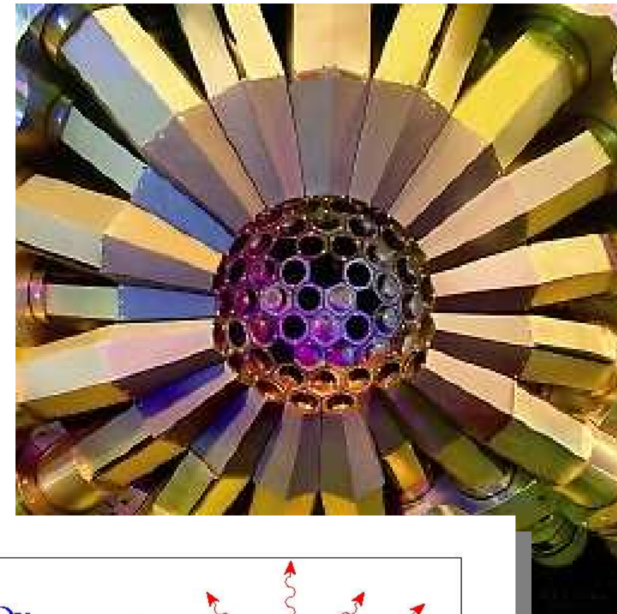
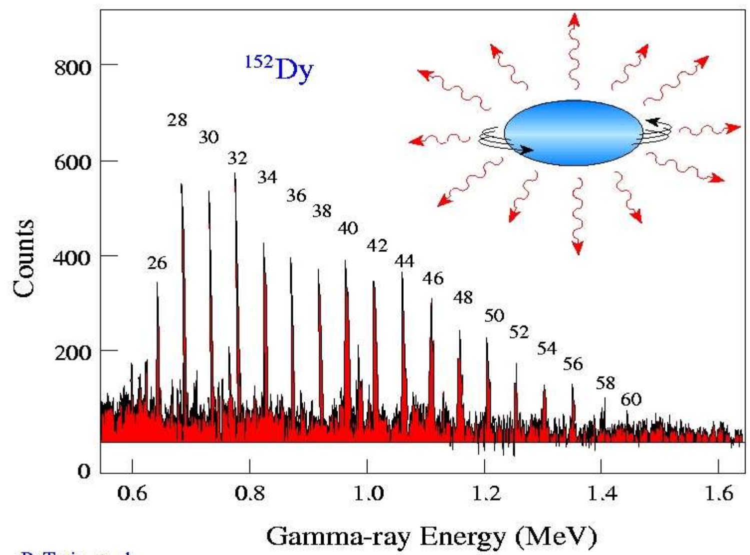
Nuclear Superdeformation

Paul Fallon NS06

Outline

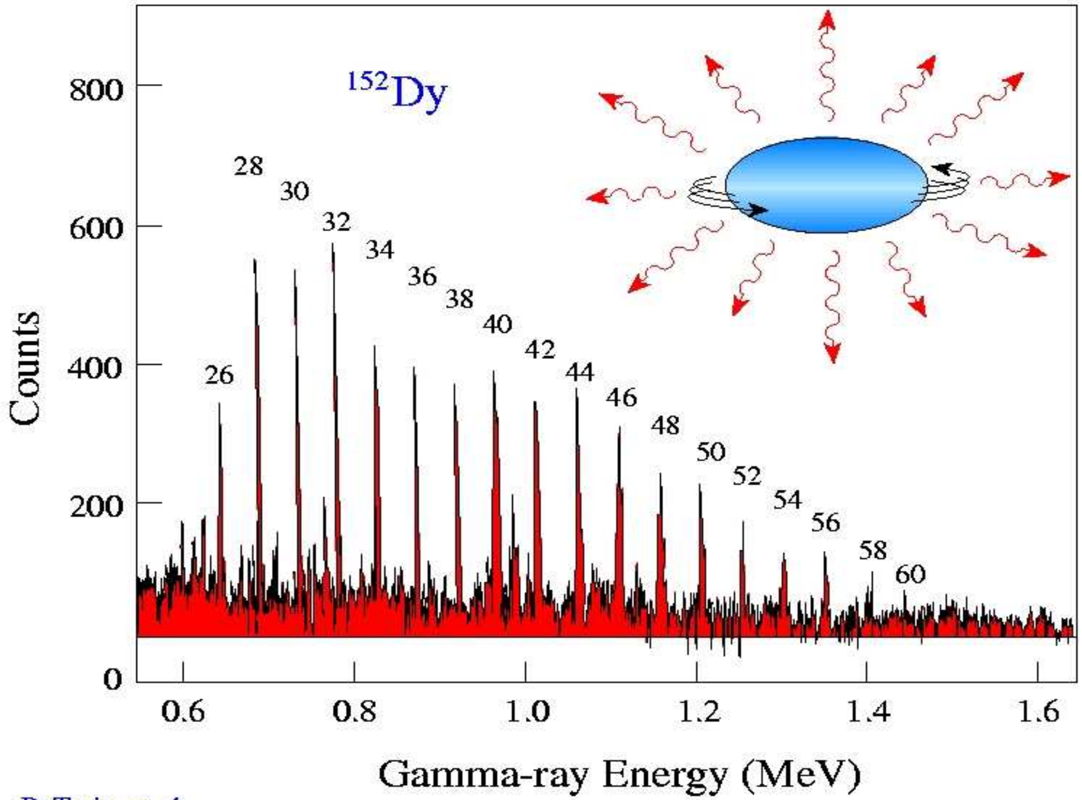
- Introduction
  - basic physics
  - the early days
  - review - what we have learned
- Selected Topics
  - Decays
  - C4
  - Identical Bands
  - New regions ^{40}Ca
  - Triaxial SD
  - Hyperdeformed
    - ^{108}Cd ….
- Future





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

Where it all began !   *(revisionist)*



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

TESSA 3 – ^{152}Dy

P.J. Twin et al PRL 57 (1986)

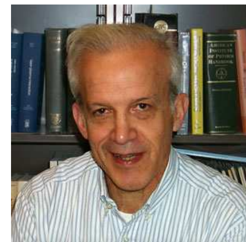
A major achievement for our field

The discovery of "high-spin" superdeformation was a major motivation and justification for the large 4π arrays Gammasphere and Euroball

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

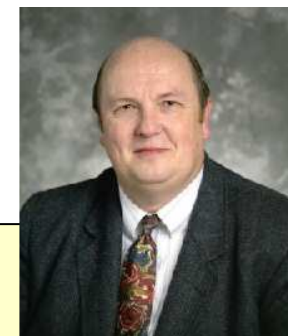
Atom cooling and atom optics

Large-scale structure of the universe

Supernova 1987A

<u>Superdeformed nuclei</u>

Buckyballs



J. Garrett
“Superdeformation - Nuclear Physics’ Supernova”

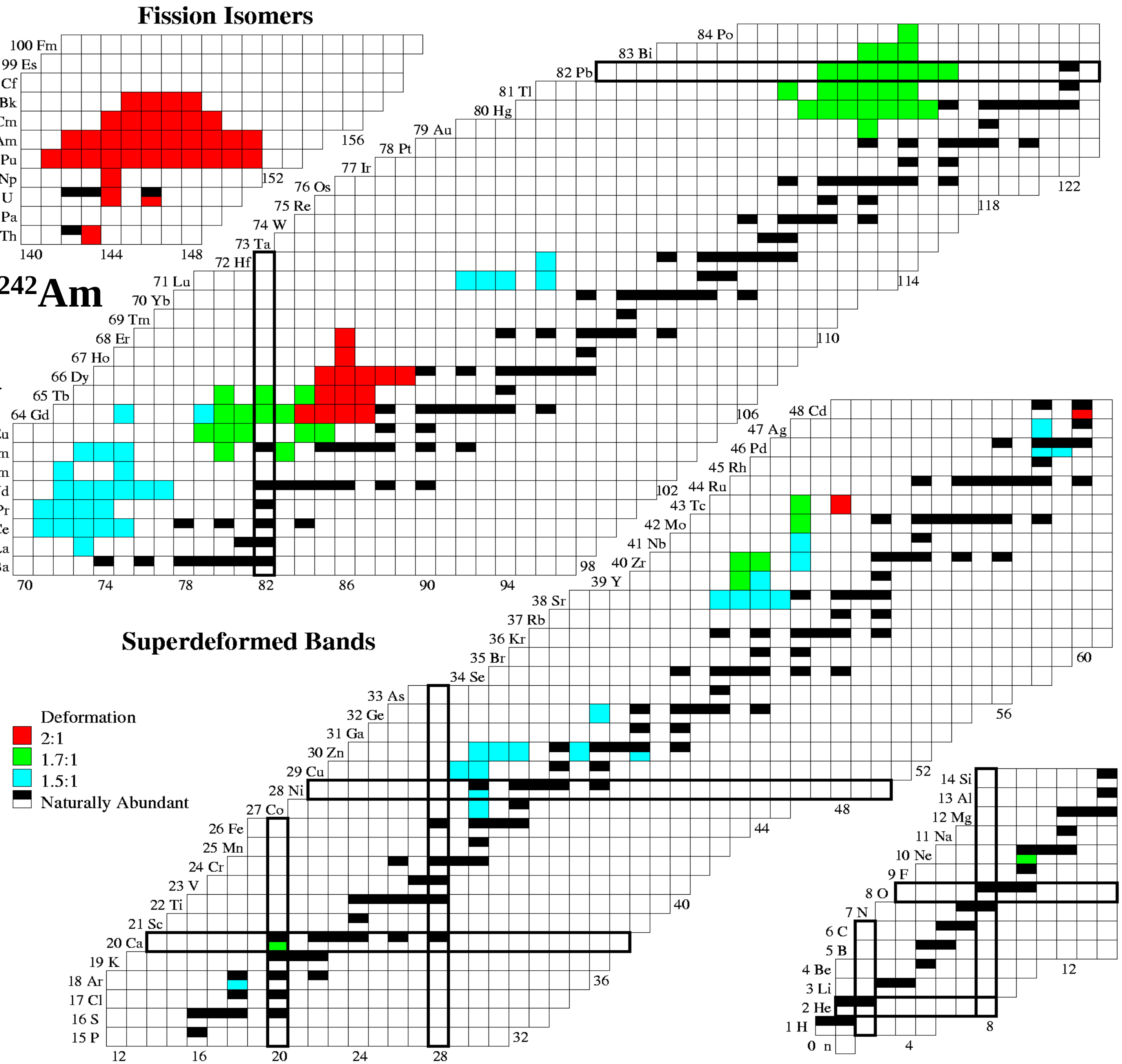
B. Mottelson
…one of Nuclear Structures finest hours ..

First Observed ^{242}Am

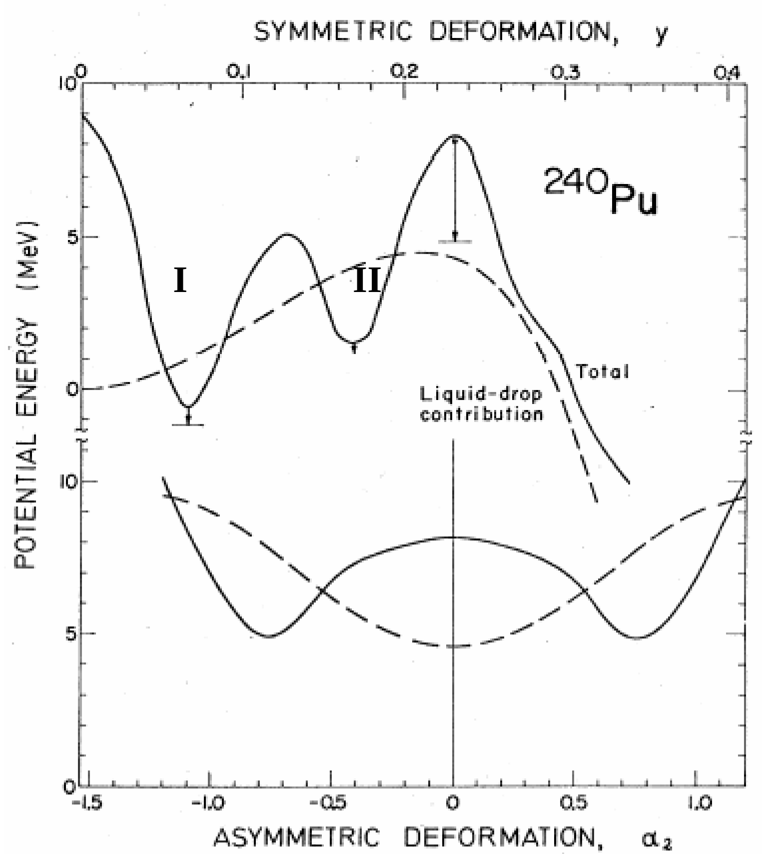
25yrs later ^{152}Dy (1986)

