To the Limits with Gamma-Ray Spectroscopy

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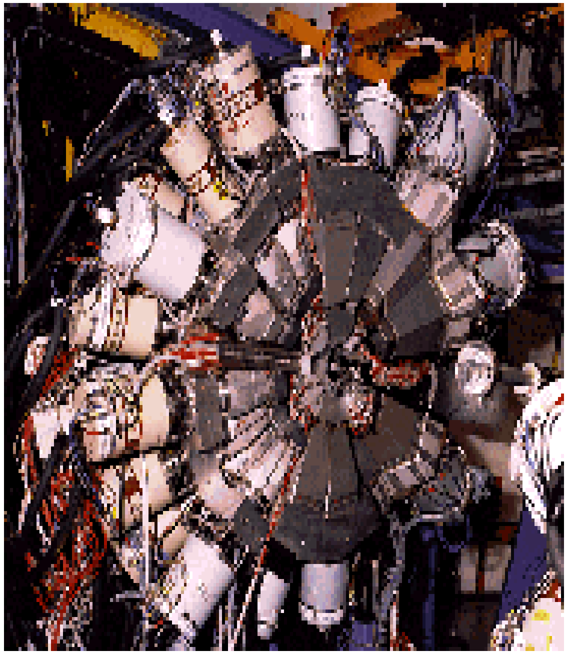
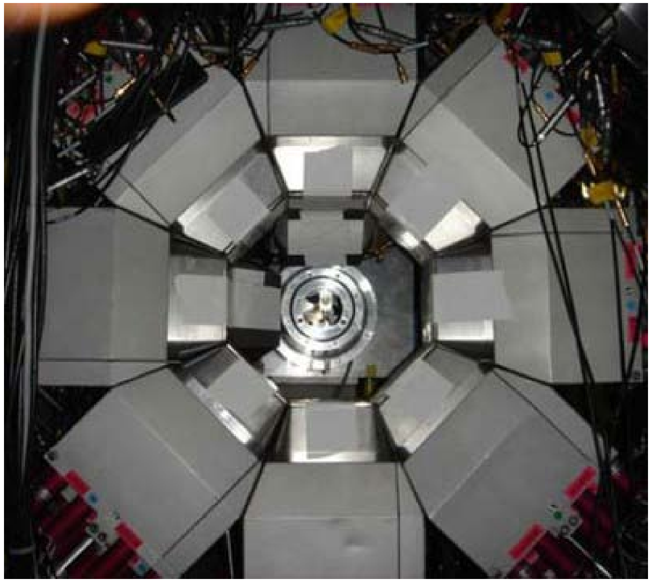
La Colle Sur Loup

Gamma-Ray Spectroscopy: Times are Changing

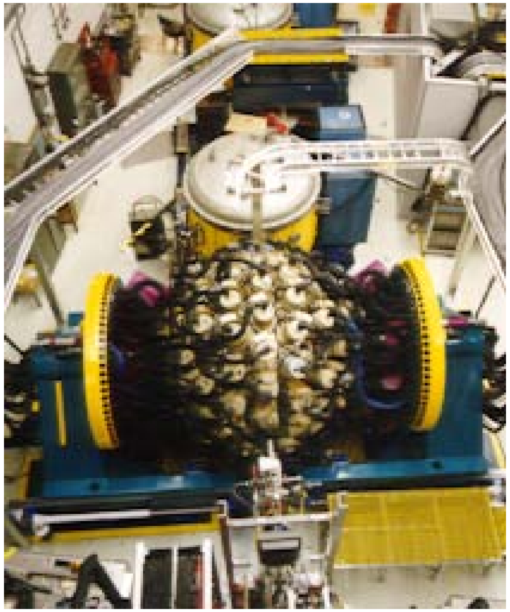
- For the last ~ 15 - 20 years, large arrays of Compton-suppressed Ge detectors such as EuroBall, JUROBALL , GASP, EXOGAM, TIGRESS and Gammasphere and others have been the tools of choice for nuclear spectroscopy.



EUROBALL



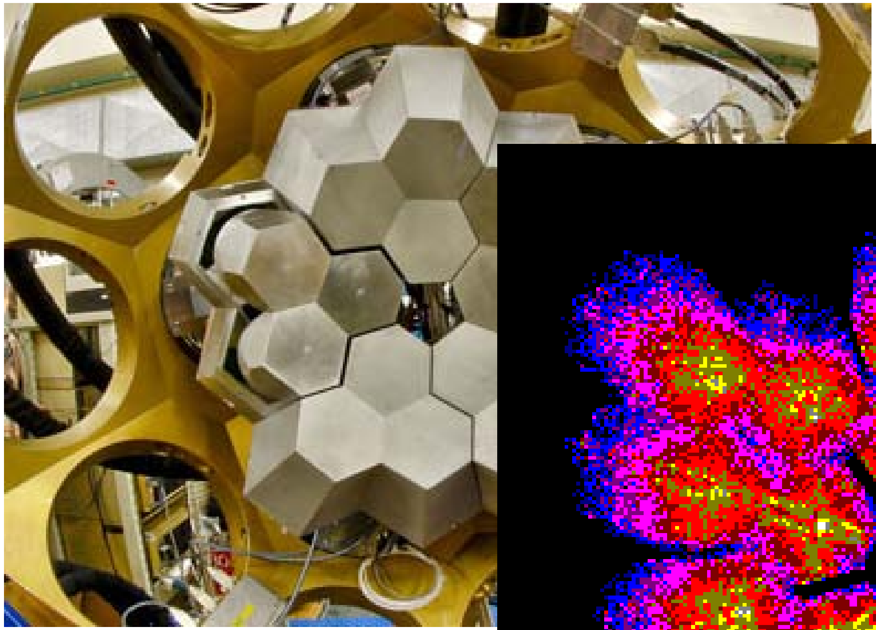
EXOGAM



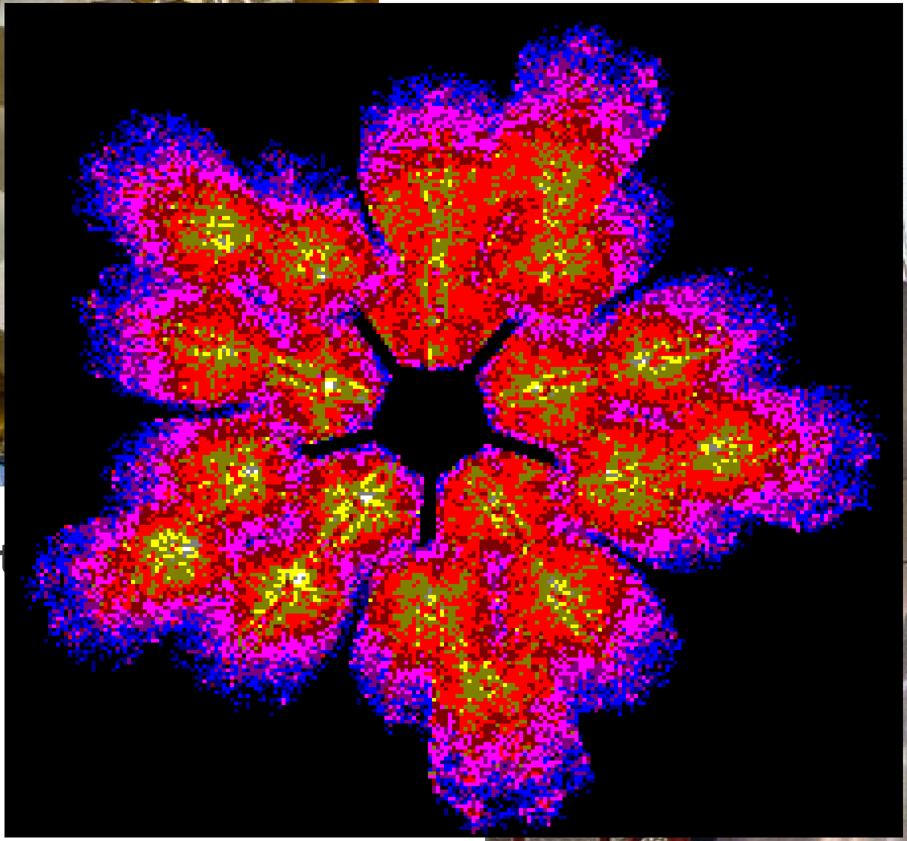
Gammasphere

Gamma-Ray Spectroscopy: Times are Changing

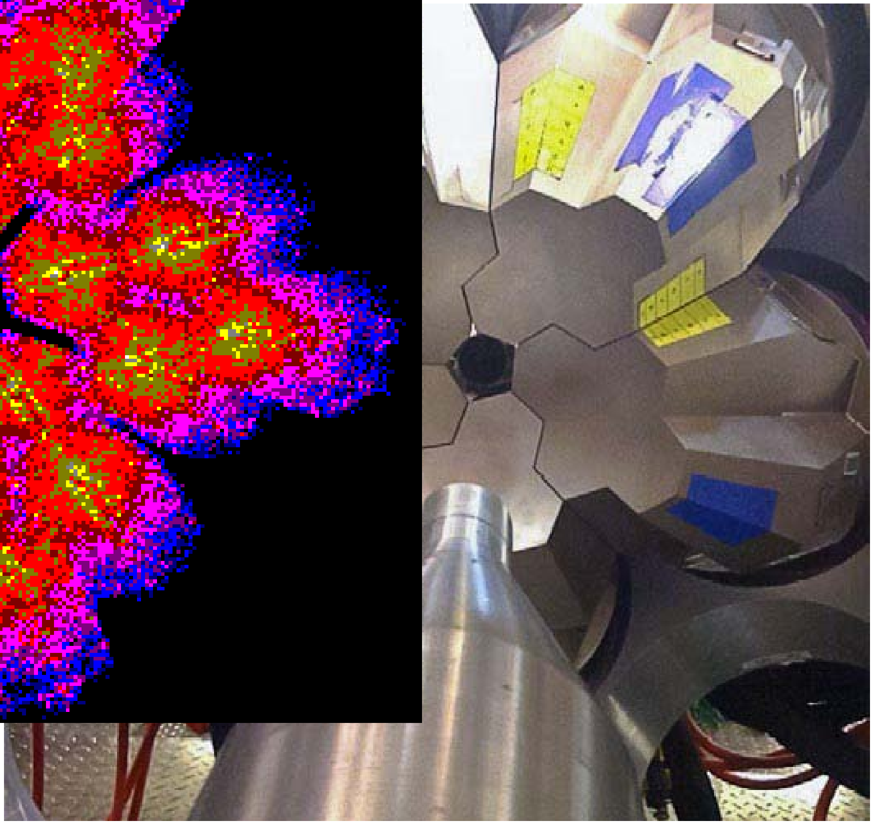
- **A new generation of gamma-ray arrays with tracking capability is (almost) here: AGATA and GRETA**



AGATA Demonst



RETINA



Lecture Purpose & Plan

- As we are about to embark on the "tracking adventure", let's

  (1) review some of the achievements of the large arrays & discuss some of the unresolved issues

  (2) discuss some more recent directions

→ *Collective Motion in Nuclei*

- → Superdeformation
- → Octupole Excitations
- → Triaxiality & Wobbling

→ *Structure of Exotic Nuclei*

- → The Heaviest Nuclei
- → Changes in Shell Structure in Neutron-Rich Nuclei

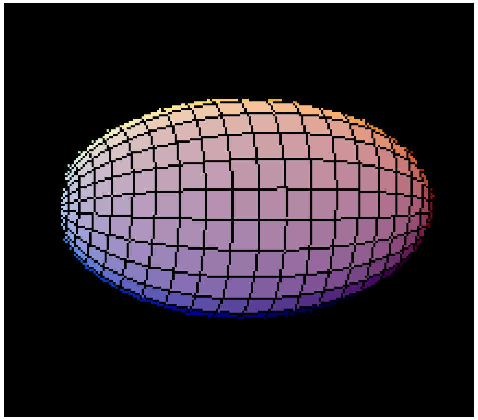
→ ***Collective Motion in Nuclei***

→ **Superdeformation**
→ **Octupole Excitations**
→ **Triaxiality & Wobbling**

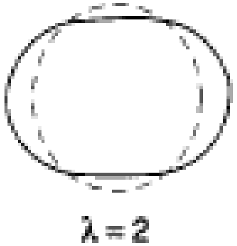
Nuclear deformation

$$R(t) = R_0\left[1+\sum_{\lambda}\sum_{\mu=-\lambda}^{+\lambda} a_{\lambda\mu}(t)\, Y_{\lambda\mu}(\vartheta,\varphi)\right]$$

Deformation can be dynamic
e.g. Y_{32} vibration

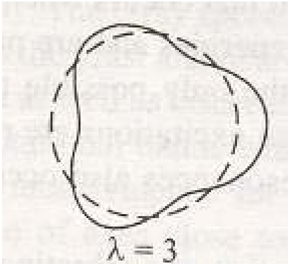


quadrupole

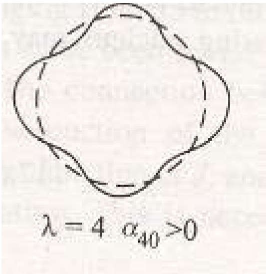


$$a_{20} = \beta\cos\gamma \qquad a_{22} = a_{2\,-2} = \frac{1}{\sqrt{2}}\beta\sin\gamma$$

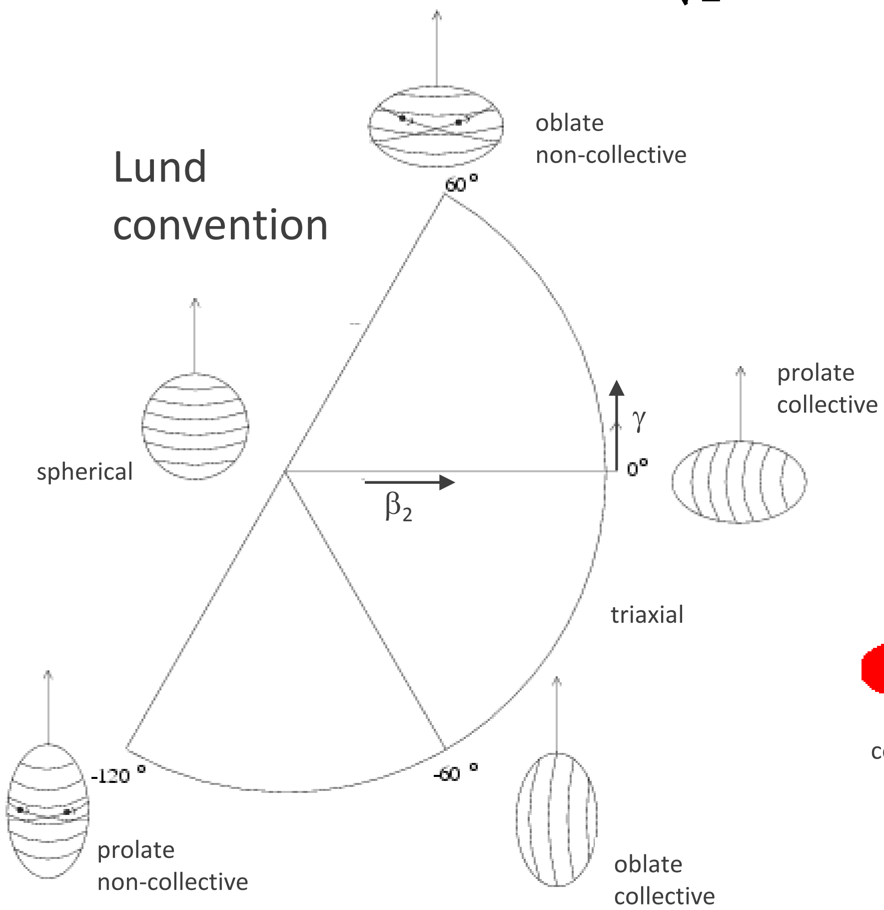
octupole

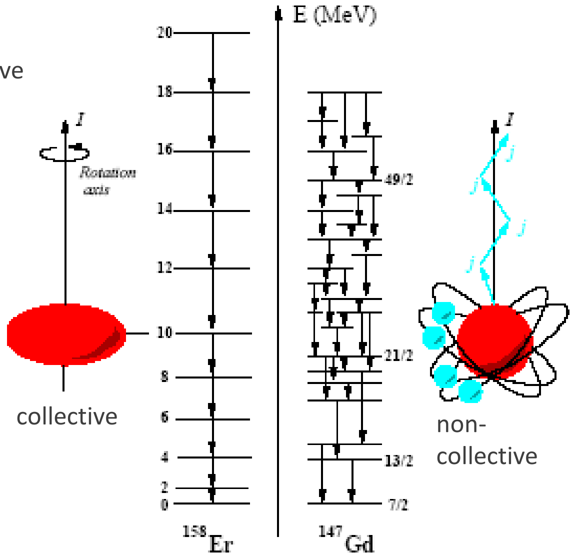


hexadecapole



Lund convention



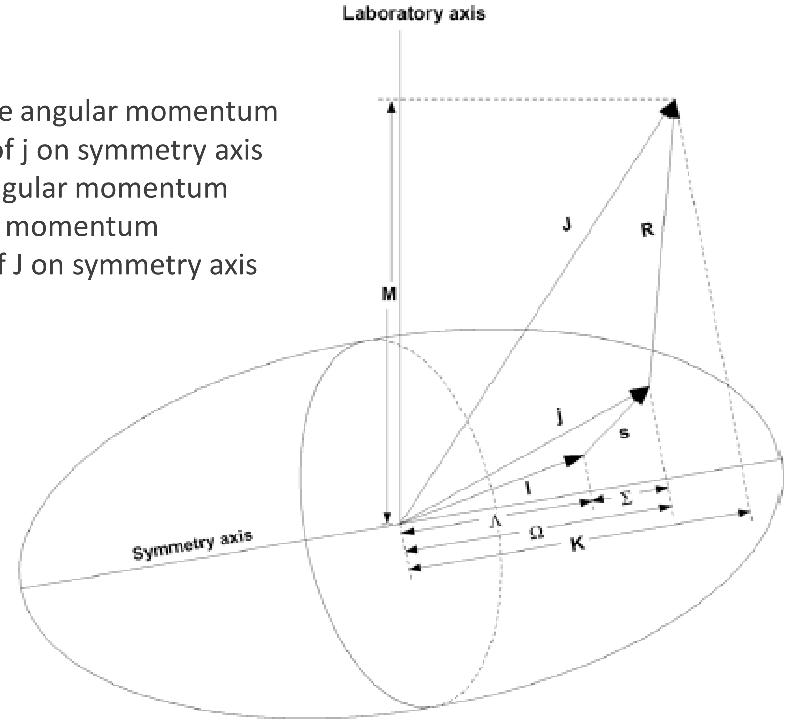


Rotation of deformed nuclei

axial symmetry:
rotational axis ⊥ symmetry axis
for K≠1/2:

$$E(I) = \frac{\hbar^2}{2\mathcal{J}}\left[I(I+1) - K^2\right]$$

j single-particle angular momentum
Ω projection of j on symmetry axis
R collective angular momentum
J total angular momentum
K projection of J on symmetry axis



kinematic moment of inertia

$$\mathcal{J}^{(1)} = I\left(\frac{\partial E}{\partial I}\right)^{-1} = \frac{I}{\hbar\omega} \approx \frac{\Delta I \langle I \rangle}{E_\gamma}$$

dynamic moment of inertia

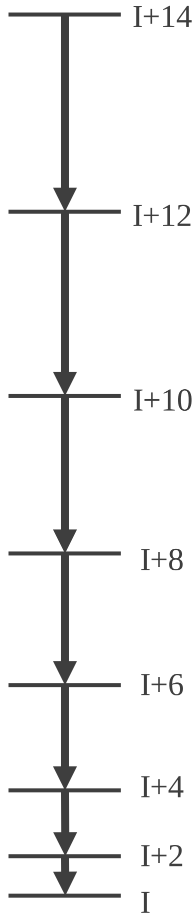
$$\mathcal{J}^{(2)} = \left(\frac{\partial^2 E}{\partial I^2}\right)^{-1} = \frac{\partial I}{\hbar \partial\omega} \approx \frac{(\Delta I)^2}{\Delta E_\gamma}$$

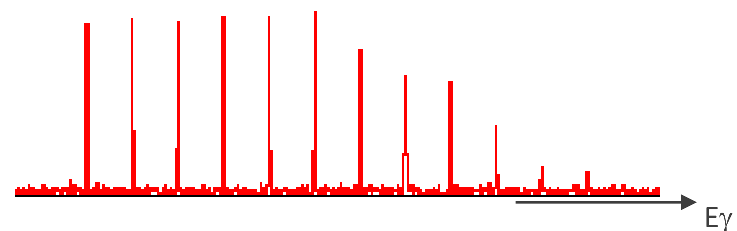
$$\mathcal{J}^{(2)} = \mathcal{J}^{(1)} + \omega\frac{\partial \mathcal{J}^{(1)}}{\partial\omega}$$

