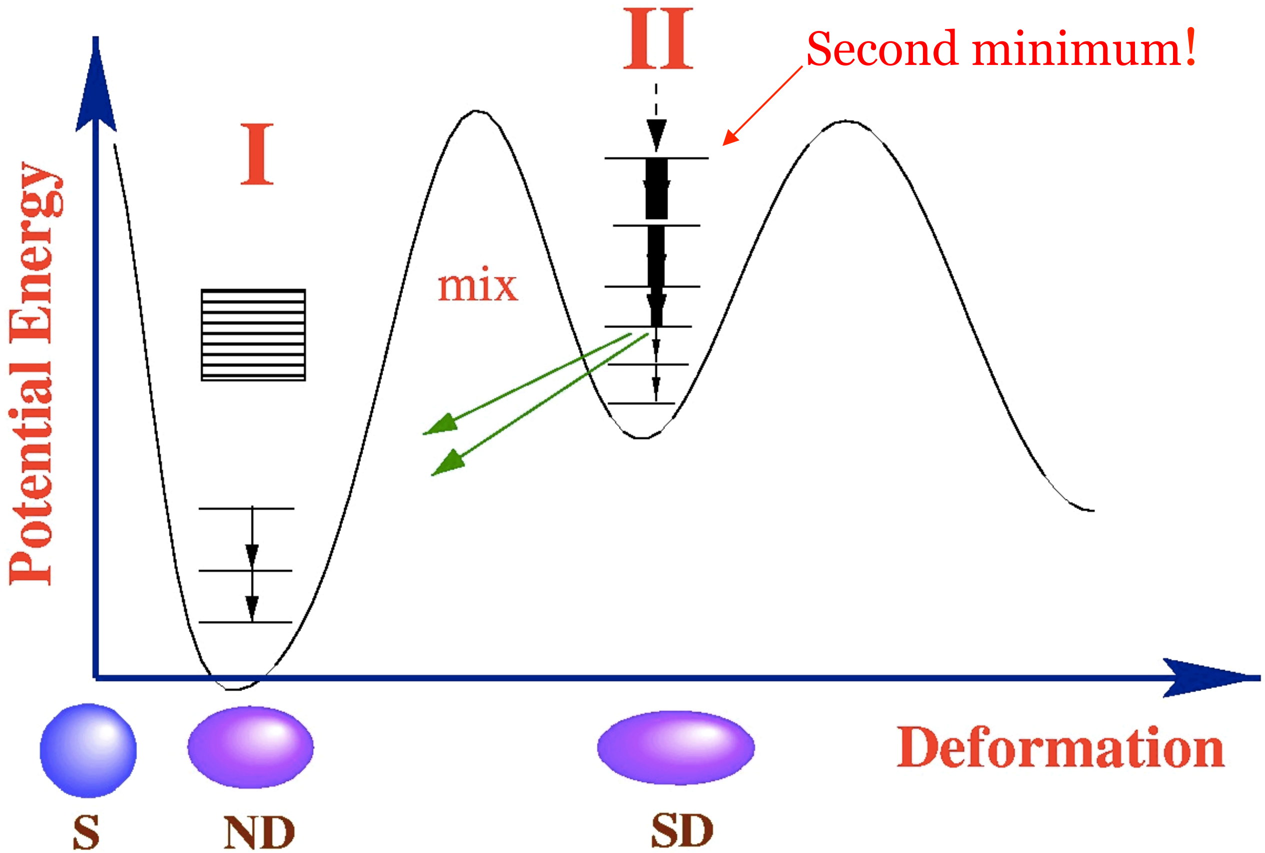
Shell Structure

Nuclear Superdeformation



Harmonic oscillator

The Nucleus at Extreme Deformation

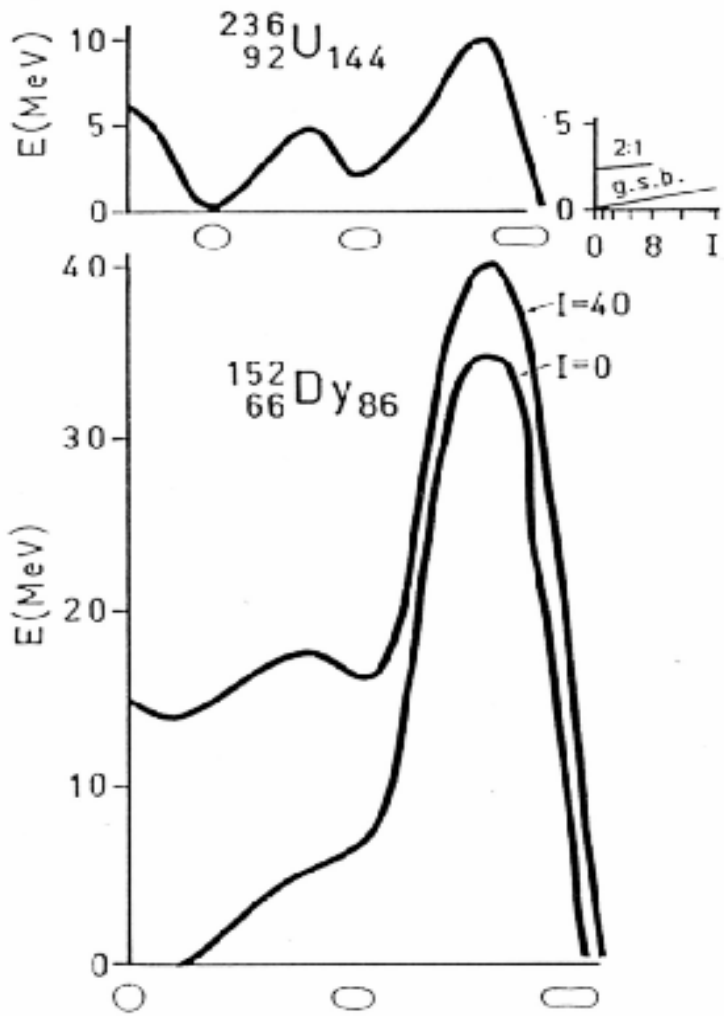


Second minimum in the nuclear potential energy!

Extremely deformed nucleus - 2:1 prolate (football shaped)

Can we create such states to investigate this new world?

Stability of Superdeformation



🡐 **Effect of Coulomb force**

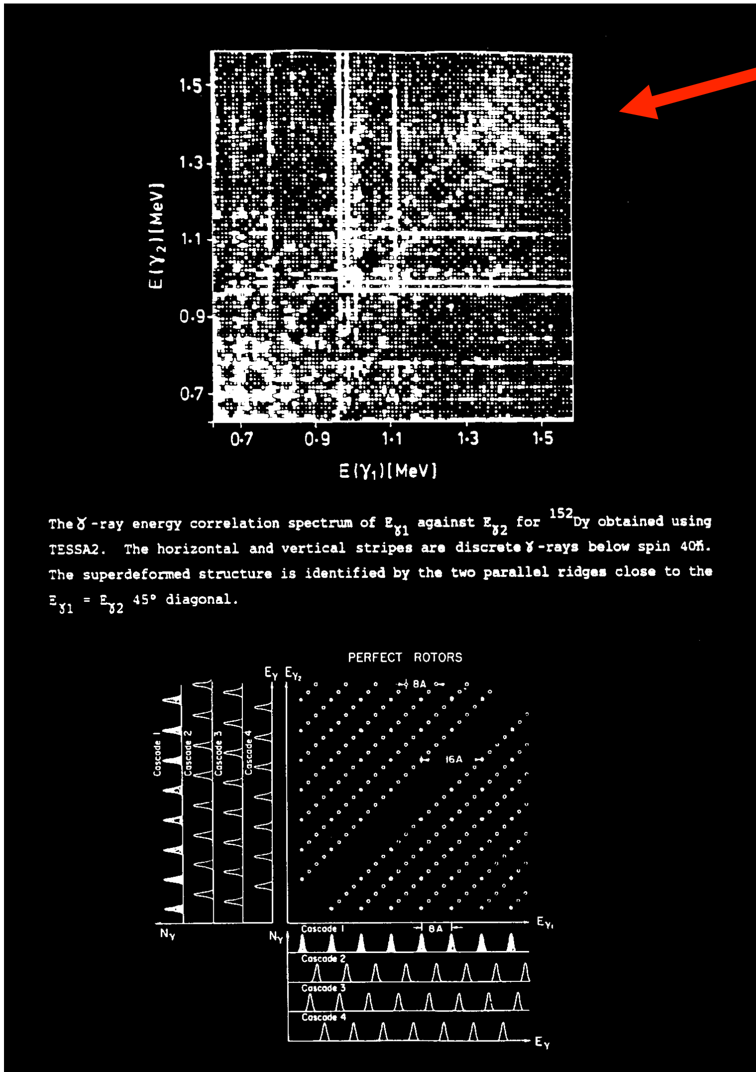
- **Reduction of fission barrier**
- **Lower the 2nd minimum**
- **SD exist at I=0**

🡐 **Effect of rotation**

- **Raise the potential more at low spin**
- **SD exist at high spin**

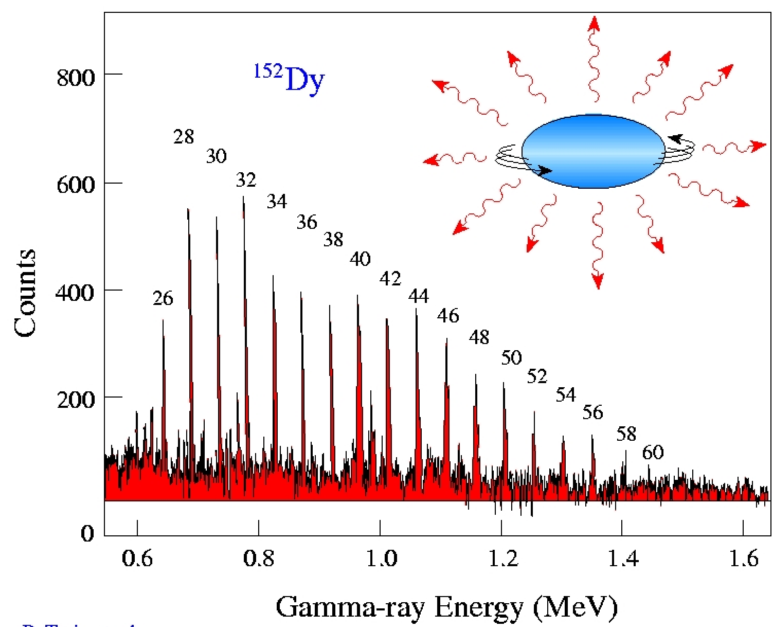
Most Famous Rotational Structure EVER!

Superdeformed Band in ^{152}Dy: (Twin, Nyako, JFSS et al)



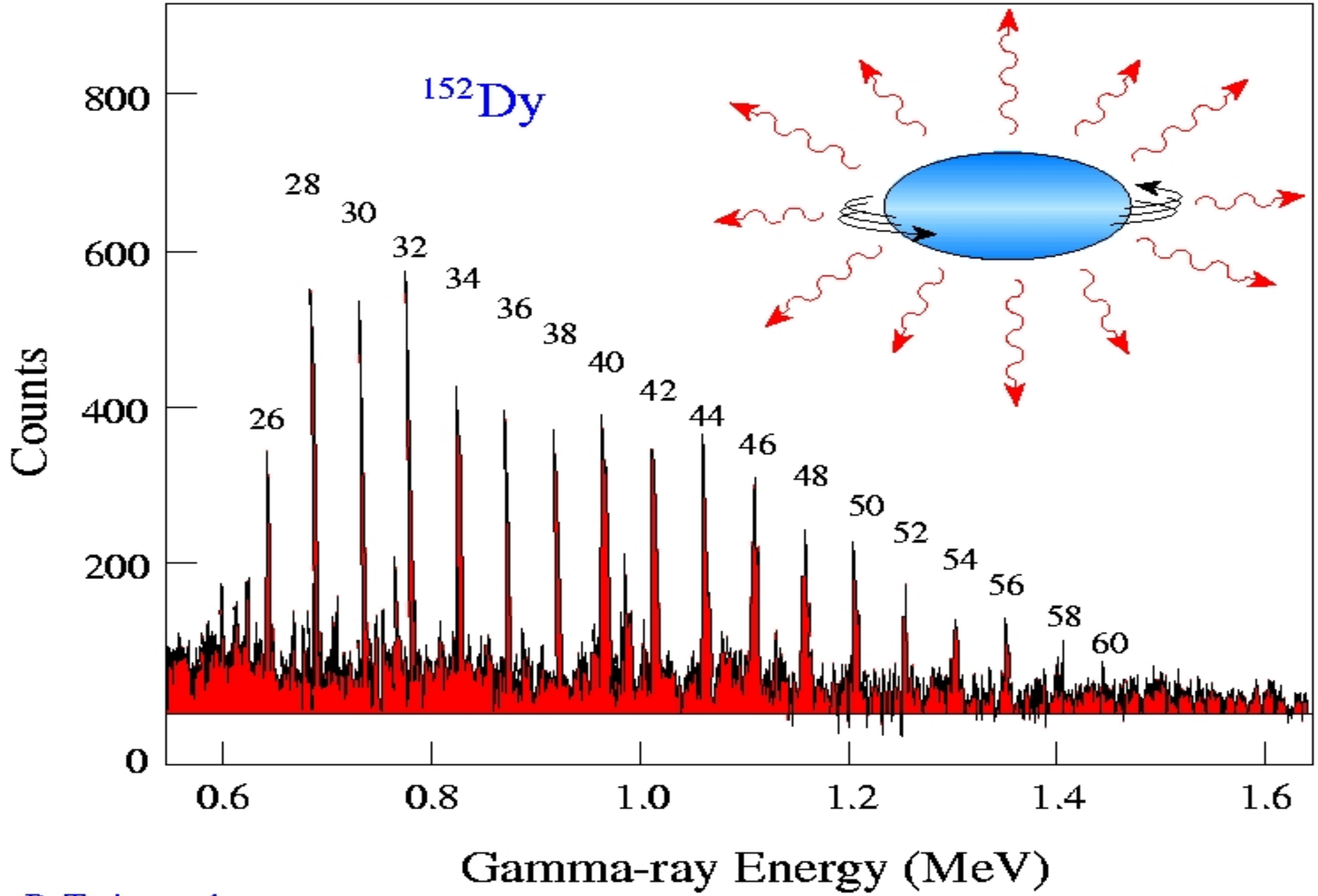
Exptal data: Note the diagonal "ridge" structure expected for a highly collective rotor, Nyako et al. PRL (1984)

Then 2 years later (after detector upgrade) the first discrete high-spin SD band revealed itself to the human race!



P. Twin et. al
Phys. Rev. Lett. 57 (1986)

The first case of a high spin superdeformed band



P. Twin et. al
Phys. Rev. Lett. 57 (1986)

Gamma-ray emission spectrum for the superdeformed band in Dy-152 (Twin 1986). Such regularity was previously unknown in nuclear physics. Superdeformed nuclei have been found to display remarkable and unexpected properties.

Nuclear Superdeformation – A Major Discovery

"Top unexpected physics discoveries of the last five years!"