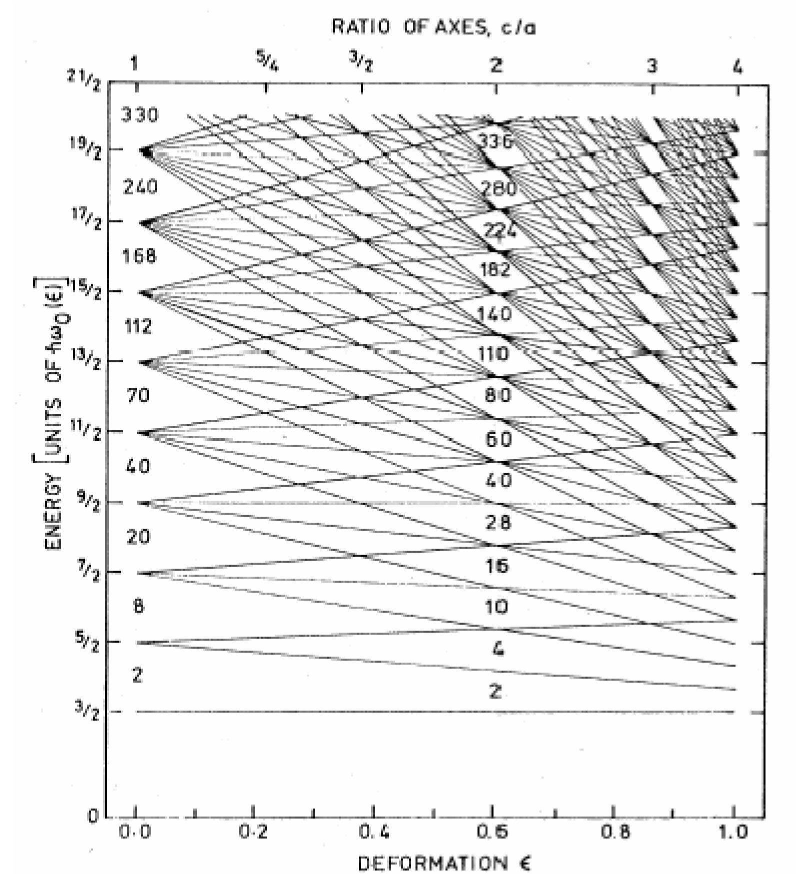
Since then …

Rapid progress- Large detector arrays



Deformed Minima/Shell gaps



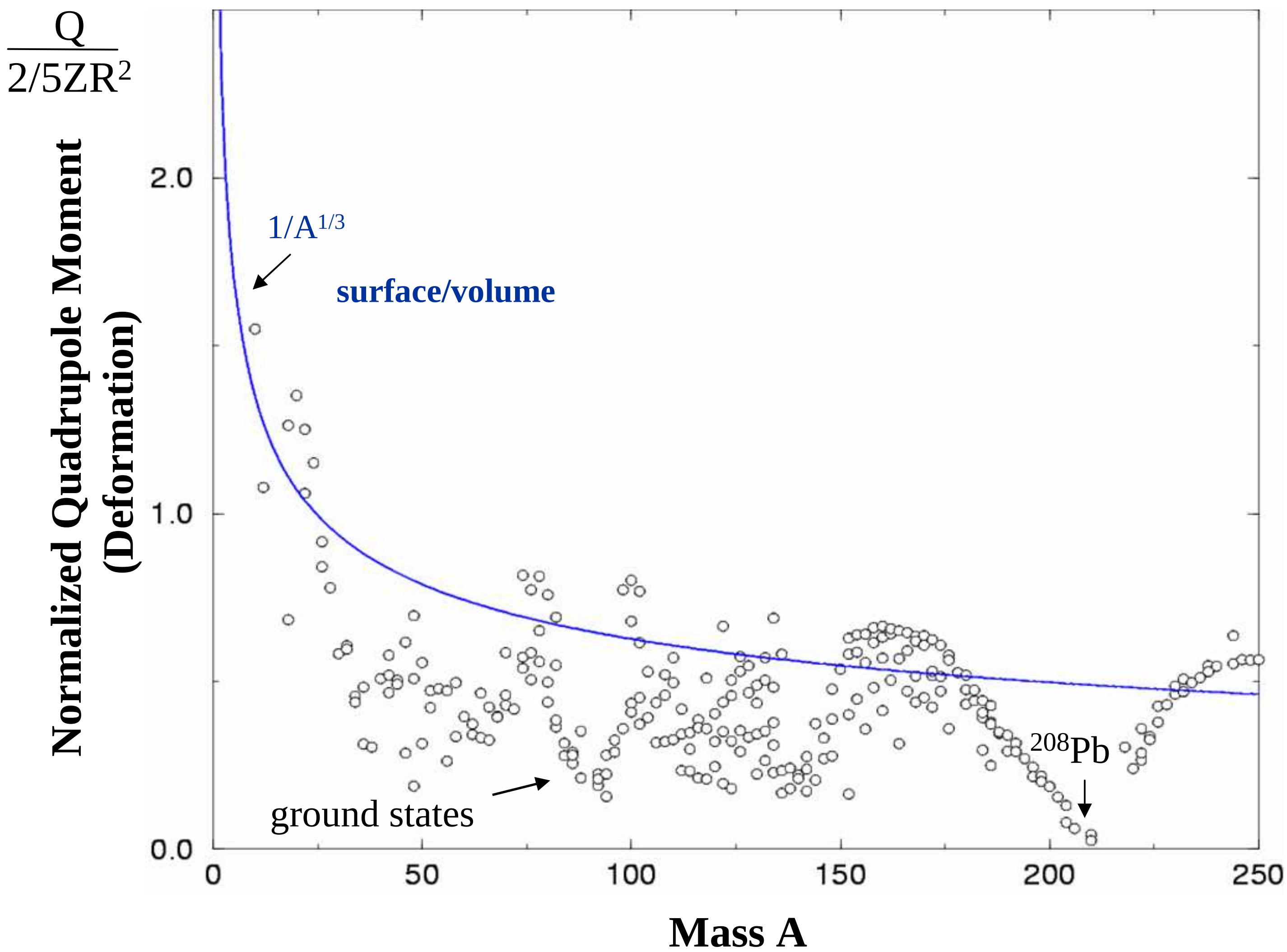


- **Coulomb Energy**
- **Rotational Energy**

If gaps due to symmetry
- deformation independent of A

Deformed analog of spherical gaps
SD distinct from normal defs

Nuclear Deformations



Nuclear Deformations

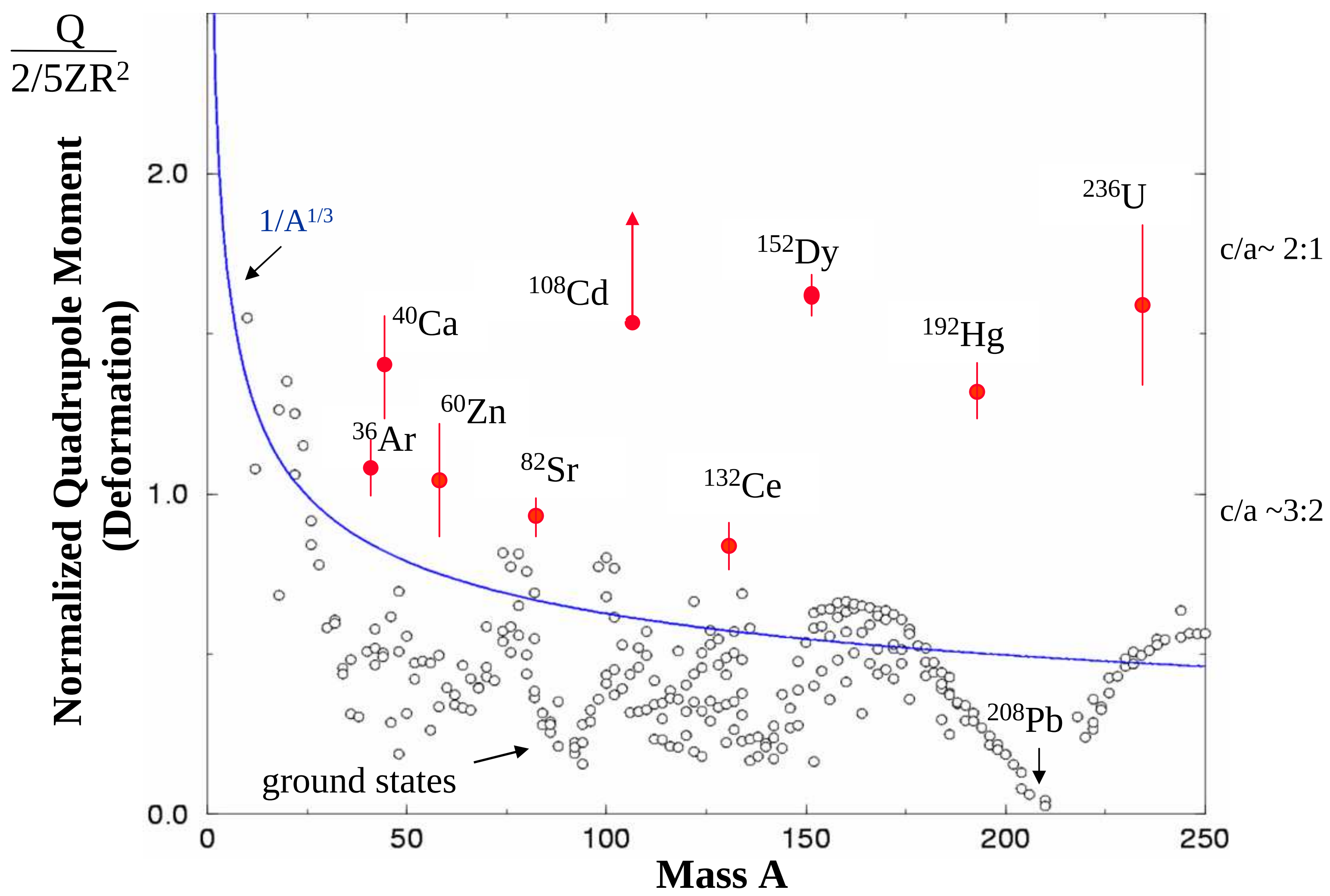
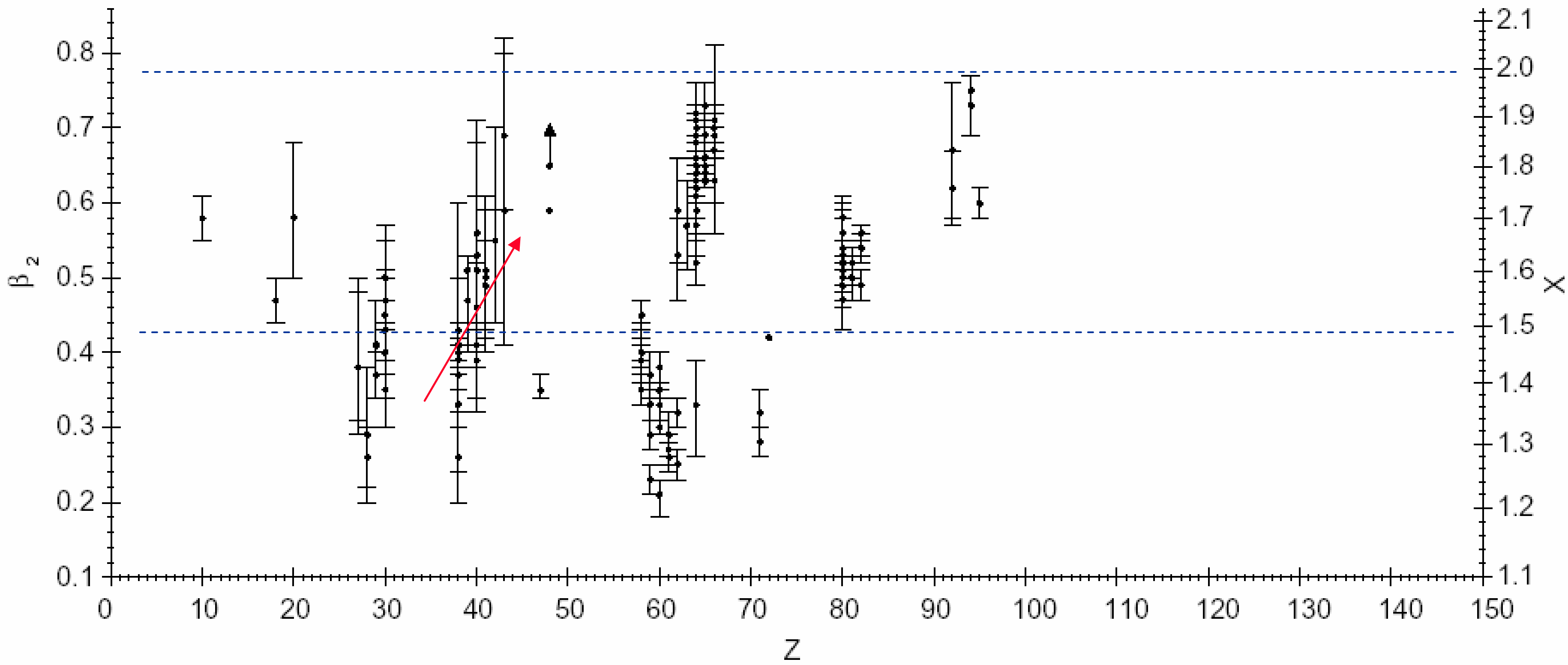


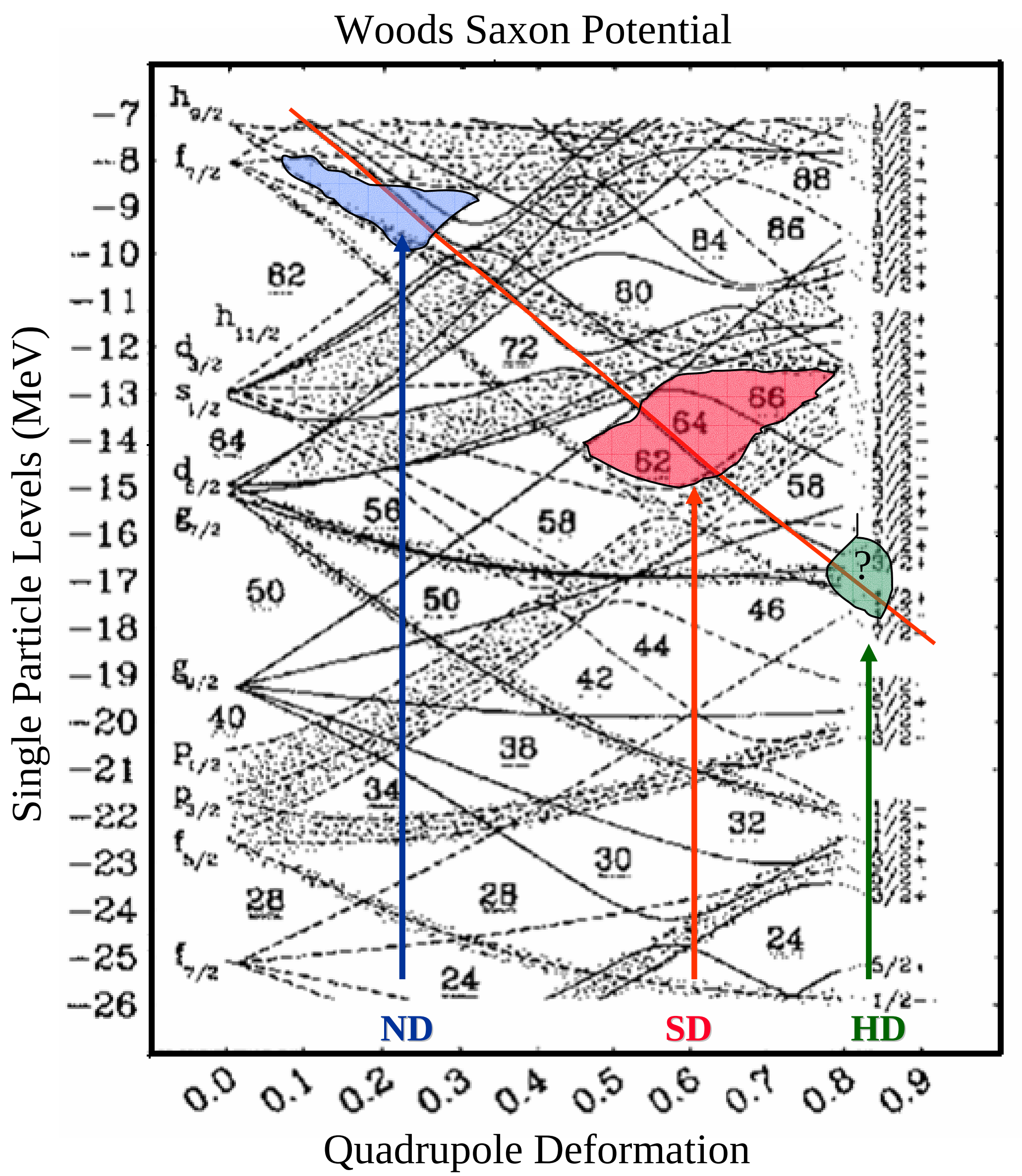
Table of Superdeformed Nuclear Bands and Fission Isomers* Third Edition (July 2002)

Balraj Singh†, Roy Zywina†, and Richard B. Firestone‡

† McMaster University, Hamilton, Ontario L8S 4M1, Canada (hispin@mcmaster.ca)
‡ Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA (rbf@lbl.gov)



Deformations Shell Structure and Intruders



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

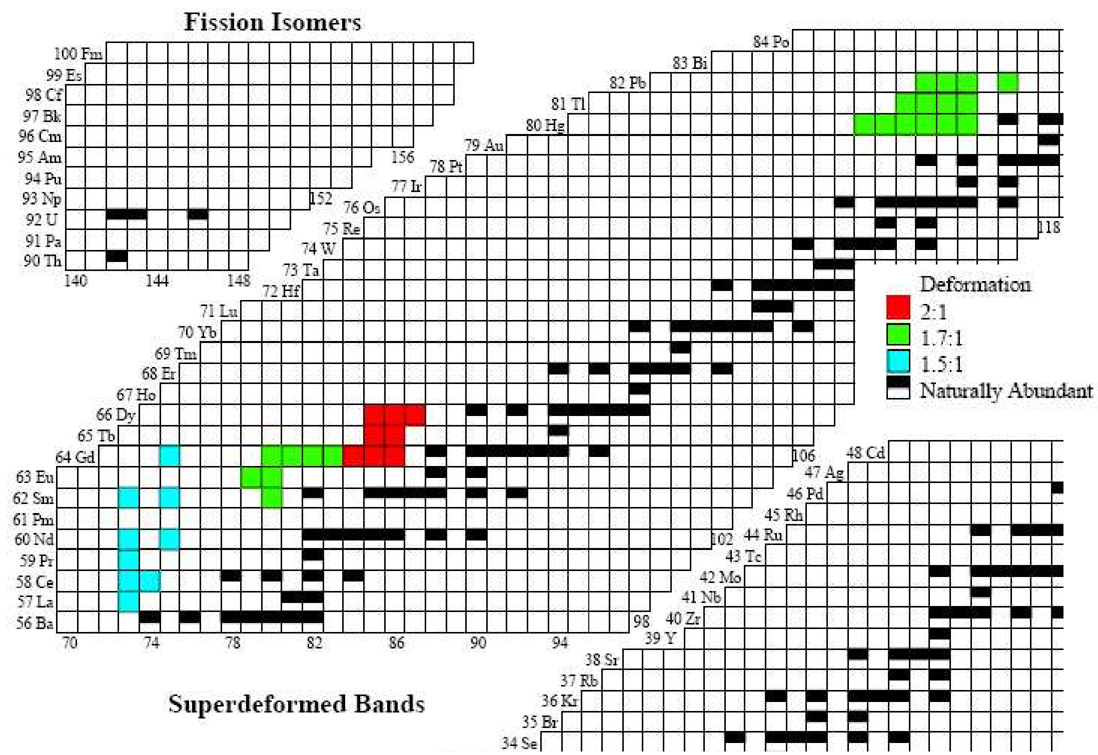
Classify the Structure by the Intruder Occupation