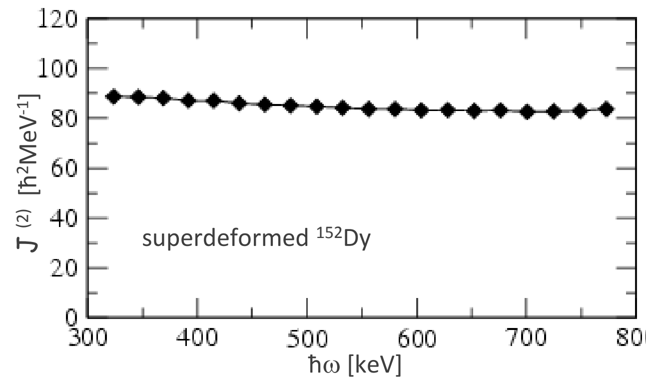
$\mathcal{J}^{(2)}$ measures the variation of $\mathcal{J}^{(1)}$
rigid rotor: $\mathcal{J}^{(2)} = \mathcal{J}^{(1)}$

rotational frequency

$$\hbar\omega = \frac{\partial E}{\partial I} \approx \frac{E_\gamma}{\Delta I}$$

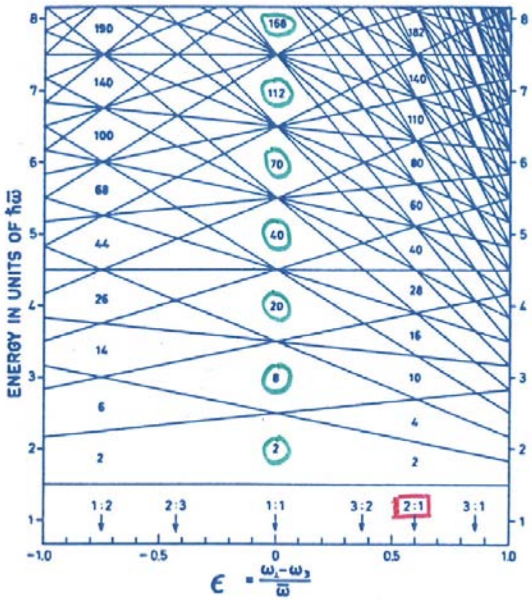




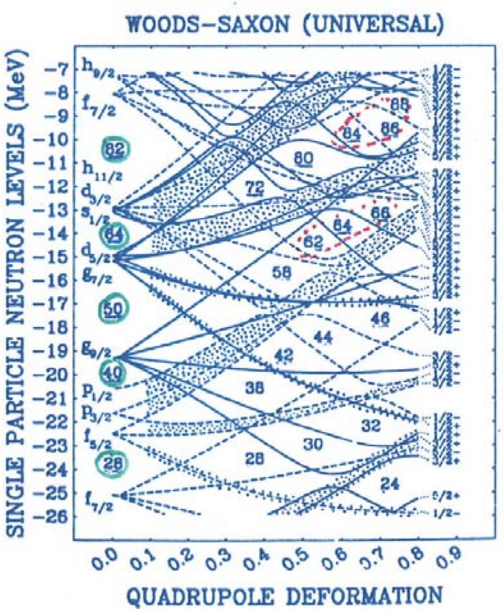


Robert V. F. Janssens,
Joliot Curie, 9/2011

Superdeformation: Shell Effects at Large Deformation

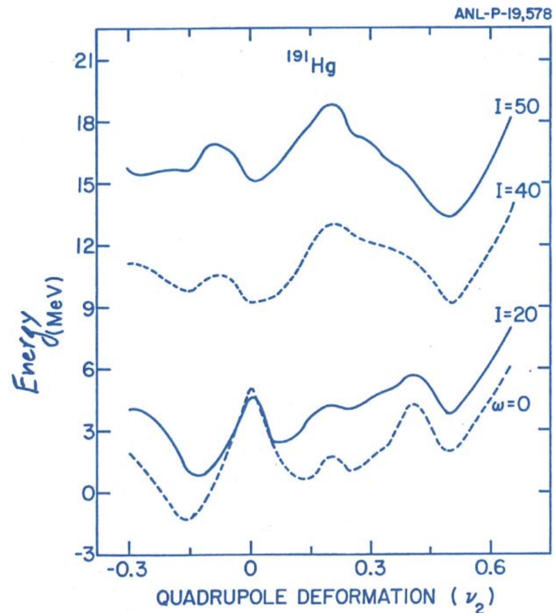


Single-particle levels for an Harmonic Oscillator potential as a function of elongation → Shell gaps at large deformation (2:1, 3:1)

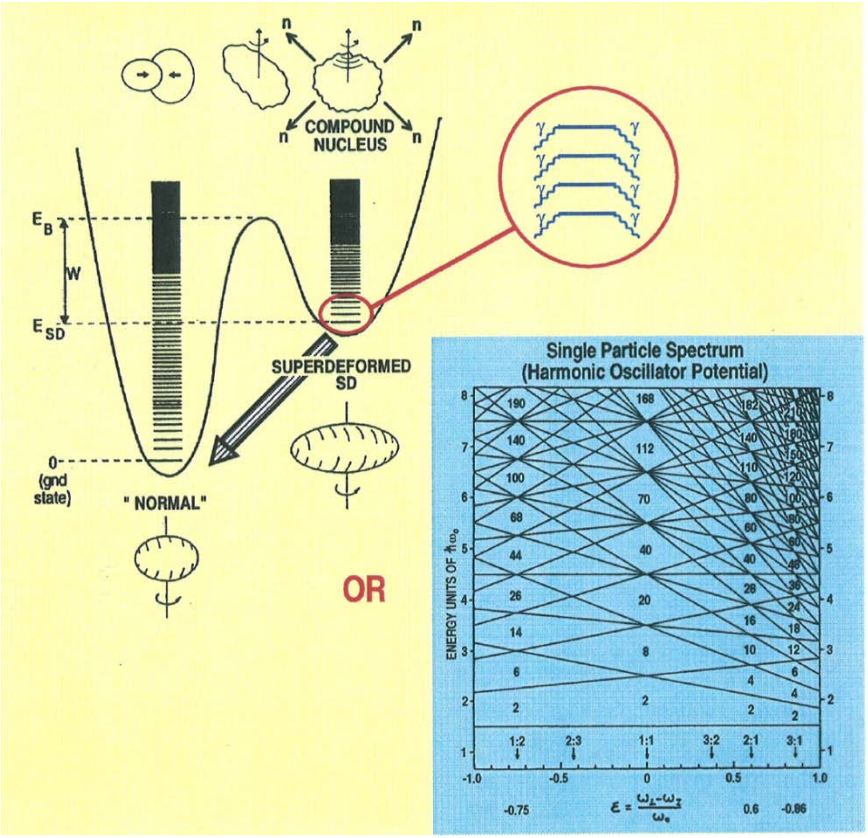


Single-particle levels for a Woods-Saxon potential (high level density regions are shaded) → Shell gaps remain, but not necessarily at 2:1 or 3:1 exactly

Role of Rotation: deepening of the SD minimum → yrast at high spin
→ use fusion-evaporation with heavy ions to generate high spin



Superdeformation: Shell Effects at Large Deformation



SUPERDEFORMATION

A UNIQUE OPPORTUNITY

(1) TO TEST OUR UNDERSTANDING OF THE IMPORTANCE OF SHELL STRUCTURE AT LARGE DEFORMATIONS

(2) TO STUDY THE DECAY FROM ONE POTENTIAL WELL INTO ANOTHER

A FEW OF THE MANY INTERESTING QUESTIONS:

- IDENTIFICATION OF ORBITALS NEAR THE FERMI SURFACE IN THE SD WELL
- ROLE OF SPECIFIC SHAPE DRIVING ORBITALS
- STIFFNESS OF THE SD WELL AND POSSIBLE COLLECTIVE EXCITATIONS
- PAIRING AT LARGE β_2
- CORIOLIS INTERACTION AND PARTICLE ALIGNMENTS AT LARGE β_2 ?
- NEW SYMMETRIES ?
- MORE SURPRISES (IDENTICAL BANDS, $\Delta I = 4$ BIFURCATION ...) ?
- WHICH PARAMETERS GOVERN FEEDING INTO & DECAY OUT OF SD WELL ?
- . . .

In this presentation: answers to SOME of the many questions about physics at 2:1 deformation:

- E*(SD), I^{π}

- Nature of Excitations in SD well

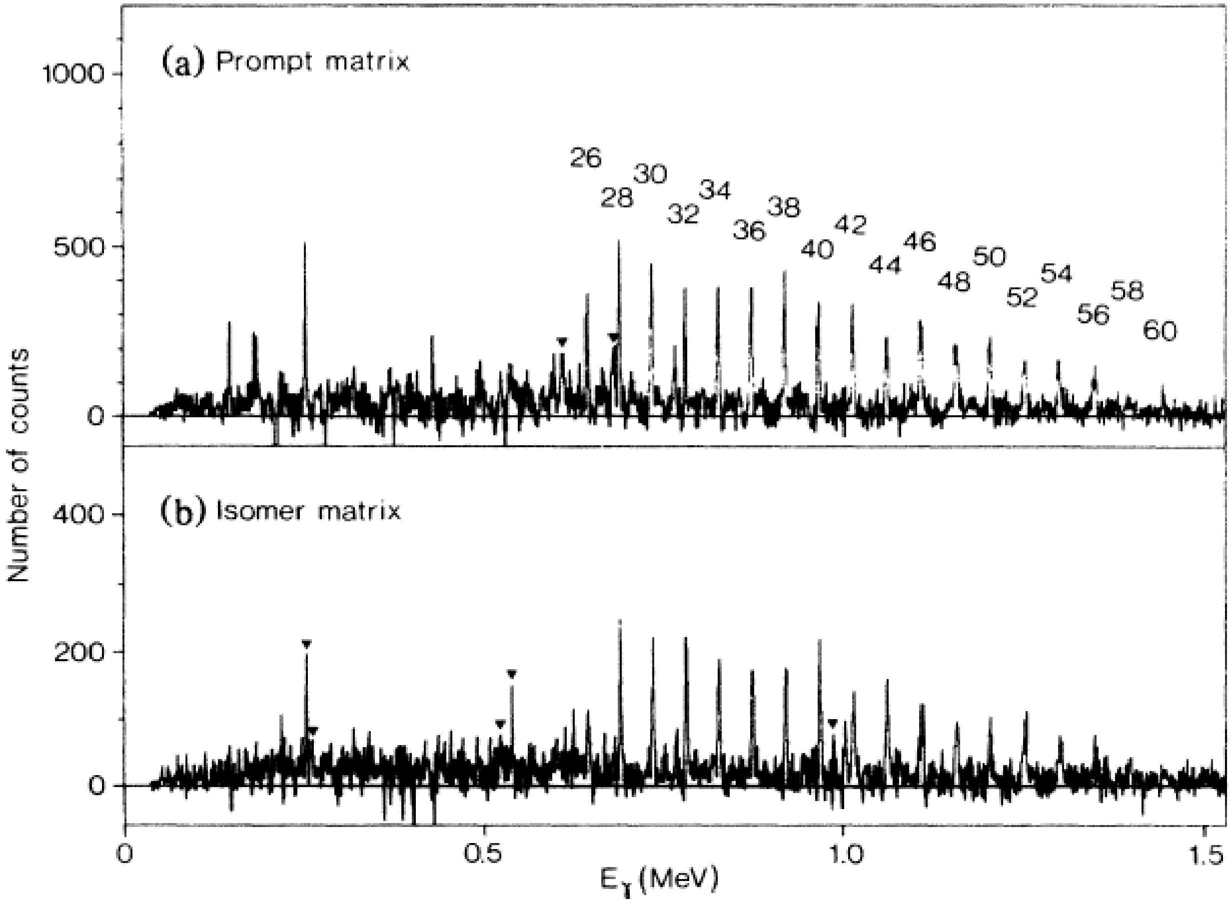
Superdeformation:

The Spectrum that helped make the case for the large arrays:

^{152}Dy

P. Twin *et al.*,

PRL 57, 811



In this presentation: answers to *SOME* of the questions about physics at 2:1 deformation:

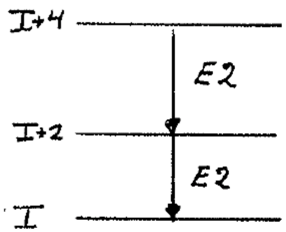
- E*(SD), I^{π}

- Nature of Excitations in SD well

Superdeformation: Some fundamentals

IMPORTANT PHYSICAL QUANTITIES:

Experimental Sign



$\Delta E = E_\gamma$

$\Delta I = 2\hbar$

E(I) ~ I(I+1)

E(I+2) ~ (I+2)(I+3)

E(I+4) ~ (I+4)(I+5)

E(I+6) ~ (I+6)(I+7)

$$E \doteq \frac{\hbar^2}{2\mathfrak{J}} I(I+1)$$

$$\omega = \frac{dE}{dI} = \frac{E_\gamma}{2} \quad \text{(for rotational band)}$$

4I

$$\mathfrak{J}^{(1)} = \frac{\hbar^2}{2}\left[\frac{dE}{d(I^2)}\right] = \hbar\frac{I}{\omega} = \frac{(2I-1)\hbar^2}{E_\gamma}$$ KINEMATICAL Moment of INERTIA

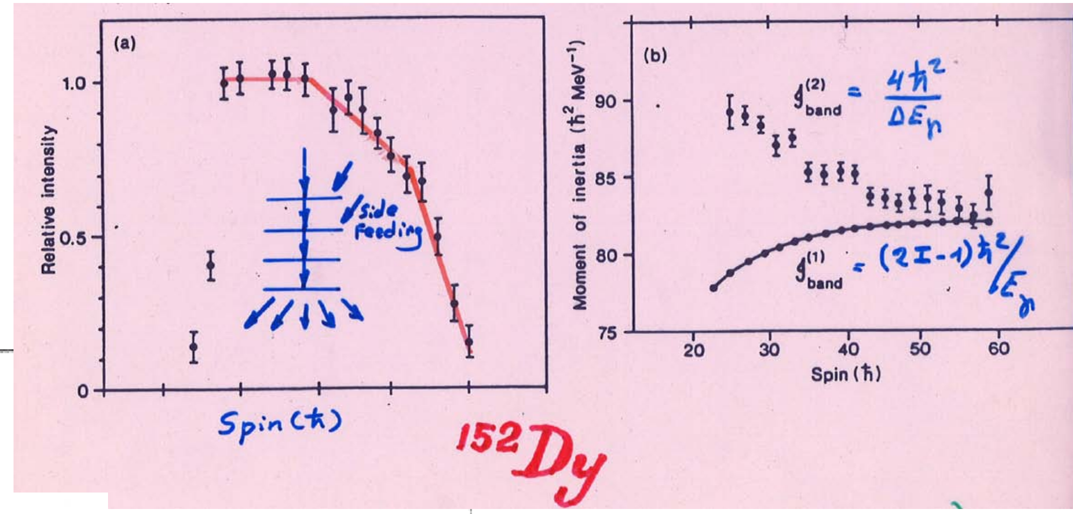
$$\mathfrak{J}^{(2)} = \hbar^2\left[\frac{d^2E}{dI^2}\right] = \hbar\frac{dI}{d\omega} = \frac{4\hbar^2}{\Delta E_\gamma}$$ DYNAMIC Moment of INERTIA

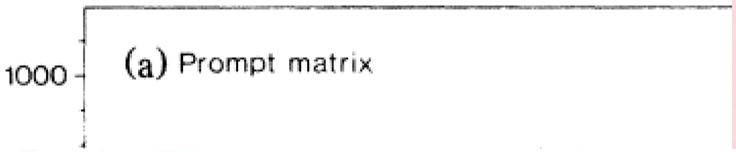
Superdeformation:

^{152}Dy

P. Twin *et al.*,

PRL 57, 811





Transition Quadrupole Moment etc...

$$Q_t(I) = \left(1.22 \langle I\,0\,2\,0 | I-2\;0\rangle^2 \tau E_\gamma^5\right)^{-1/2}$$

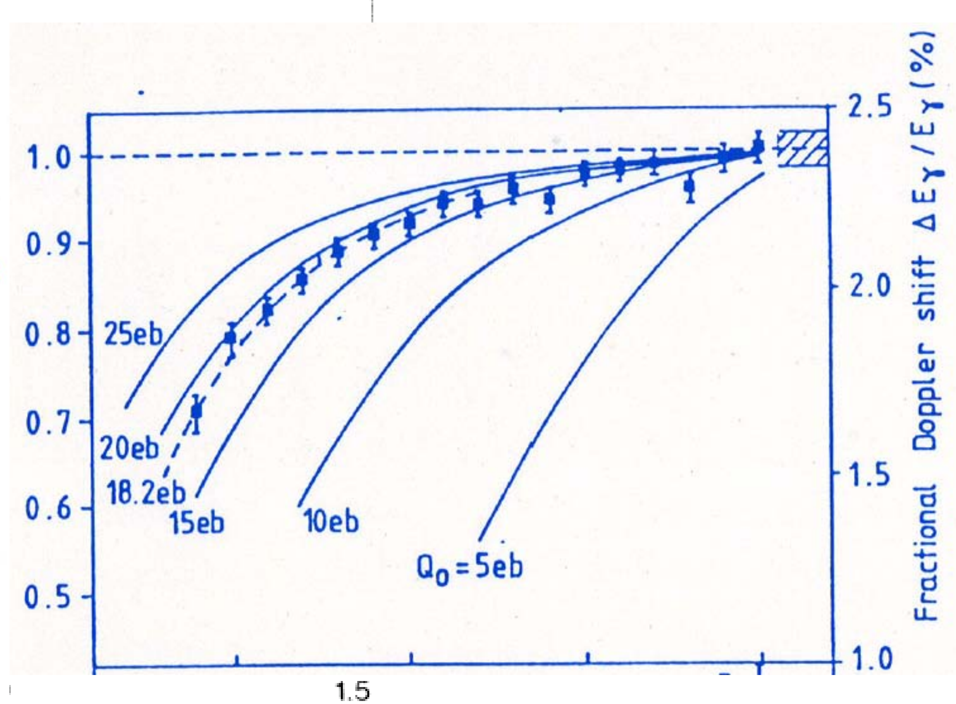
Q_t can be related to the deformation through a model expression

(ex: $Q_0 = 3(5\pi)^{-1/2} R_0^2 Z \beta_0$)

$$B(E2) = (8.1672 * 10^{-2}) / \tau(s) E_\gamma^5 (MeV)$$

$$B(E2) = \frac{5}{16\pi} \langle I\,0\,2\,0 | I-2\;0\rangle^2 Q_t^2$$

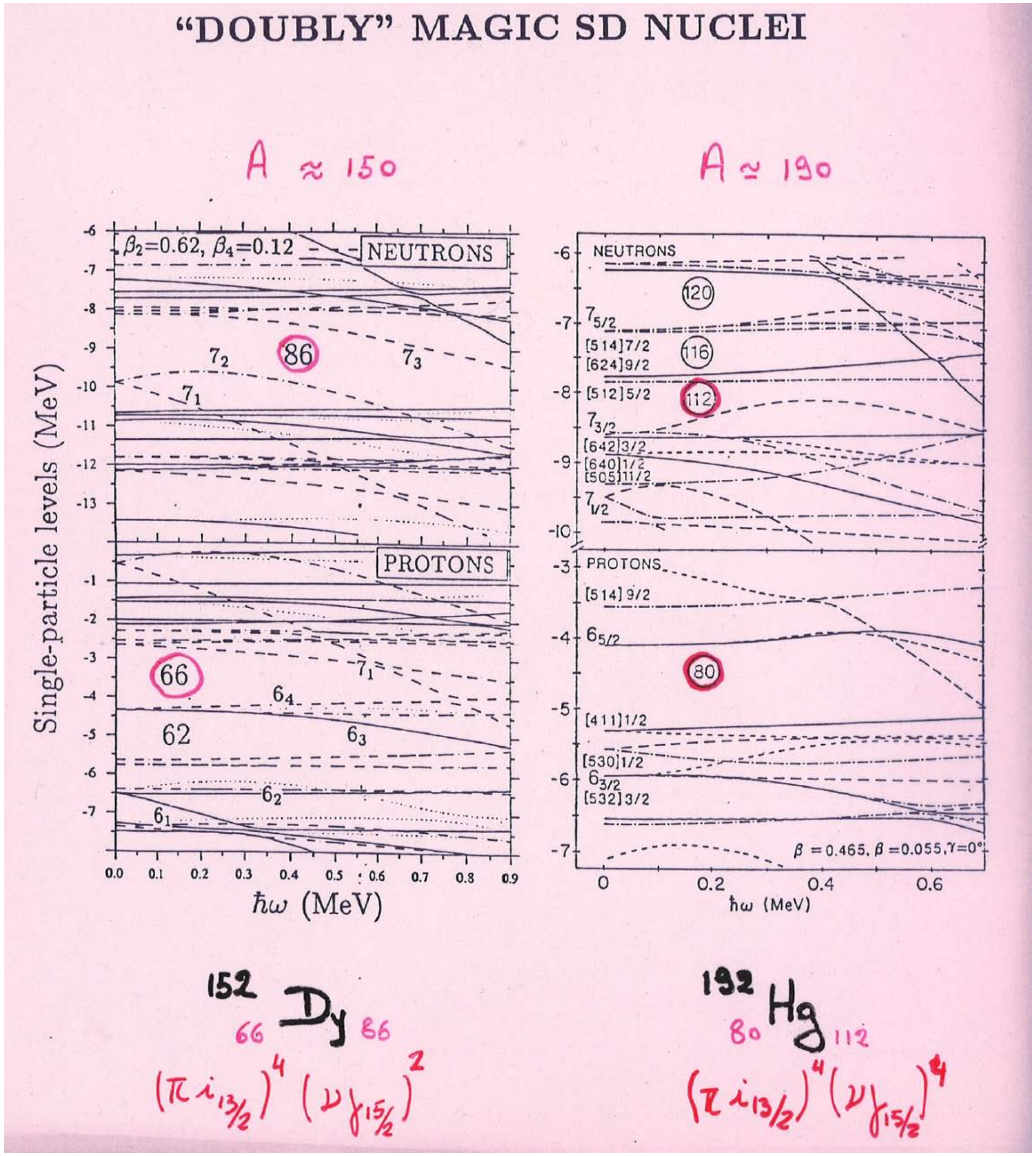
$$B(E2)_{W.U.} = 0.0595\, A^{4/3} (e^2 fm^4)$$