PHYSICS TODAY December 1991

Daniel Kleppner
Lester Wolfe Professor of Physics at MIT

High temperature superconductivity

Atom cooling and atom optics

Large-scale structure of the universe

Supernova 1987A

<u>Superdeformed nuclei</u>

Buckyballs

J. Garrett
"Superdeformation - Nuclear Physics' Supernova"

B. Mottelson
…one of Nuclear Structures finest hours ..

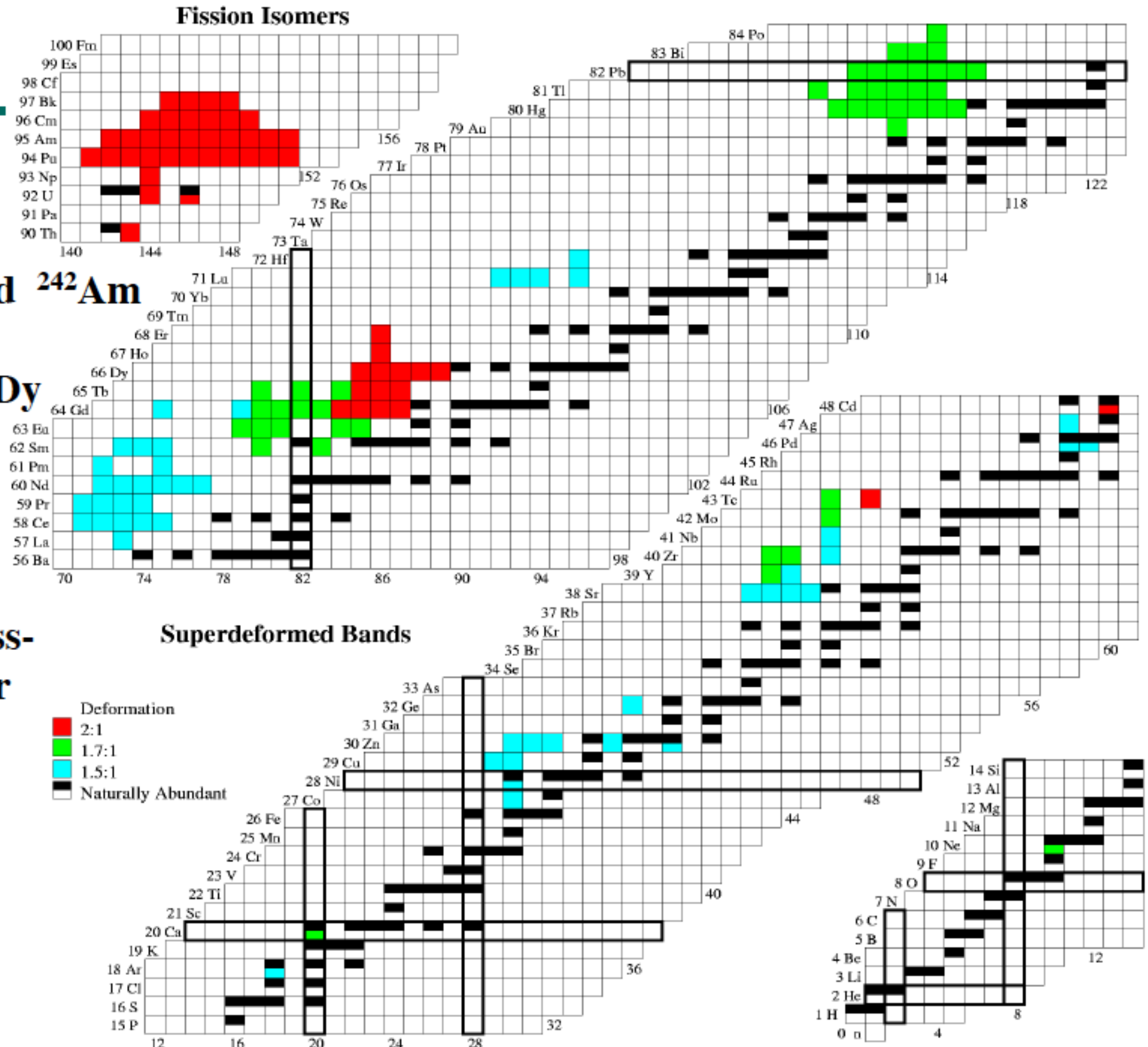
Paul Fallon

First Observed ^{242}Am

25yrs later ^{152}Dy (1986)

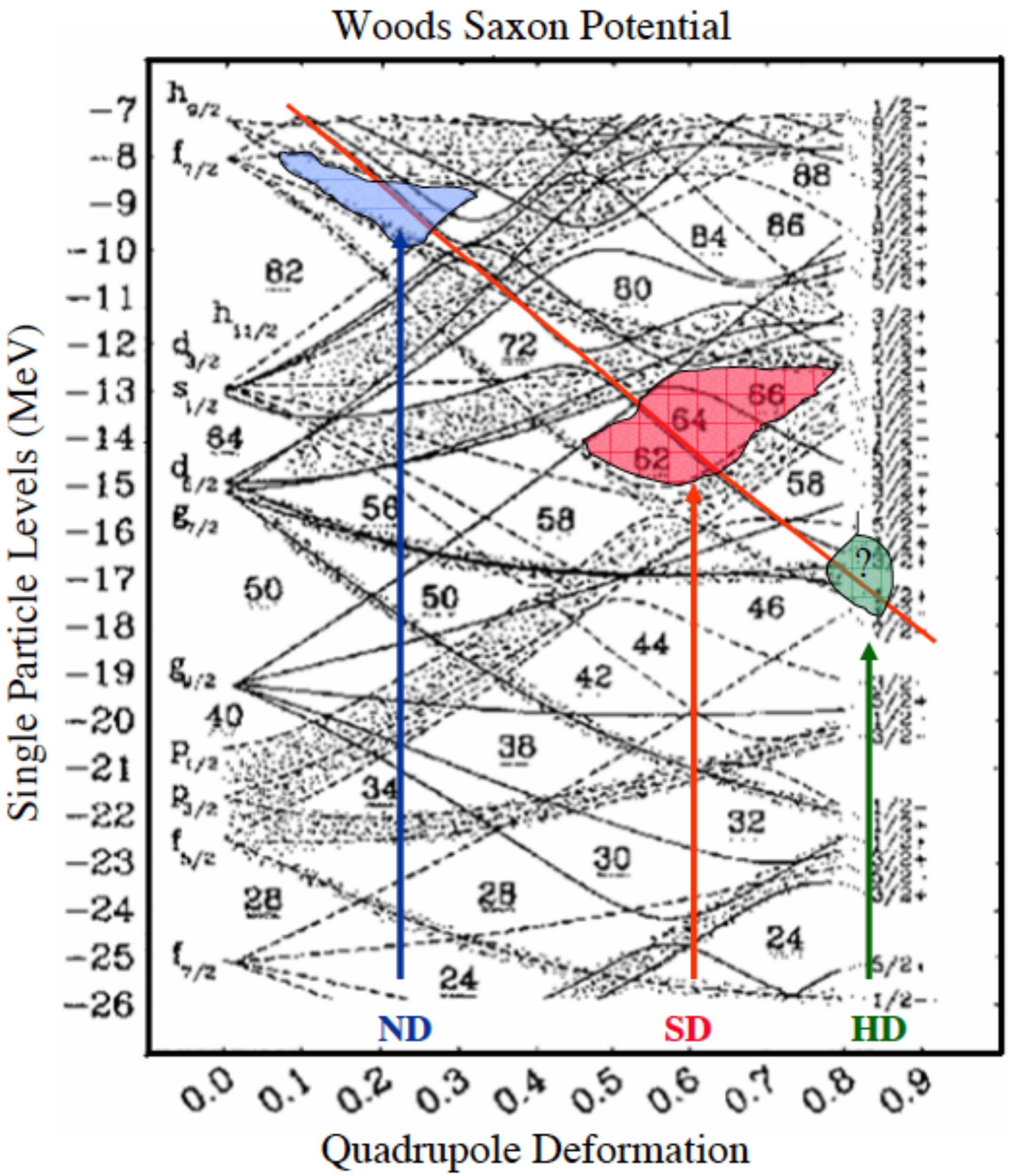
Since then …

Rapid progress- Large detector arrays



Paul Fallon

Deformations Shell Structure and Intruders



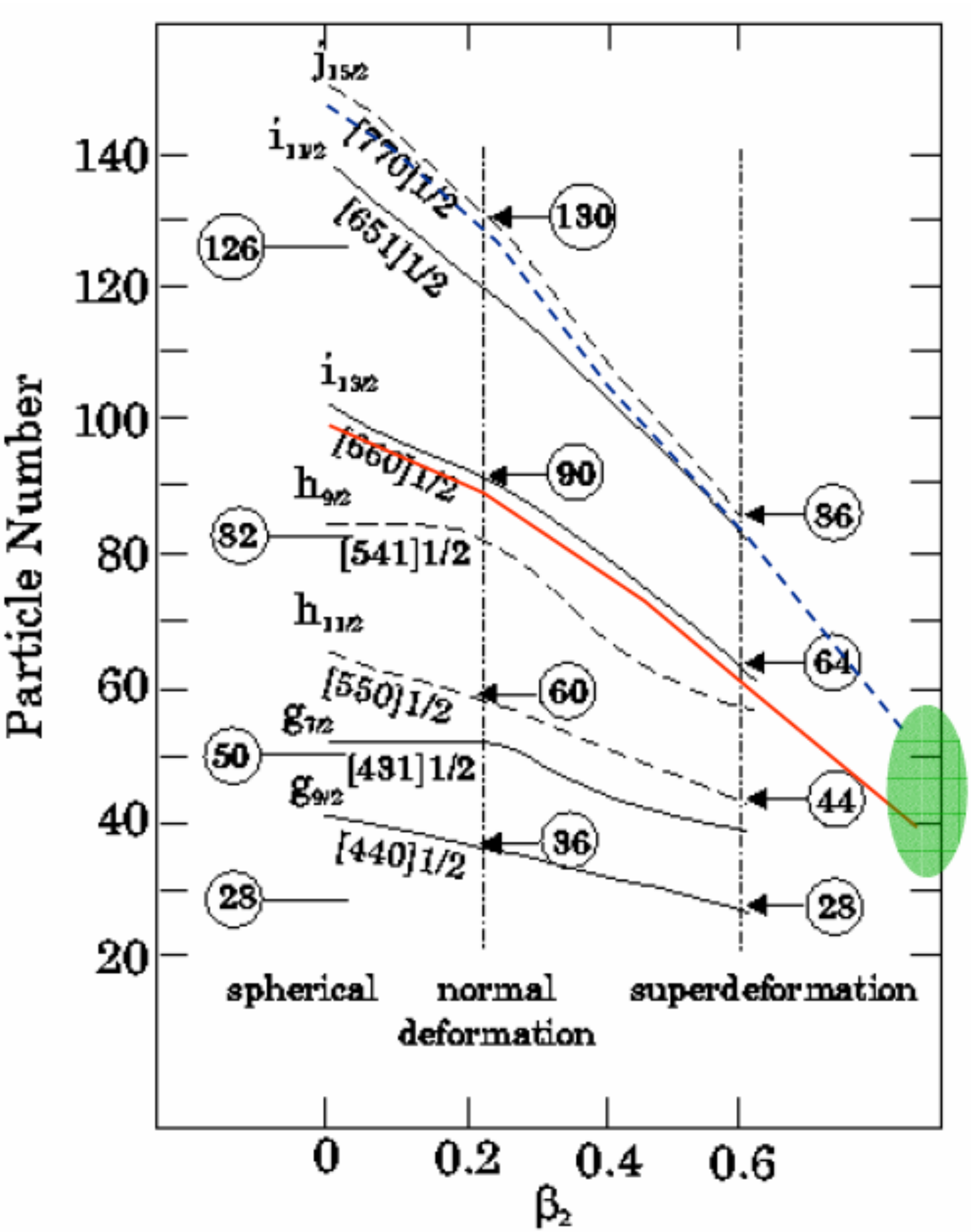
Classify the Intruder by the number of major oscillator shells it has moved

Classify the Structure by the Intruder Occupation

	ND	SD	HD
Intruder	N+1	N+2	N+3
Z~50	$g_{9/2}$	$h_{11/2}$	$i_{13/2}$

Has some benefits compared with definition based strictly on axis ratio

Paul Fallon



Intruder states at the Fermi surface in SD nuclei are from 2 shells up!

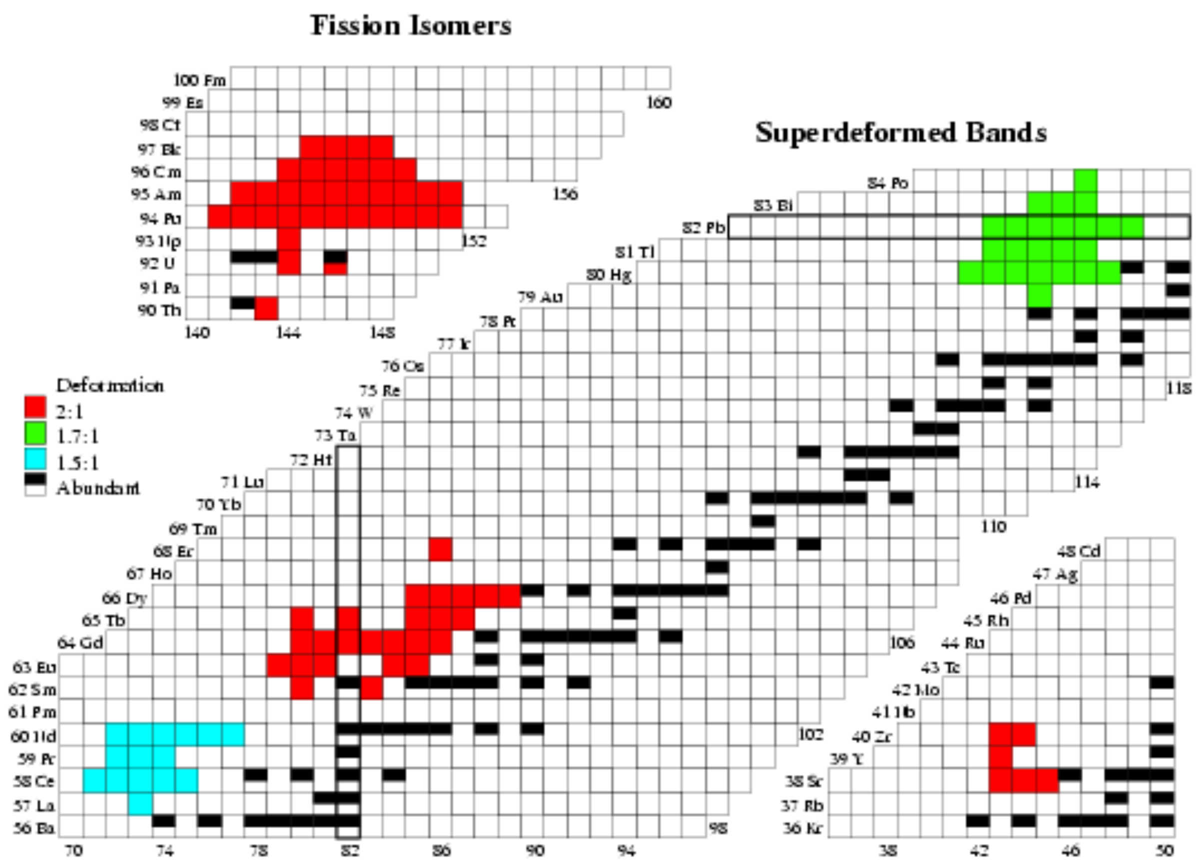
Nazarewicz

Known Regions of Superdeformation

Table of Superdeformed Nuclear Bands and Fission Isomers

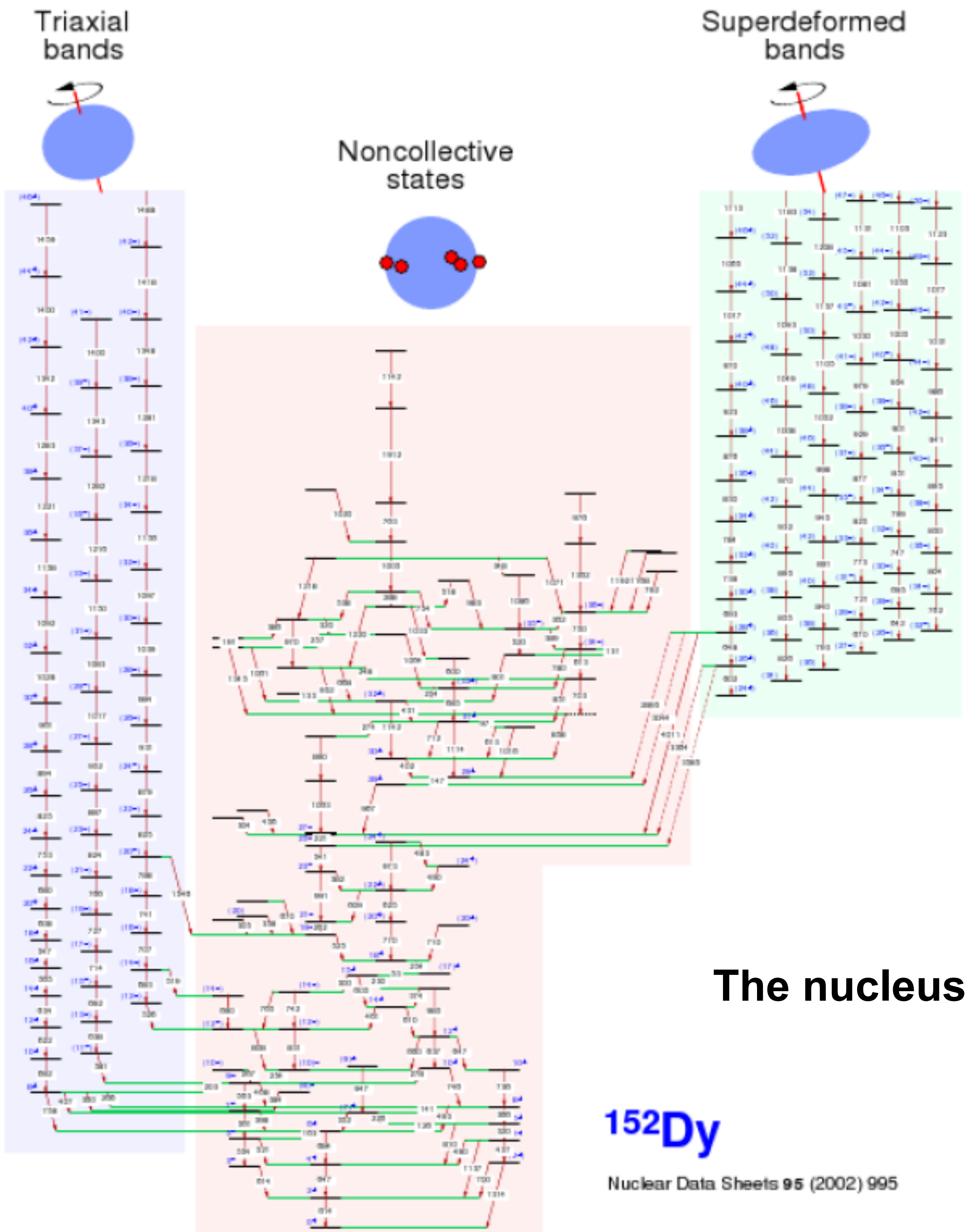
WWW Edition. Updated June, 1997

by Balraj Singh, Richard B. Firestone, and S.Y. Frank Chu



Each region has been found to posses special characteristics. Amazingly rich spectroscopy!