	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

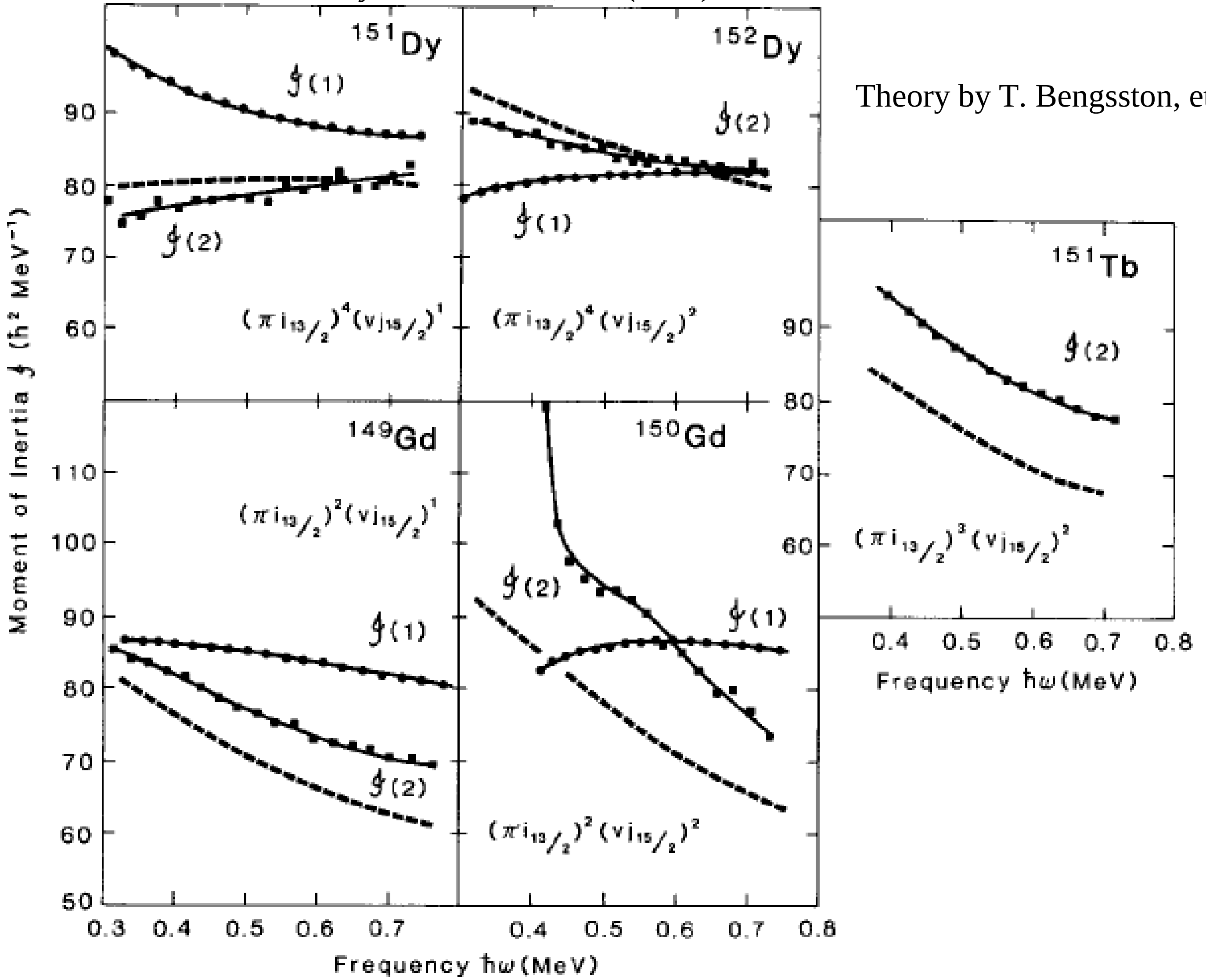
The early days (1986-1992)

- Observation (A~130,150,190)
- Structure – $J^{(2)}$
- Identical Bands



Mapping the single-particle (high-j intruder) configurations

P.Fallon et al. Physics Letters B, 218 (1989)137

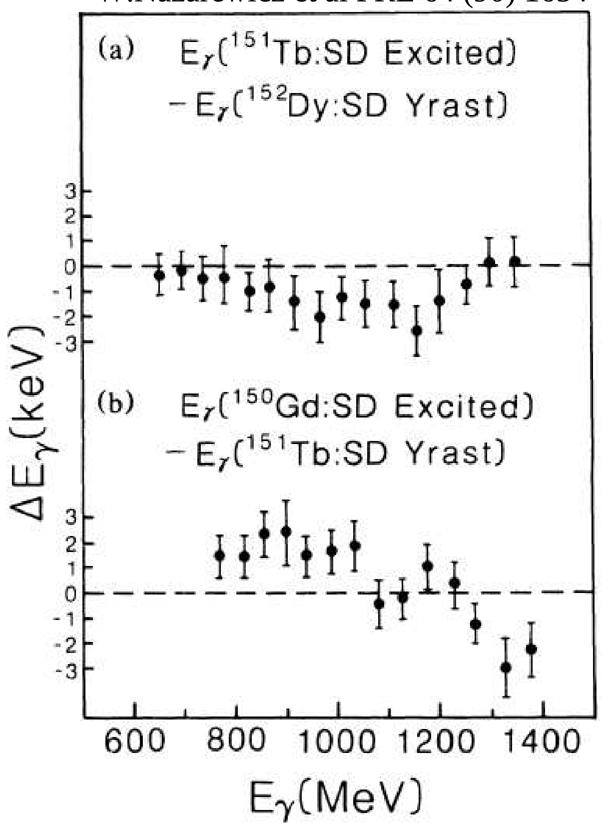


Theory by T. Bengsston, et al. PLB 208 (1988) 39,

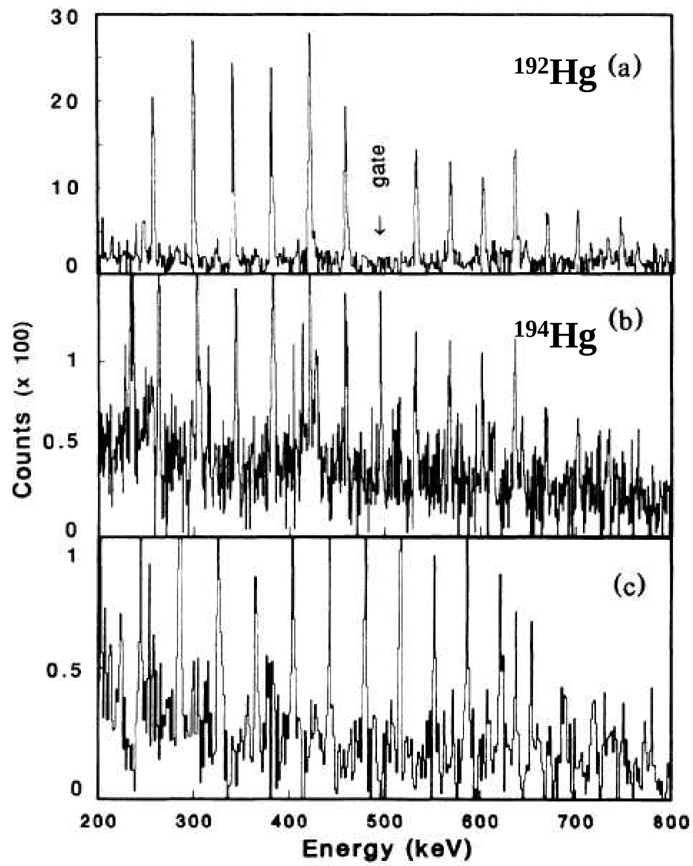
1990: Identical Superdeformed bands

T.Bryski et al PRL 64(90) 1650

W.Nazarewicz et al PRL 64 (90) 1654



F.S.Stephens et al., PRL 64 (1990) 2626



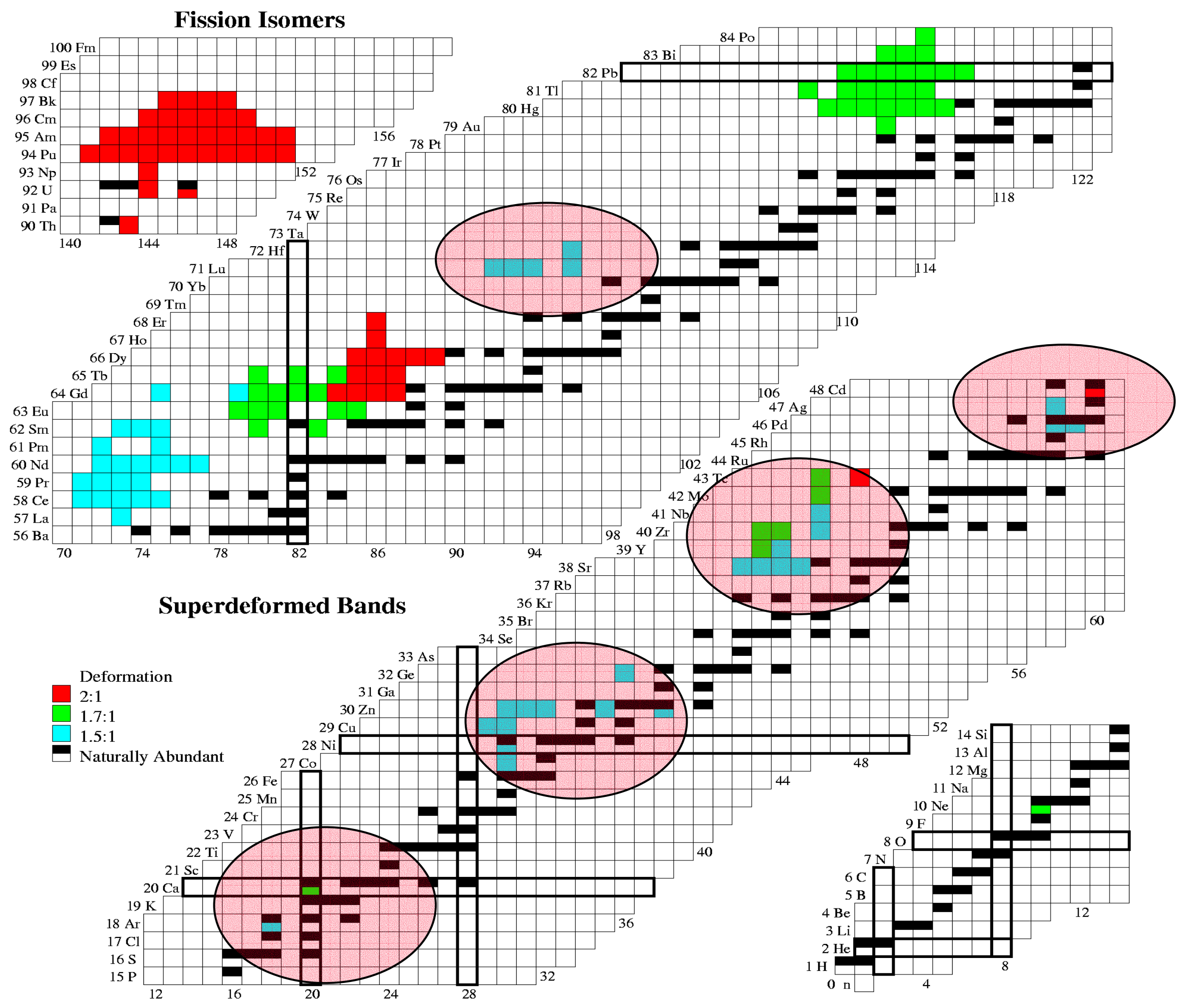
Heroic? **New insight? Pseudo-spin alignment (1 Unit Spin Difference !)**

or

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

Superdeformation and the large arrays

- Data explosion – new regions, multiple bands – new physics
- Precision measurements (Transition energies and rates, deformations, linking the normal and superdeformed minima)
- New phenomena – C4, Triaxial, order-to-chaos



Superdeformation – highly polarized systems

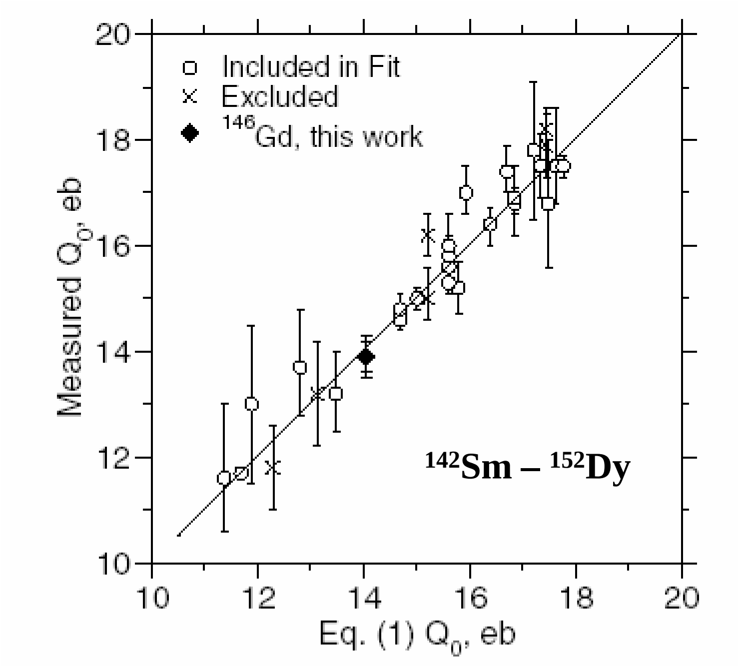
Tool to study many aspects of nuclear structure - Elementary Modes of Excitation

Shell Structure; Exotic states; Extreme Single-Particle Motion (shell model); Collective Modes; Pairing

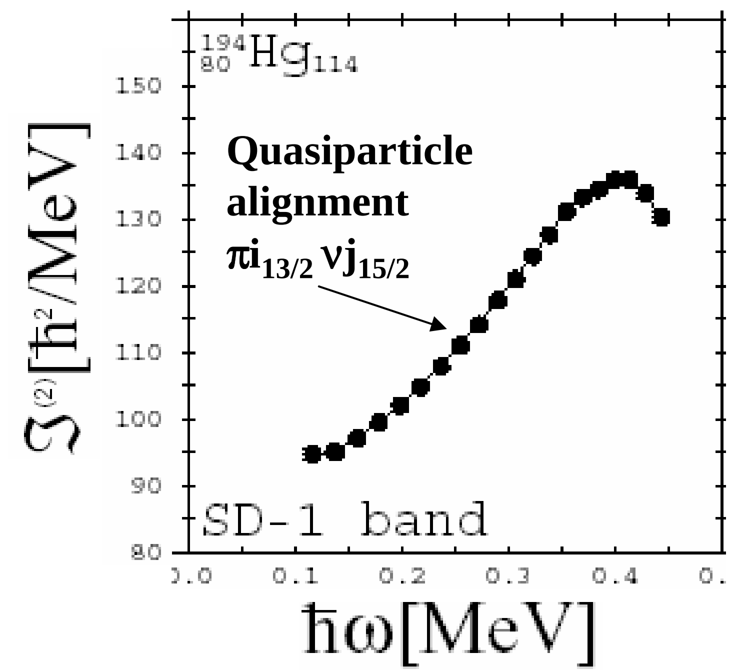
Extreme single-particle motion

Residual correlations are washed out

$$Q_0[abcd] = Q_c - a \cdot \overline{q}_a - b \cdot \overline{q}_b - c \cdot \overline{q}_c - d \cdot \overline{q}_d$$



Pairing Correlations



Excitations

- ~ 250 SD bands – most involve excitations within the second minimum

- Vast majority are single-particle excitations

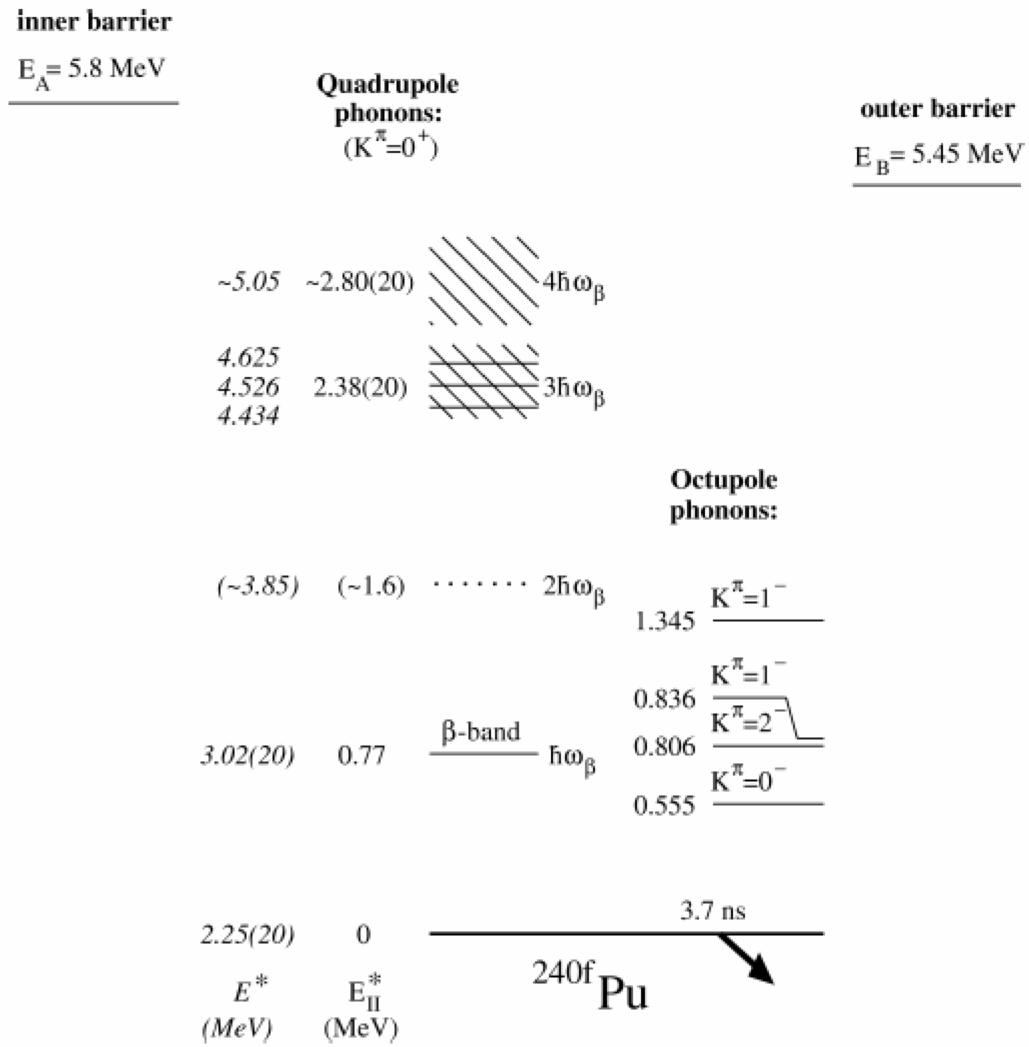
- limited number of collective excitations (vibrations)

  — concentrated in heavier systems.