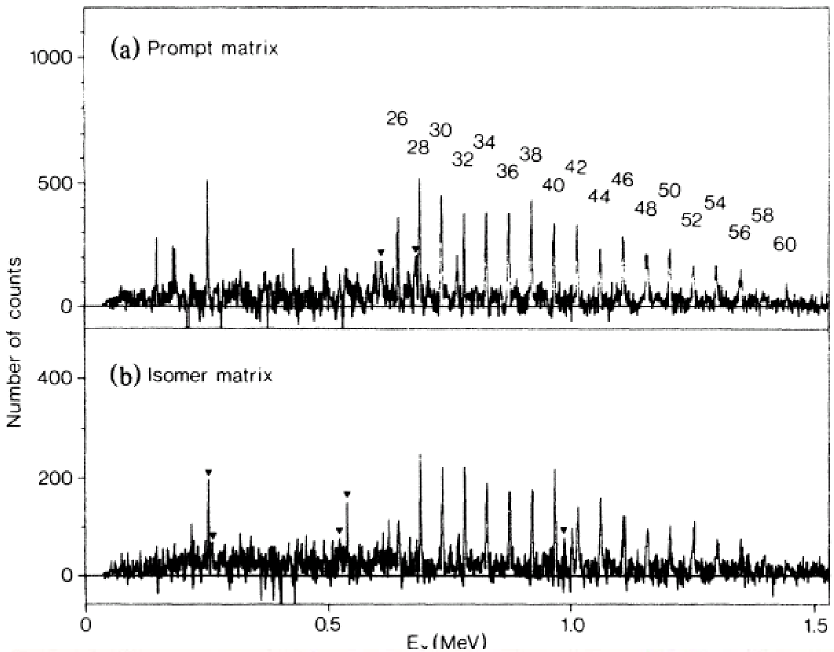
$Q_0 = 18 \pm 3$ e.b

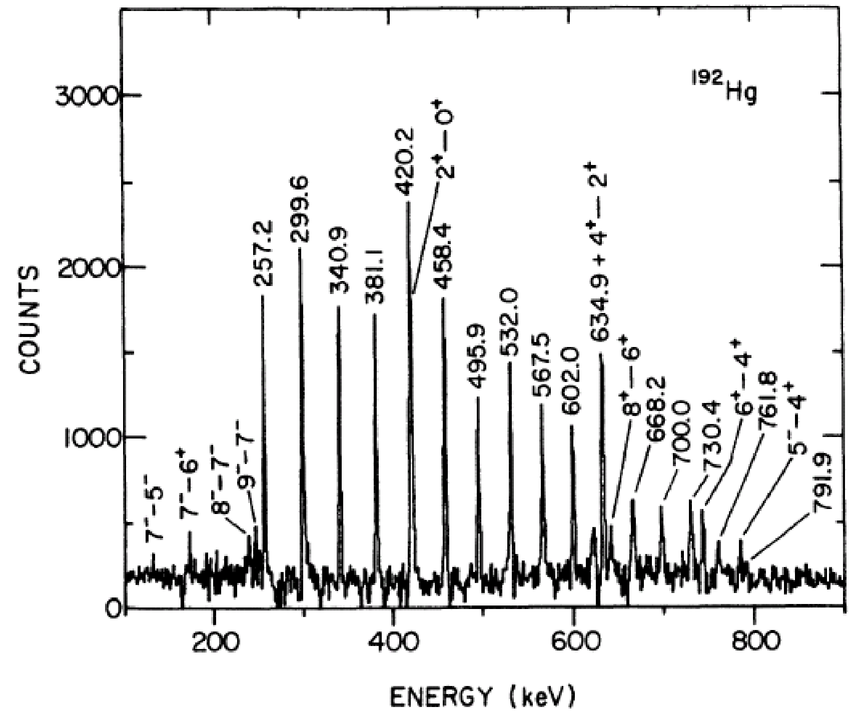
$B(E2) = 2390$ W.U.

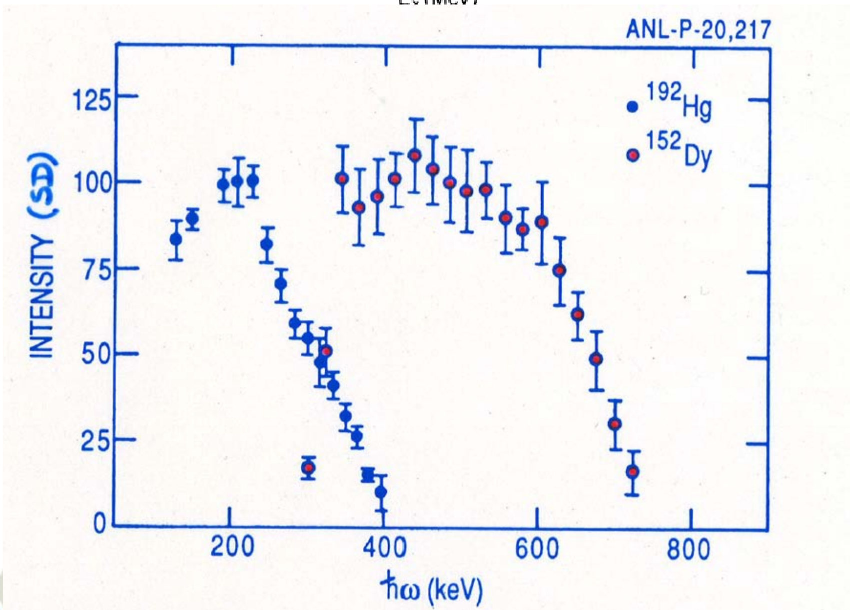
Superdeformation: Shell Effects at Large Deformation



Superdeformation: Magic SD Nuclei

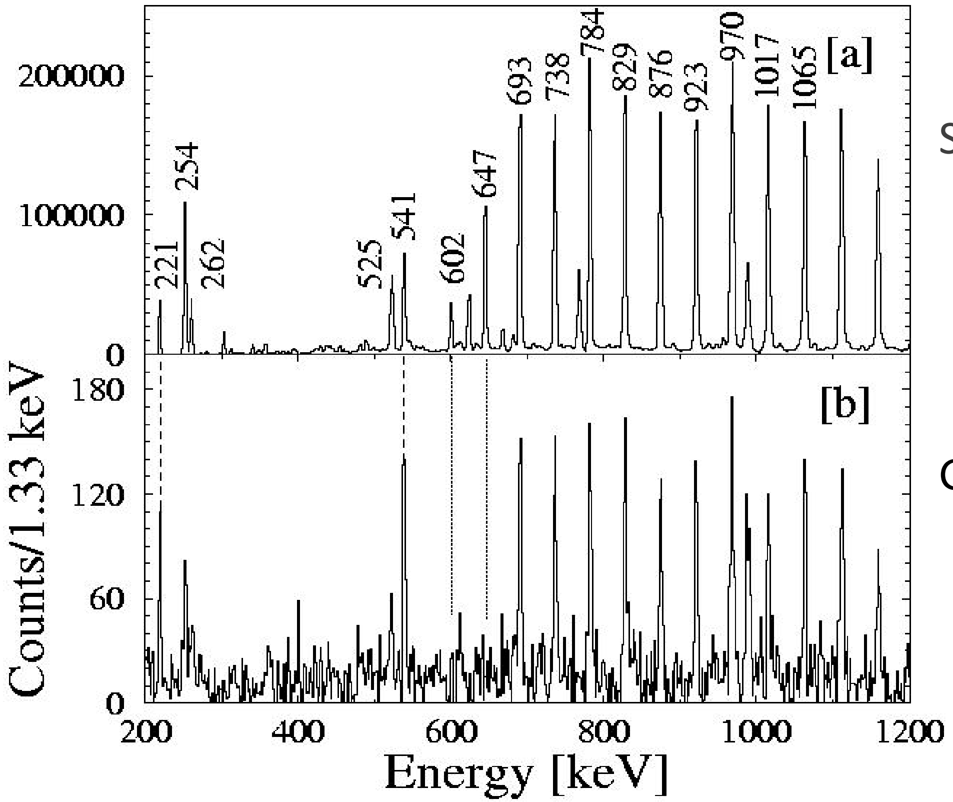






Lower Frequency at A~190
SD trapping to lower spin

15 Years Later: SD band is linked



Sum of clean SD gates (Band-1)

Gate on main 4011 keV linking transition

$^{108}Pd(^{48}Ca,4n)^{152}Dy$

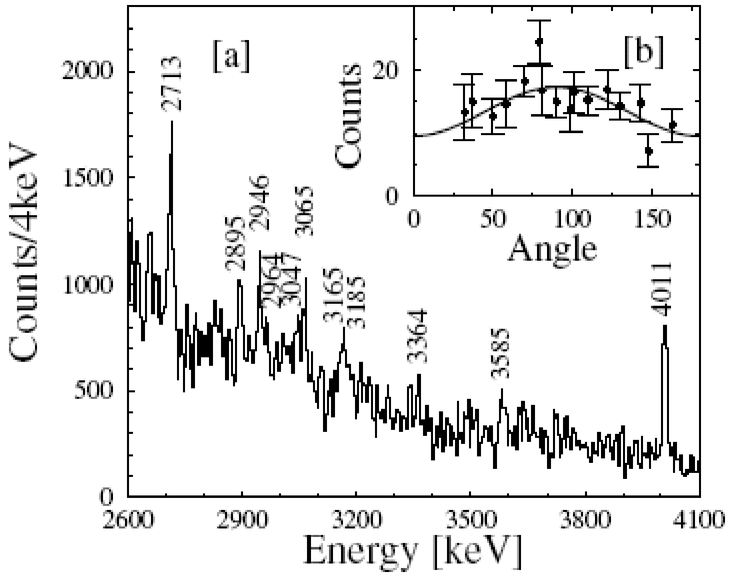
38 shifts (12 days)

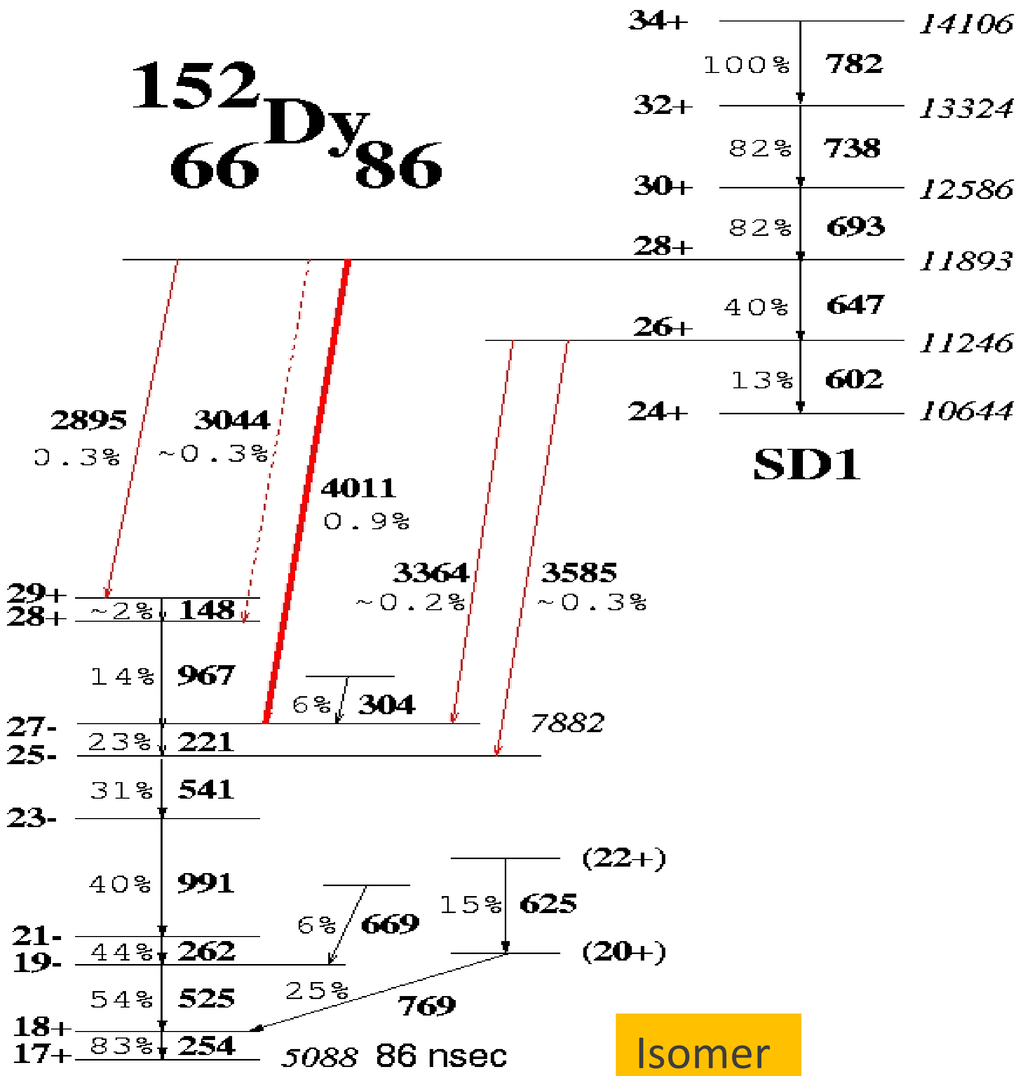
Isomer tagging (87 nsec isomer)

T. Lauritsen *et al*. PRL 88, 42501

Superdeformation:

15 Years Later: SD band is linked





E* and I$^{\pi}$ established

Decay mechanism understood

T. Lauritsen *et al*. PRL 88, 42501

The Strength of the Shell Effects

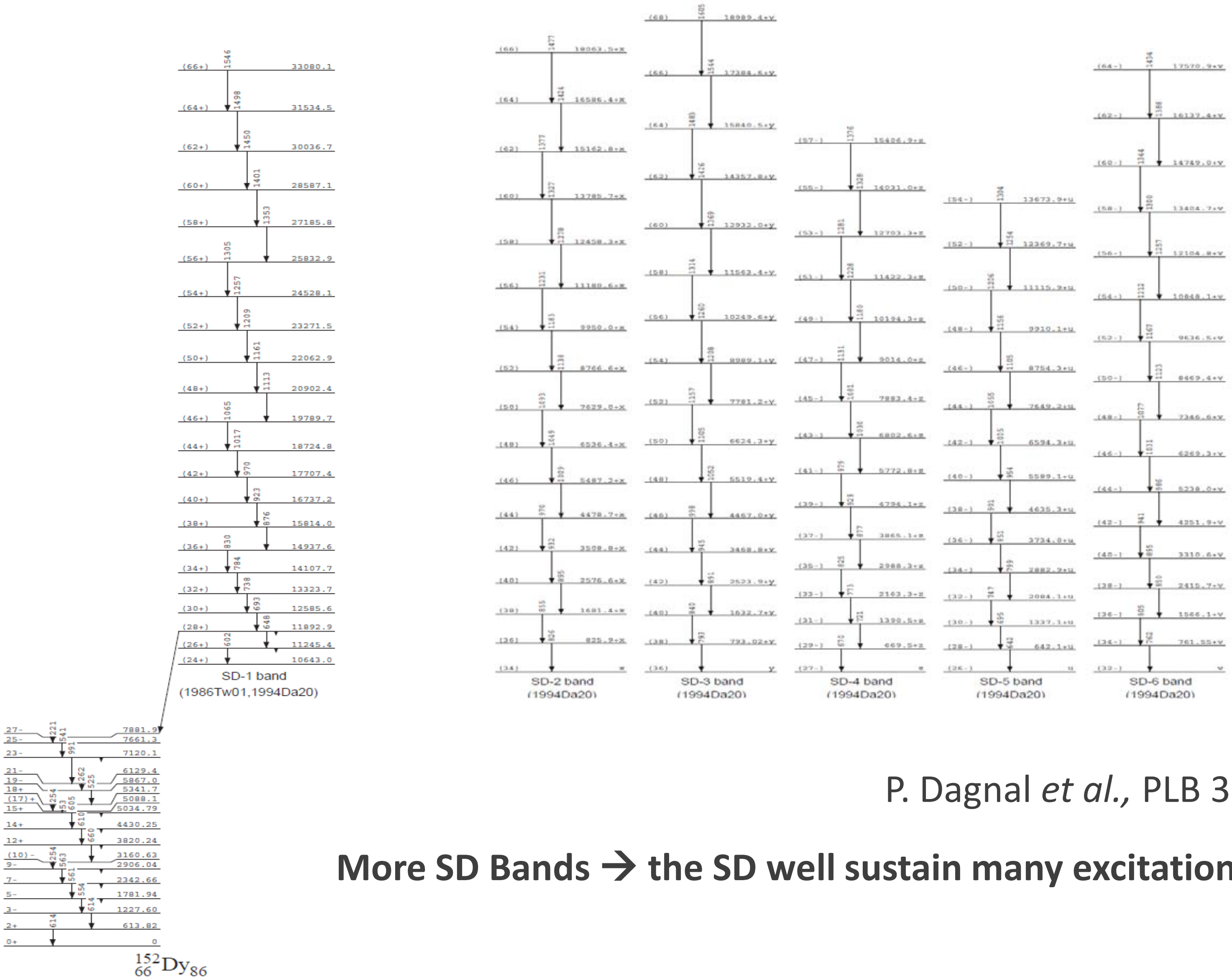
Experiment: **Lowest State in SD band:**

$I^{\pi} = 24^{+}$ $E(0^{+}) = 7.5$ MeV

Calculations:

Nilsson – Strutinsky	26^{+}	8.8 MeV	I. Ragnarsson NP A557, 167
Woods – Saxon	22^{+}	8.4 MeV	J. Dudek et al., PR C38, 940
Relativistic Mean Field	24^{+}	8.3 MeV	A.V. Afanasjev et al., NP A634, 395
Hartree Fock Bogoliubov	24^{+}	7.1 MeV	J.L. Egido et al., PRL 85, 26

Superdeformation:

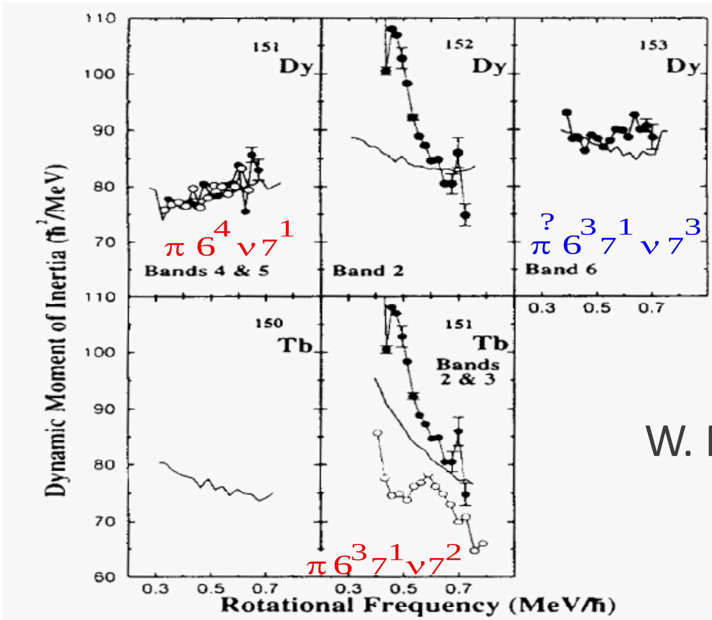


P. Dagnal *et al.*, PLB 335, 313

More SD Bands → the SD well sustain many excitations

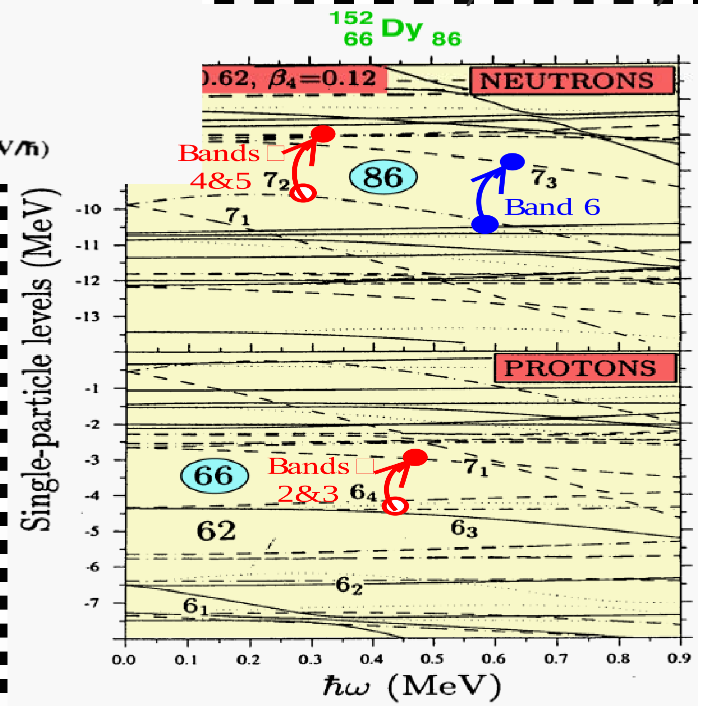
Superdeformation:

Nature of the excitations in the SD well



P. Dagnal *et al.*, PLB 335, 313

W. Nazarewicz et al., NP A503, 285



Most excitations a
quasi-particle exci
role of high-j intru

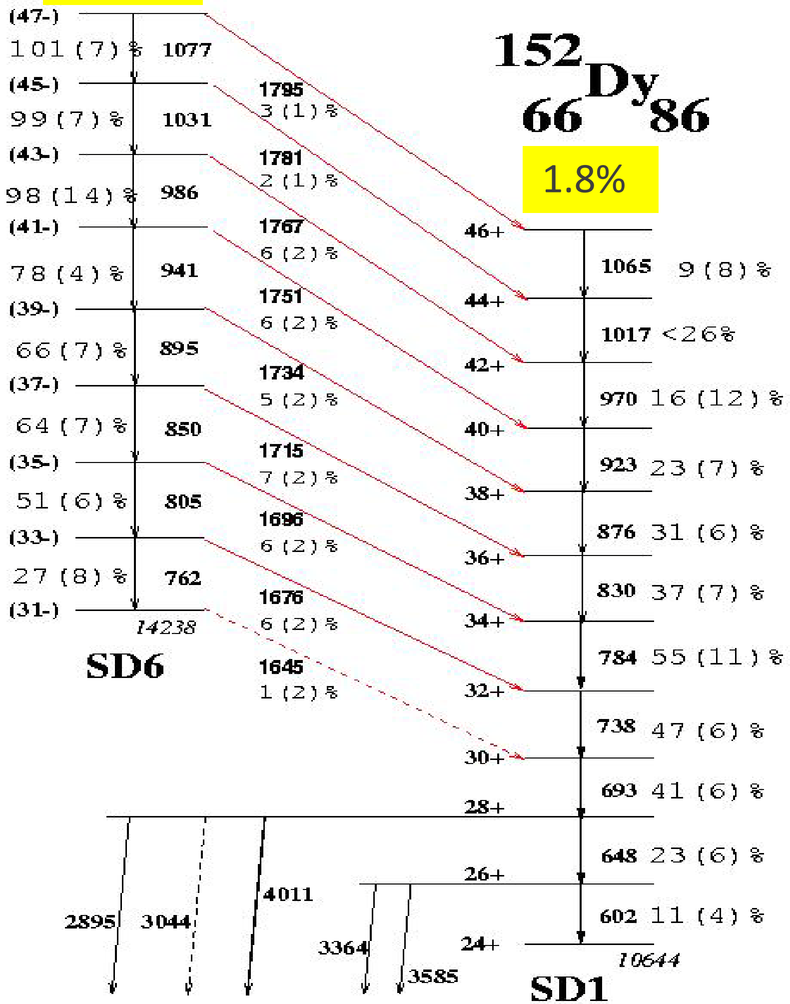
"The picture of extreme single particle motion applies, the best example of the application of the shell model at extremes of angular momentum and deformation"

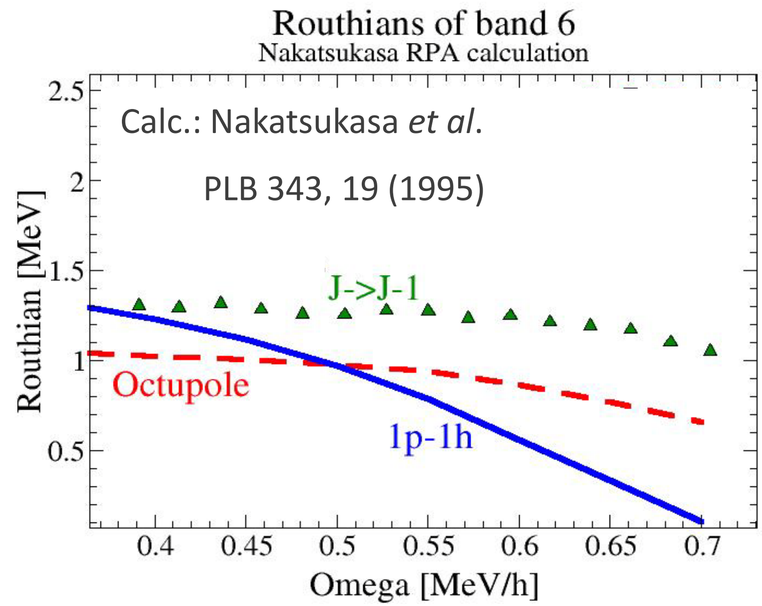
Superdeformation:

Collective excitation in the SD well T. Lauritsen *et al.*, PRL 89, 282501

→ Linking transitions competing with fast E2 in-band transitions

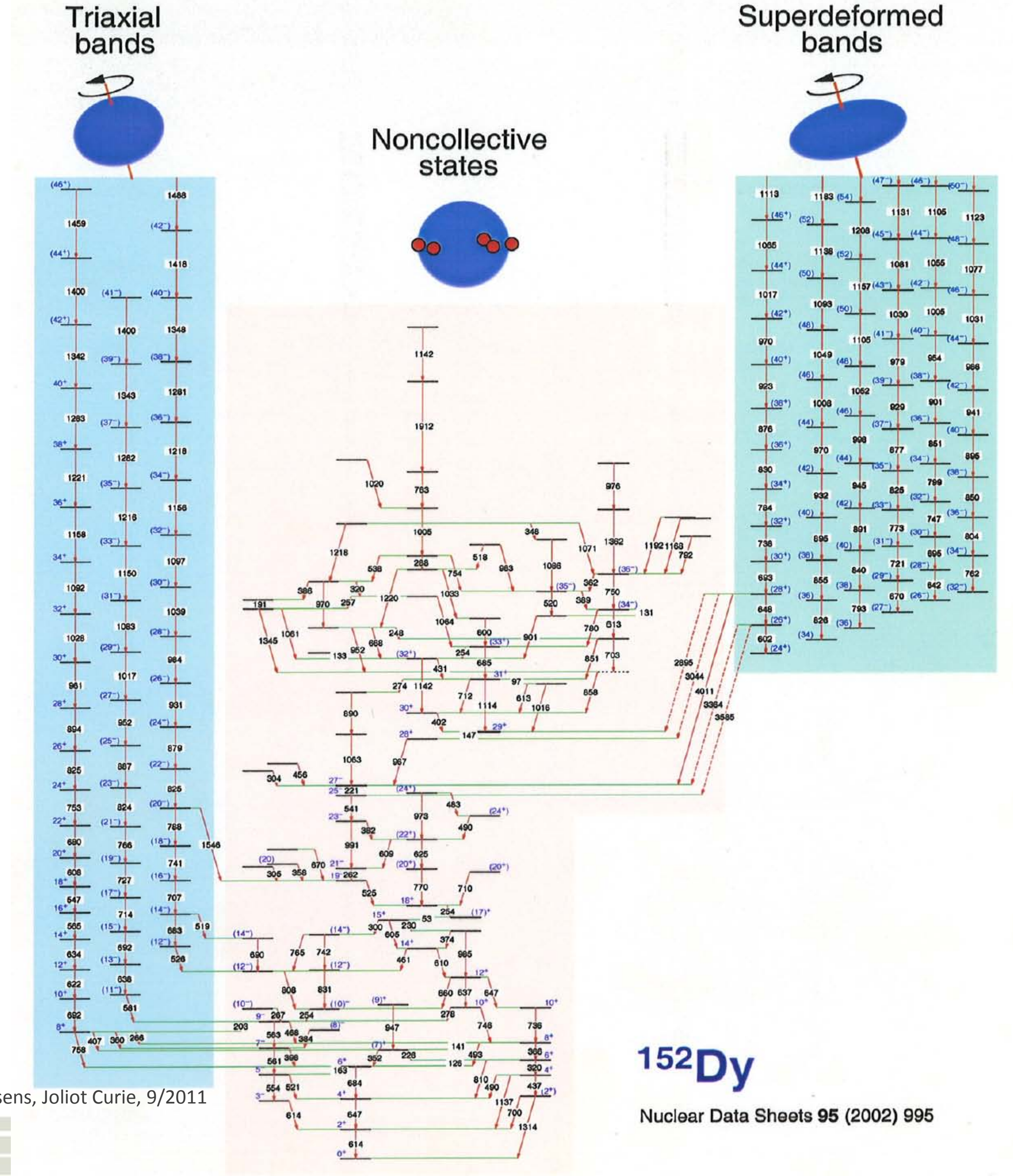
0.07% **→ Collective E1 transitions**





The presence of intruder orbitals ($j_{15/2}$ neutrons and $i_{13/2}$ protons) near the Fermi surface, close to levels of opposite parity with $\Delta l = 3$ ($g_{9/2}$ neutrons and $f_{7/2}$ protons) results in octupole vibration as favored collective mode

^{152}Dy: A laboratory to study generation of angular momentum



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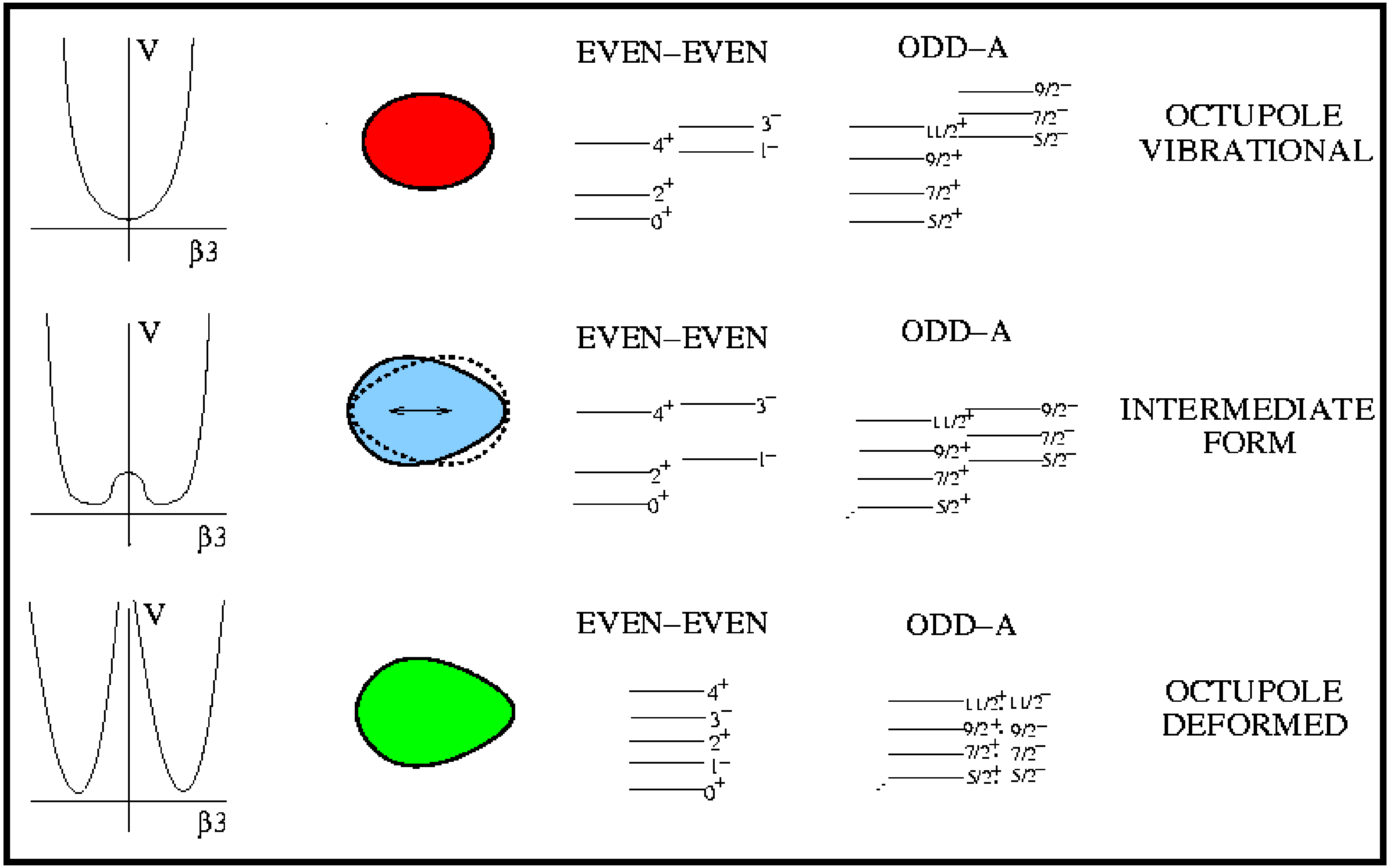
Octupole Correlations: Traditional View



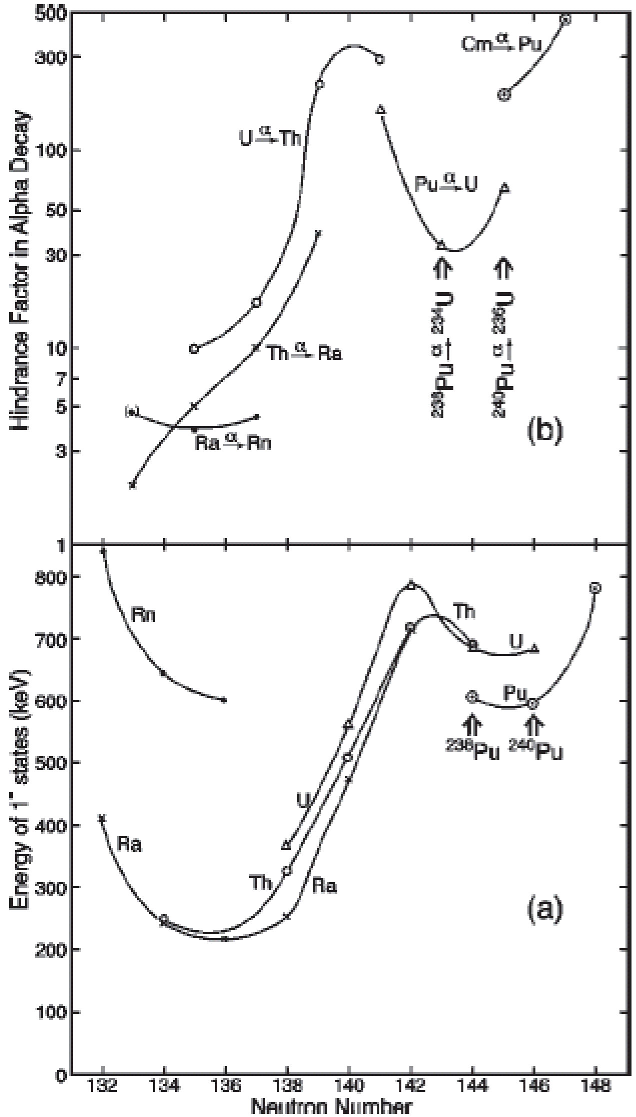
Octupole correlations originate from the long-range interactions between valence nucleons occupying states with $\Delta j = \Delta l = 3$

In actinide nuclei:

$\nu j_{15/2} \otimes g_{9/2}$

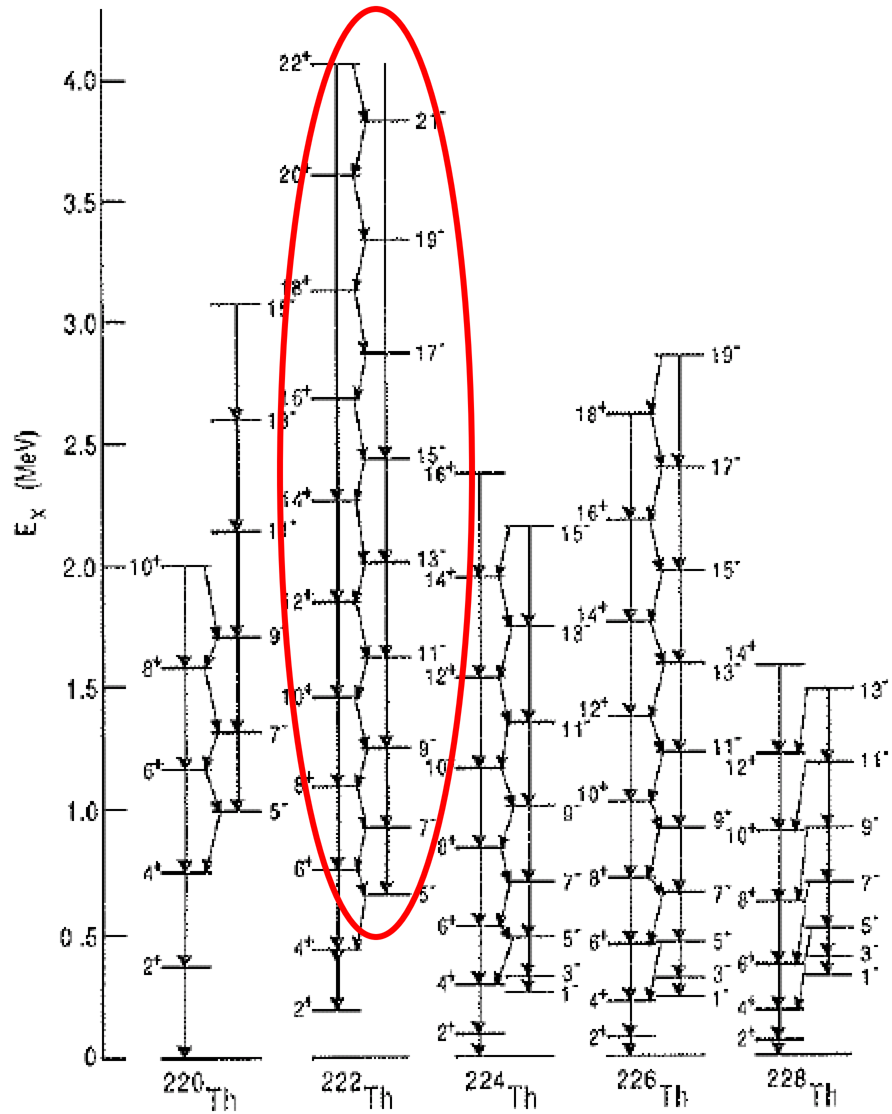
$\pi i_{13/2} \otimes f_{7/2}$

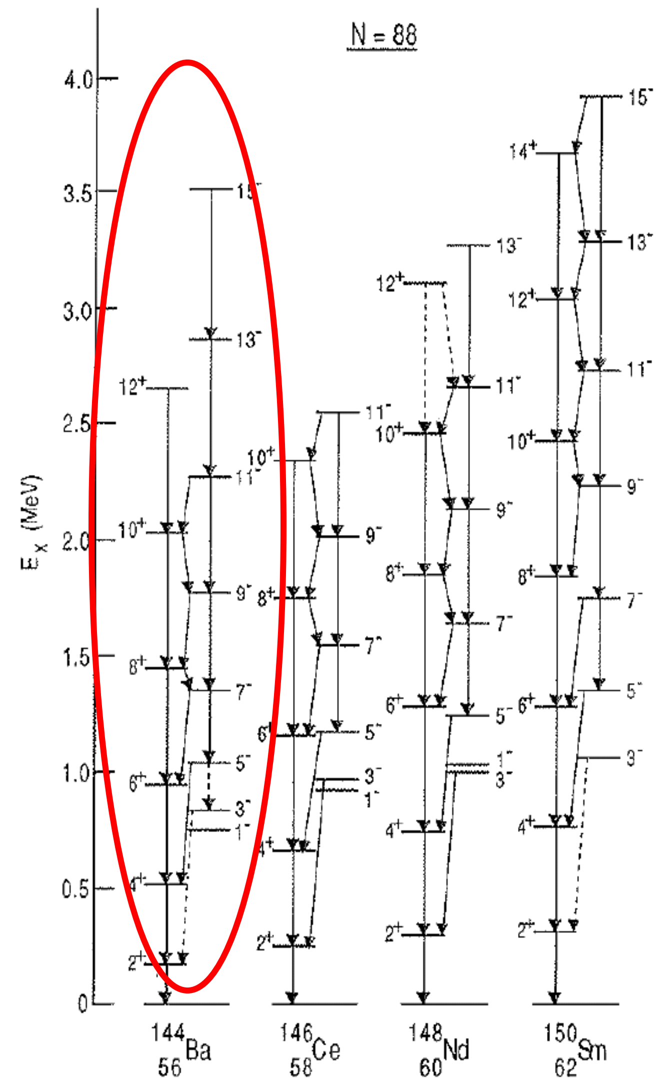
Octupole Rotation: signatures



Signature 1: 1^- energy & hindrance in α decay

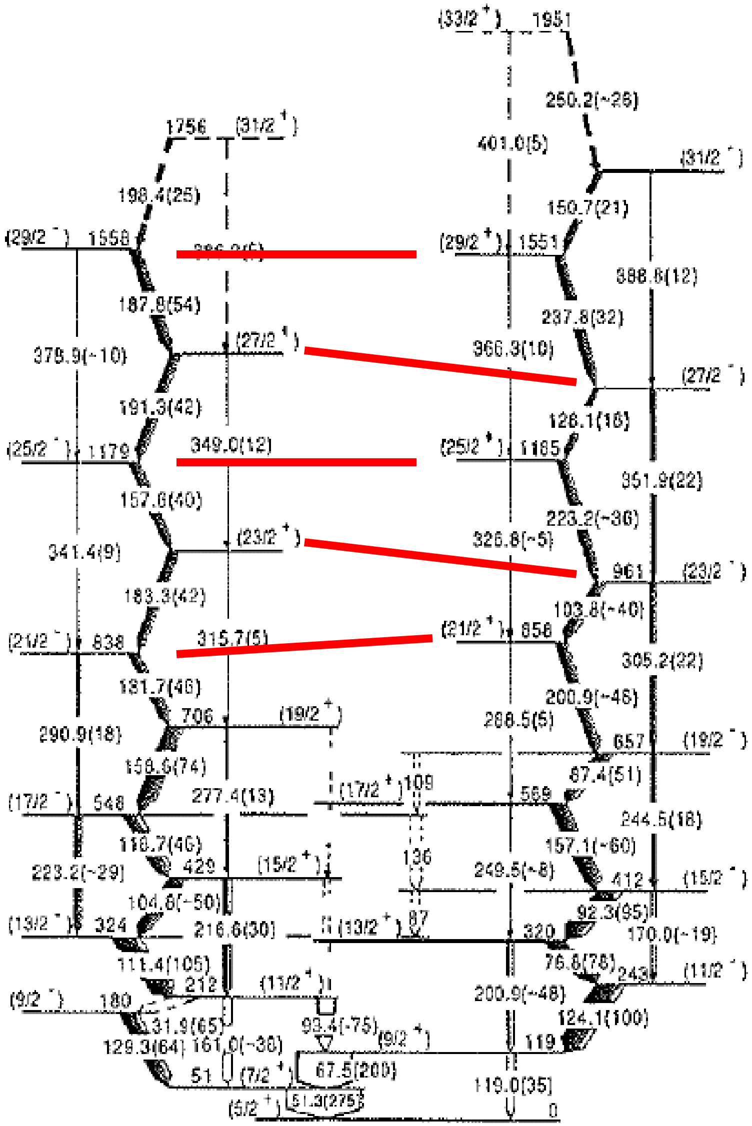
Octupole Rotation: signatures





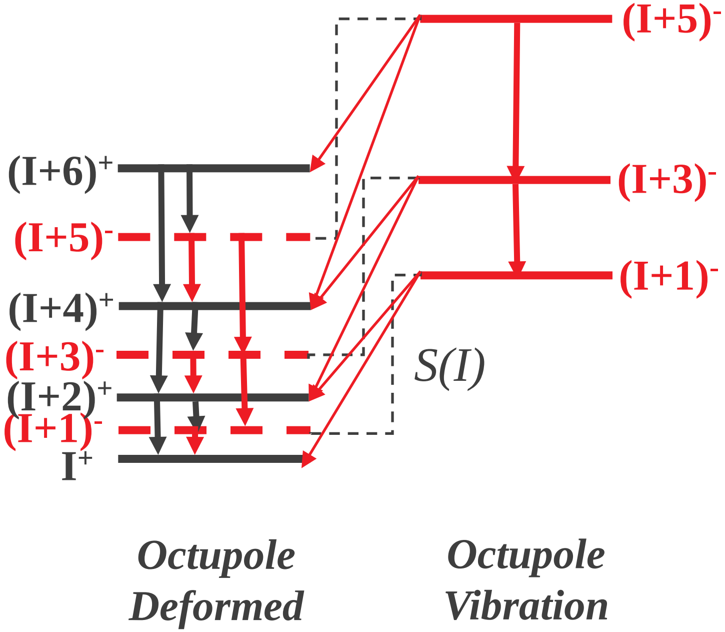
Signature 2: E1 "zig-zag" transitions

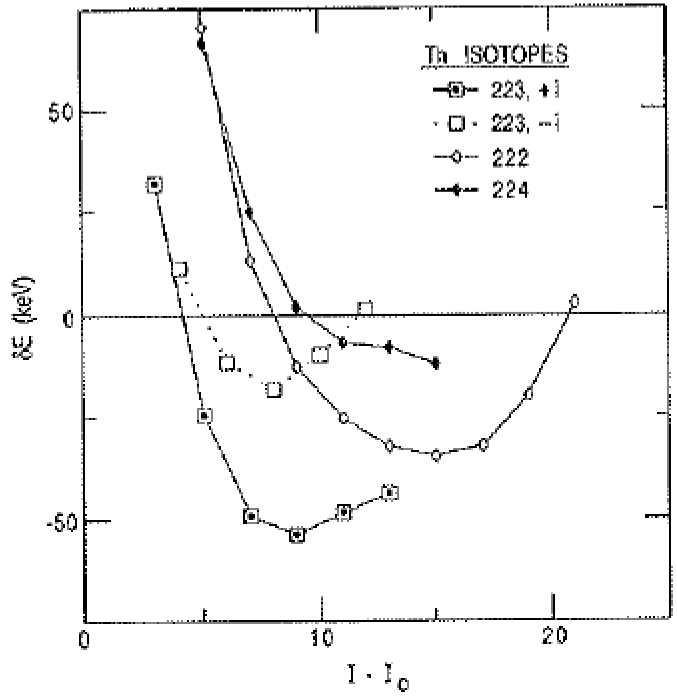
Octupole Rotation: signatures



Signature 3: Parity Doublets

Octupole Rotation: signatures





$$S(I) \equiv E_I - \frac{(I+1)\cdot E_{I-1} + I\cdot E_{I+1}}{2I+1}$$

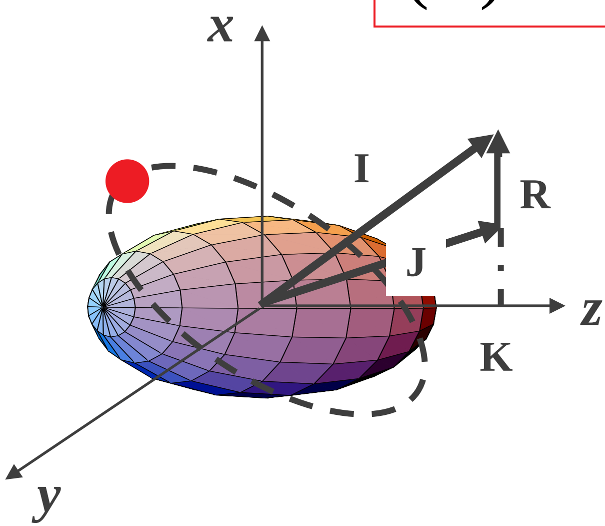
Signature 4: Energy Staggering

Octupole Rotation: signatures

Signature 5: Delay in Alignment

$$e'(\omega) = E'(\omega) - E_g'(\omega)$$

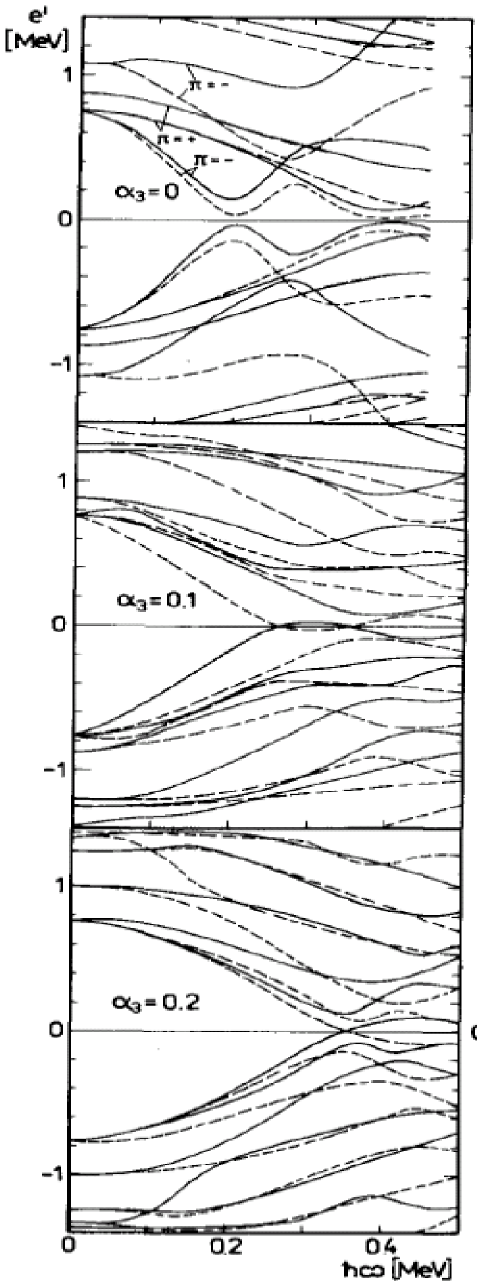
$$i(\omega) = I_x(\omega) - I_x^g(\omega)$$



$$\omega(I) = \frac{E(I+1) - E(I-1)}{I_x(I+1) - I_x(I-1)}$$

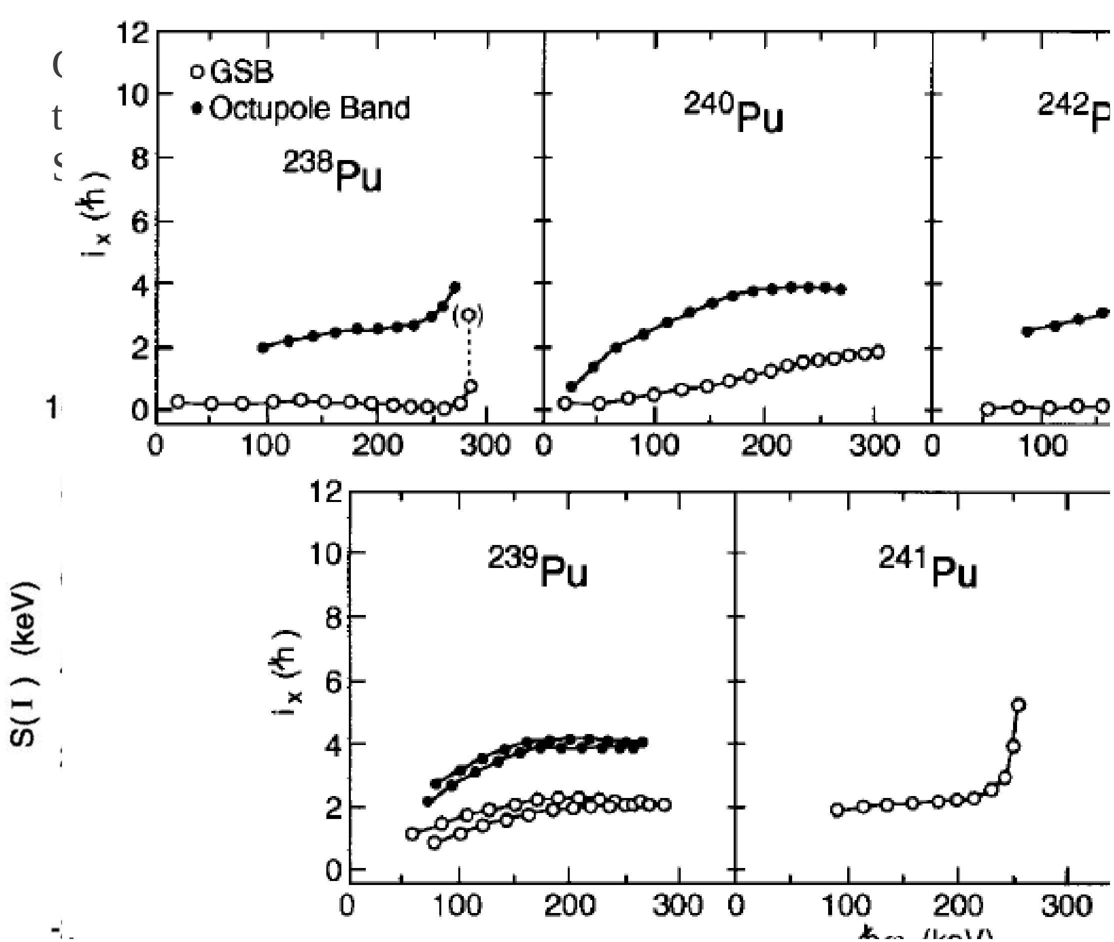
$$I_x(I) = \sqrt{(I+1/2)^2 - K^2}$$

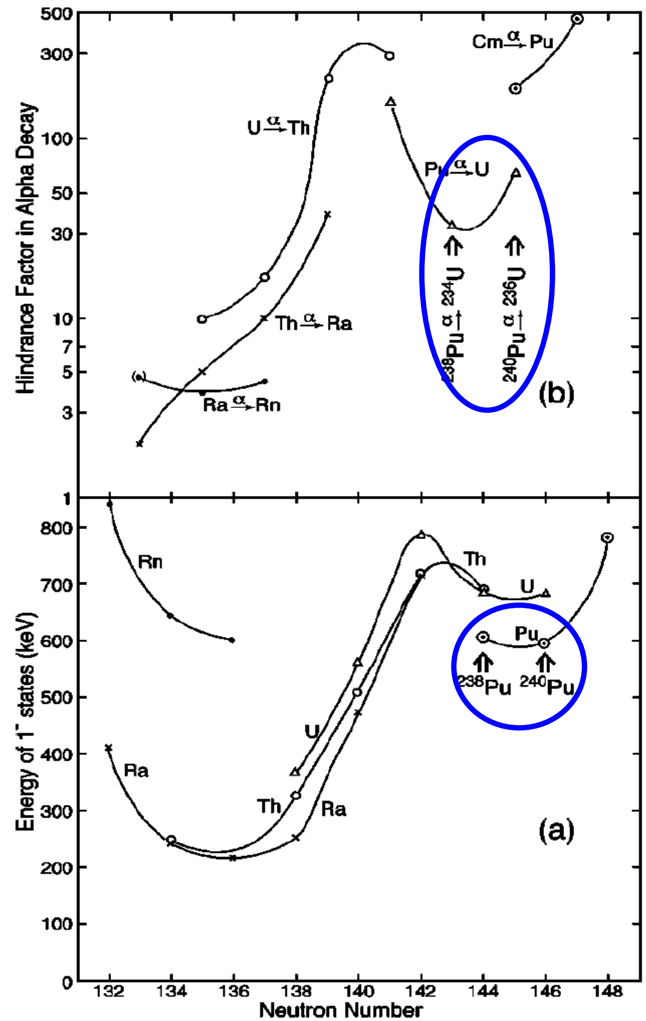
$$E'(\omega) = (E(I+1) + E(I-1))/2 - \omega I_x(I)$$



S. Frauendorf and V.V. Pashkevich, Phys. Lett. B **141**, 23 (1984)

Octupole Correlations around ^{239,240}Pu: Rotation, Vibration or something else?