Coexistence of collective and noncollective motion

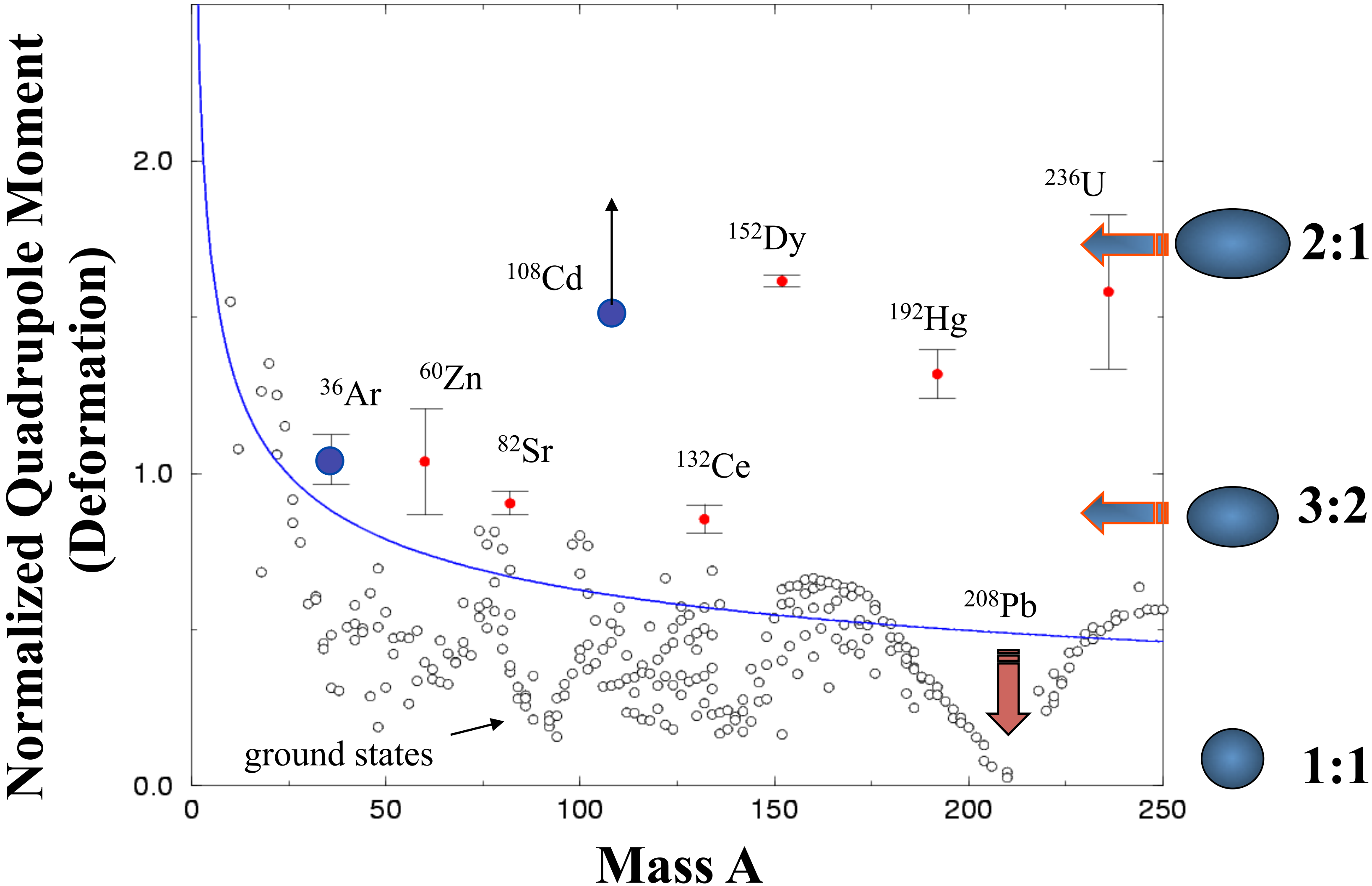


The nucleus that changed the world!

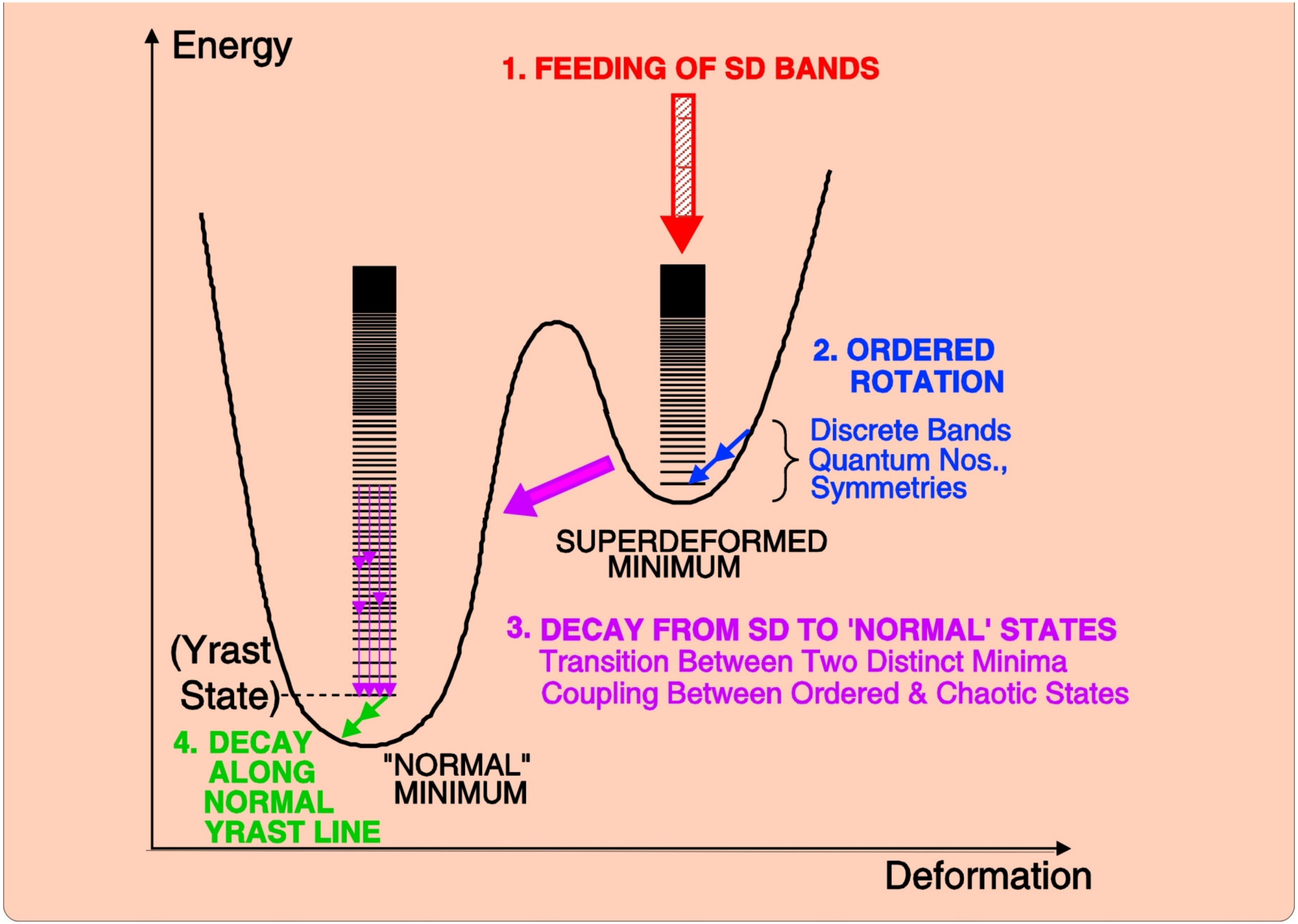
^{152}Dy

Nuclear Data Sheets **95** (2002) 995

Superdeformation: Extreme nuclear behavior!



Decay out of superdeformed states?



1990: Identical Superdeformed Bands in Different Nuclei!

^{152}Dy	^{151}Tb*
693	692
738	738
784	783
829	828
876	876
923	922
970	970
1017	1016
1064	1063
1112	1112
1161	1160
1209	1207
1256	1256
1305	1305
1353	1353

^{192}Hg	^{194}Hg*	^{194}Pb
258	262	256
300	303	298
341	343	340
381	382	380
421	420	420
459	458	458
496	495	496
532	532	532
568	567	568
602	601	603

Back to back PRL's,Bryski et al PRL 64(90) 1650 & Nazarewicz et al PRL 64 (90) 1654

At first many thought it was a case of mistaken identity. Faulty experimental work!

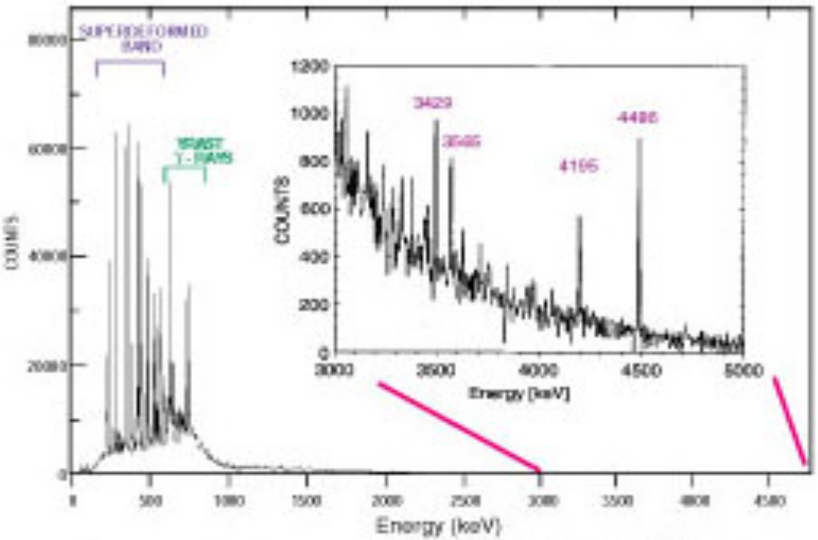
35 yr veteran of nuclear physics, "most amazing set of numbers he had ever seen."

Heroic? New insight? Pseudo-spin alignment or

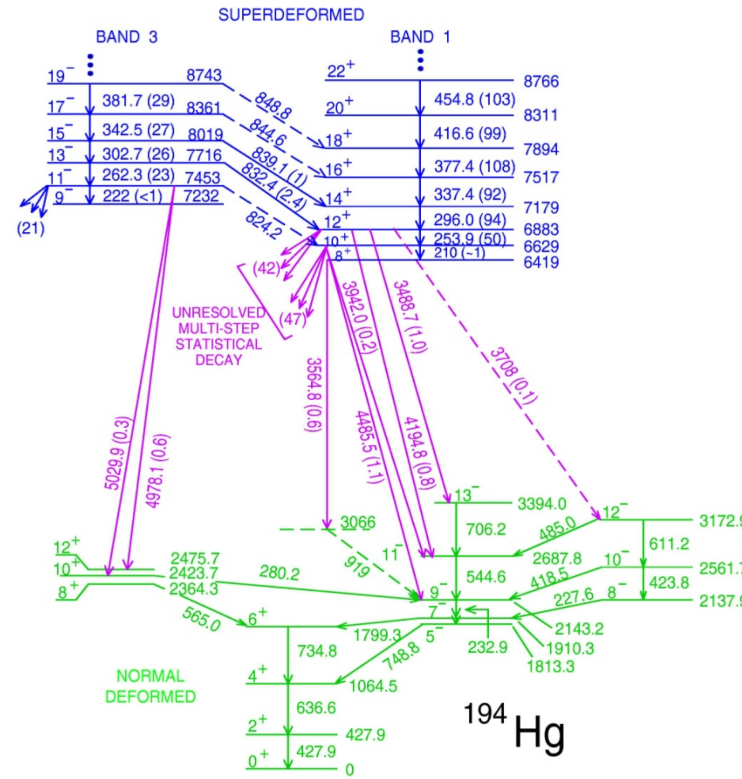
Non-Heroic? : Chance cancellations between pairing & deformation effects?

- **Identical Bands: Does "Seeing Double" Mean We Learn Twice as Much?**
- Paul Fallon and David Ward review article, Advances in Nuclear Physics, Vol 24, 1999.

Direct links between high spin superdeformed and normal energy minima finally observed



Gamma ray spectrum for band 1 in ^{194}Hg showing the weak direct one-step discrete high energy (3.4 - 4.5 MeV) decays linking the superdeformed and normal deformed minima.

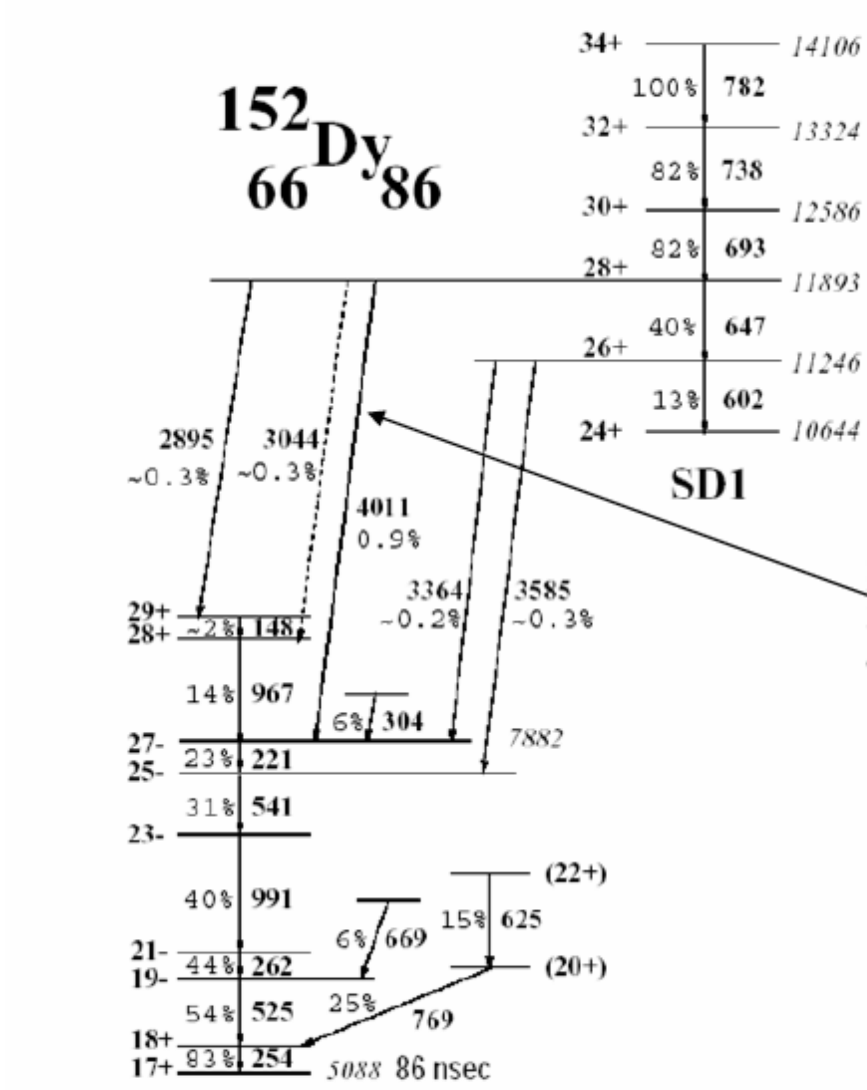


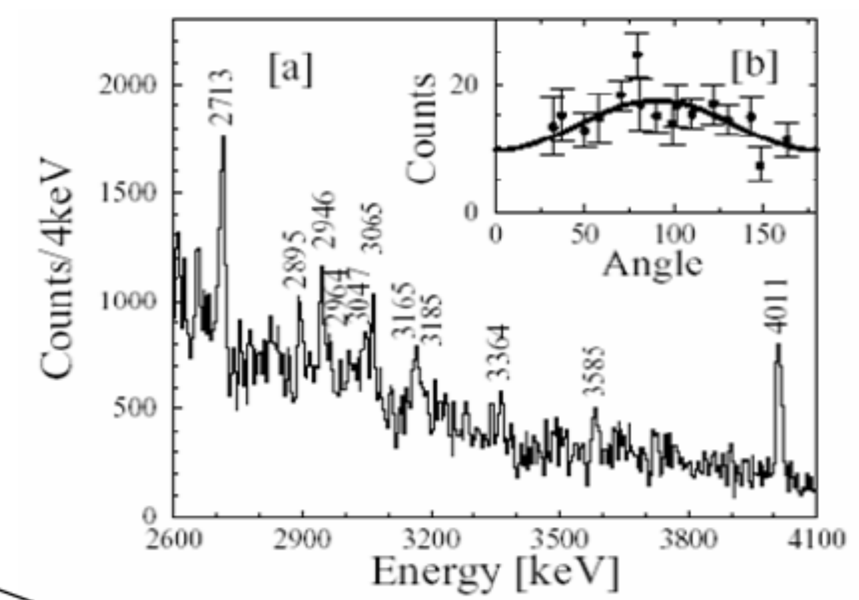
This observation unambiguously defined the excitation energies, spins and probable parities of superdeformed bands in the A = 190 region for the first time.