- Identical bands (very stringent test of theory – def. pairing, alignments)

Collective excitations

M. Hunyadi et al. / Physics Letters B 505 (2001) 27–35



- **A = 240**
  Quadrupole and Octupole
  ^{240}Pu

- **A = 190**
  Octupole Vibrations
  $^{190,194}Hg$, $^{196,198}Pb$

- **A = 150**
  Octupole Vibrations
  ^{152}Dy

Superdeformation Physics and Phenomena

- Identical Bands – Decay out (links)
- Q_0's
- C4
- Triaxiality
- A=40
- ^{108}Cd Towards Hyperdeformation
- ……

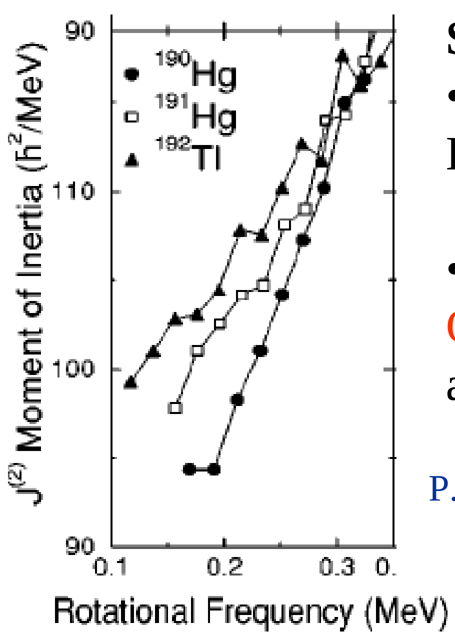
Identical Bands - Spins

- Increase in SD Data – identical band systematics in A=150, A190 regions

- Key development – establish spins in ^{194}Hg, an identical band

- Confirm existence of unit spin difference

→ What is origin of unit alignment ?

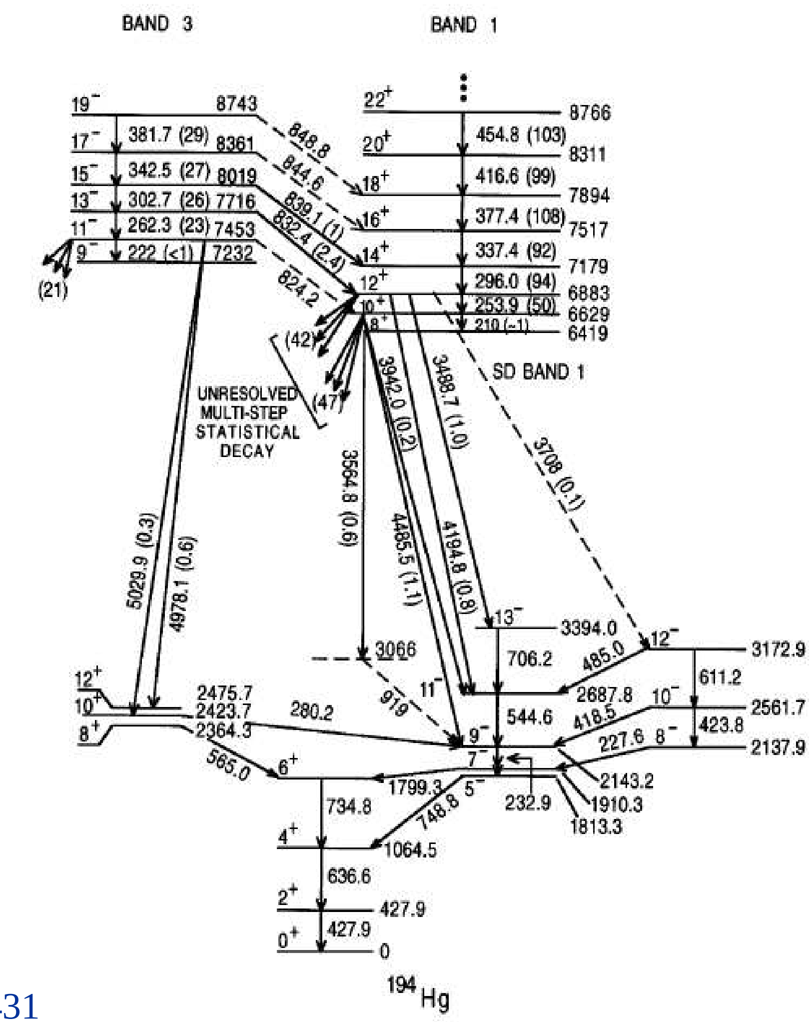


Systematic Study

- Comparison – Data and Theory

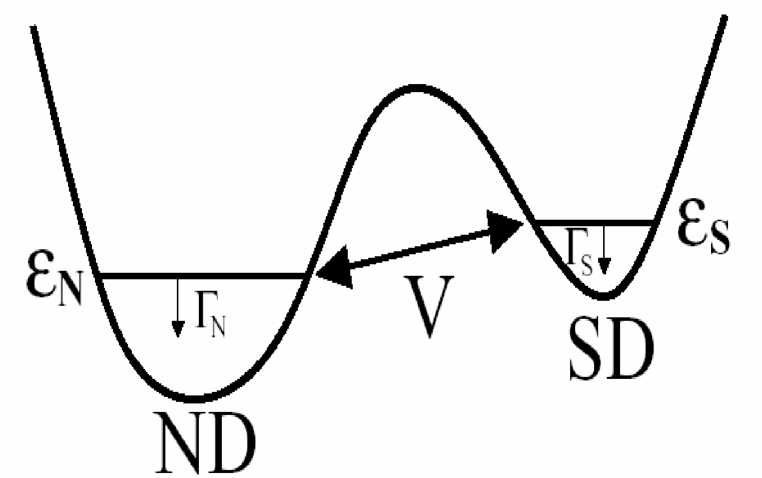
- Suggests – Quasiparticle alignment and Pairing

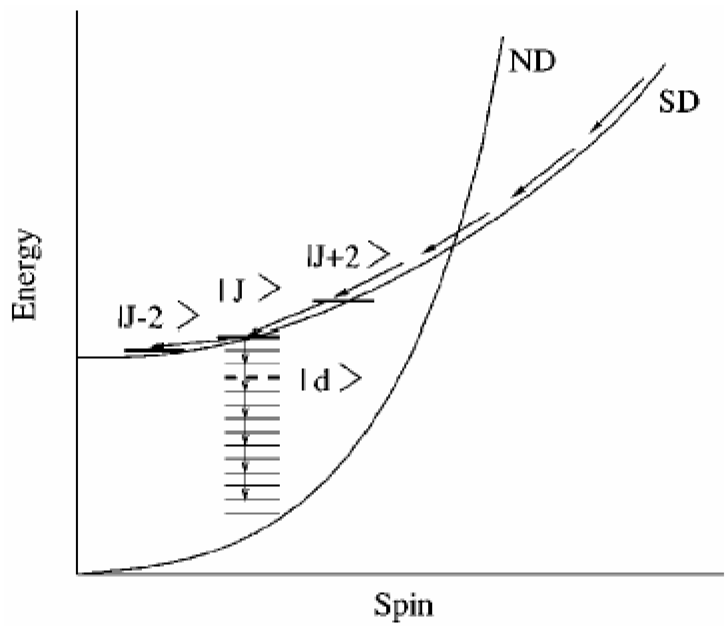
P.Fallon et al, PRC 60 (1999) 04431



G.Hackman et al, PRL 79 (1997) 4100

Decays from the second minimum



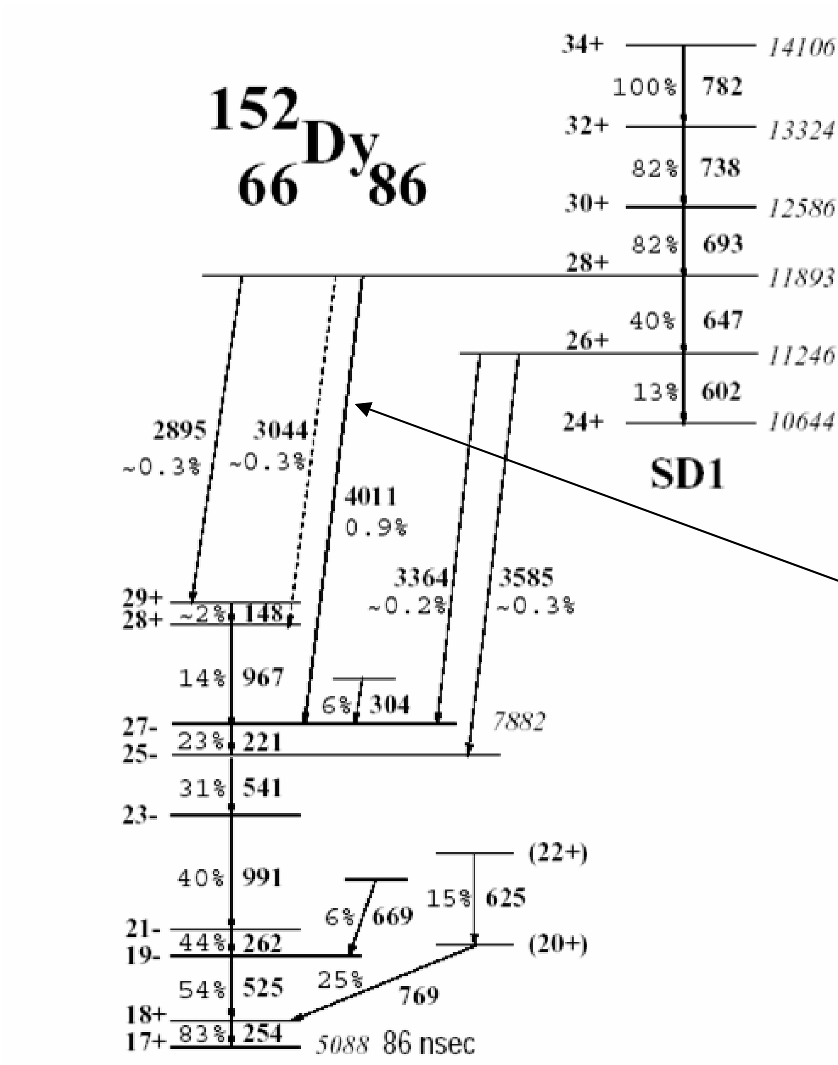


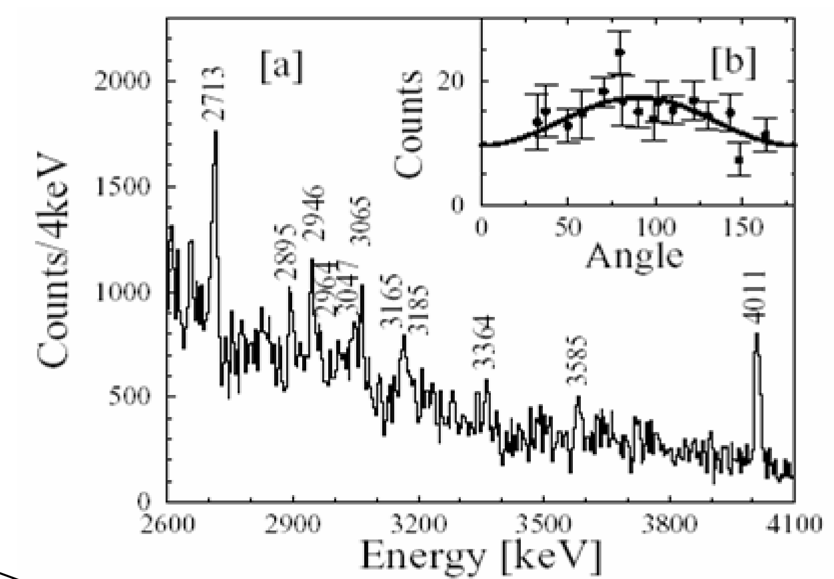
Distinct States (two minima)

- **Tunneling**
- **Statistical (compound) ?**
- **Dependence on excitation energy ? (mass region)**
- **Status**
  - **A~40 "All" linked**
  - **A~60 (~50% linked)**
  - **A~80 (1 linked)**
  - **A~130 (~50% linked)**
  - **A~150 (^{149}Gd, ^{152}Dy)**
  - **A~190 (^{194}Hg, ^{194}Pb, ^{192}Pb)**
  - **A~240 (^{236,238}U)**

^{152}Dy Fifteen Years …

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





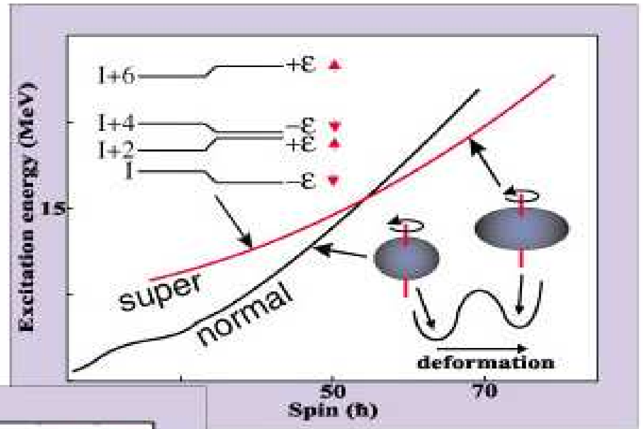
4011 keV Determines Ex. Energy
Dipole Character (E1)
τ ~ 2.9ps
B(E1) ~ 2x10^{-6} WU

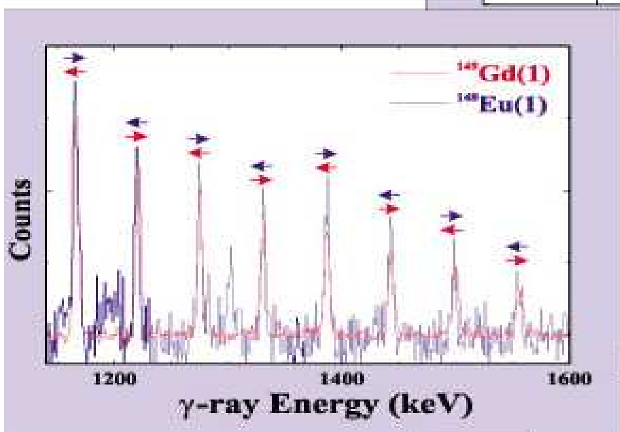
Other gammas placed > Fixed spins
- 2 hbar higher than original estimate
- Can test calculations

E1 decays (similar for ^{194}Hg)

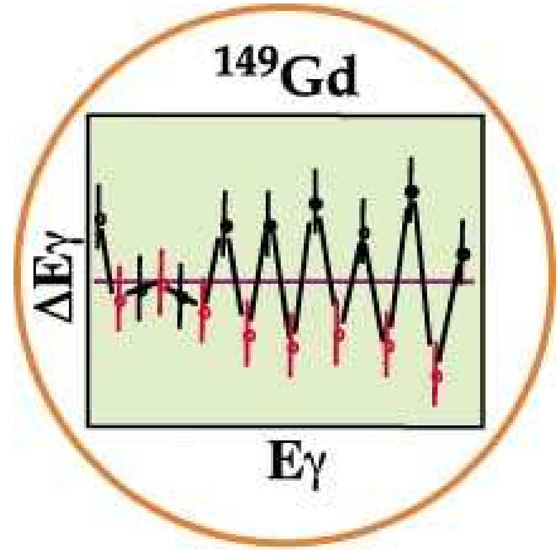
C4 Staggering – An unanswered puzzle

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.

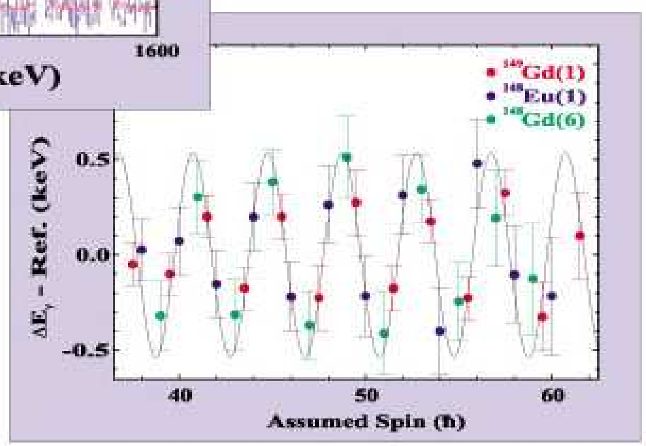


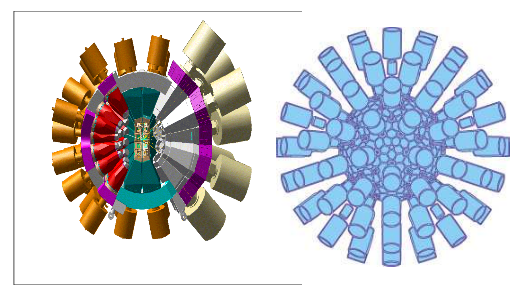
S.Flibotte et al, PRL 71 (93) 4299

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

D.Haslip et al., PRC 58 (98) R2649

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.