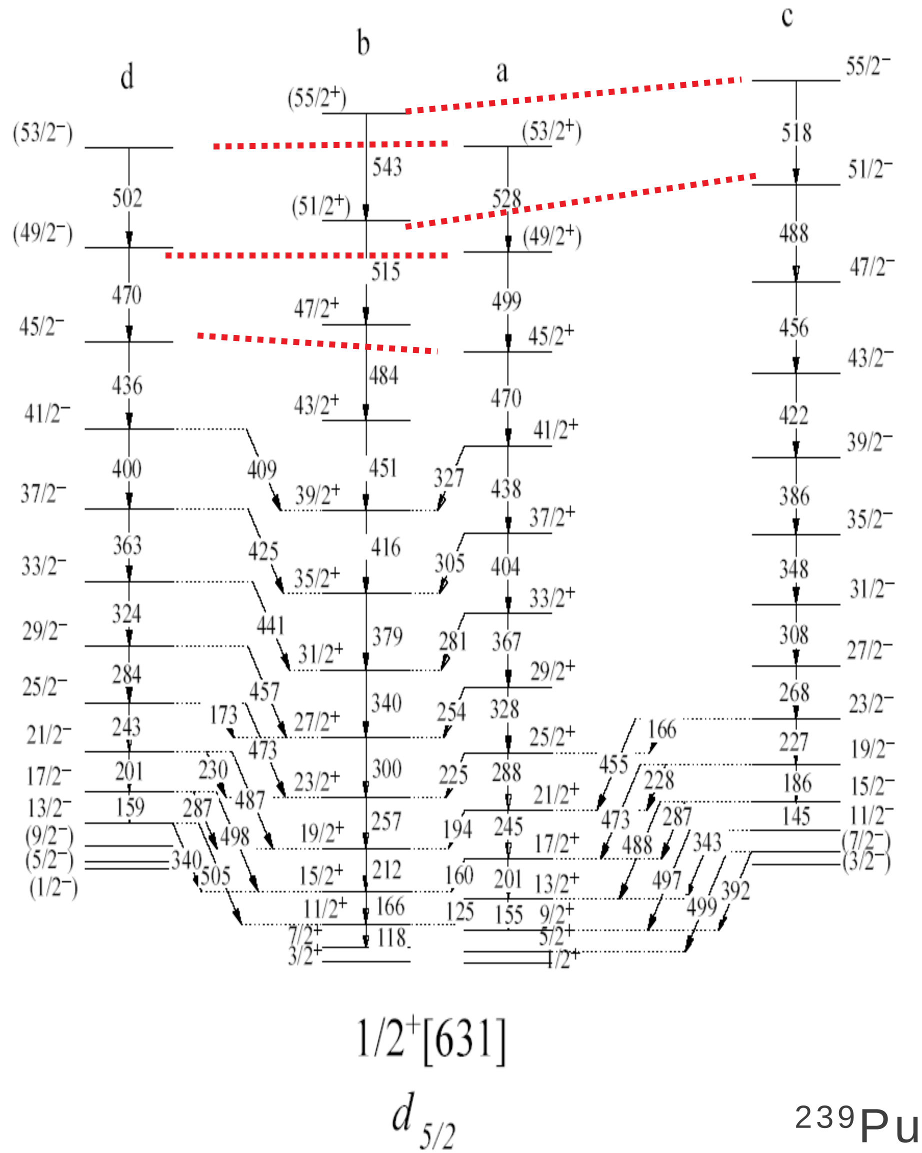




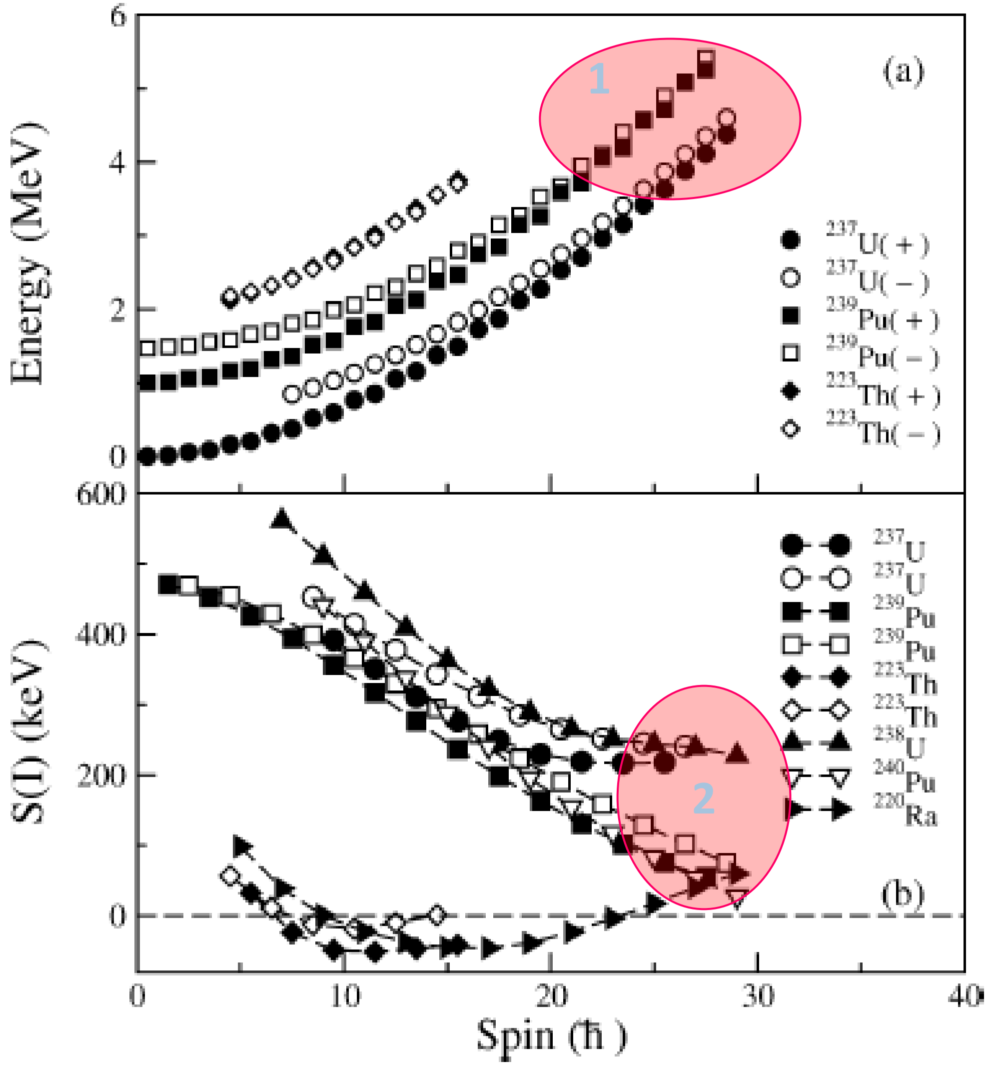
Evidence for strong correlations at high spin: I^+ & I^- form 1 band at high spin, parity doublets in ^{239}Pu alignments, E(1$^-$), hindrance factors

I. Wiedenhöever et al., Phys. Rev. Lett. 83, 2143 (1999).
S. Zhu et al., Phys. Lett. B618, 51 (2005).
R. K. Sheline & M. A. Riley, Phys. Rev. C 61, 057301 (2000).

Octupole Correlations around ^{239,240}Pu: Rotation, Vibration or something else?



^{237}U and ^{239}Pu: contrasting behaviors



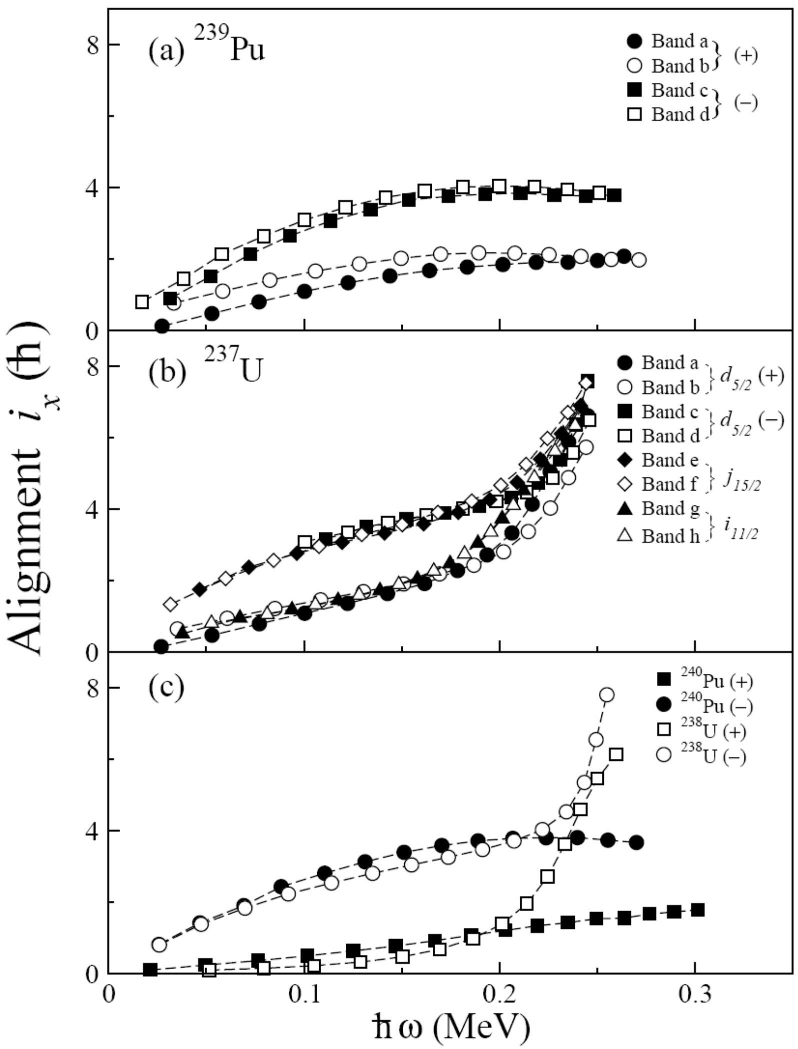
1. Parity Doublets in ^{239}Pu
2. S(I): ^{239}Pu: ~ 0 keV
   ^{237}U: ~ 200 keV
3. Decoupling Parameters
   ^{239}Pu:
   a^{+}=-0.45(2)
   a^{-}= 0.30(1)
   ^{237}U:
   a^{+}=-0.30(1)
   a^{-}= 0.03(1)
4. Dipole moments:
   ^{239}Pu: D_0=0.035(2) *efm*
   ^{237}U: D_0=0.020(2) *efm*

S. Zhu *et al*., Phys. Lett. **B618**, 51 (2005).

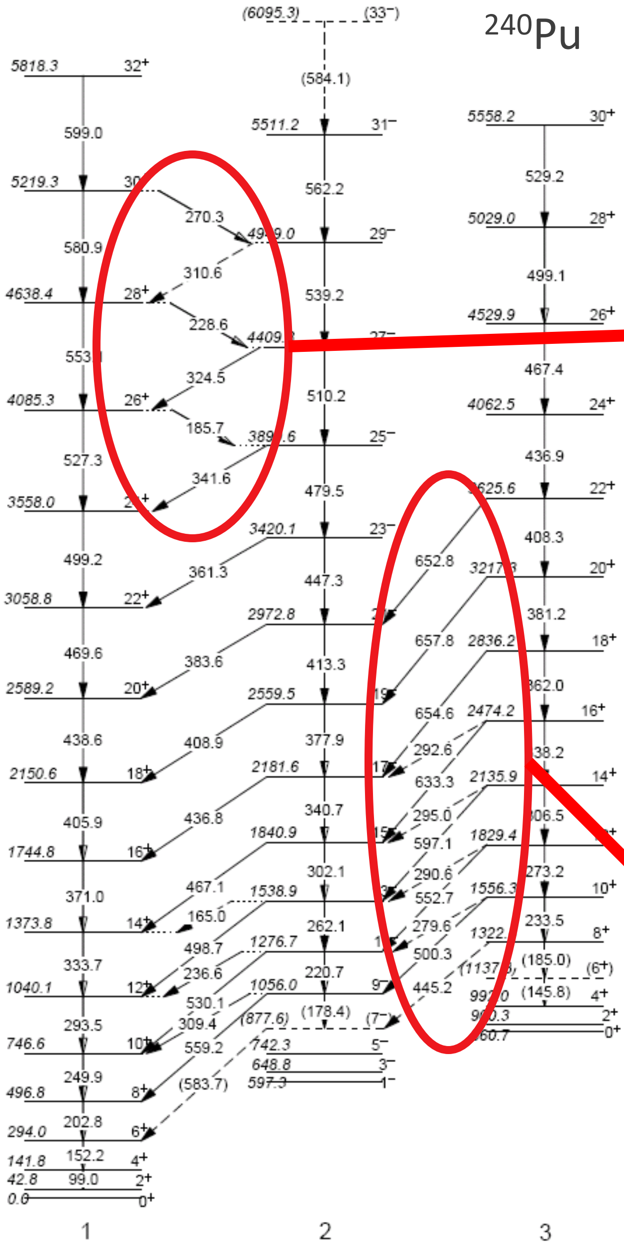
$$E_I = \varepsilon - \frac{1}{2}\frac{\hbar^2}{2\Im} + \frac{\hbar^2}{2\Im}\left[I(I+1) + a(-1)^{I+1/2}(I+1/2)\right] - B\left[I(I+1) + a(-1)^{I+1/2}I(I+1/2)\right]^2$$

Octupole Correlations around $^{239,240}Pu$: Rotation, Vibration or something else?

$^{237,238}U$ and $^{239,240}Pu$: contrasting behaviors ← delay in alignment



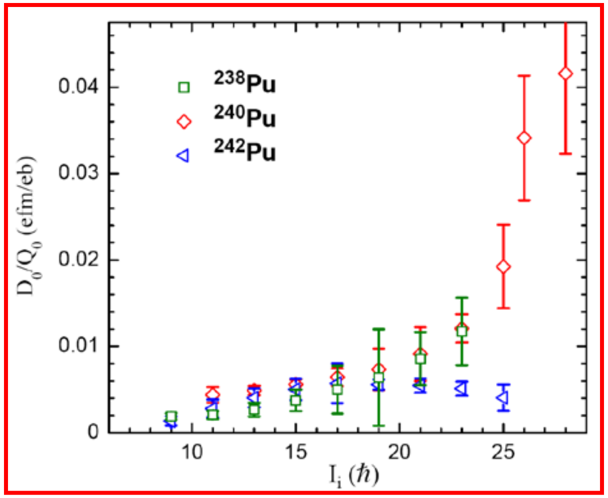
Octupole Correlations: New Results for ^{240}Pu



Experiment: “Unsafe” Coulomb Excitation of ^{240}Pu with a ^{208}Pb beam ~ 15% above the barrier

Observations:

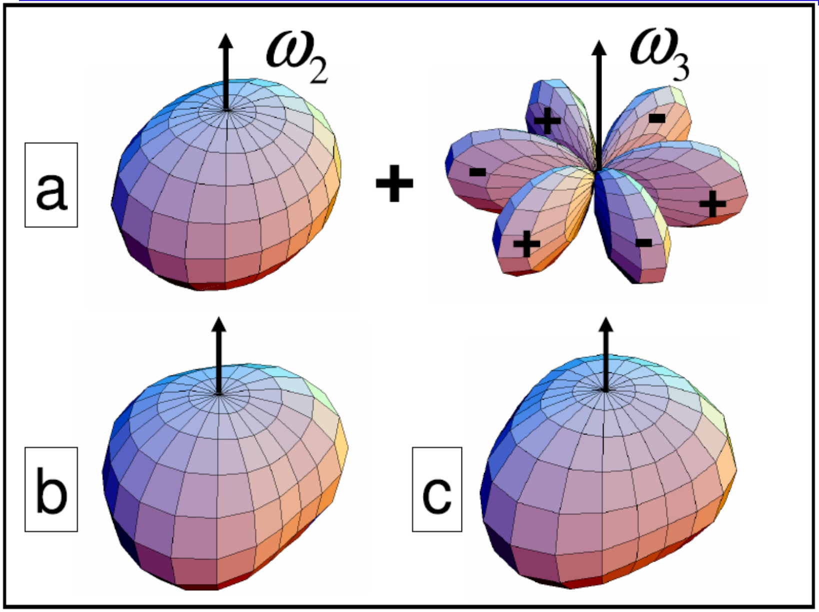
(1) “zig-zag” pattern of E1 transitions between states of bands 1 (+ parity) and 2 (- parity) at high spin just like in octupole deformed rotors



(2) strong E1 transitions between band 3 (+ parity) and band 2 (- parity). To the best of our knowledge this is a “first”!

X. Wang et al., PRL 102, 122501 (2009)

Evidence for Octupole Condensation?

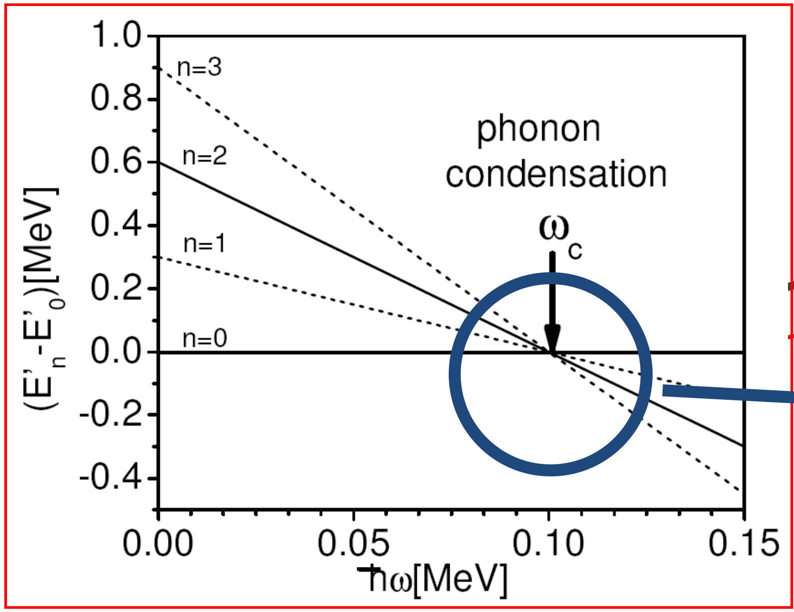


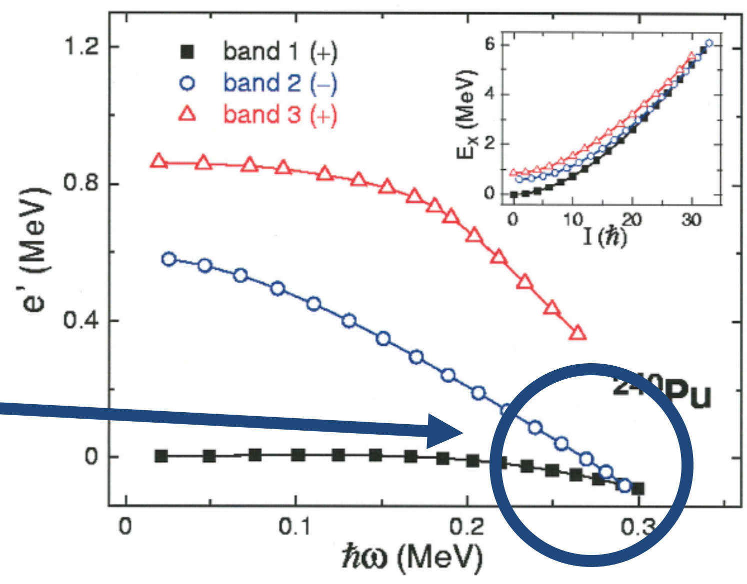
S. Frauendorf, PR C77, 021304(R) (2008)
Octupole Condensation concept:

Rotation of a prolate deformed nucleus with a super-imposed octupole vibration with phonon spin aligned with rotational axis

Band 1 → 0 phonon, Band 2 → 1 phonon, Band 3 →2 phonons

Accounts for observations, i.e., bands, energies, alignments, branching ratios etc.

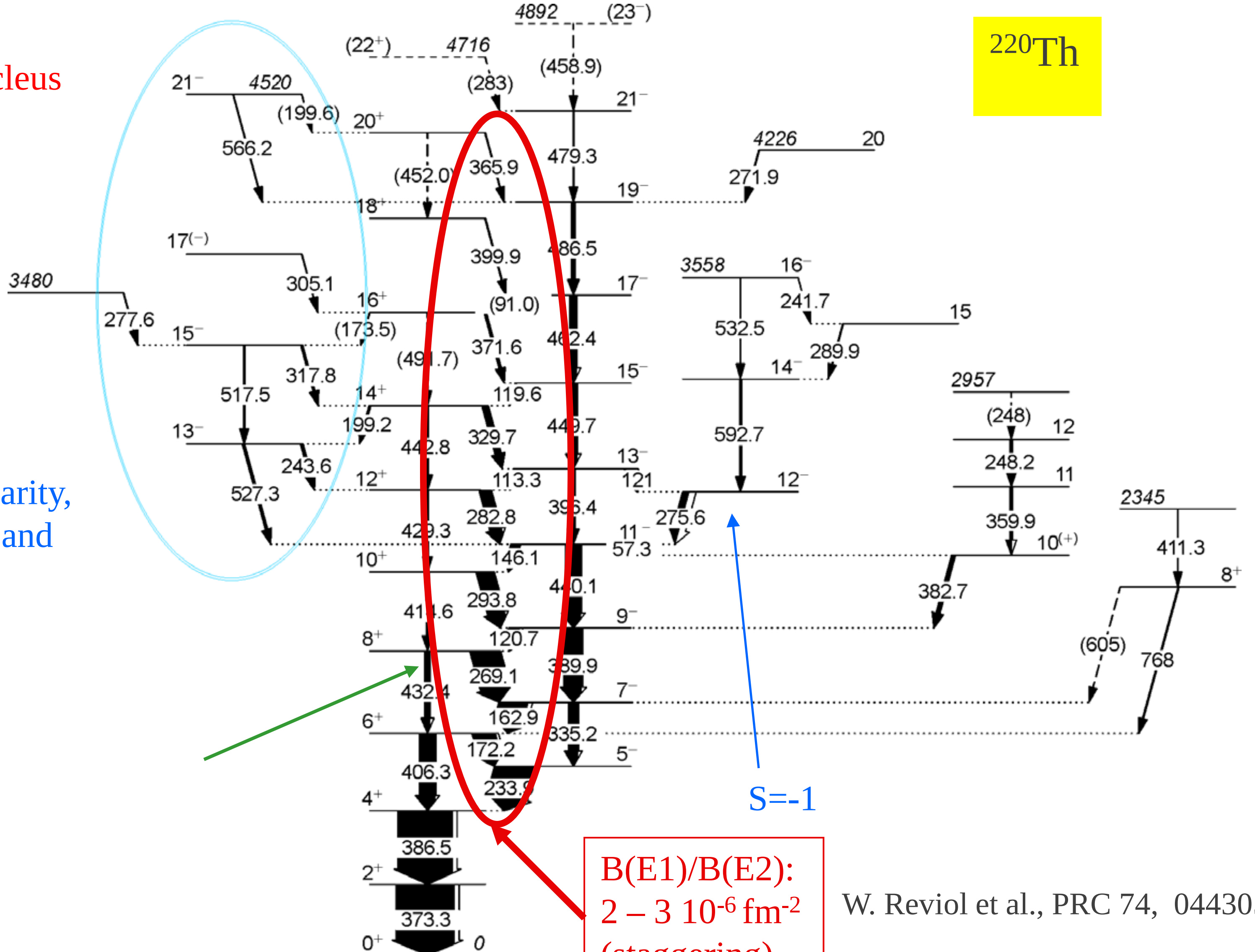




X. Wang et al., PRL 102, 122501 (2009)

Octupole Correlations: Generalization of Picture → Tidal Waves

Vibrational nucleus



^{220}Th

second negative-parity, odd-spin band

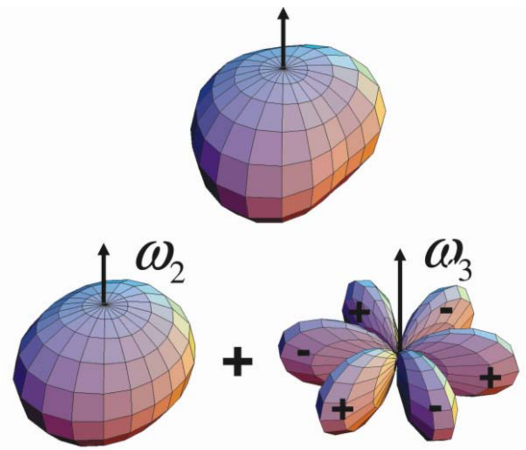
S=-1

B(E1)/B(E2): $2 – 3\ 10^{-6}\ fm^{-2}$ (staggering)