Khoo et al, PRL 76(96)1583

^{152}Dy Fifteen Years …

T.Lauritsen et al., PRL **88** (2002) 042501





4011 keV Determines Ex. Energy
Dipole Character (E1)
τ ~ 2.9ps
B(E1) ~ 2x10^{-6} WU

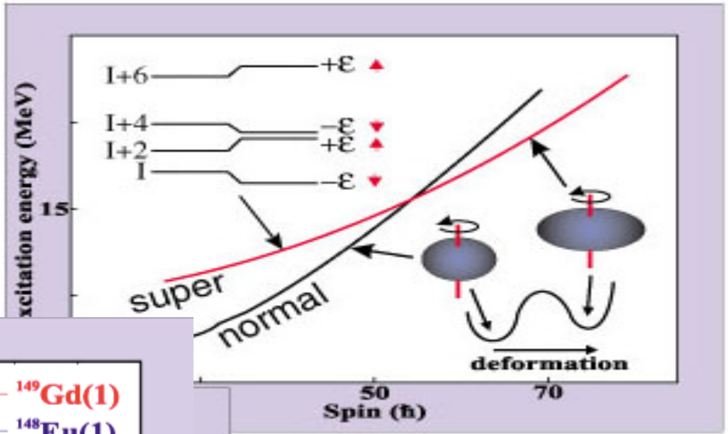
Other gammas placed > Fixed spins
- 2 hbar higher than original estimate
- Can test calculations

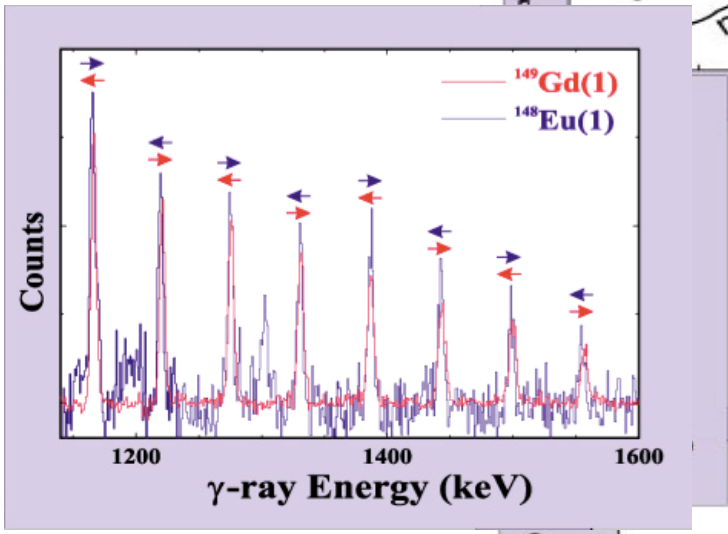
E1 decays (similar for ^{194}Hg)

Then things became even more strange!

ΔI=4 Bifurcation in Identical Superdeformed Bands

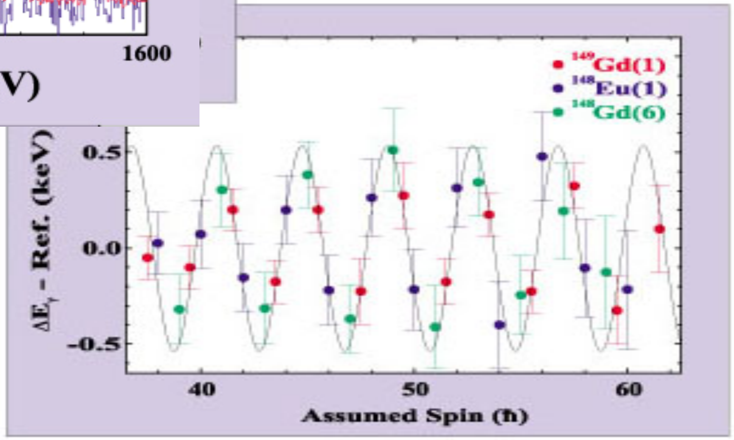
ΔI = 4 bifurcation occurs when alternate levels in a superdeformed band are perturbed by one part in a million, in opposite directions.

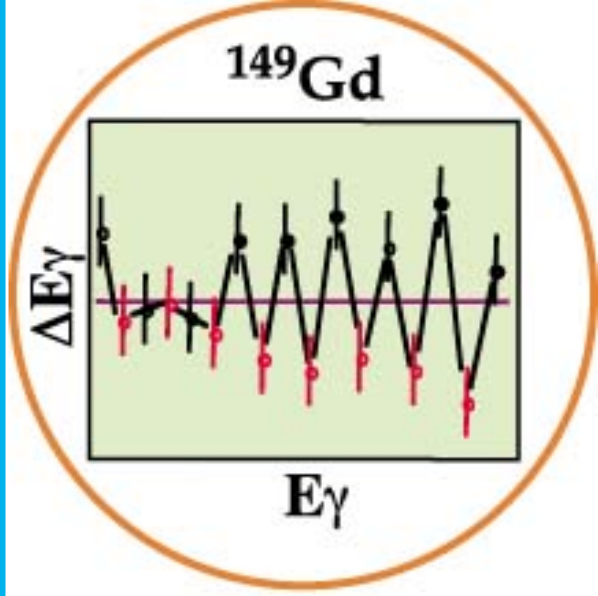




The transitions in these neighboring nuclei are nearly identical, but the direction of the tiny shift is reversed.

When the small shifts in three bands are plotted as a function of spin, they show a remarkable correlation which is not understood at this time.

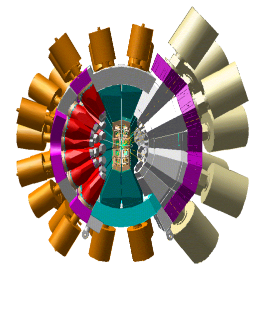


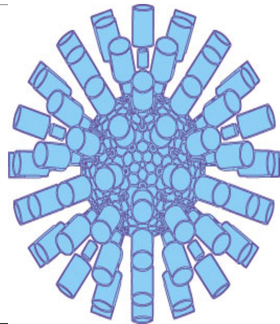


Flibotte et al, PRL 71 (93) 4299

Haslip *et al.*, PRL 78, 3447 (1997).

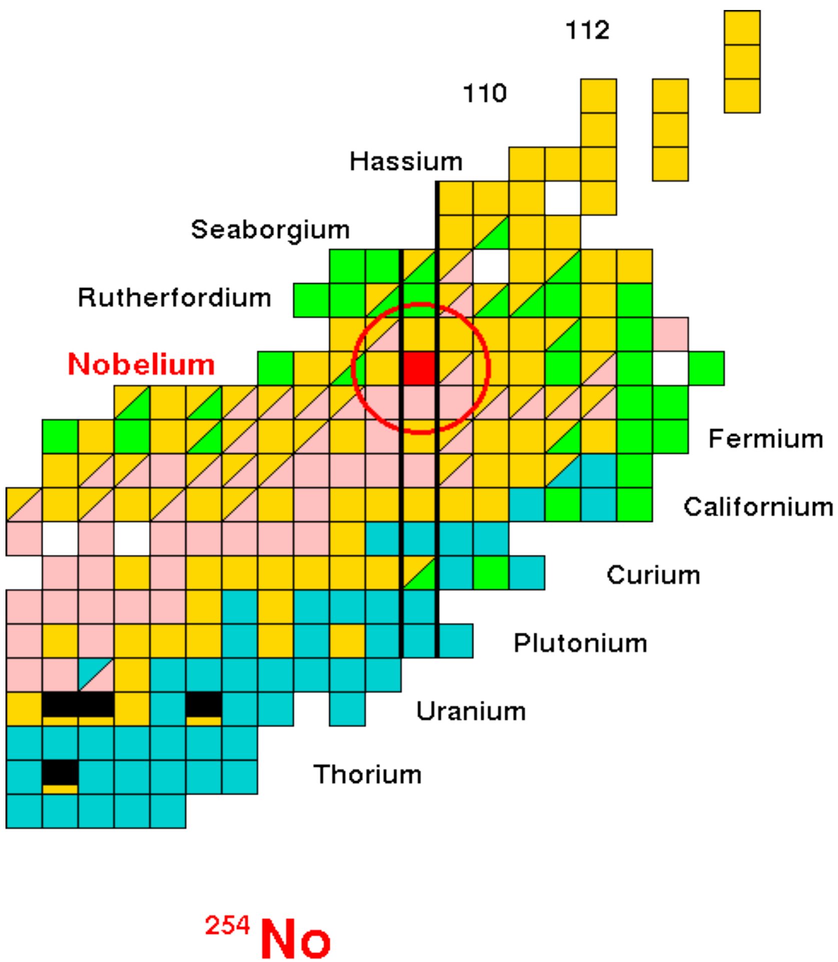
Haslip et al., PRC 58 (98) R2649





Super Heavy Nuclei

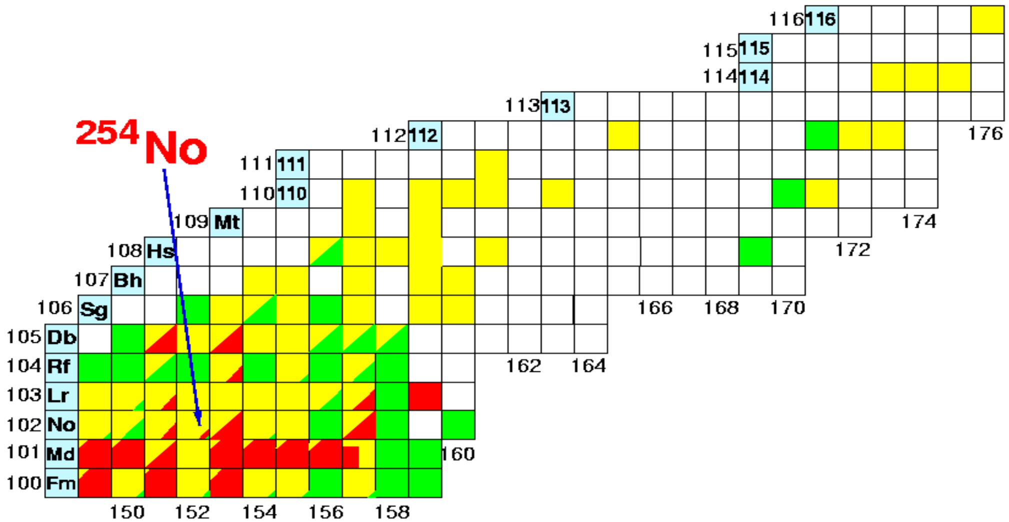
Extremes of Mass and Charge



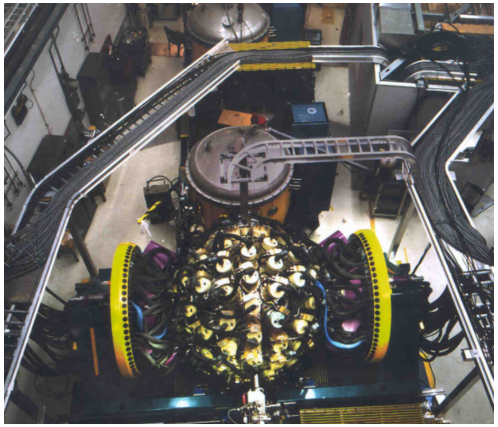
- Investigations of the heaviest nuclei probe the role of the Coulomb force and its interplay with quantal shell effects in determining the nuclear landscape
- Without shell effects nuclei with more than 100 protons would fission instantaneously
- However, 'superheavies' with Z up to 118 have been identified !
- Experts in the audience…

Forging the Heaviest Elements :

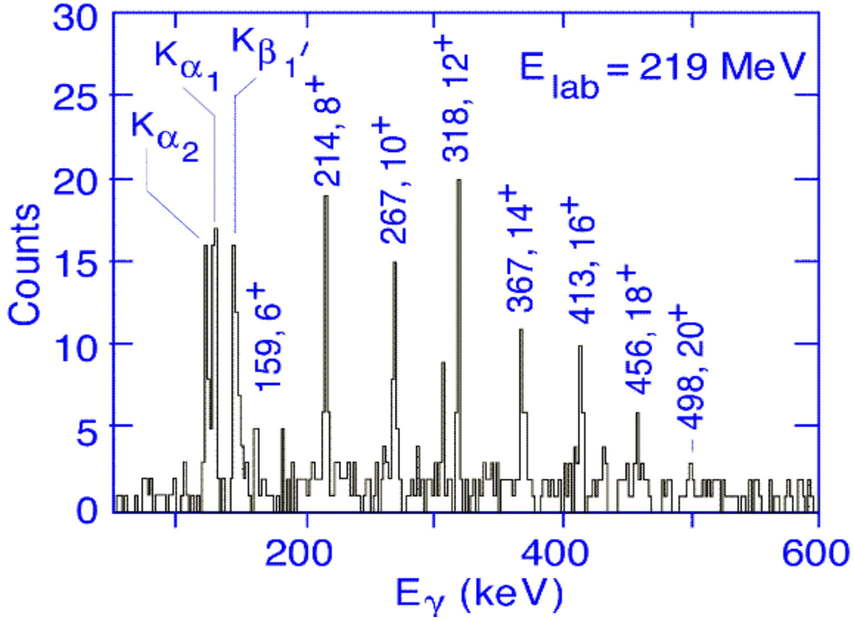
Surprises in the survival of the species. (Reiter et al., PRL 84 (2000) 3542)



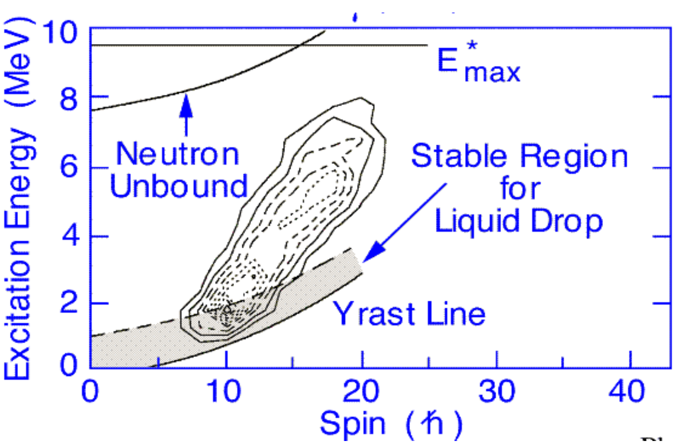
Current chart of nuclides for Z>99.
yellow - α decay,
green - spontaneous fission,
red - β decay.



GS+FMA



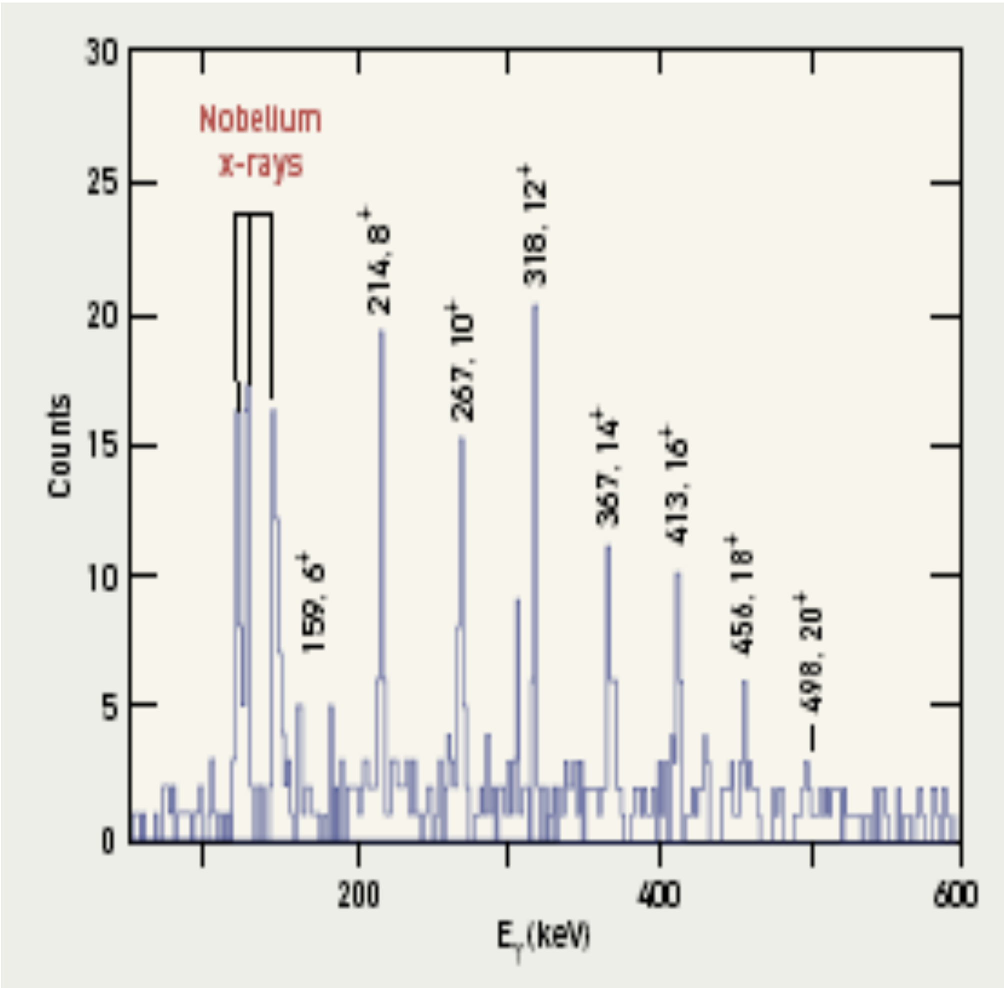
The spectrum of rotational transitions in ^{254}No