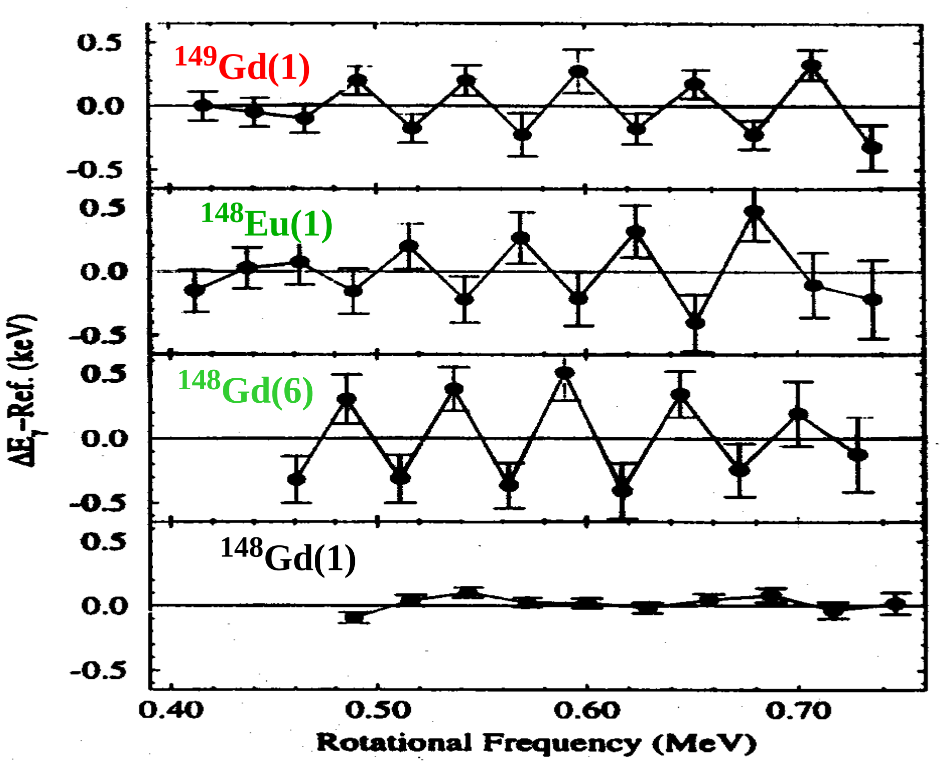


Identical Bands and C4

GS expt by Haslip et al., PRL 78 (1997) 3447

$^{29}Si + ^{124}Sn \rightarrow ^{148}Eu + p4n$

$\rightarrow ^{148}Gd + 5n$

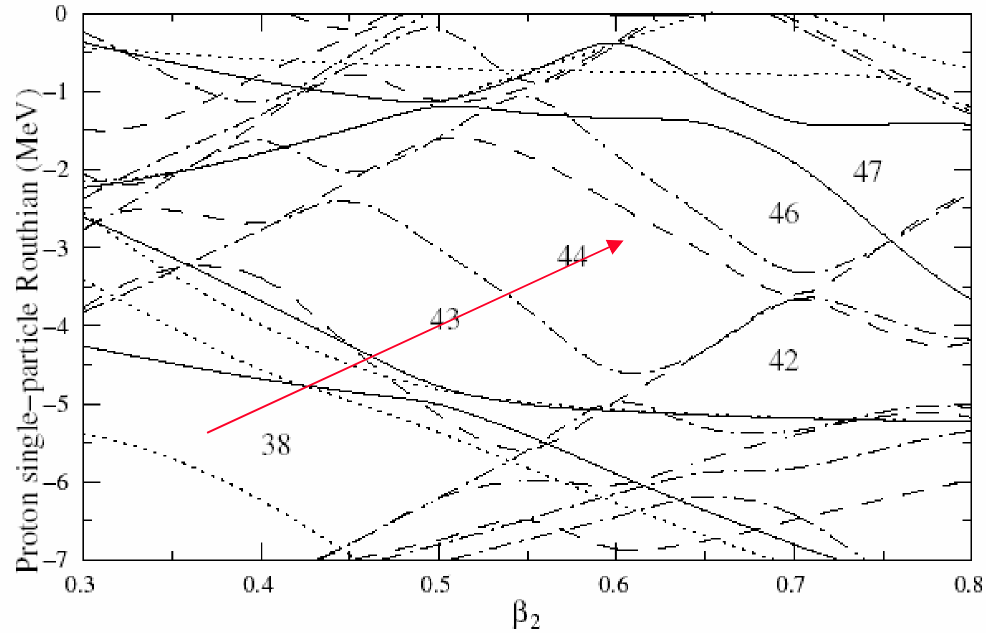


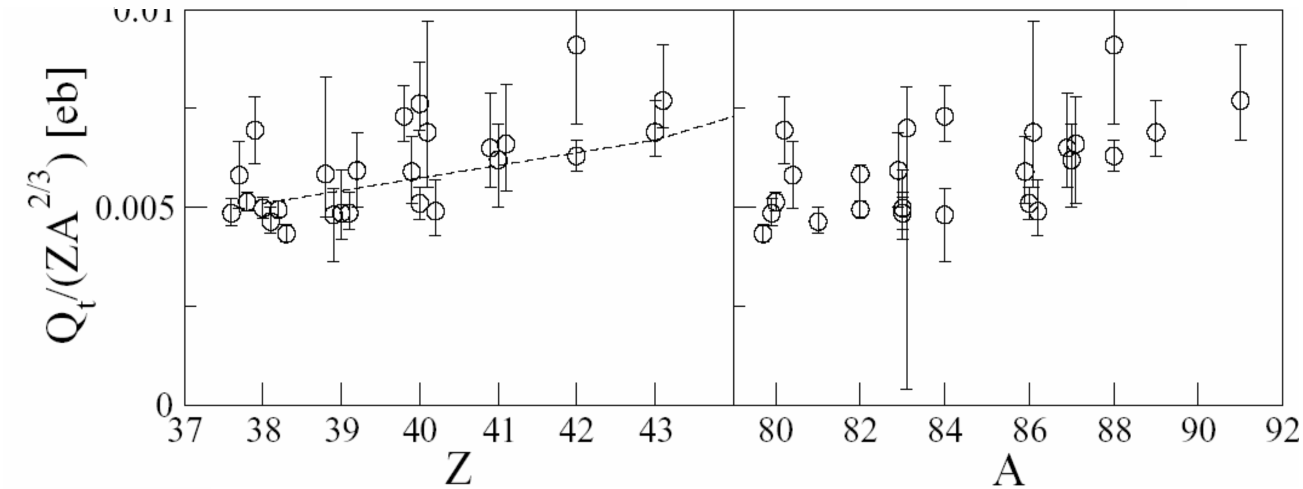
Lots of new bands!

We can use other bands as a reference!

See also Haslip et al., PRC 58 (1998) R2649 for systematic survey

Precision Measurements: Deformation Systematics A~80

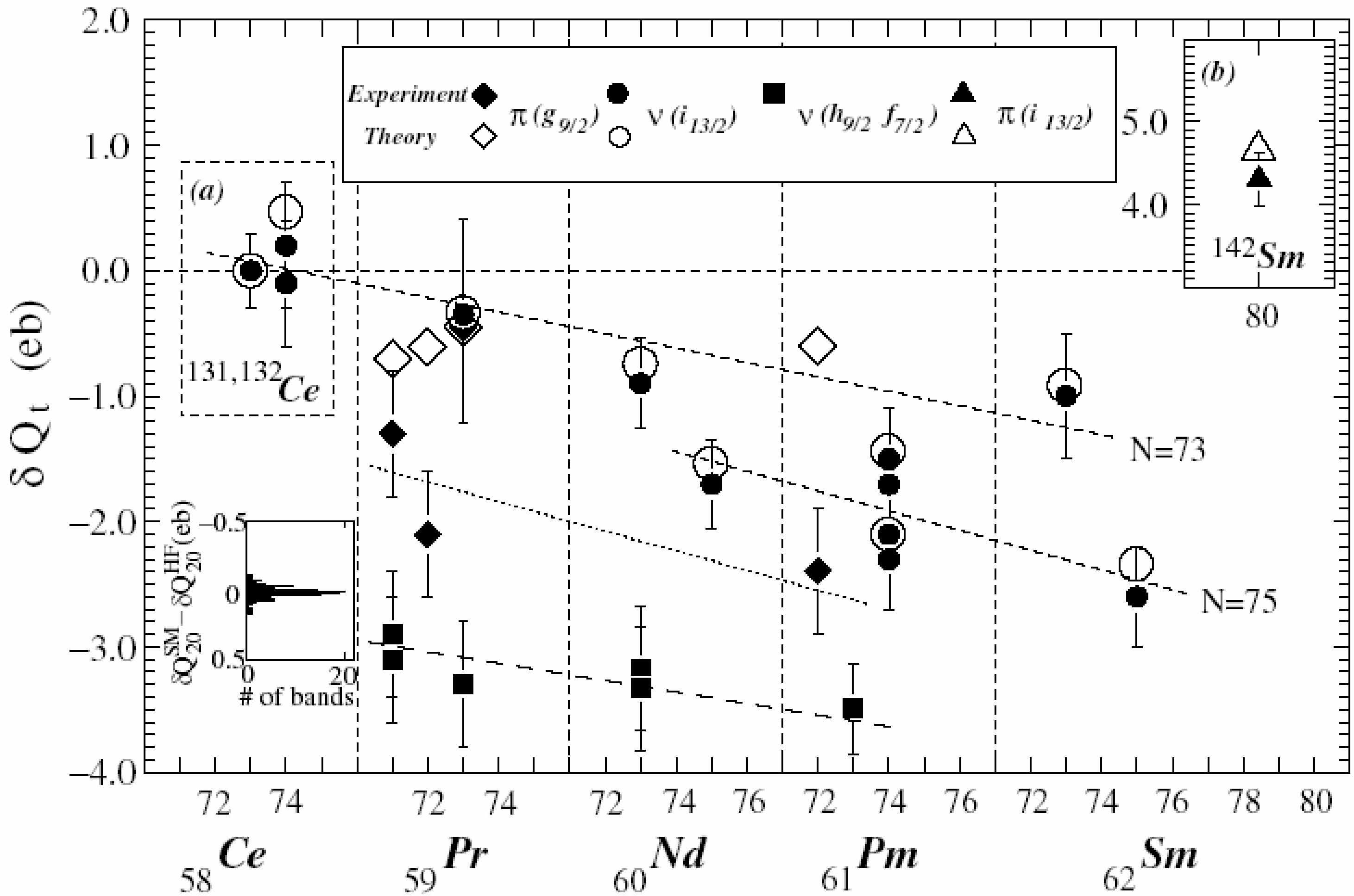




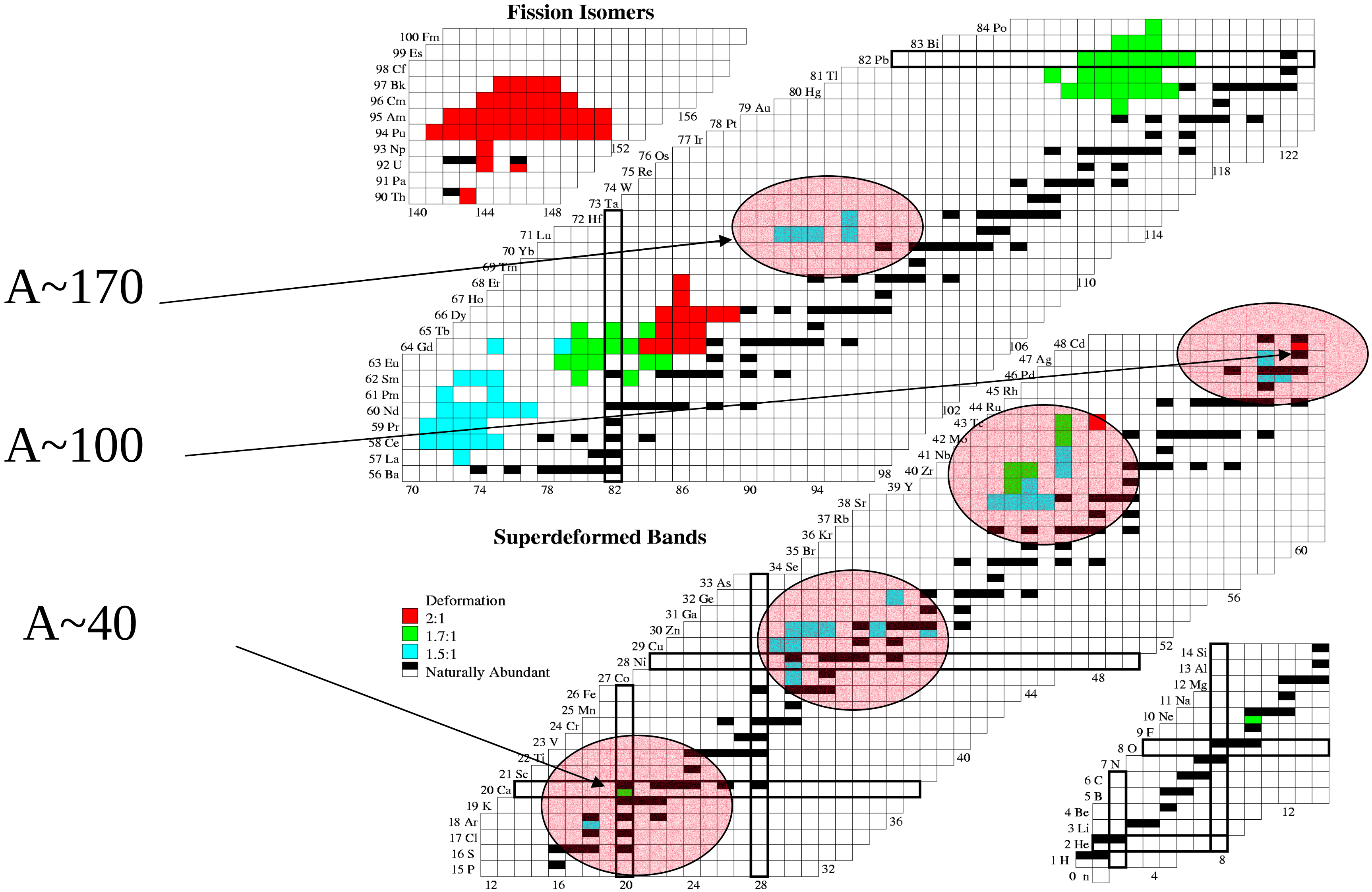
F.Lerma et al., PRC 67 (2003) 044310; K. Lagergren et al., PRC 68 (2003) 064309

Precision Measurements: A~130 Quadrupole Moments

R.W.Laird et al Phys. Rev. Lett. 88 (2002) 152501

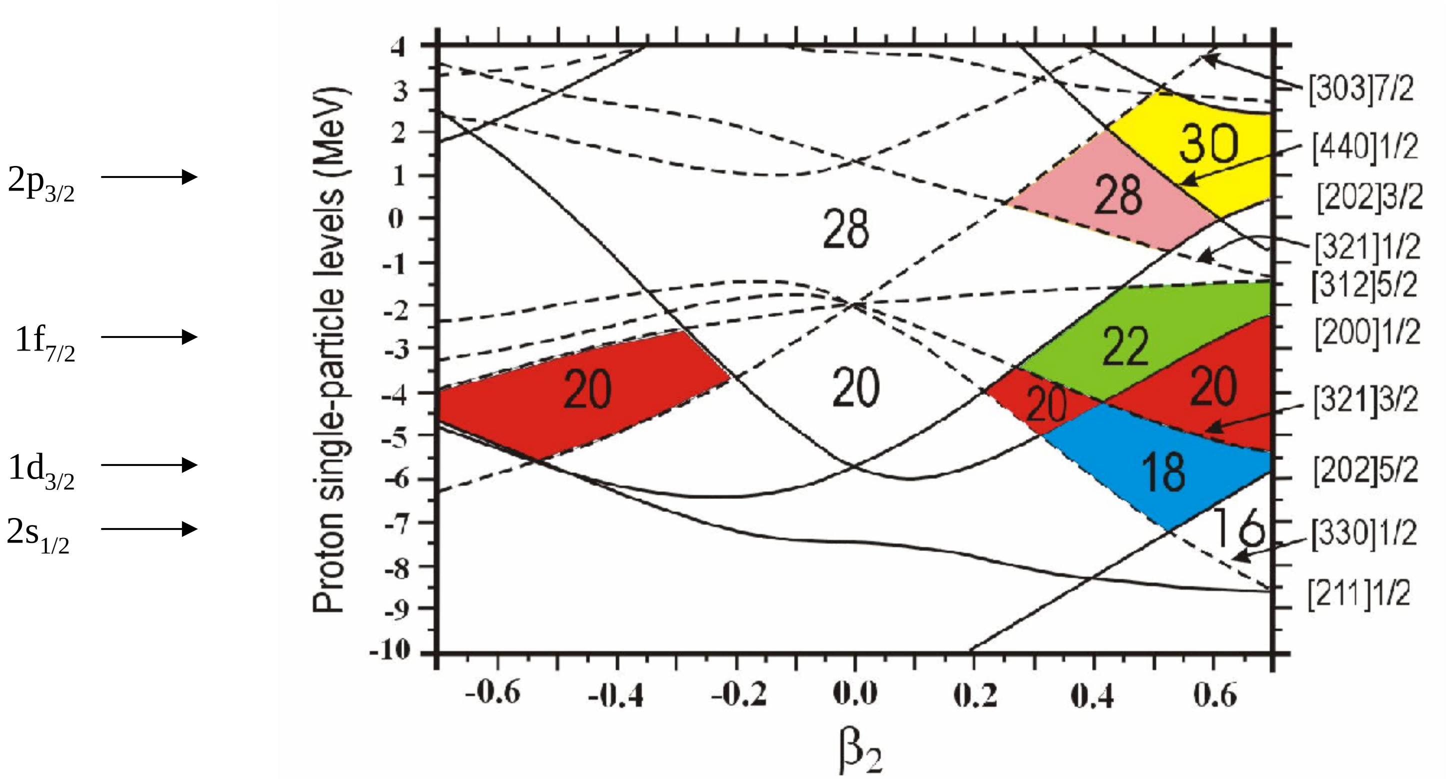


New regions - new physics



A~40 Superdeformed Nuclei

- Microscopic understanding of collective motion
  - Connect deformed intrinsic states (rotational motion) with microscopic wavefunctions (lab system) – ^{20}Ne, ^{24}Mg (sd), ^{48}Cr (pf)