W. Reviol et al., PRC 74, 044305 (2006)

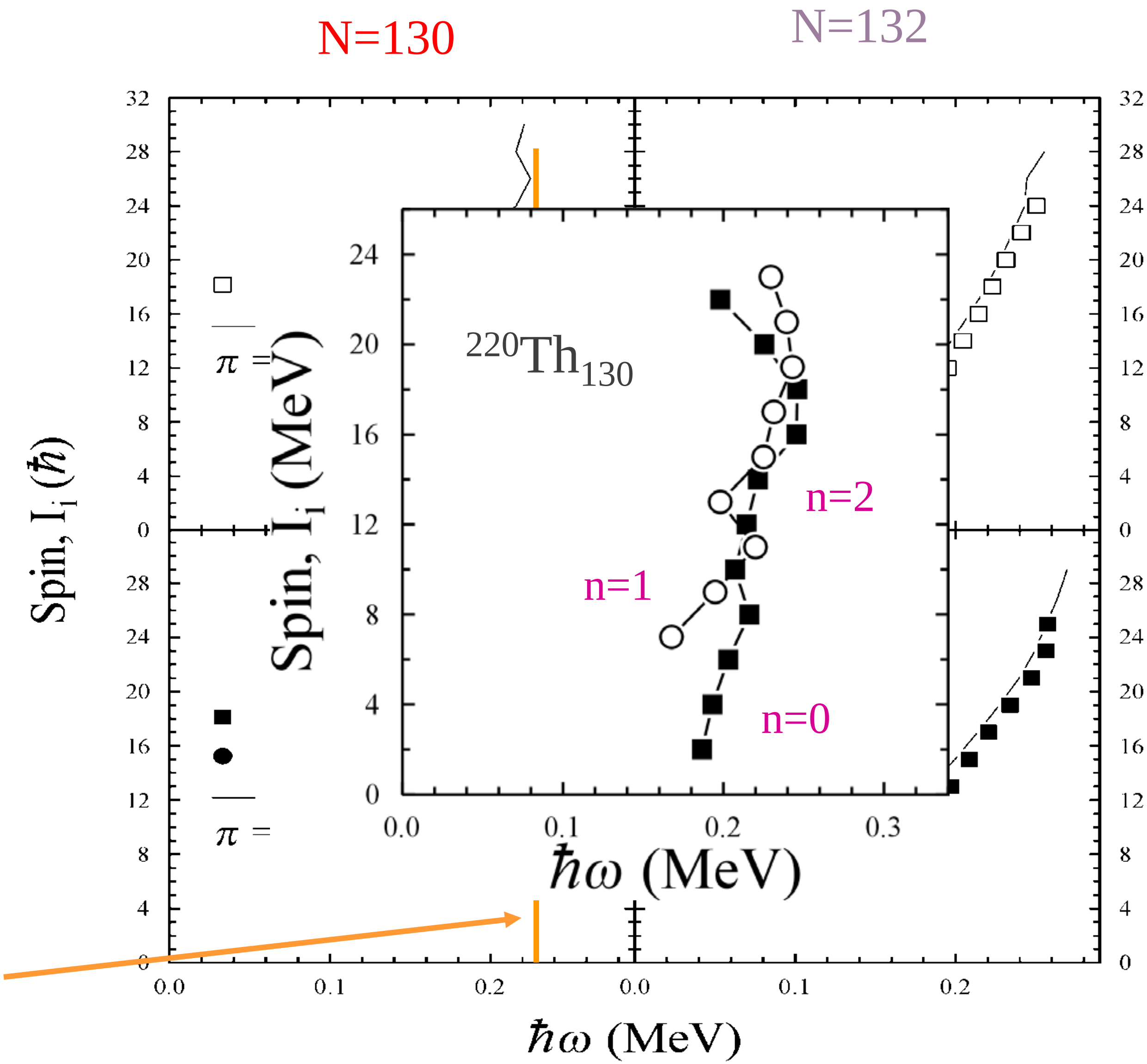
Octupole Correlations: Generalization of Picture → Tidal Waves

N=130 vs. N=132
Less "rotational-like" (weakly deformed), but Octupole features persist.



Superposition of two surface waves with ω_2=1/2 E_γ and ω_3=1/3$\Delta E_{\Delta I=3}$

$h\omega_c$ = 0.21 MeV
(constant ω)

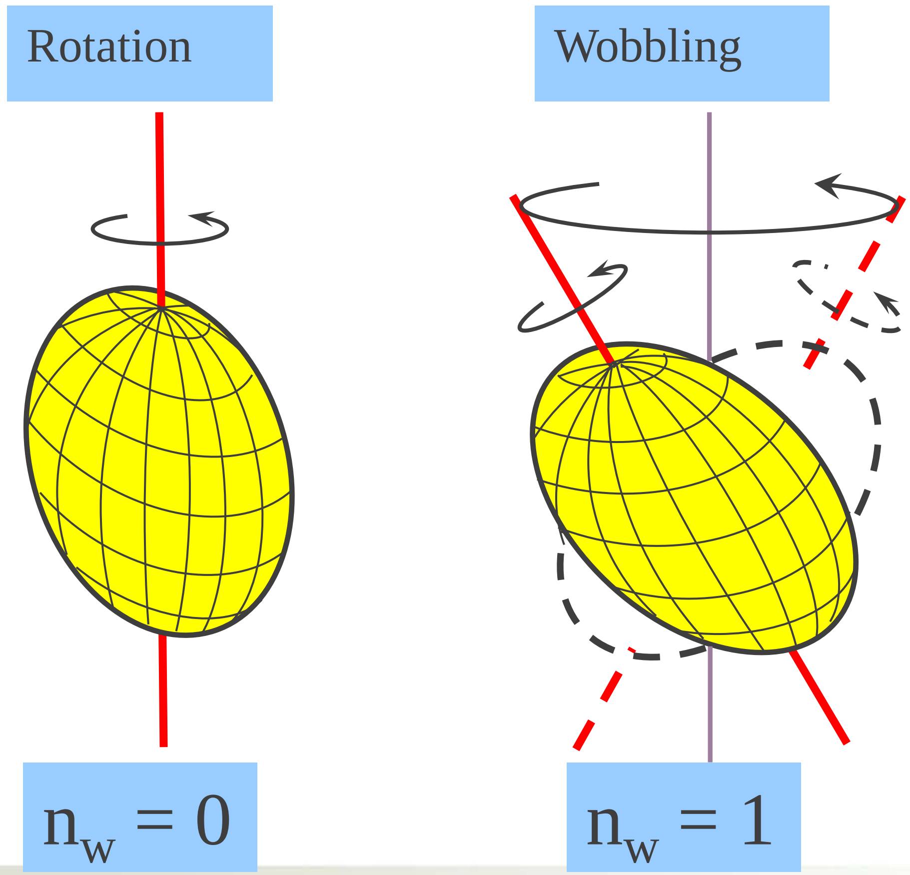


W. Reviol et al., PRC 74, 044305 (2006)

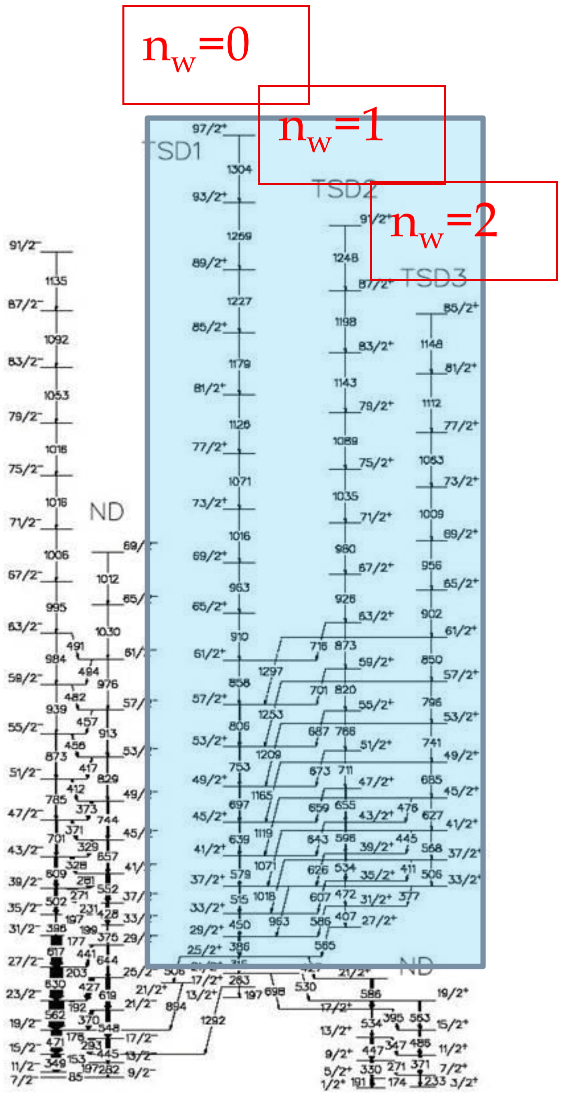
Further exploration of the deformation space: Triaxial rotors ??

Triaxiality in nuclei is a longstanding prediction of theory, but has proved very difficult to establish experimentally beyond any doubt.

During the last decade, **evidence** for rotation of a **triaxial shape** has come from two collective modes: **wobbling** ← focus of this talk
chiral bands

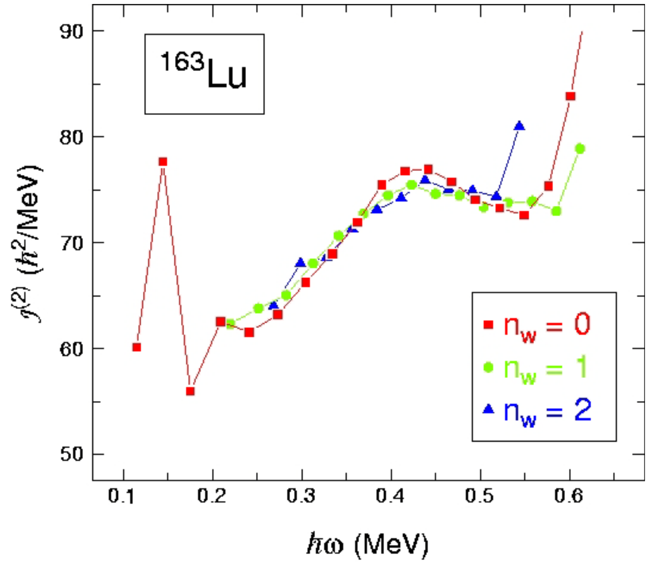


^{163}Lu: a good wobbler



^{163}Lu

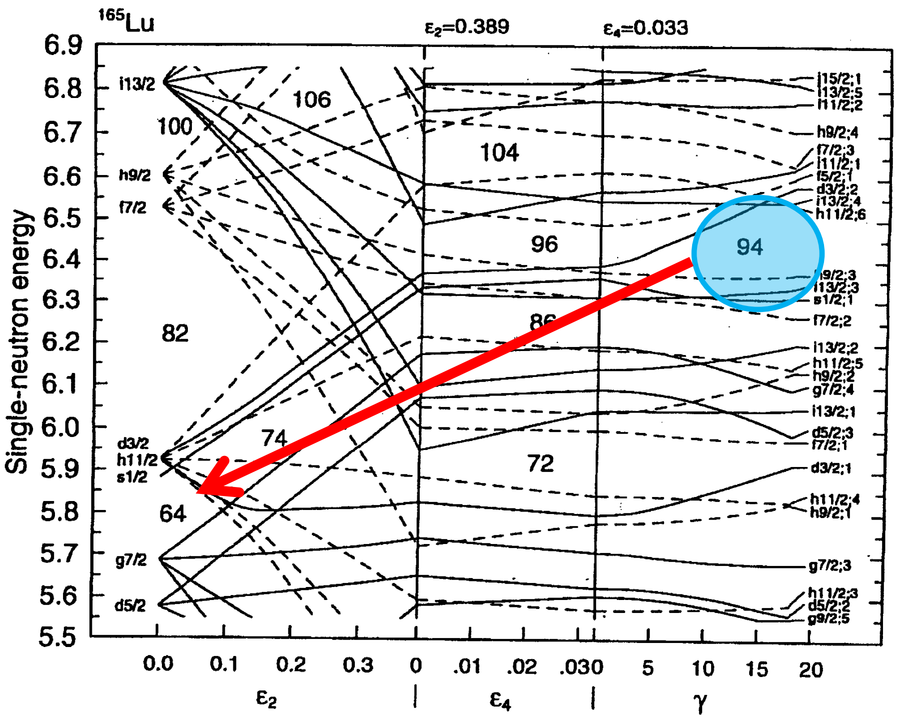
- A series of bands are created where the higher lying bands are associated with an increasing phonon number
- Each band is about 300 keV above the previous
- Based on $i_{13/2}$ orbital



- Because all bands in the family are based on the same orbital, they should have nearly identical characteristics, such as alignment, quadrupole moment, and dynamic moment of inertia $\mathcal{J}^{(2)}$
- There are also distinct deexcitation patterns

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

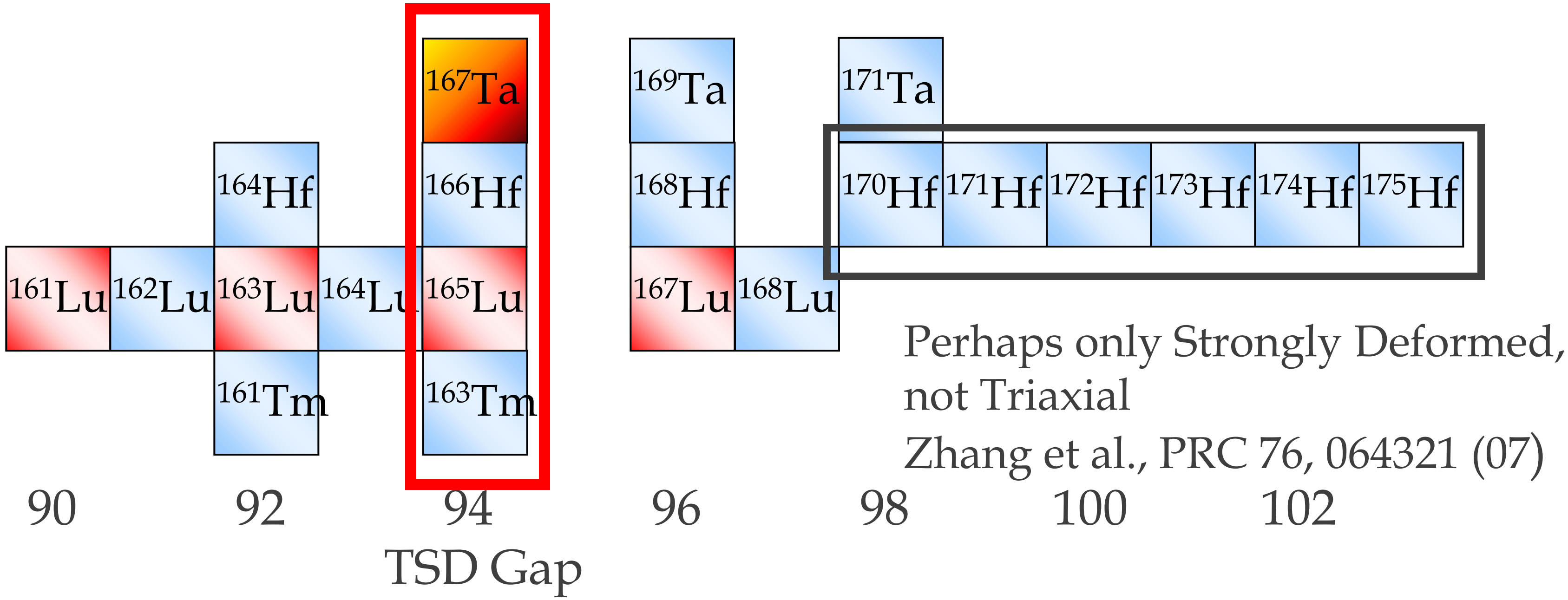
^{163}Lu a good wobbler: where else to look?



H. Schnack-Peterson, R. Bengtsson, et al., NPA 594, 175 (1995)

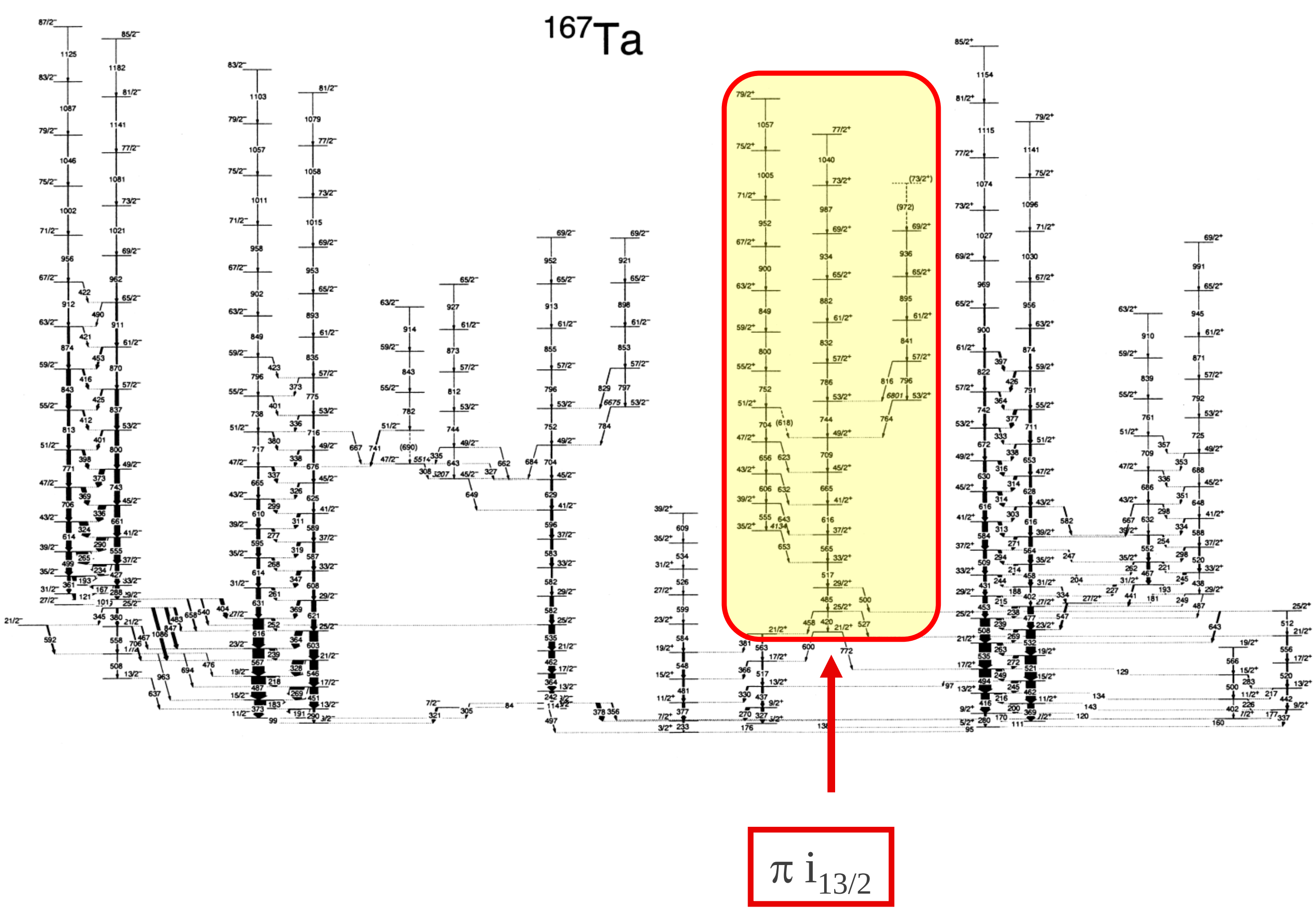
- Proton $i_{13/2}$ orbital creates larger quadrupole deformation (isolated from other orbitals)
- When $\gamma = 20^o$, a gap as large as the 64 spherical subshell forms at 94 in the neutron energy levels
- Wobbling in ^{161}Lu, ^{163}Lu, ^{165}Lu, & ^{167}Lu, and in other nuclei with proton $i_{13/2}$ orbital near the Fermi surface

Wobbling: a general phenomenon?