Entry distribution in spin and excitation energy for ^{254}No

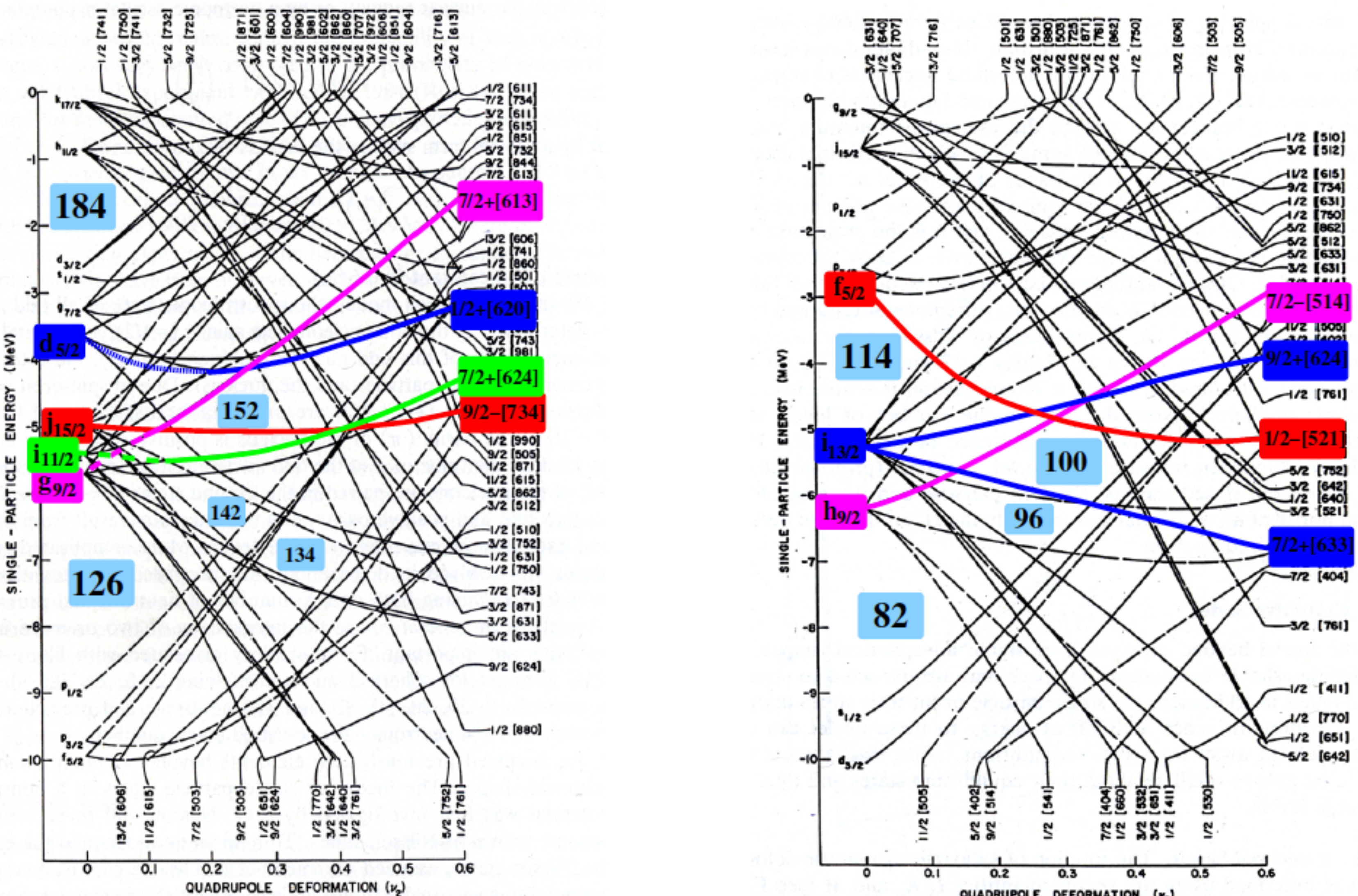
Janssens

Superheavies at High Spin



- The ground-state rotational band of ^{254}No (Z=102) has been identified up to spin 20^+ (at least!)
- The energy spacing of the levels is consistent with a sizeable prolate deformation with an axis ratio 4:3
- Isomers are giving wonderful configuration info too!

Single-Particle Orbitals in Region of ^{254}No

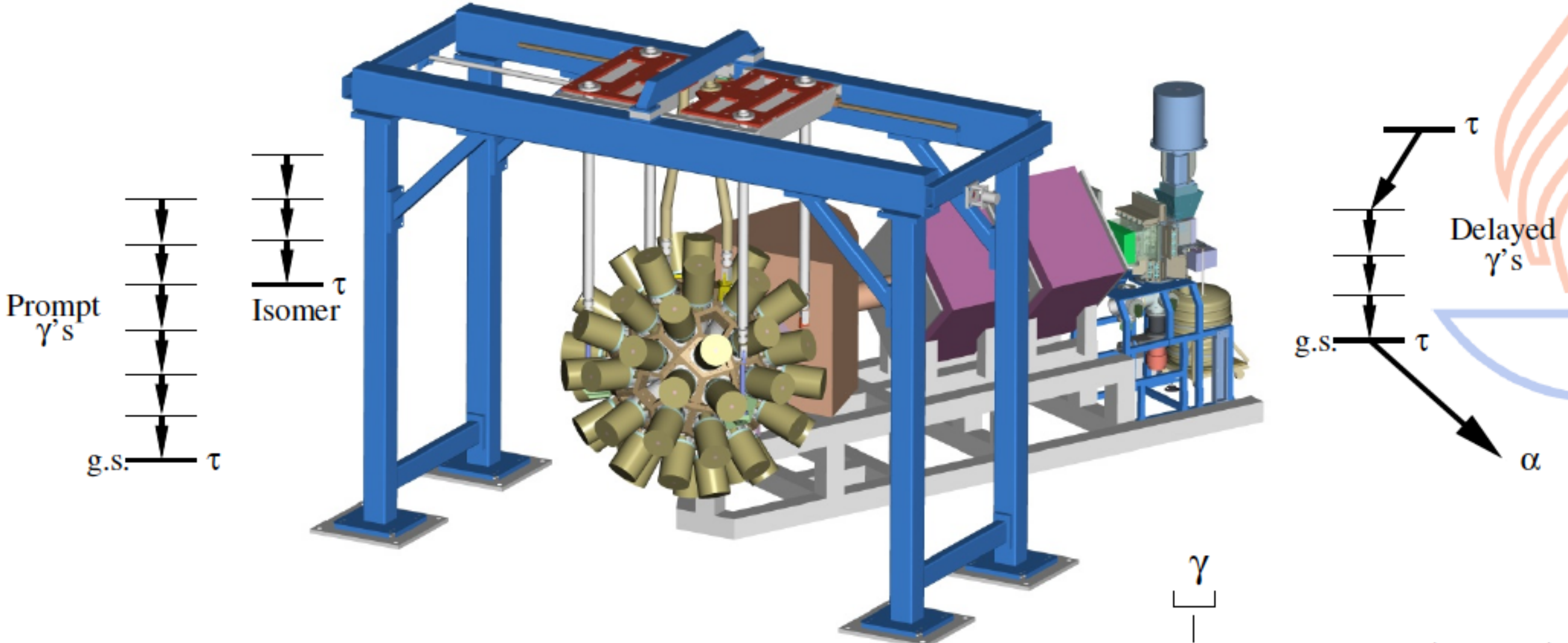


R.R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)

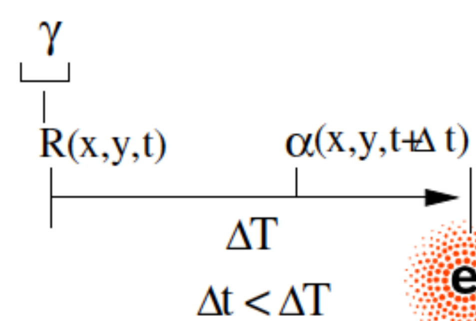
Tagging Techniques

Recoil, Recoil–Decay, Isomer

HOMEWORK!!

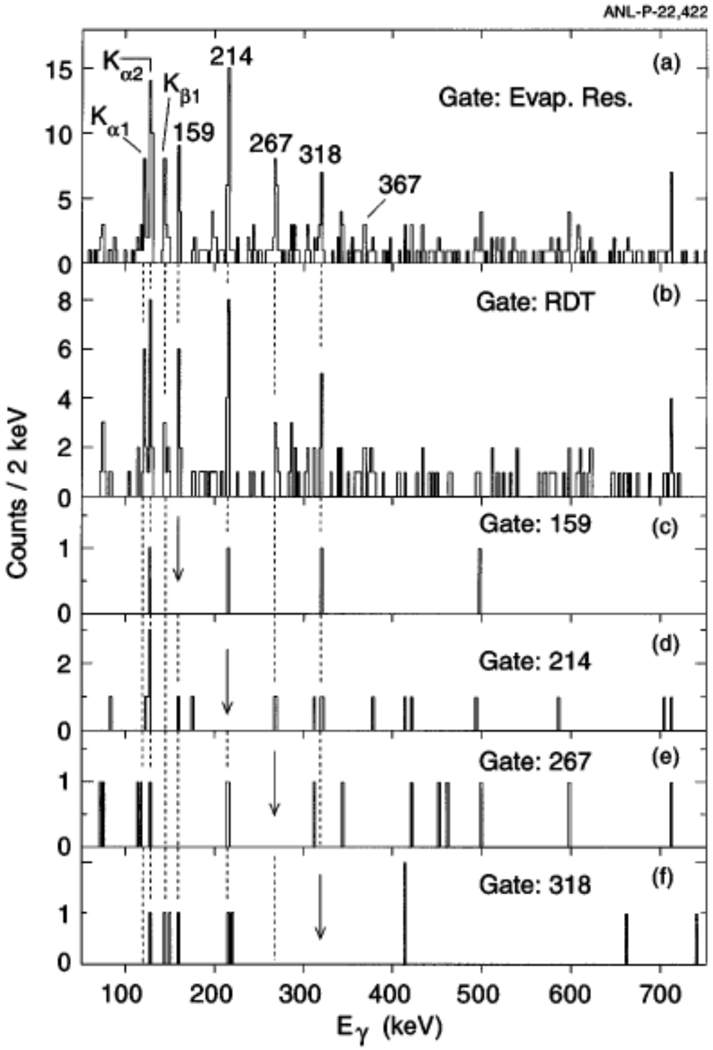


Time Line:



In-beam studies in region of ^{254}No

P.Reiter et al., PRL **82**, 509 (1999)



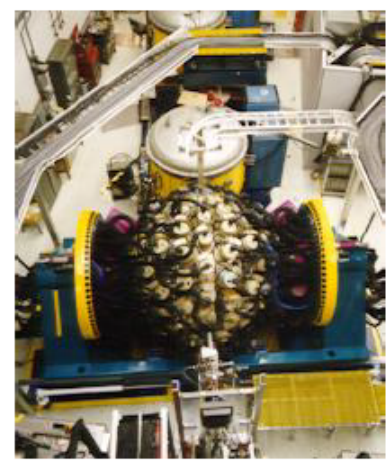
VOLUME 82, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1999

Ground-State Band and Deformation of the Z = 1 2 Isotope ^{254}No

P. Reiter,[1] T.L. Khoo,[1] C.J. Lister,[1] D. Seweryniak,[1] I. Ahmad,[1] M. Alcorta,[1] M.P. Carpenter,[1] J.A. Cizewski,[1,3] C.N. Davids,[1] G. Gervais,[1] J.P. Greene,[1] W.F. Henning,[1] R.V.F. Janssens,[1] T. Lauritsen,[1] S. Siem,[1,8] A.A. Sonzogni,[1] D. Sullivan,[1] J. Uusitalo,[1] I. Wiedenhöver,[1] N. Amzal,[2] P.A. Butler,[2] A.J. Chewter,[2] K.Y. Ding,[3] N. Fotiades,[3] J.D. Fox,[4] P.T. Greenlees,[2] R.-D. Herzberg,[2] G.D. Jones,[2] W. Korten,[5] M. Leino,[6] and K. Vetter[7]

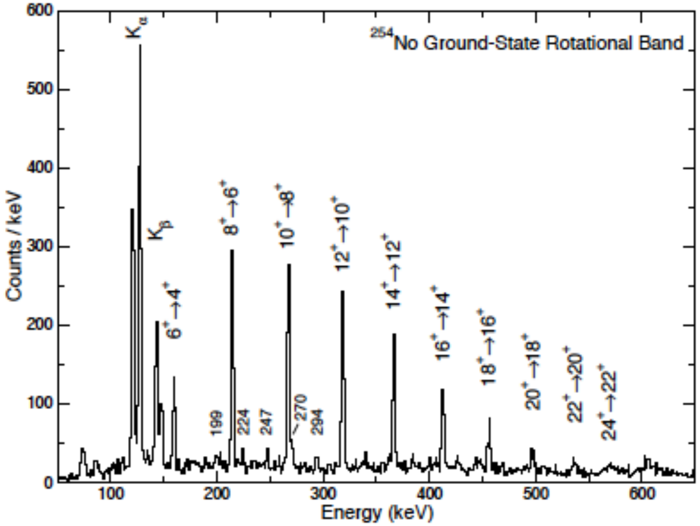
[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*University of Liverpool, Liverpool L69 7ZE, England*
[3]*Rutgers University, New Brunswick, New Jersey 08903*
[4]*Florida State University, Tallahassee, Florida 32306*
[5]*DAPNIA/SPhN, CEA Saclay, F-91191 Gif-sur-Yvette Cedex, France*
[6]*University of Jyväskylä, Jyväskylä, Finland*
[7]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[8]*University of Oslo, Oslo, Norway*
(Received 21 October 1998)

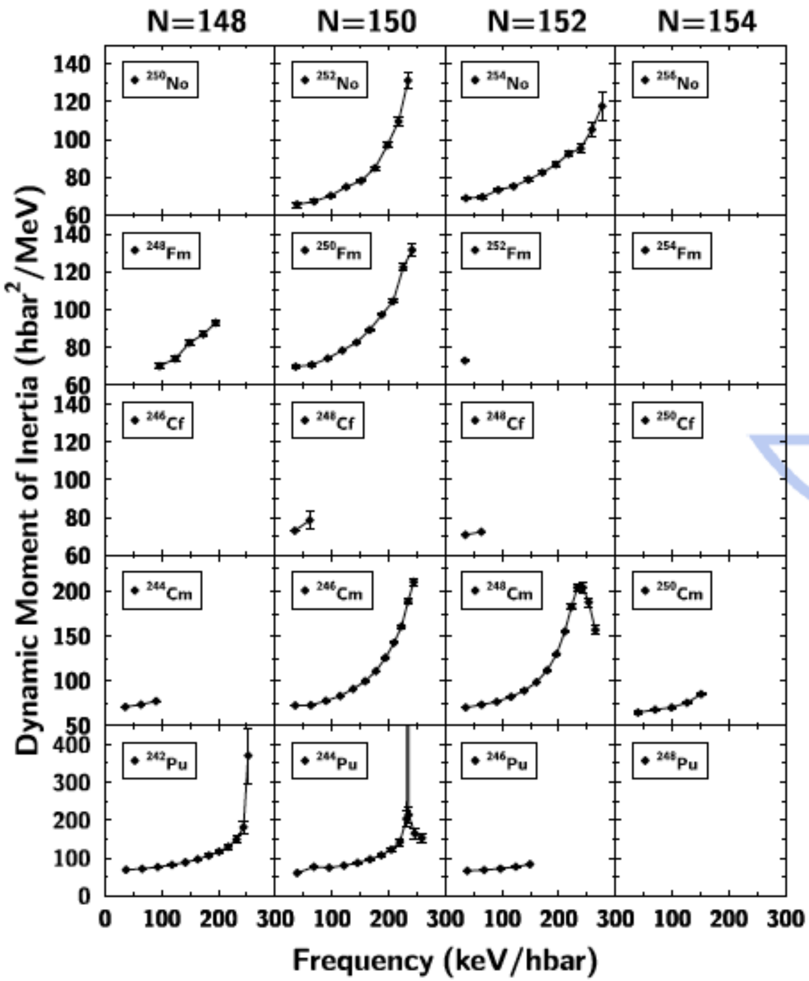
The ground-state band of the $Z = 1\ 2$ isotope ^{254}No has been identified up to spin 14, indicating that the nucleus is deformed. The deduced quadrupole deformation, $\beta = .27$, is in agreement with theoretical predictions. These observations confirm that the shell-correction energy responsible for the stability of transfermium nuclei is partly derived from deformation. The survival of ^{254}No up to spin 14 means that its fission barrier persists at least up to that spin. [S0031-9007(98)08223-4]