- Truncations/approximations (theory) are necessary - must be tested by experiment
- Nuclei around A~40 are an ideal place to carry out these studies
  - Deformed shell gaps ($f_{7/2}$ intruder, N=3)

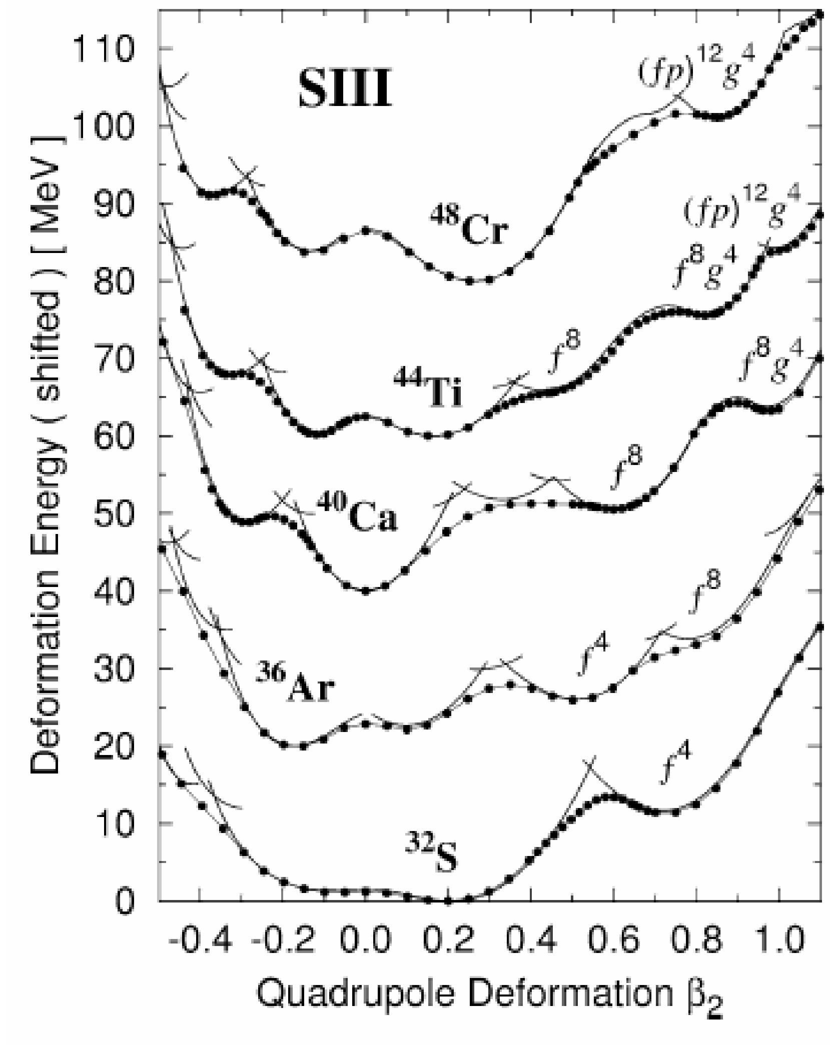
Data on A~40

- ^{32}S, not seen 4p-12h
- ^{36}Ar, 4p-8h ($\pi 3^2$, $\nu 3^2$)
  C.E.Svensson et al., PRL 85 (2000) 2693
- ^{38}Ar, 4p-6h ($\pi 3^2$, $\nu 3^2$)
  D.Rudolph et al., PRC 65 (2002) 034305
- ^{40}Ca, 8p-8h ($\pi 3^4$, $\nu 3^4$)
  E.Ideguchi et al., PRL 85 (2001) 222501
- ^{44}Ti, 8p-4h ($\pi 3^4$, $\nu 3^4$)
  C.O'Leary et al., PRC 61 (2000) 064314

Determined - Energies, Spins, Parities, B(E2).

Observed to Band head (excited O^+)

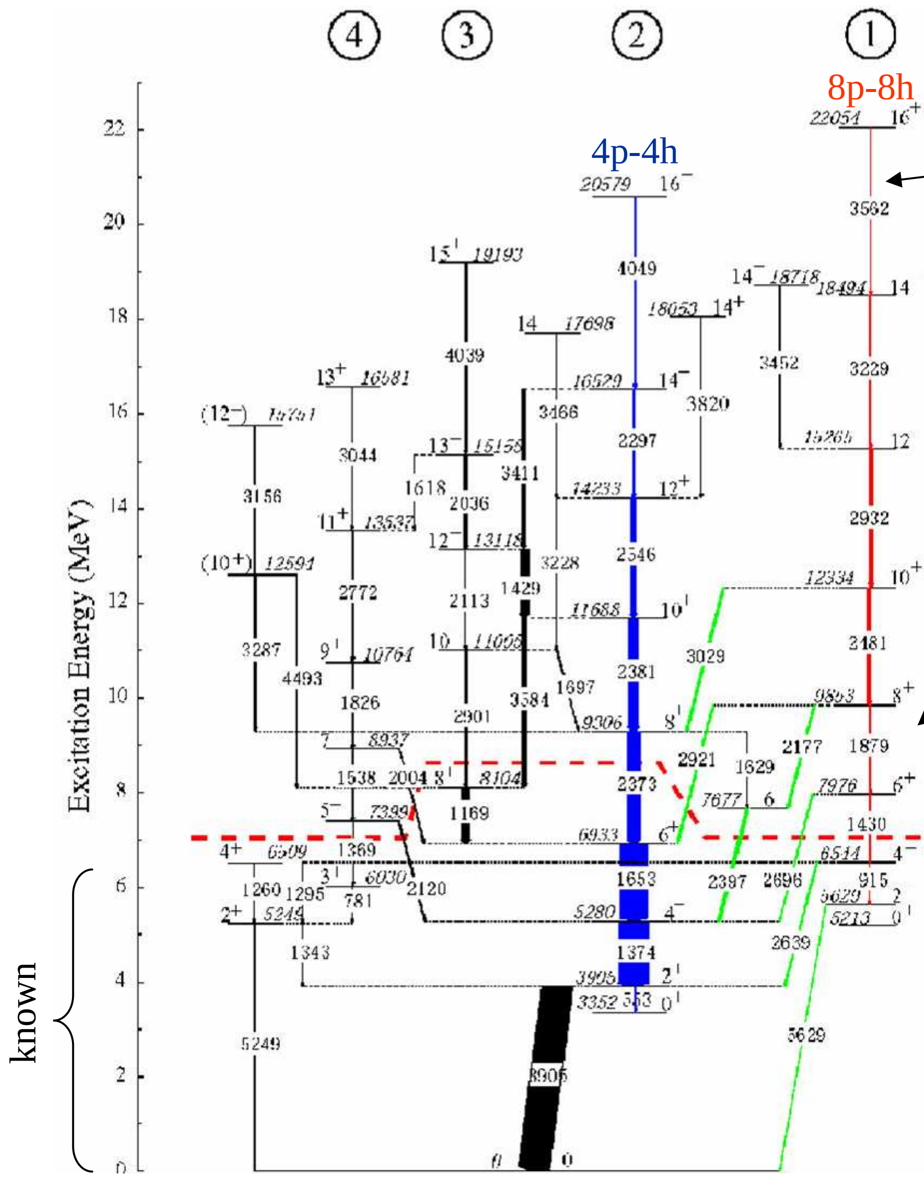
Allows detailed comparison with theory.



T. Inakura et al. / Nuclear Physics A 710 (2002) 261–278

^{40}Ca

E. Ideguchi et al., PRL **87** 222501 (2001) ; C.J. Chiara et al., PRC 67 041303 (2003)



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

$Q_t = 1.30 \pm 0.05\ e\,\mathrm{b}$ β_2 ~0.59

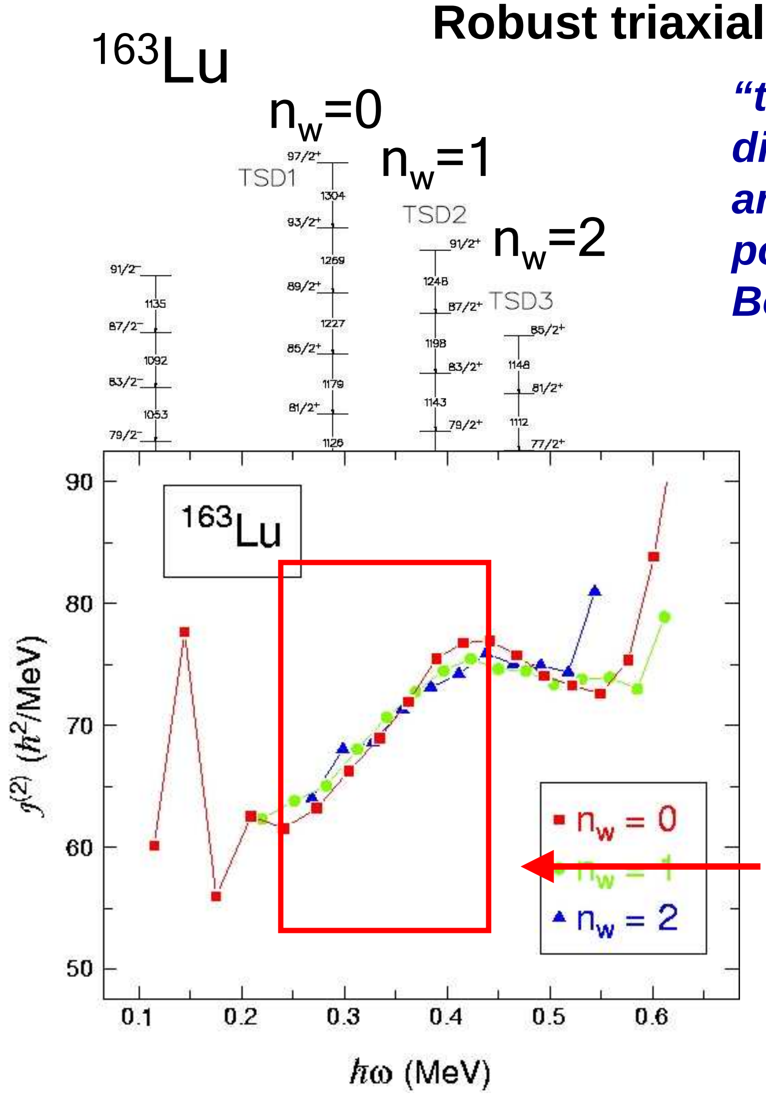
- New expt ^{24}Mg(^{24}Mg,2α)^{40}Ca

$Q_t(\mathrm{high}) = 1.81^{+0.41}_{-0.26}\ e\,\mathrm{b}$

$Q_t(\mathrm{low}) = 1.18^{+0.06}_{-0.05}\ e\,\mathrm{b}$,

Triaxial Shapes and The Wobbling Mode

Robust triaxial shapes have been sought after for decades!



D.R. Jensen *et al.*, PRL **89**, 142503 (02)

"the rotational families contain an added dimension, and the rotational relationships are correspondingly more complex .. it is potentially a field of broad scope."
Bohr and Mottelson Vol. 2 page 176

- Triaxial nucleus allows rotation about all 3 axes
- Total ang. momentum vector lies off principal axis - precession
- Amount it lies off axis quantized into wobbling phonons (n_w)
- See a family of bands based on same configuration (different n_w)
- Bands are linked together
  - $\Delta I = 1$ have dominant E2 nature
- Bands have similar properties
  - Moments of inertia, quadrupole moment, alignment

A Brief Status of TSD

- Best evidence for triaxiality is in ^{163}Lu
  - See “wobbling” excitations based on $\pi i_{13/2}$ structure
- Evidence of wobbling seen in ^{165}Lu & ^{167}Lu
- Ultimate Cranker predicts ^{164,166}Hf are good candidates
  - But no TSD bands found
- Multiple bands in heavier Hf (yet no definite evidence for wobbling)

Questions - role of triaxial N=94 gap, is odd-proton doing at all ?

^{163}Hf	^{164}Hf	^{165}Hf	^{166}Hf	^{167}Hf	^{168}Hf 3	^{169}Hf	^{170}Hf 1	^{171}Hf ?	^{172}Hf ?	^{173}Hf 1	**^{174}Hf 8**	**^{175}Hf 2**
^{162}Lu 3	^{163}Lu 4	^{164}Lu 8	^{165}Lu 4	^{166}Lu	^{167}Lu 5	^{168}Lu 2	^{169}Lu	^{170}Lu	^{171}Lu	^{172}Lu	^{173}Lu	
N = 91		93	94								102	

M.K. Djongolov *et al.*, PLB **560**, 24 (03)

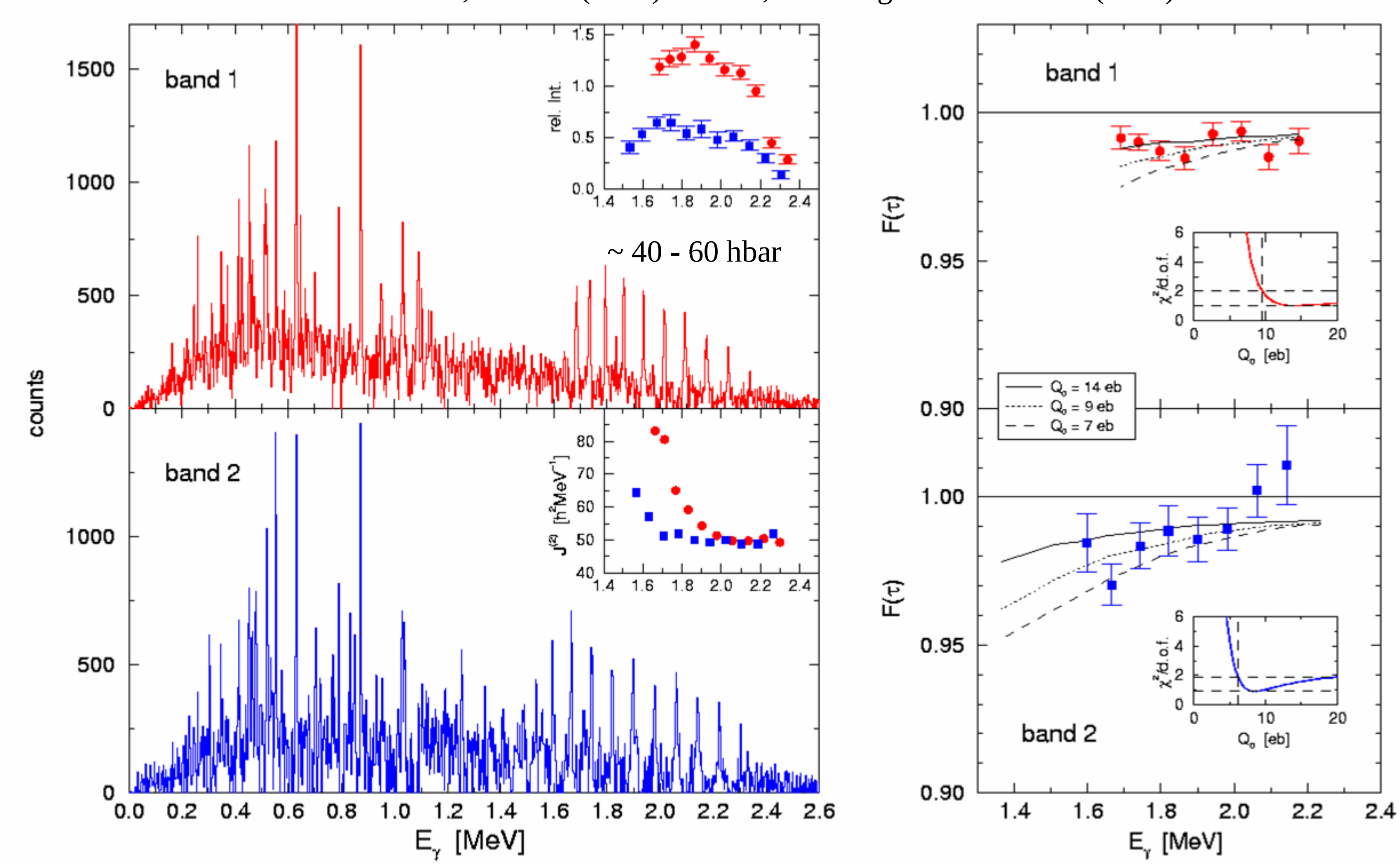
G. Schönwaßer *et al.*, PLB **552**, 9 (03)

H. Amro *et al.*, PLB **553**, 197 (03)

S.W. Ødegård *et al.*, PRL **86**, 5866 (01)

The ^{108}Cd Superdeformed Bands

R.M. Clark et al., PRL 87 (2001) 202502; A. Goergen et al PRC 65 (2002) 027302

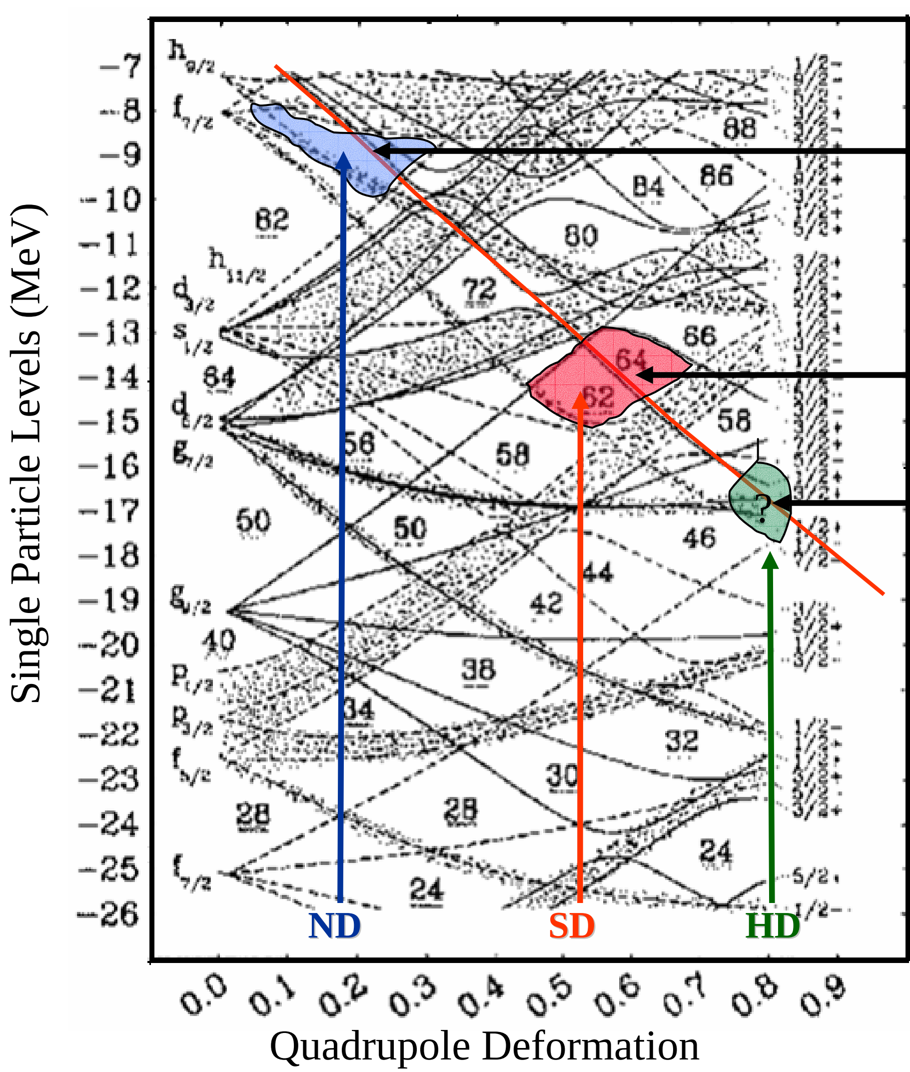


High spin (multiplicity) states selected by a “K” cut

Deformation β_2 ~ 0.6 (lower limit)

^{108}Cd: Towards Hyperdeformed Nuclei

Woods Saxon Potential



^{235}U: *“normal-intruder”*

^{152}Dy: *“super-intruder”*

^{108}Cd: **$i_{13/2}$ *“hyper- intruder”***

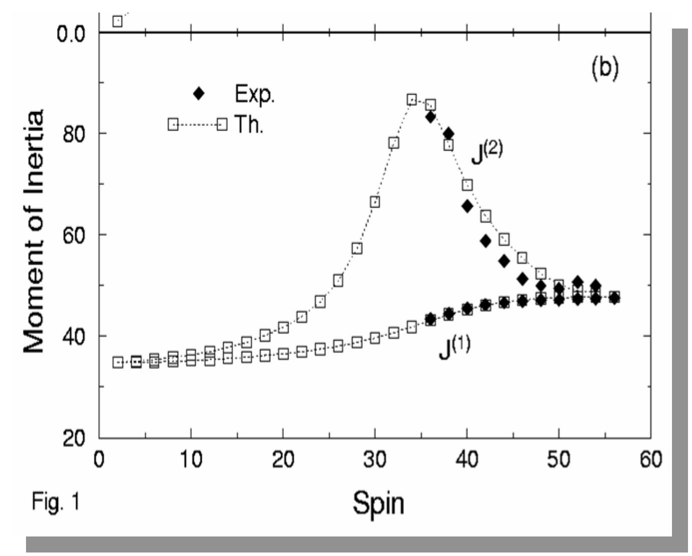
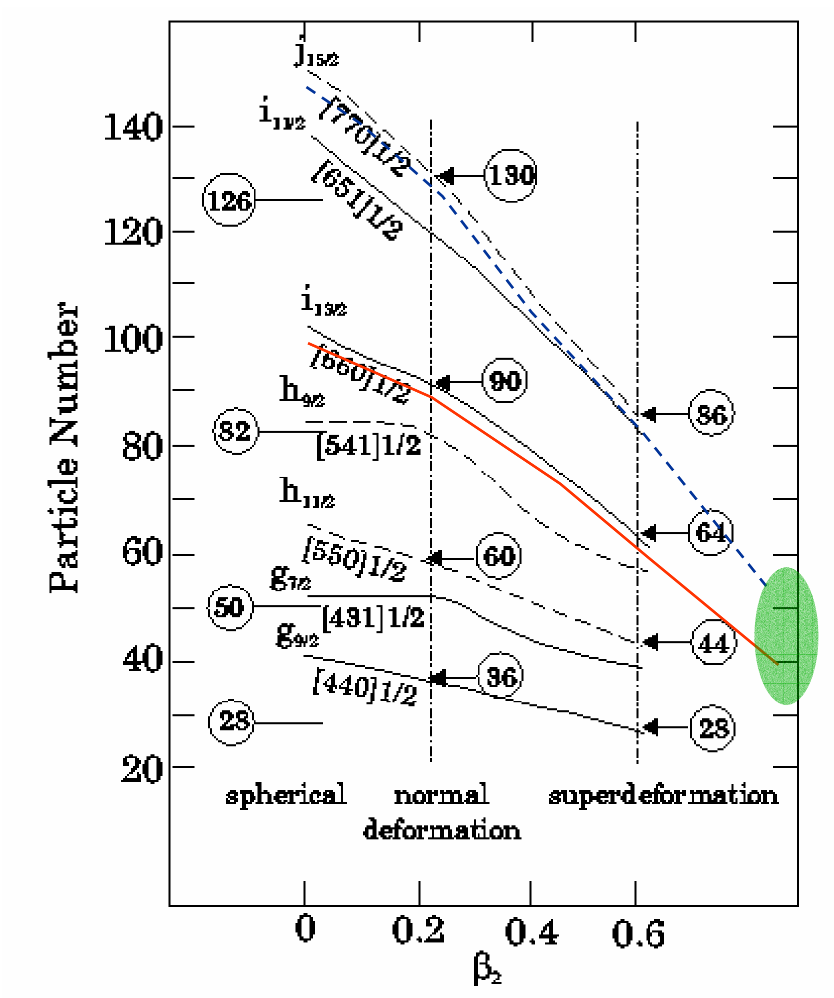


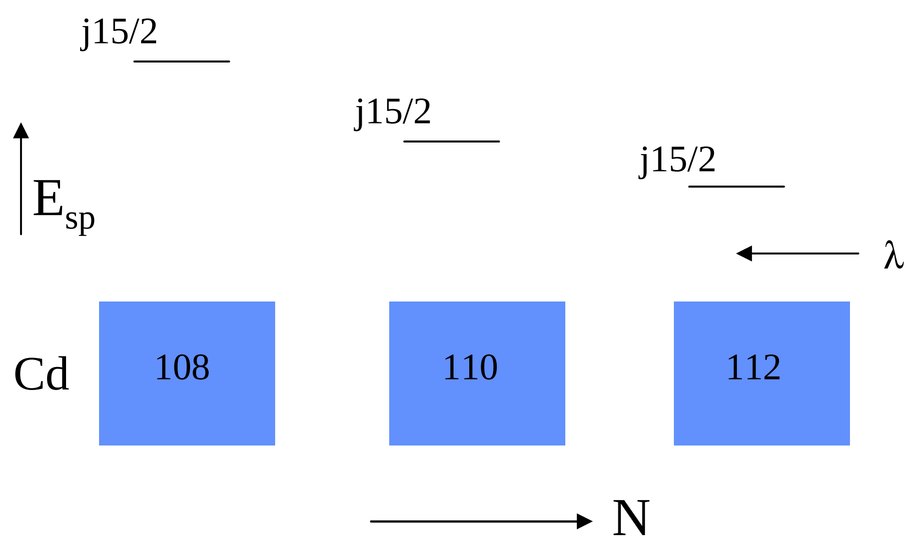
Fig. 1

^{108}Cd: Towards Hyperdeformed Nuclei

For Z~50 and A~110 the **$\pi i_{13/2}$** and **$\nu\ j_{15/2}$** are the "hyper-intruder" (N+3) states



$\pi i_{13/2}$ *"hyper-intruder"* occupied in ^{108}Cd



Calculations suggest **$\nu j_{15/2}$** occupied at N=64 *(close to ^{108}Cd, N=60)*

Exciting possibility for Hyperdeformation (both N+3 intruders !)

Future Prospects “where do we go from here”

Future Progress (example from *super* to *hyper*)

- Tools (*apart from imagination*)
  - **Beams**
    - RIBS
  - **Detectors**
    - Gamma-ray tracking arrays

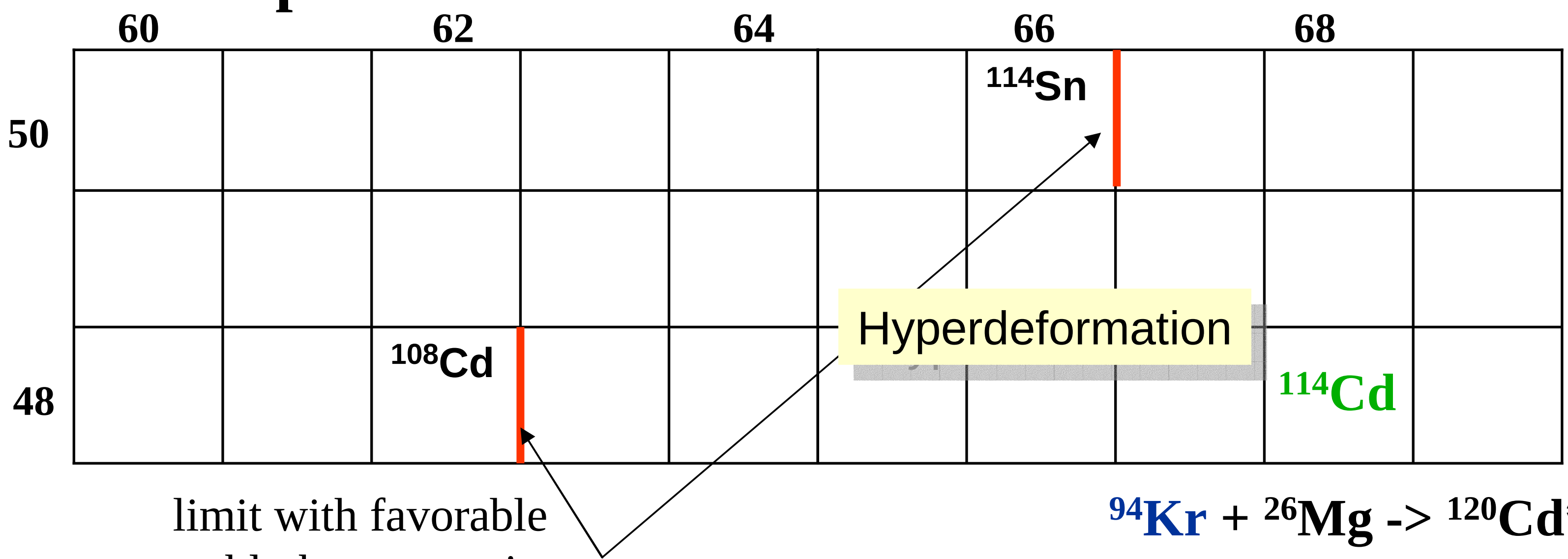
- RIB Beams *(not usually discussed in this context)*
  - Extend towards the n-rich (back to the Cd story)
    - Even a few (6) extra neutrons can make a difference in observed physics (hyperintruders - need neutron levels)
    - More neutrons, more spin

- Gamma-ray detectors
  - Ge Shell (GRETA) – increased efficiency, inverse reactions

Hyperdeformation: Production and Population

A New Region and Increasing the Spin limit

An example…



limit with favorable stable-beam reactions

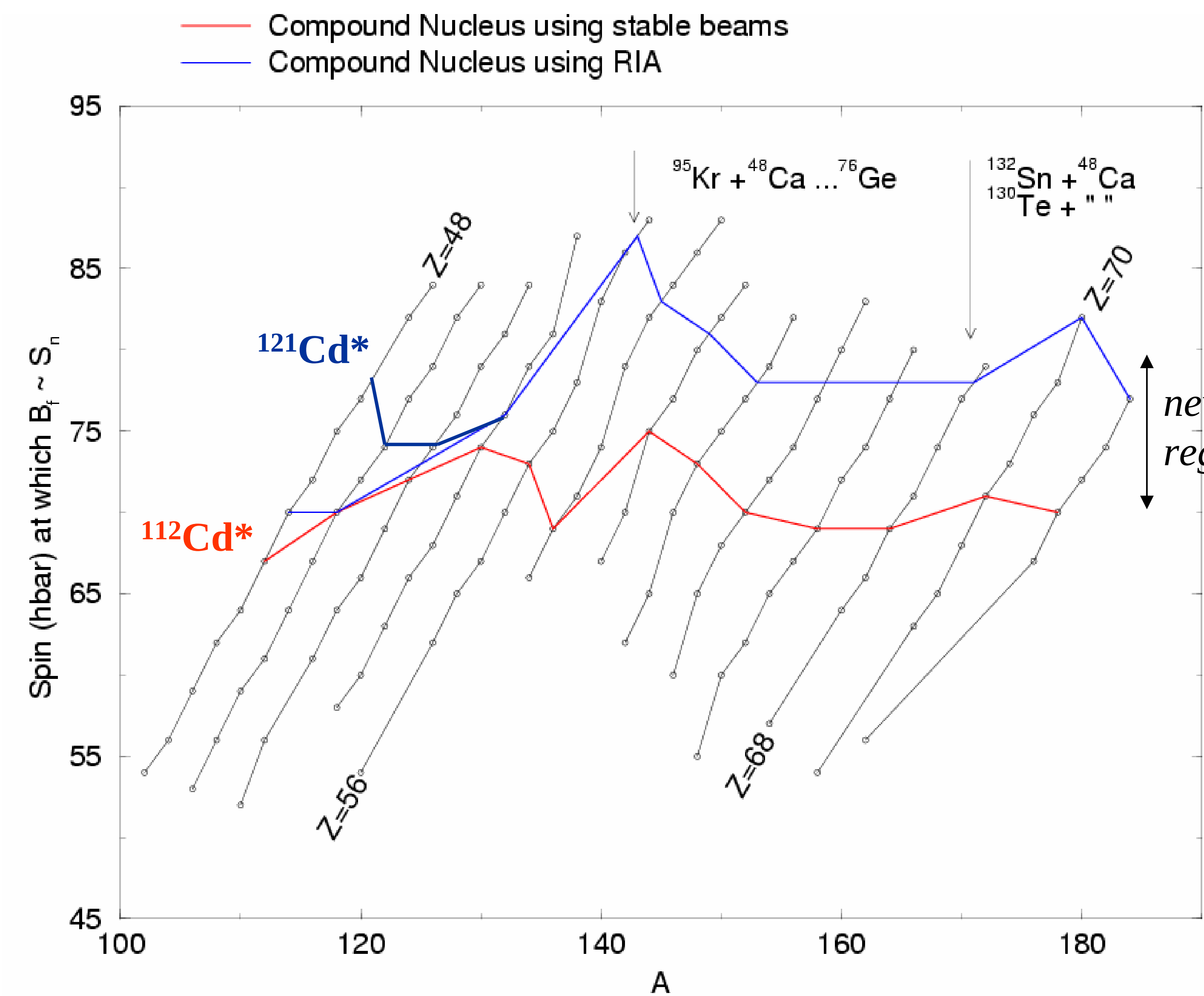
^{94}Kr + ^{26}Mg -> ^{120}Cd*

"Dream Experiment"

- l_{max} ~ 62 ħ in ^{108}Cd and 70 ħ in ^{114}Cd
- ^{108}Cd produced with stable beams: ^{48}Ca+^{64}Ni at 207 MeV
- ^{114}Cd produced with "RIA" beams: ^{94}Kr+^{26}Mg at 500 MeV

Also 170-180 region ^{132}Sn + ^{48}Ca –> ^{180}Yb*
130-140 region ^{94}Kr + ^{48}Ca -> ^{142}Ba*