In-beam studies in region of ^{254}No

S. Eeckhaudt, P.T. Greenlees et al., EPJA **26**, 227 (2005)





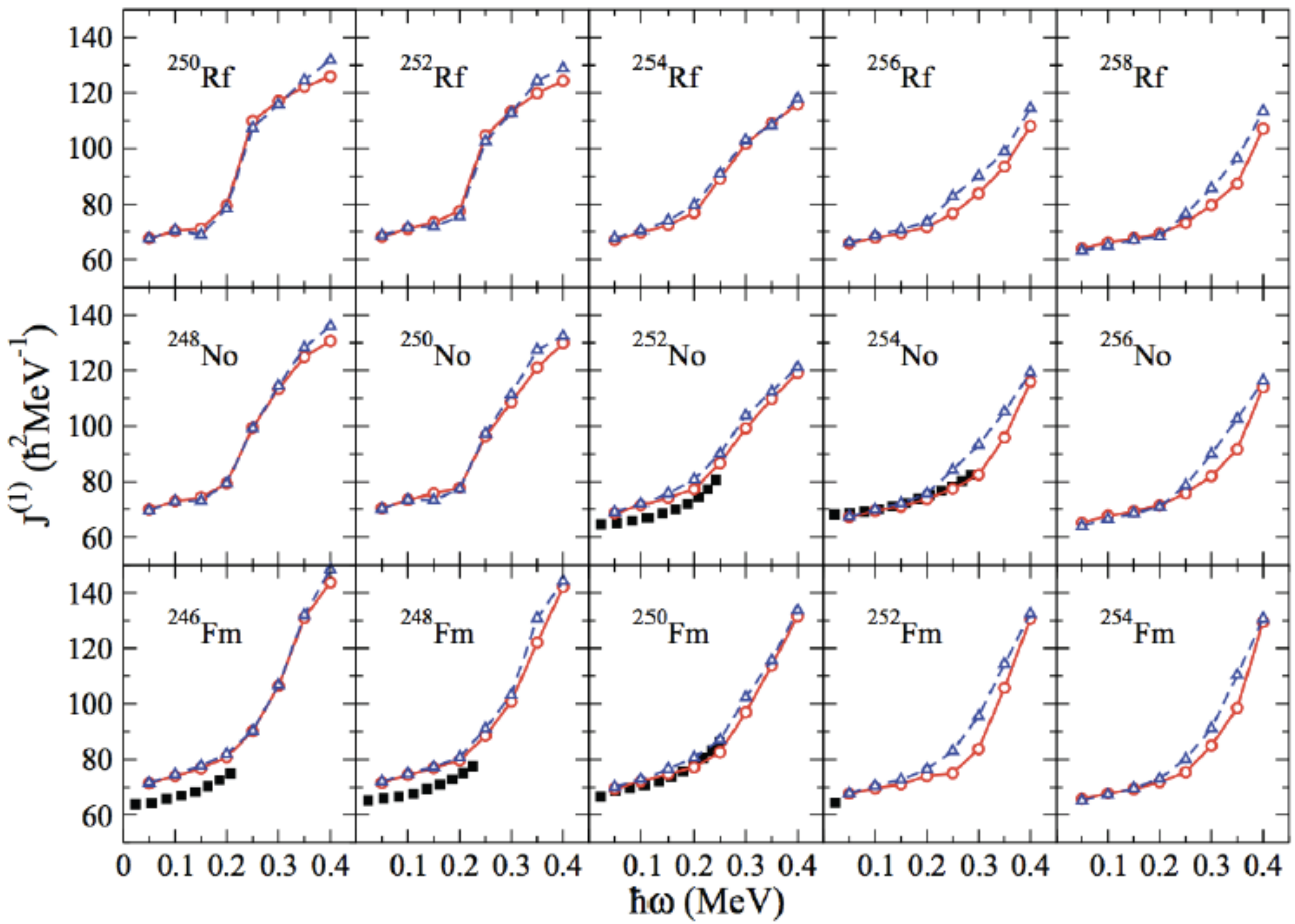
- Confirmed deformed nature of nuclei around ^{254}No
- Showed fission barrier robust with spin ($> 20\hbar$)
- Faster alignment at N=150 compared to N=152 ($\pi i_{13/2}, \nu j_{15/2}$)
- Excellent testing ground for theory; e.g. Duguet et al., NPA **679**, 427 (2001), Bender et al., NPA **723**, 354 (2003), Afanasjev et al., PRC **67**, 024309 (2003), Egido and Robledo, PRL **85** 1198 (2000)

Theory - N=150 vs. N=152

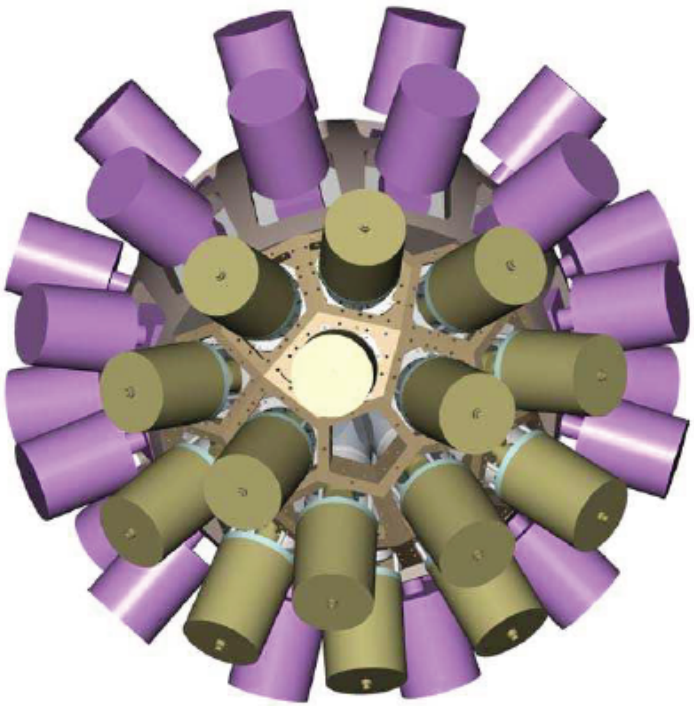
PHYSICAL REVIEW C **86**, 011301(R) (2012)

Understanding the different rotational behaviors of ^{252}No and ^{254}No

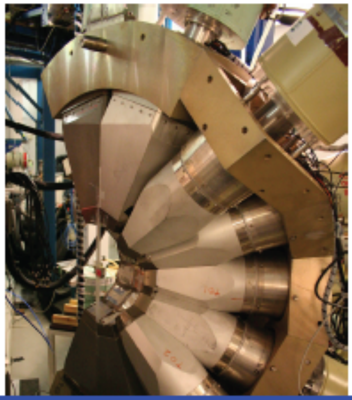
H. L. Liu,[1,*] F. R. Xu,[2] and P. M. Walker[3,4]

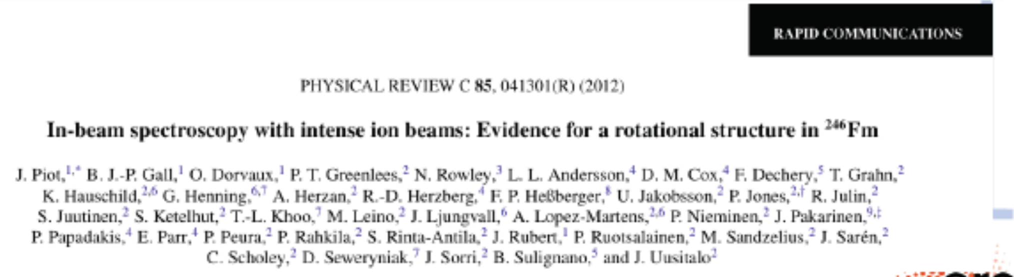


The JUROGAM II Germanium Array



- 24 Clover and 15 Tapered Ge detectors - GAMMAPOOL resource
- Total Photopeak Efficiency $\simeq$6% @ 1.3 MeV
- Excellent γ-γ efficiency
- Autofill system built by University of York, part of GREAT
- Instrumented with TNT2 / Lyrtech digital electronics
- Higher counting rates, higher beam intensities
- 20,000 hours in-beam γ-ray spectroscopy passed in 2011





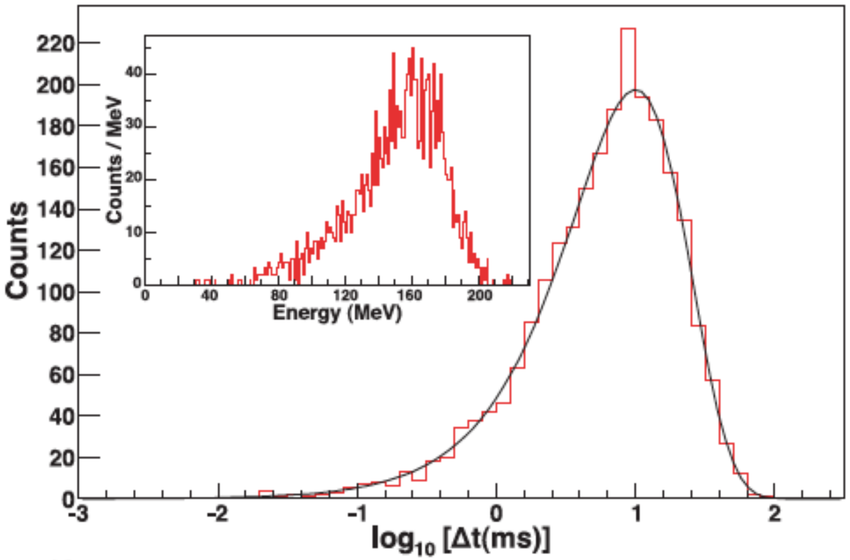
RAPID COMMUNICATIONS

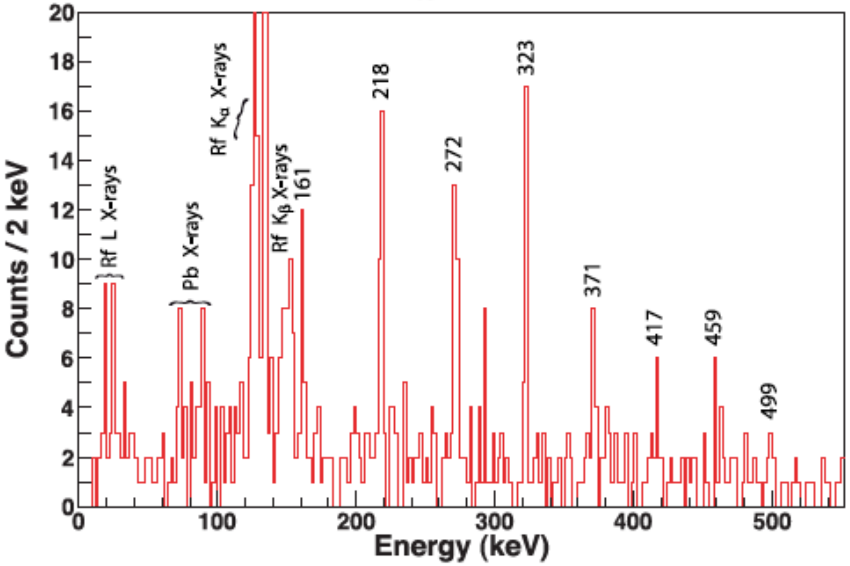
PHYSICAL REVIEW C **85**, 041301(R) (2012)

In-beam spectroscopy with intense ion beams: Evidence for a rotational structure in ^{246}Fm

J. Piot,[1,*] B. J.-P. Gall,[1] O. Dorvaux,[1] P. T. Greenlees,[2] N. Rowley,[3] L. L. Andersson,[4] D. M. Cox,[4] F. Dechery,[5] T. Grahn,[2] K. Hauschild,[2,6] G. Henning,[6,7] A. Herzan,[2] R.-D. Herzberg,[4] F. P. Heßberger,[8] U. Jakobsson,[2] P. Jones,[2,†] R. Julin,[2] S. Juutinen,[2] S. Ketelhut,[2] T.-L. Khoo,[7] M. Leino,[2] J. Ljungvall,[6] A. Lopez-Martens,[2,6] P. Nieminen,[2] J. Pakarinen,[9,‡] P. Papadakis,[4] E. Parr,[4] P. Peura,[2] P. Rahkila,[2] S. Rinta-Antila,[2] J. Rubert,[1] P. Ruotsalainen,[2] M. Sandzelius,[2] J. Sarén,[2] C. Scholey,[2] D. Seweryniak,[7] J. Sorri,[2] B. Sulignano,[5] and J. Uusitalo[2]

In-beam spectroscopy of SHE: ^{256}Rf





Experimental Details

- $^{50}Ti + ^{208}Pb \Rightarrow ^{256}Rf + 2n$
- JUROGAM II, RITU, GREAT
- Enriched ^{50}Ti beam from MIVOC
- 450 hours, 29pnA beam, 2210 observed fissions
- Cross section 17 nb

P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

Collaboration

PRL **109**, 012501 (2012)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 6 JULY 2012

Shell-Structure and Pairing Interaction in Superheavy Nuclei: Rotational Properties of the Z=104 Nucleus ^{256}Rf

P. T. Greenlees,[1,*] J. Rubert,[2] J. Piot,[2] B. J. P. Gall,[2] L. L. Andersson,[3] M. Asai,[4] Z. Asfari,[2] D. M. Cox,[3] F. Dechery,[5] O. Dorvaux,[2] T. Grahn,[1] K. Hauschild,[6] G. Henning,[6,7] A. Herzan,[1] R.-D. Herzberg,[3] F. P. Heßberger,[8] U. Jakobsson,[1] P. Jones,[1,†] R. Julin,[1] S. Juutinen,[1] S. Ketelhut,[1] T.-L. Khoo,[7] M. Leino,[1] J. Ljungvall,[6] A. Lopez-Martens,[6] R. Lozeva,[2] P. Nieminen,[1] J. Pakarinen,[9] P. Papadakis,[3] E. Parr,[3] P. Peura,[1] P. Rahkila,[1] S. Rinta-Antila,[1] P. Ruotsalainen,[1] M. Sandzelius,[1] J. Sarén,[1] C. Scholey,[1] D. Seweryniak,[7] J. Sorri,[1] B. Sulignano,[5] Ch. Theisen,[5] J. Uusitalo,[1] and M. Venhart[10]

[1]*Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland*
[2]*Institut Pluridisciplinaire Hubert Curien, F-67037 Strasbourg, France*
[3]*Department of Physics, University of Liverpool, Oxford Street, Liverpool, L69 7ZE, United Kingdom*
[4]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[5]*CEA, Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*
[6]*CSNSM, IN2P3-CNRS, F-91405 Orsay Campus, France*
[7]*Argonne National Laboratory, Argonne, Illinois, Illinois 60439, USA*
[8]*GSI, Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany*
[9]*CERN-ISOLDE, Building 26, 1-013, CH-1211 Geneva 23, Switzerland*
[10]*Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*

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ELSEVIER

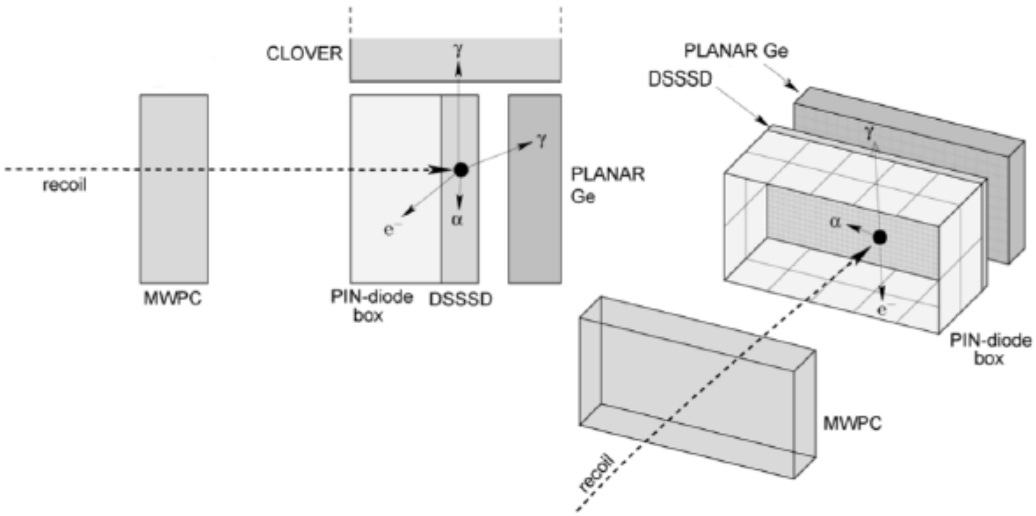
First intense isotopic titanium-50 beam using MIVOC method

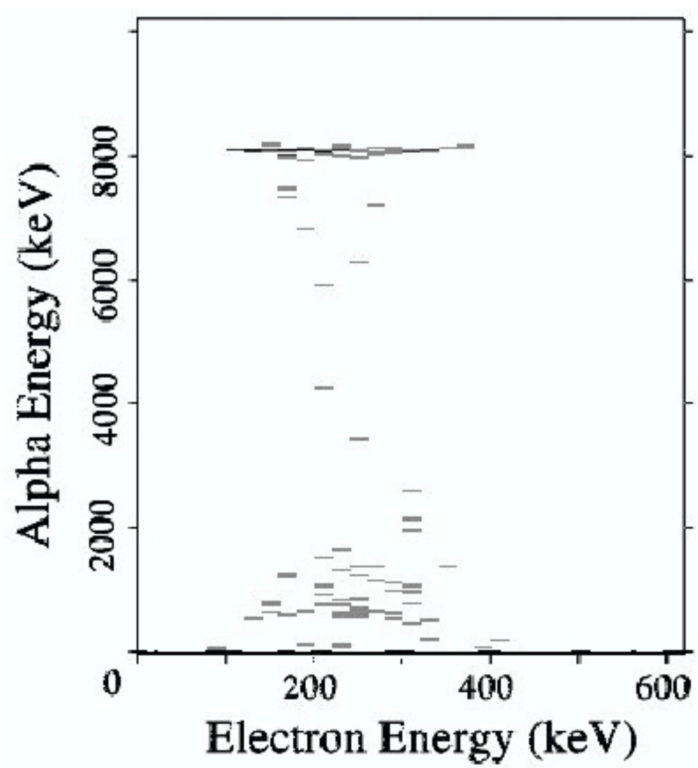
J. Rubert[a], J. Piot[a,1], Z. Asfari[b], B.JP. Gall[a,*], J. Ärje[c], O. Dorvaux[a], P.T. Greenlees[c], H. Koivisto[c], A. Ouadi[a], R. Seppälä[c]

[a] *Département de Recherches Subatomiques, Institut Pluridisciplinaire Hubert Curien, UMR 7178, Université de Strasbourg/CNRS-IN2P3, 23 rue du Loess, F-67037 Strasbourg, France*
[b] *Laboratoire d'Ingénierie Moléculaire Appliquée à l'Analyse (DSA), Institut Pluridisciplinaire Hubert Curien, UMR 7178, Université de Strasbourg/CNRS-IN2P3, 23 rue du Loess, F-67037 Strasbourg, France*
[c] *Department of Physics, University of Jyväskylä, P.O. Box 35 (YFL), Jyväskylä FI-40014, Finland*

Studies of K-Isomerism - Calorimetric Method

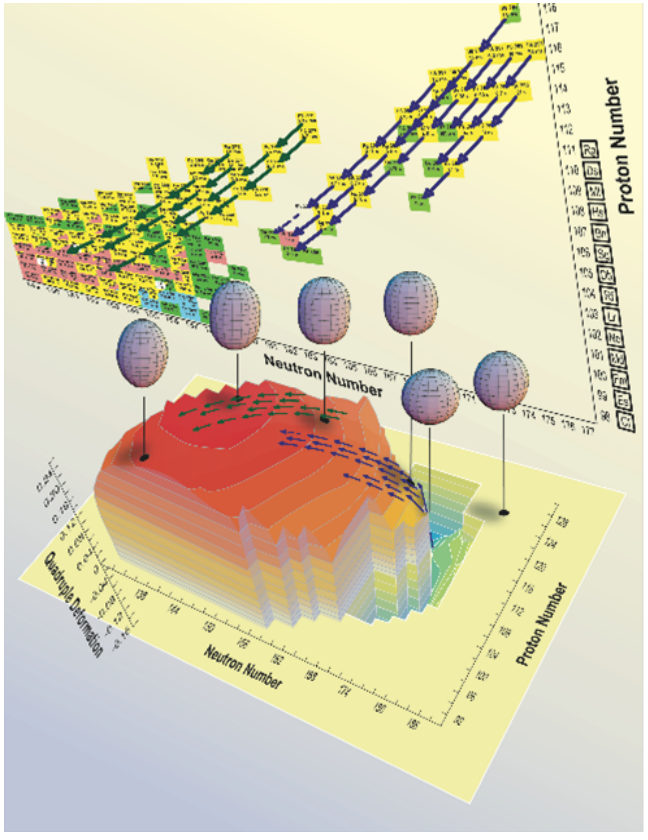
- Isomeric states in ^{250}Fm and ^{254}No first postulated by Ghiorso et al., PRC **7**, 2032 (1973)
- Powerful method proposed by Jones, NIM **A488**, 471 (2002)
- Low-energy transitions highly converted, look for Recoil-electron-α correlated chains in DSSSD





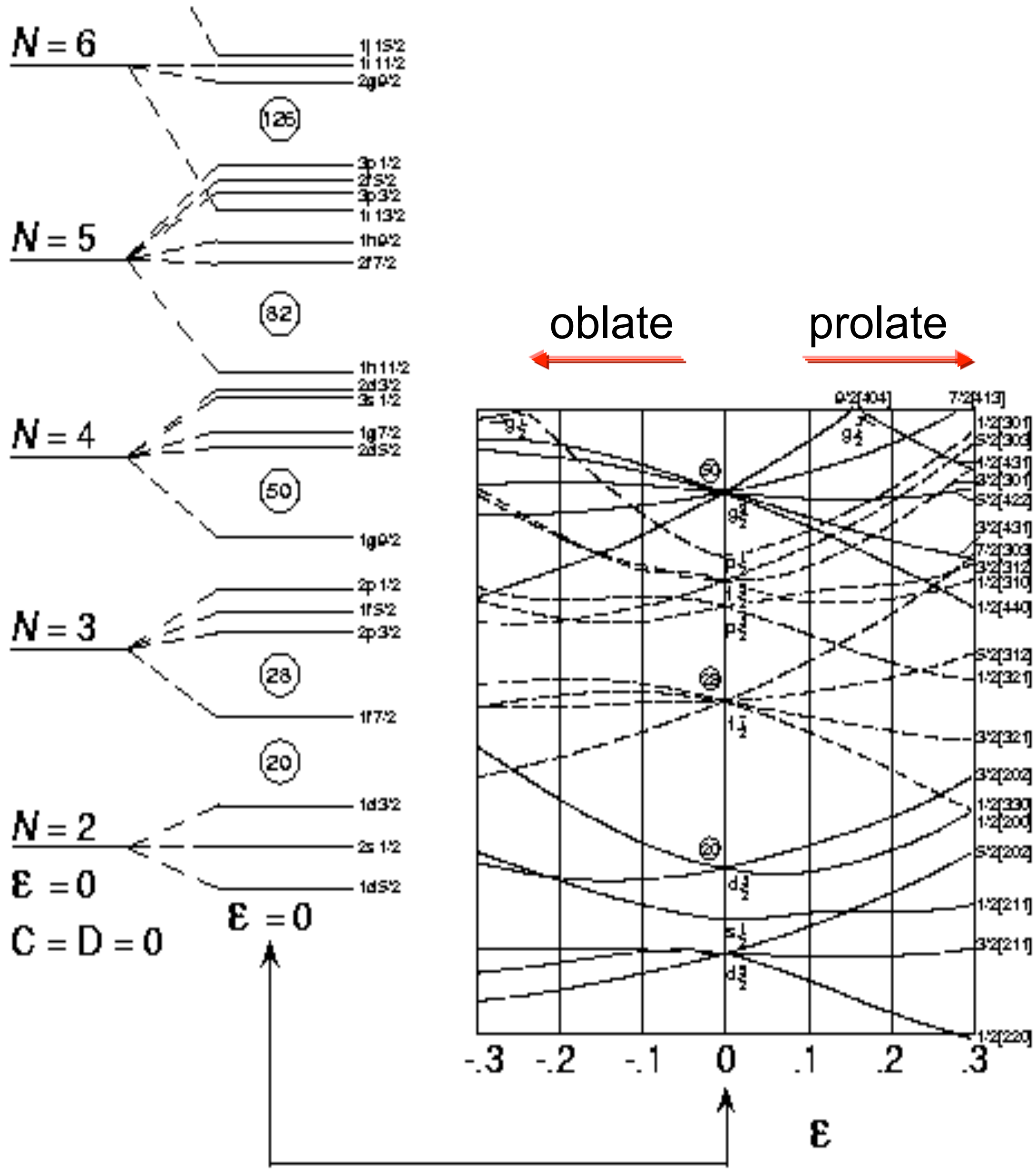
Superheavy Spectroscopy

- Very exciting indeed! Lots of ongoing work both in the US and in Europe (Jyvaskla).

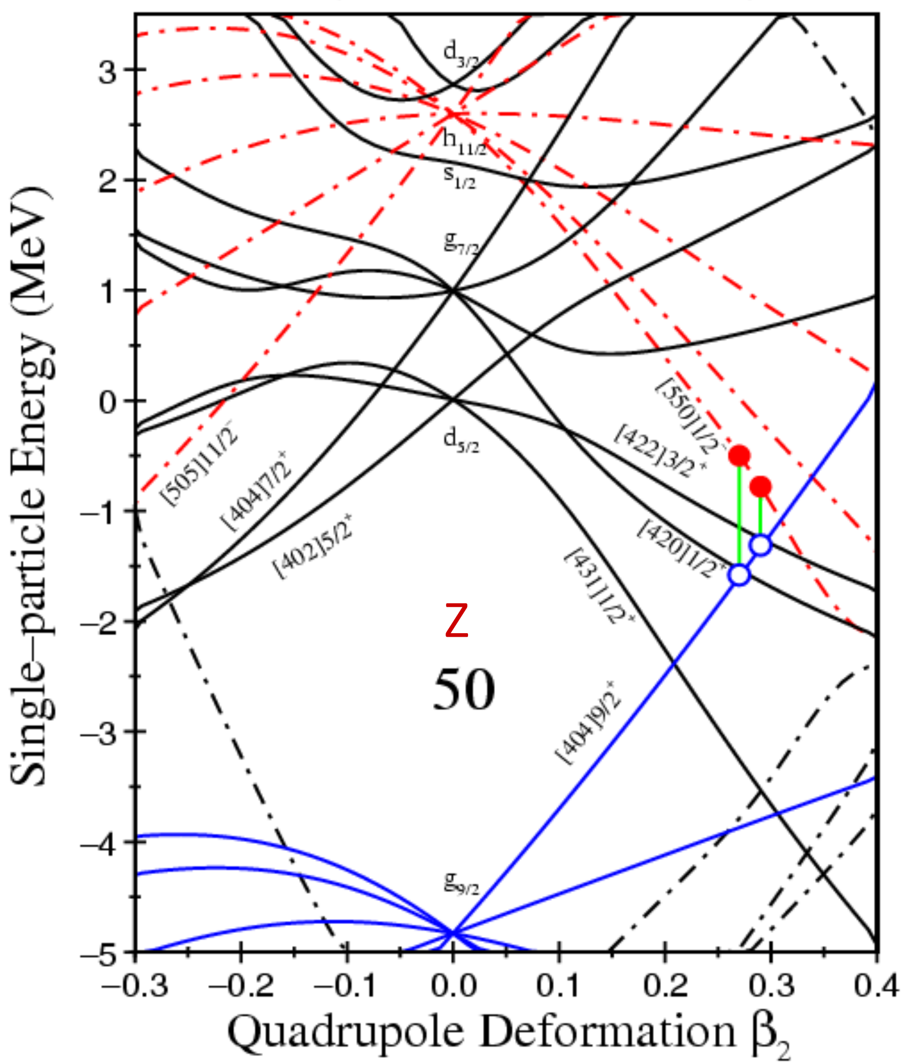


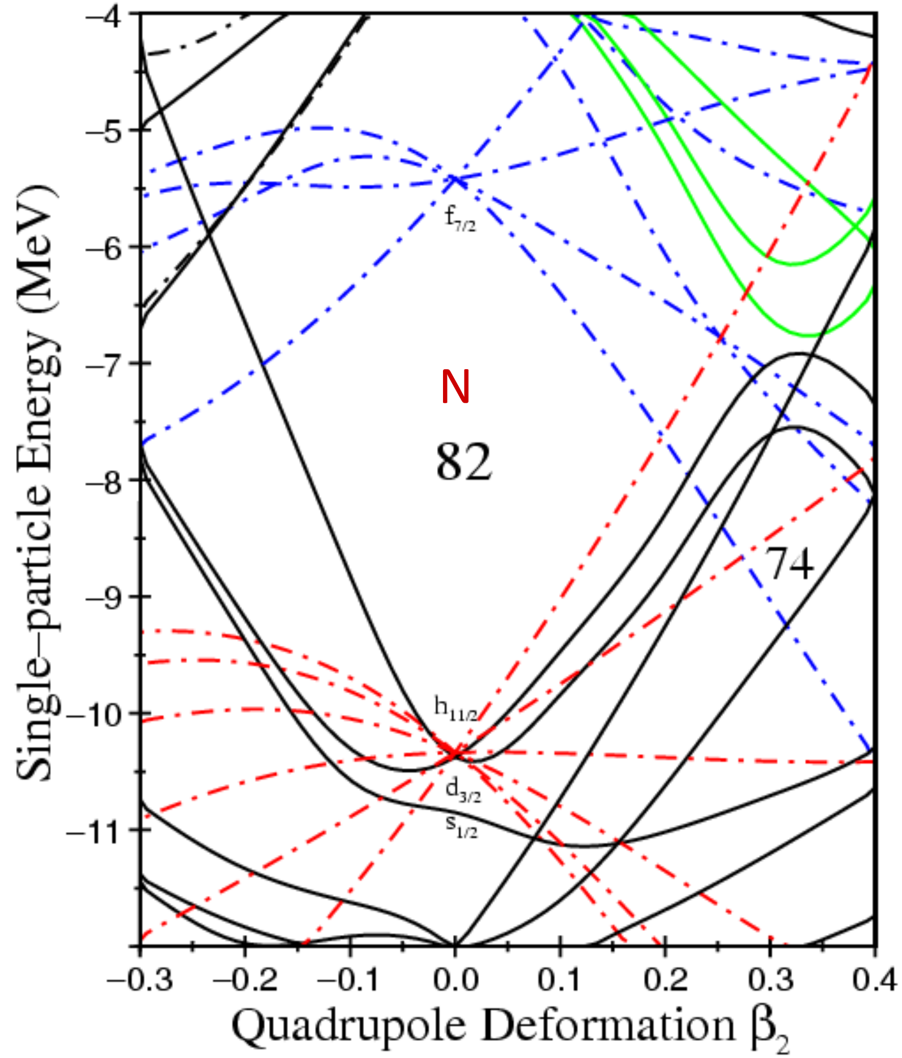
END EPISODE 2

Nilsson Diagram (Energy vs. def)

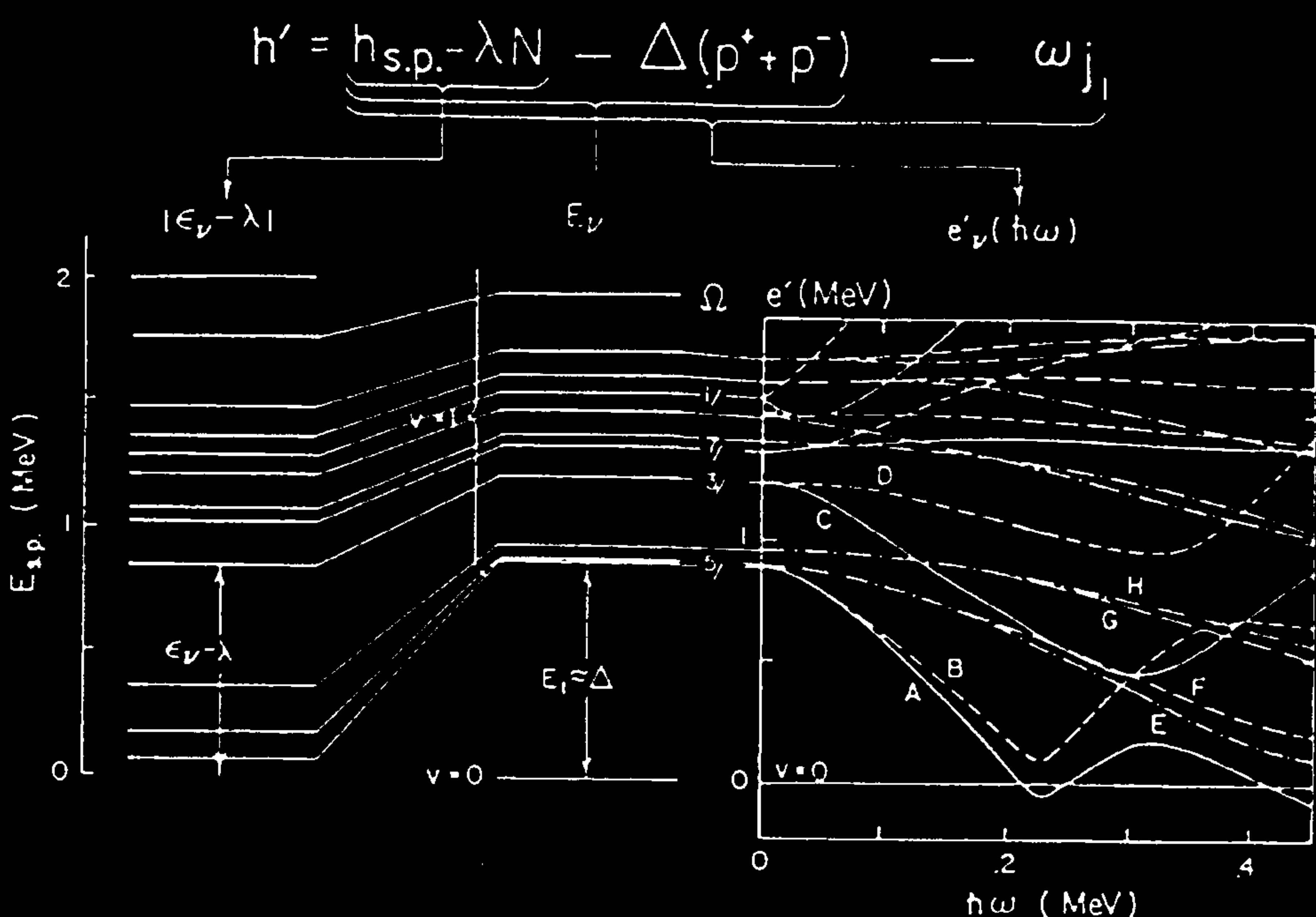


Nilsson Single-Particle Diagrams



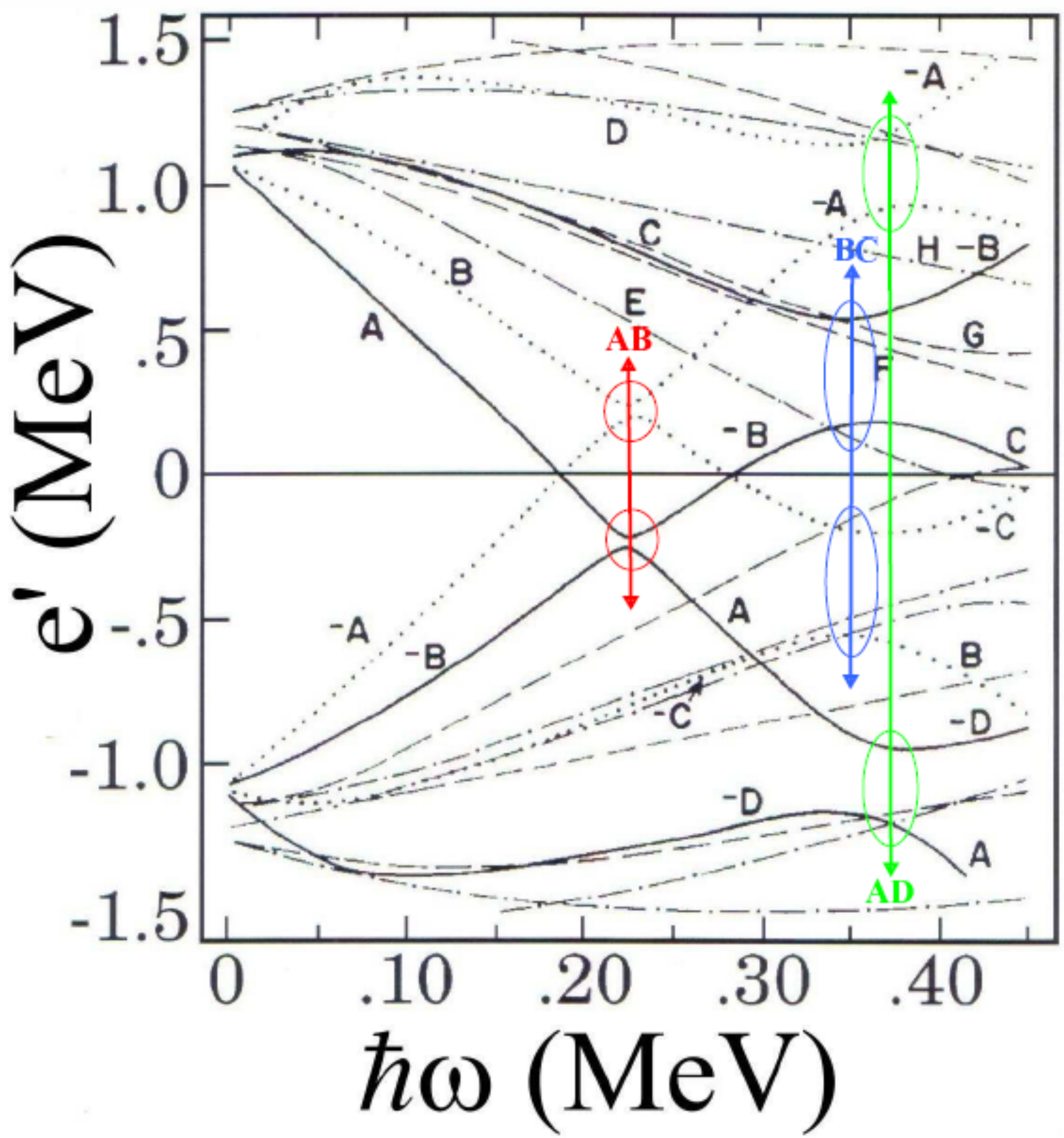


If this is complicated wait until you put rotations, pairing, higher def terms in!