Angular Momentum Limit

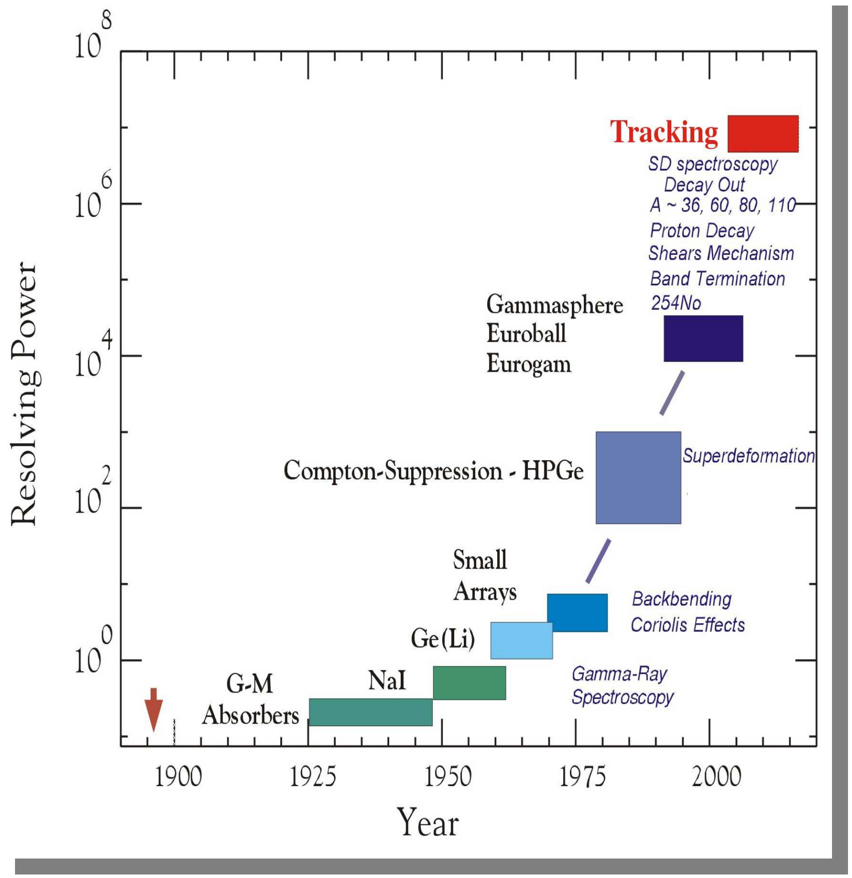


Gain 1-2 hbar per neutron

new spin regime

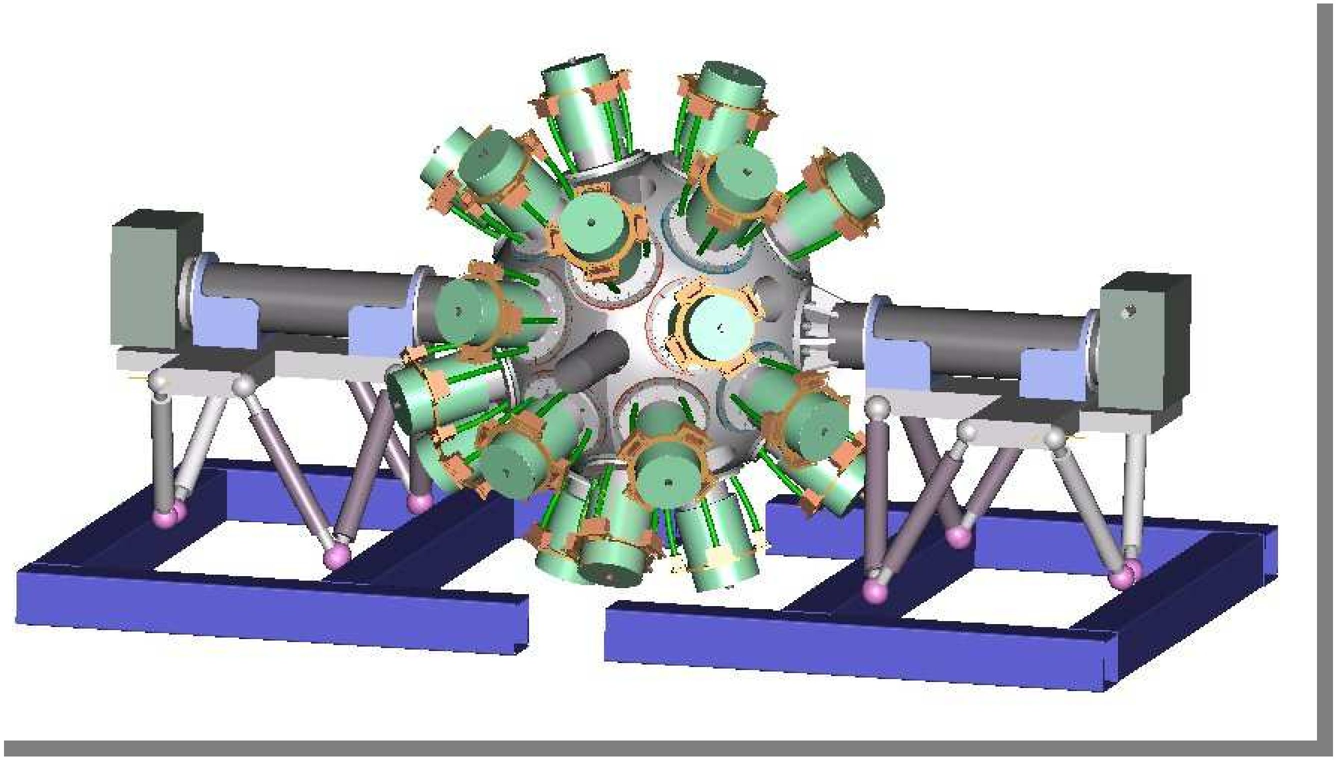
Gamma-ray Detector Development

Central Role in Nuclear Physics



- **Advances in detector technology have resulted in new discoveries.**
- **Innovations have improved detector performance.**
  - **— Energy resolution**
  - **— Efficiency**
  - **— Peak-to-total ratio**
  - **— Position resolution**
  - **— Directional information**
  - **— Polarization**
  - **— Auxiliary detectors**
- **Tracking is feasible, will provide new opportunities and meet the challenges of new facilities.**

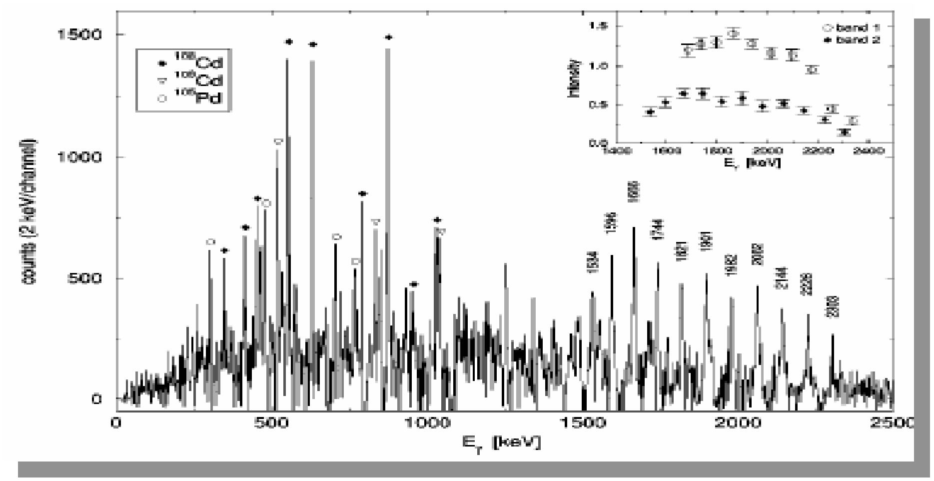
The 4π Array GRETA

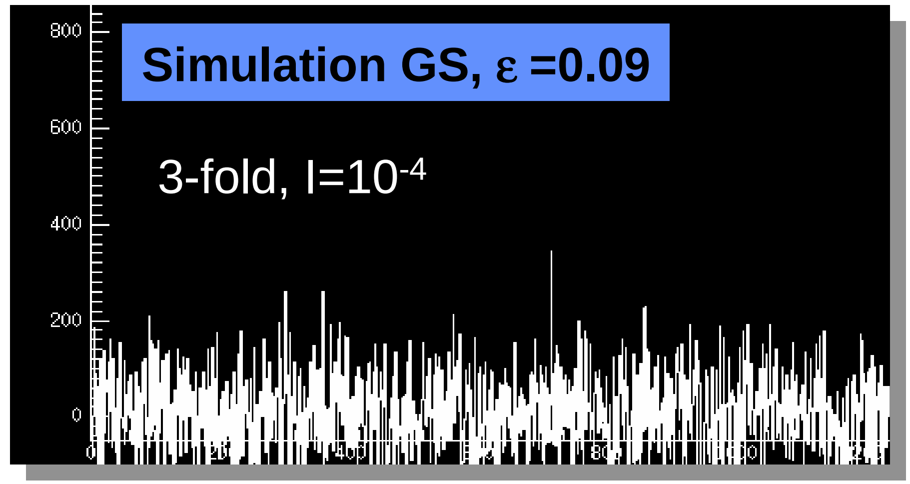


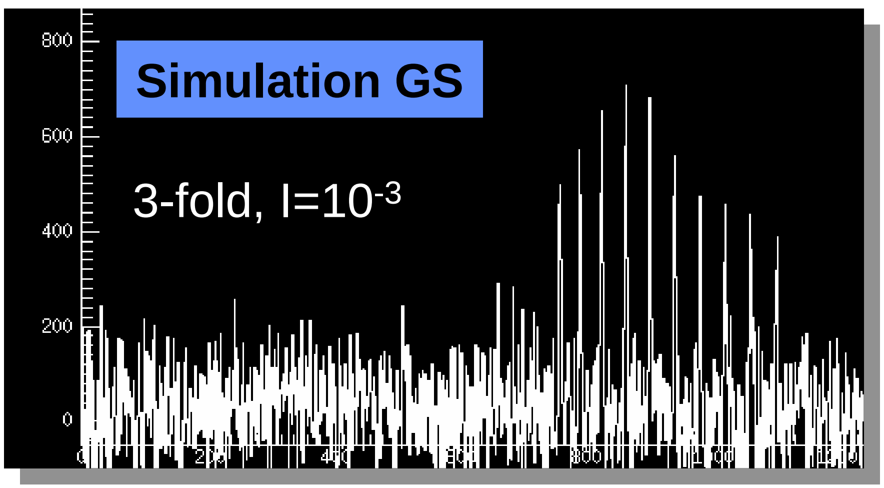
GRETA High spin state from fusion reactions

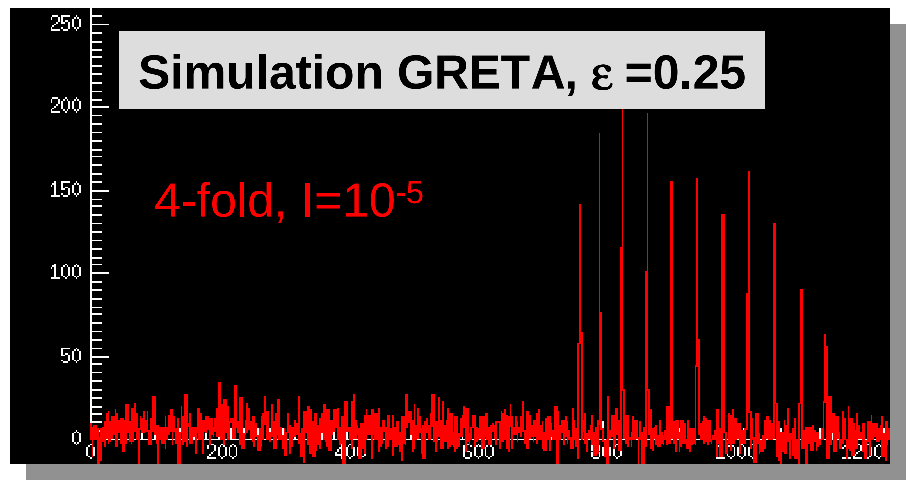
^{64}Ni (^{48}Ca, 4n) ^{108}Cd, Gammasphere

v/c=0.04









Future Directions

- Hyperdeformation
  - — location, new physics
- Higher Temperatures (SD unique – shell gap)
  - — feeding, damped nucleonic and rotational motions
  - — GDR
- Decay
- Fission Isomers
- Connections to cluster states
- Periodic orbits (Semi-classical approaches)
-

Concluding observations…

Just as the discovery of Superdeformation had a major impact, so too has Gammasphere .. built a community, a base for the future

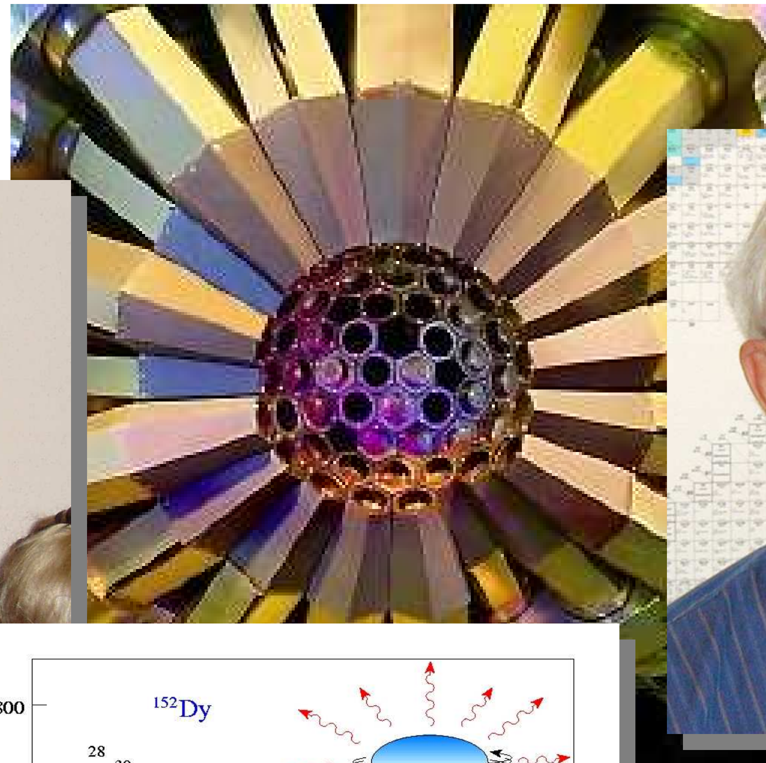
Gammasphere (Euroball) - The best of a kind. Can't build a better spectrometer using this technology

What's next - The Ge shell – built on the new technology of highly segmented Ge.

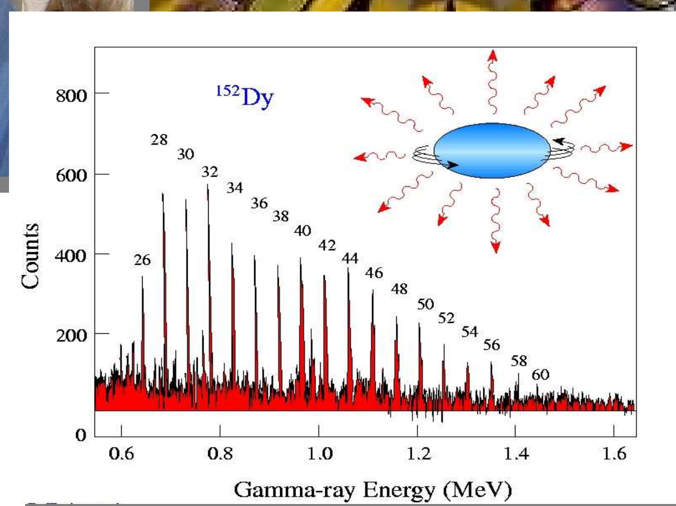
Tools – (i) Beams (stable and RIBS). (ii) Instruments (+ *imagination*)
As we maximize our capabilities, advanced Instrumentation can give the competitive edge
→ important today, maybe more so than ever …

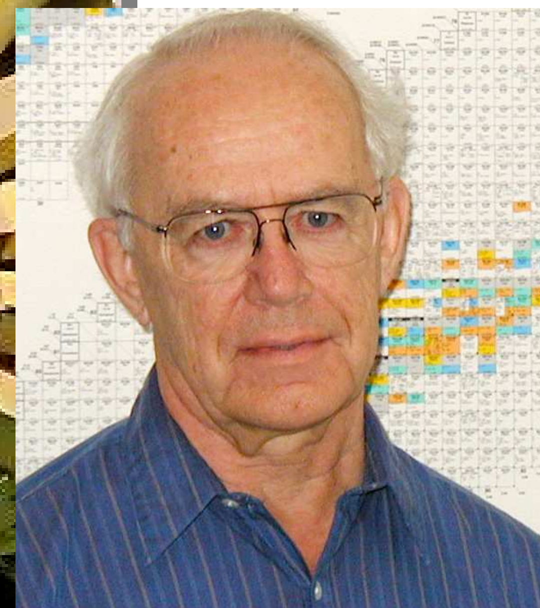
- A 4π tracking array (GRETA) is essential for these studies

Thanks ….



Peter Twin





Frank Stephens

Still going …

END