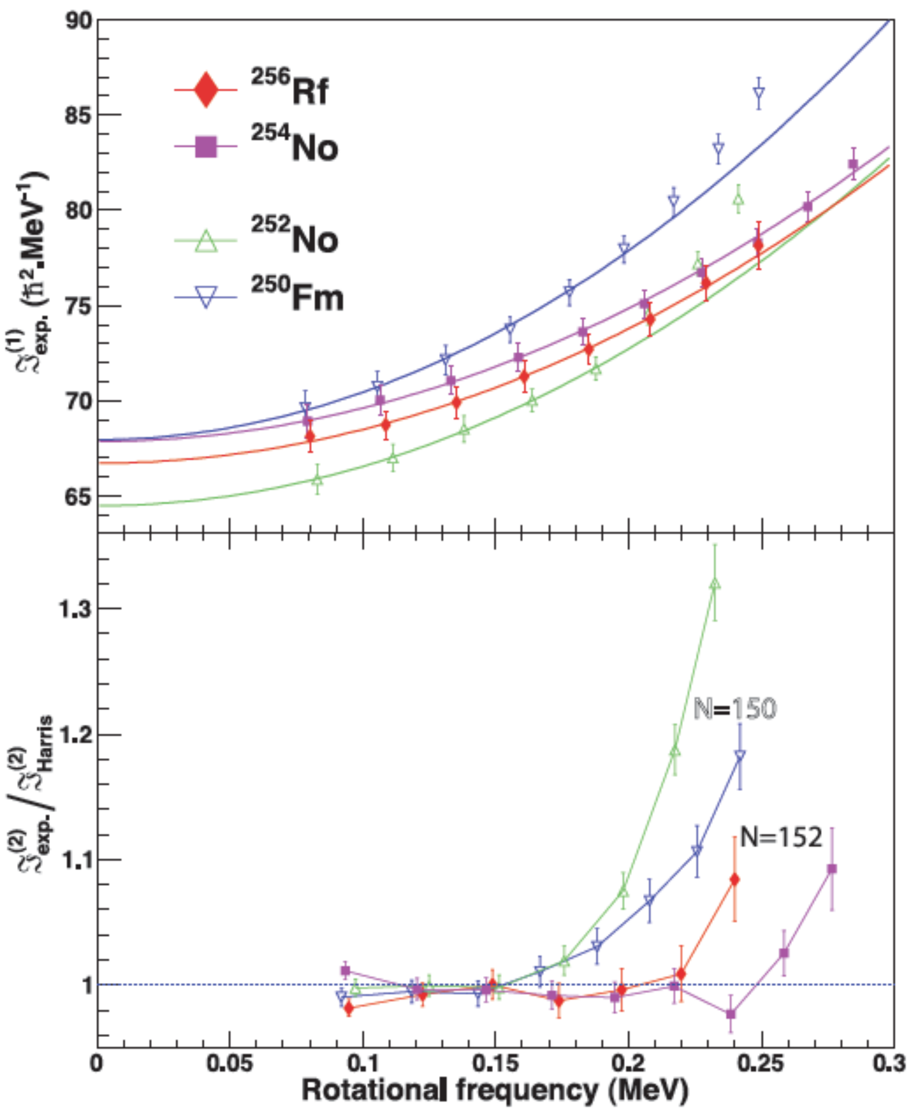


h′ = h s.p. − λN − Δ(p⁺ + p⁻) − ω j1
|ε ν − λ|
E ν
e′ ν (ħω)
E s.p. (MeV)
ε ν − λ
E1 ≈ Δ
v = 0
Ω
e′ (MeV)
A
B
C
D
E
F
G
H
ħω (MeV)

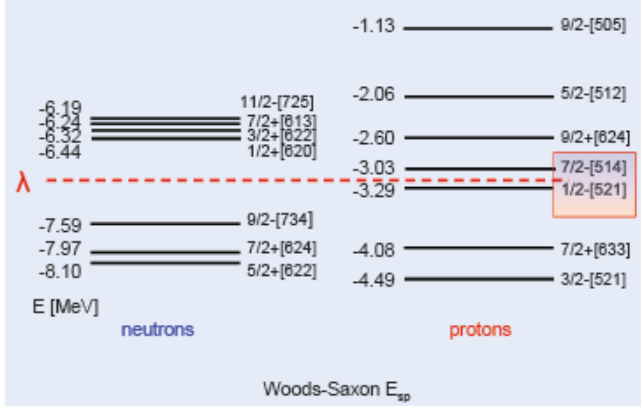
Quasiparticle levels and rotation

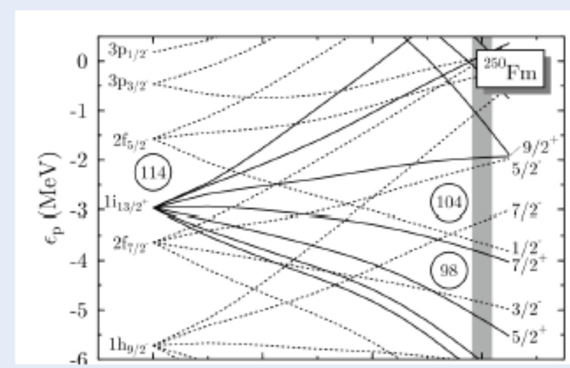


In-beam spectroscopy of SHE: ^{256}Rf



Single-particle energies





P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

Magnetic Rotation: Another Surprise!

The Shears Mechanism

R.M.Clark, A.O.Macchiavelli et al.

Annu. Rev. Nucl. Part. Sci. 2000. 50: 1–36

THE SHEARS MECHANISM IN NUCLEI*

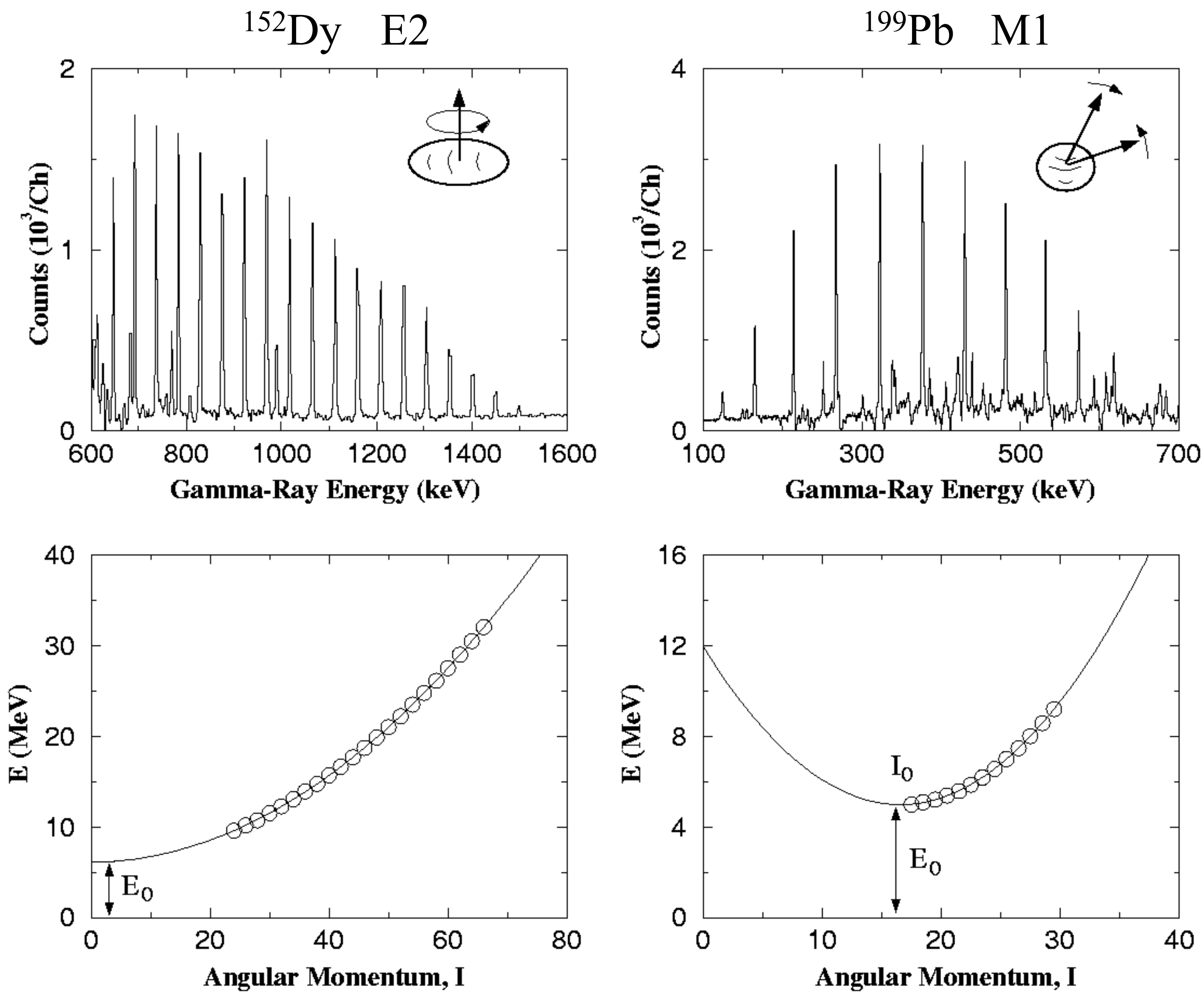
R. M. Clark and A. O. Macchiavelli

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720; e-mail: rmclark@lbl.gov, aom@lbl.gov

– Experimental Proof

– Semi-classical Interpretation

Shears Bands (The puzzle)

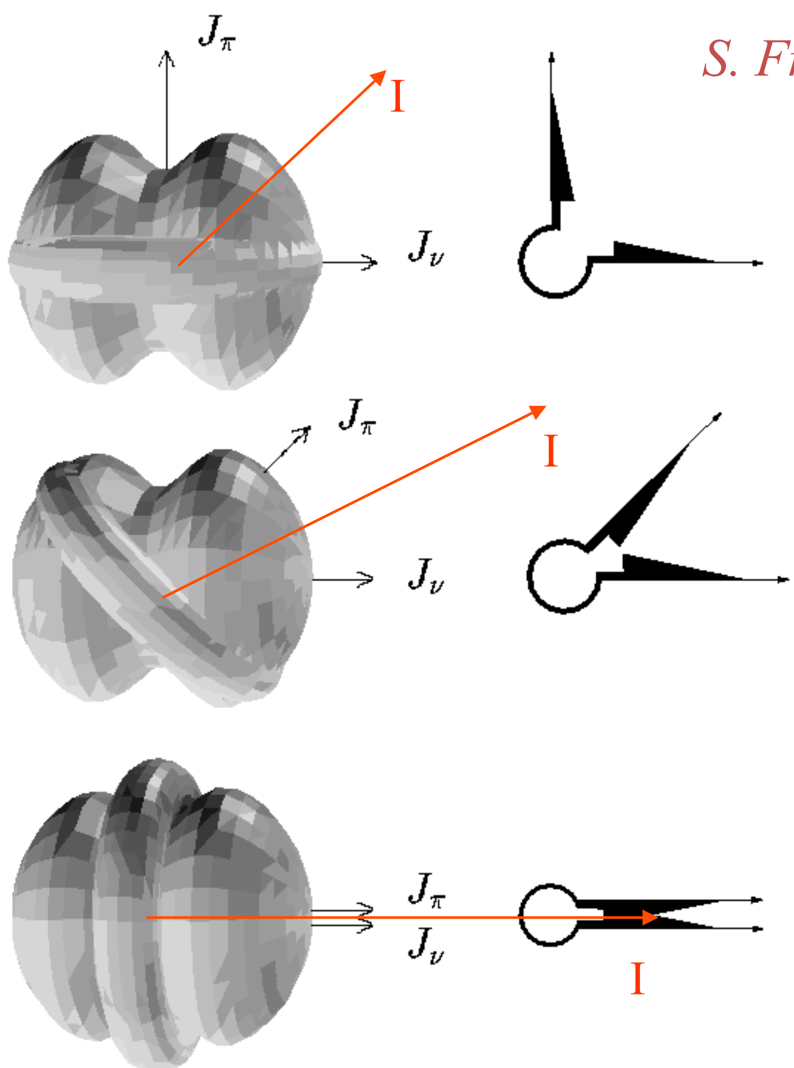


<u>Characteristics</u>

- "rotational-like" $E-E_0 \sim (I-I_0)^2$
- strong M1's large B(M1)
- weak E2's low B(E2)
- near spherical nucleus

The Shears Mechanism (Tilted Axis Cranking)

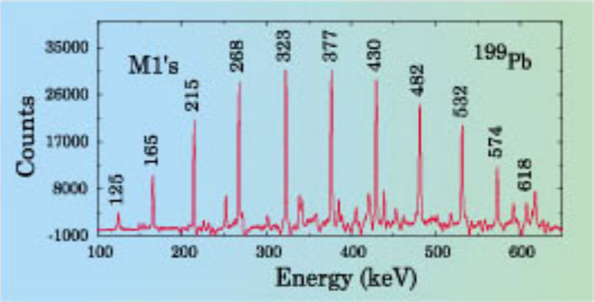
S. Frauendorf NPA 557 (1993) 259c

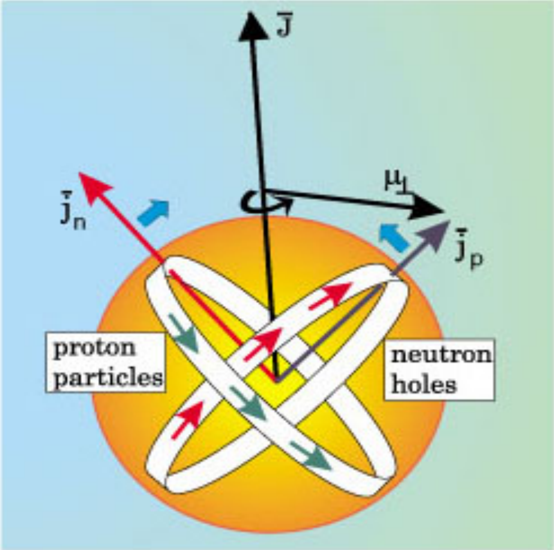


- **Angular momentum comes from a few valence neutron holes and proton particles**
- **Lowest energy corresponds to spin vectors at 90°**
- **Increasing spin generated by closing the angle between the spin vectors**

Magnetic Rotation and the "Shears Mechanism"

Equally spaced gamma-ray transitions normally imply collective rotational motion due to a non-spherical nuclear shape. However, for a band in ^{199}Pb (among others) collective rotation is not the answer. The nuclear shape is near-spherical and a new process has been proposed to generate angular momentum, the so-called "Shears Mechanism".





It has been suggested that these bands arise due to a new type of rotation where rotational symmetry is broken by the anisotropic arrangement of nucleonic currents. A few valence proton and neutron holes couple to form two "long" angular momenta, j_p and j_n (blades of the shears) which in turn couple to give the total spin J. Increasing spin is generated by closing the angle between j_p and j_n. A magnetic moment arises and rotates around the total spin, giving the characteristic M1 radiation. This phenomenonhas become known as magnetic rotation.

The strength of the M1 transition is proportional to the size of the perpendicular component of the magnetic moment $\mu_\perp$. Confirmation of the "Shears Mechanism" came with the observation in a GAMMASPHERE experiment that the strength of the Magnetic Dipole Transition rates *DECREASE* with increasing rotational speed.