- Wobbling bands now observed in several odd-A Lu nuclei near N = 94
- Could not find any Strongly Deformed bands in ^{164,166}Hf
- Several Strongly Deformed bands found in Tm, Hf, & Ta but no evidence for wobbling ← how sure can one be that they are triaxial?
- No wobbling on the N=94 isotones Tm & Hf
- → recent study of ^{167}Ta (D. Hartley et al.)

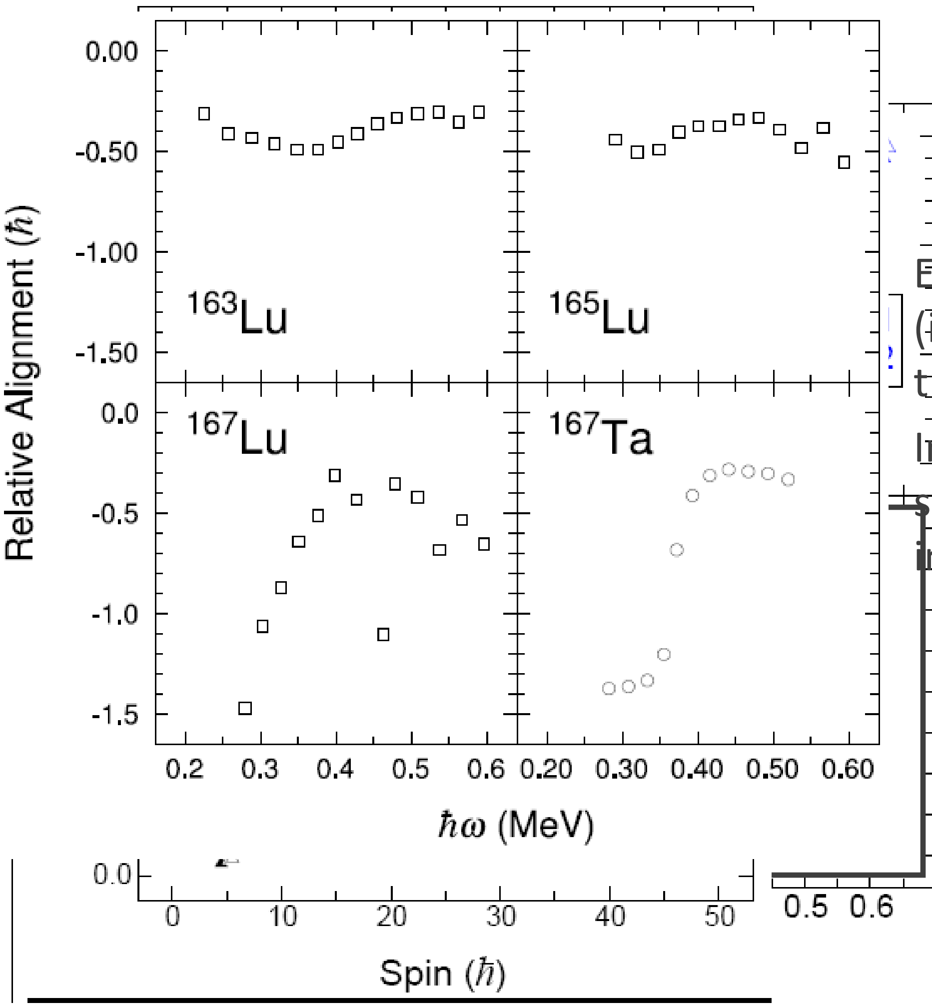
^{167}Ta: New experiment at Gammasphere



D. J. Hartley, Phys. Rev. C80, 041304

^{167}Ta: a wobbler

Relative alignment between bands



- Difference between the alignment of TSD 1 and TSD 2
- Nearly constant in ^{163}Lu and ^{165}Lu
- Similar effect seen in ^{167}Lu and ^{167}Ta
- Current thinking: evolution from small γ to real trixial γ ~20° minimum with frequency

Energy difference between TSD 1 ($i_{13/2}$) and TSD 2 ($\pi\omega$=1) is similar to that seen in ^{165}Lu

In both cases, the two bands get slightly closer in energy as spin increases

- The alignment of the two bands in ^{167}Ta look similar, although a little different below 0.35 MeV
- Clear difference in $\mathcal{J}^{(2)}$ and low frequency, similar at high spin

D. J. Hartley, Phys. Rev. C80, 041304

Wobbling: where do we stand ?

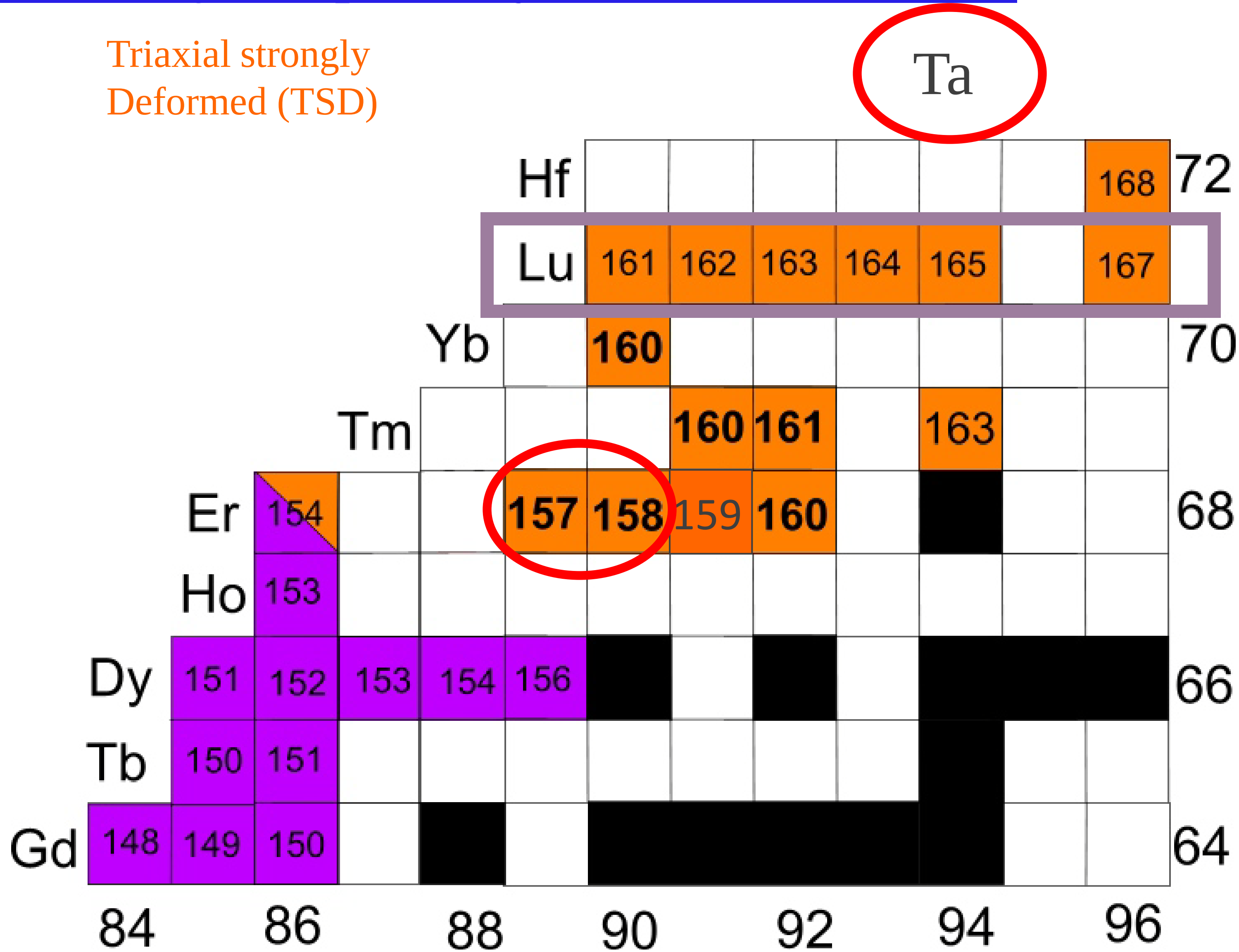
- Wobbling was once limited to a few odd-A Lu nuclei
- Newly found $i_{13/2}$ & n_w=1 band in ^{167}Ta appear to be first case of wobbling outside of Lu
- N = 94 gap seems to be well established

BUT

- Role of the proton Fermi surface is not clear
- Actual deformation in ALL wobblers needs work as:
  - Where available Q_0 moments are smaller than calculated
  - Where available Q_0 moments decrease smoothly with frequency, i.e. is deformation (β_2 or γ) changing with spin?
- MORE Experimental and Theoretical work needed

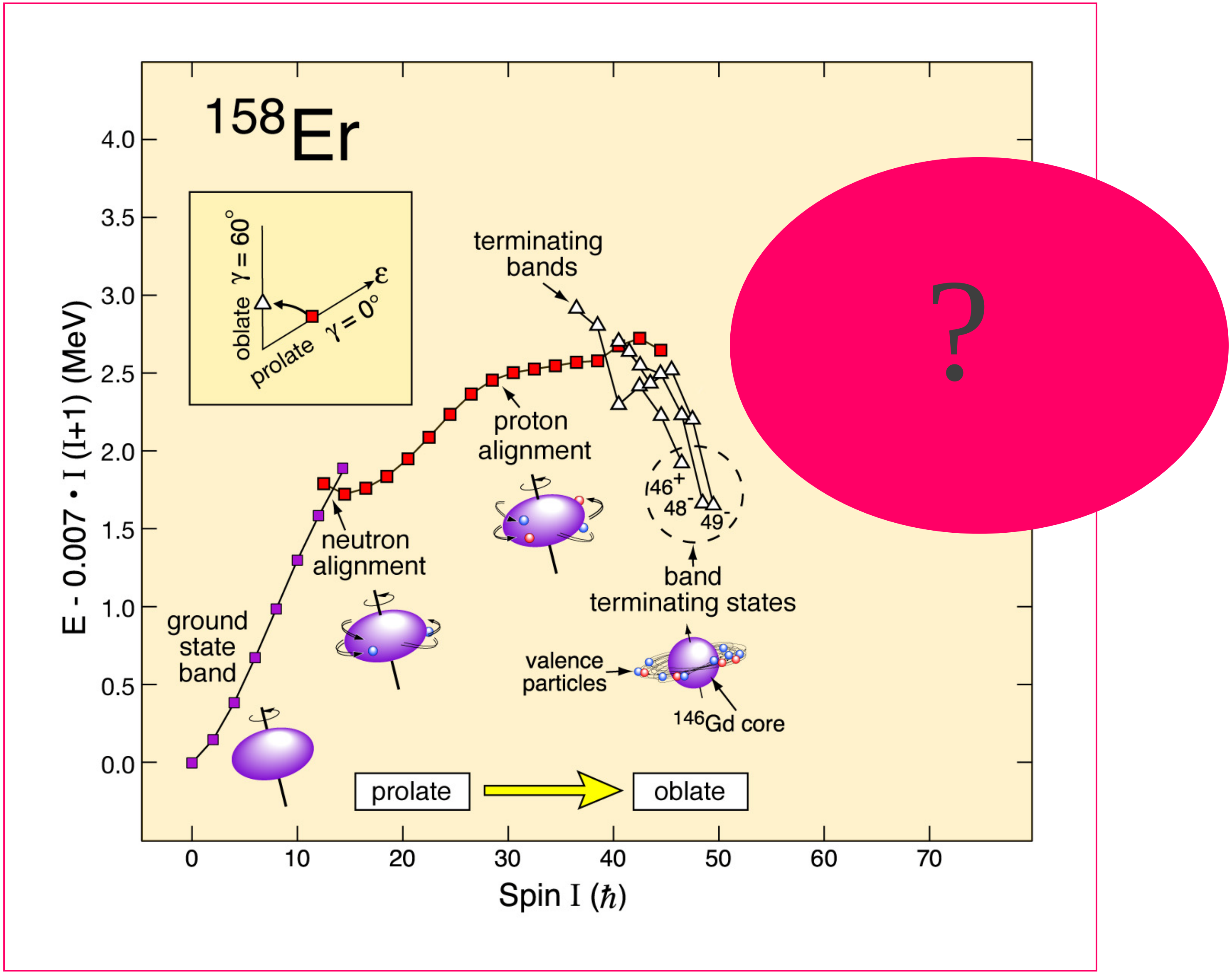
Nuclei at the highest spins: Beyond band termination

Triaxial strongly
Deformed (TSD)



Superdeformed (SD)

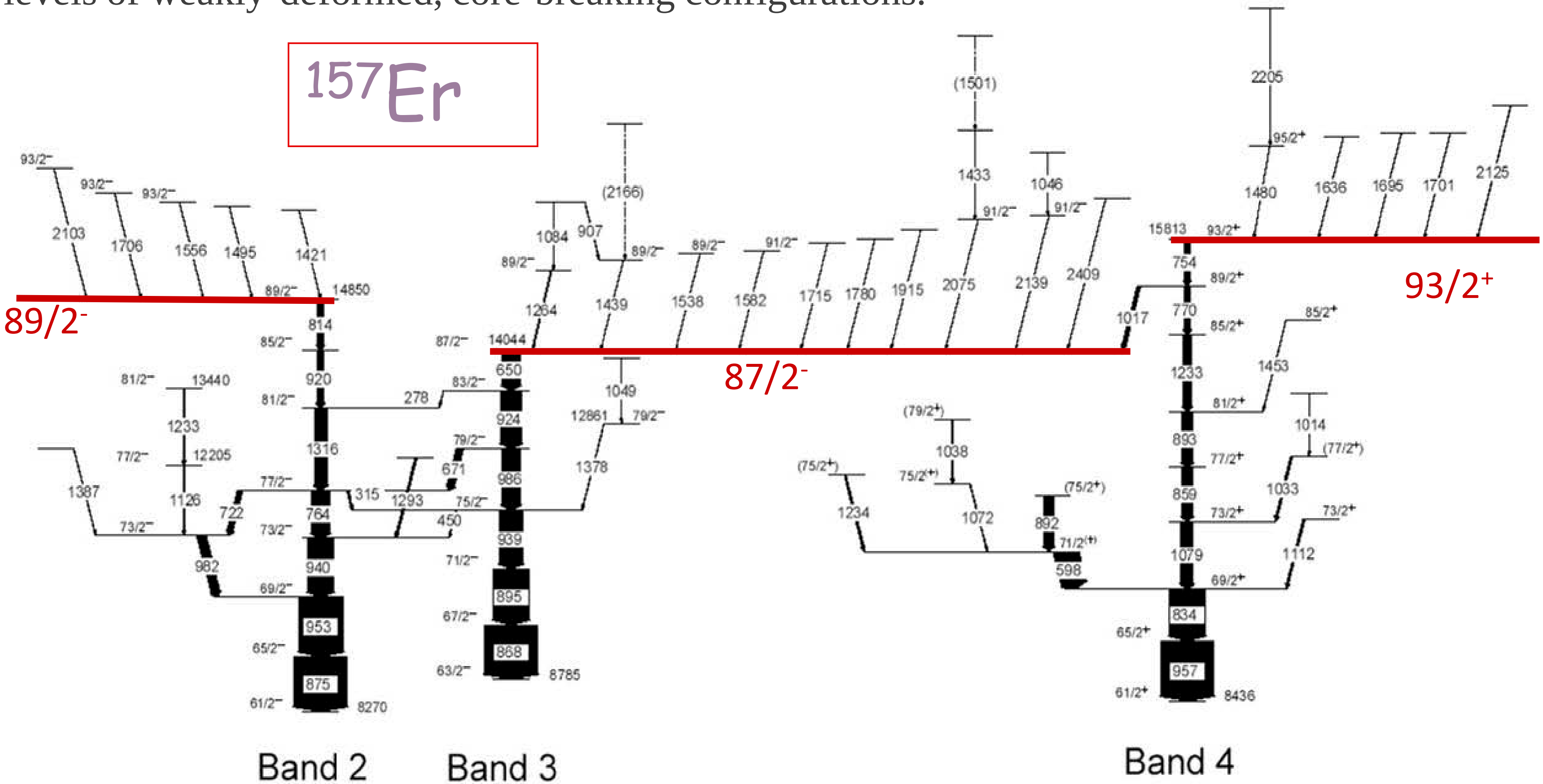
Mid-90's: From collective rotation to band termination



J. Simpson et al., Phys. Lett. B 327, 187 (1994)

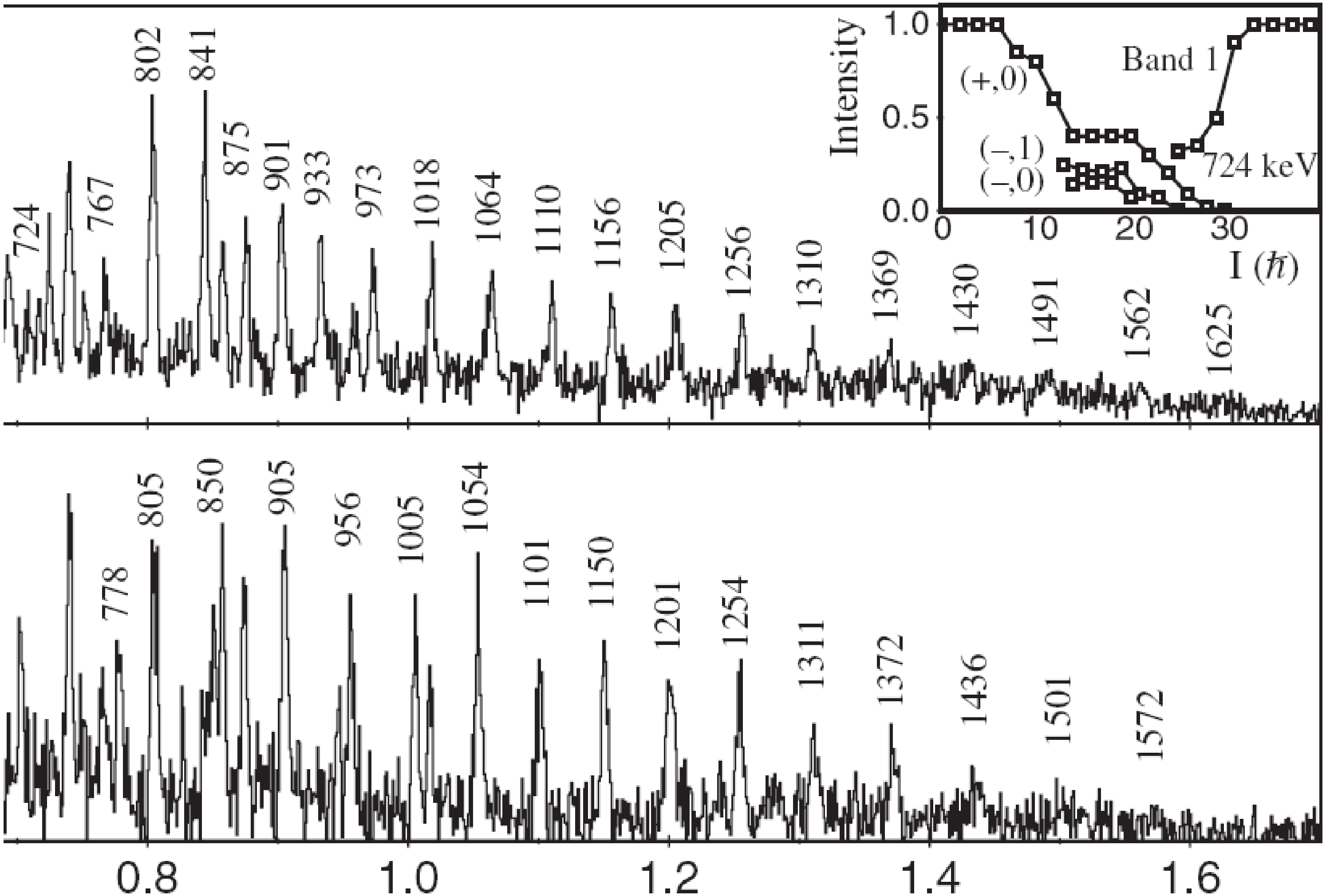
Mid-2000's: Feeding of the terminating states

The very weak feeding transitions originate from the levels of weakly-deformed, core-breaking configurations.



Evans et. al., Phys. Rev. Lett. 92, 252502 (2004)

2007: Evidence for return to collectivity

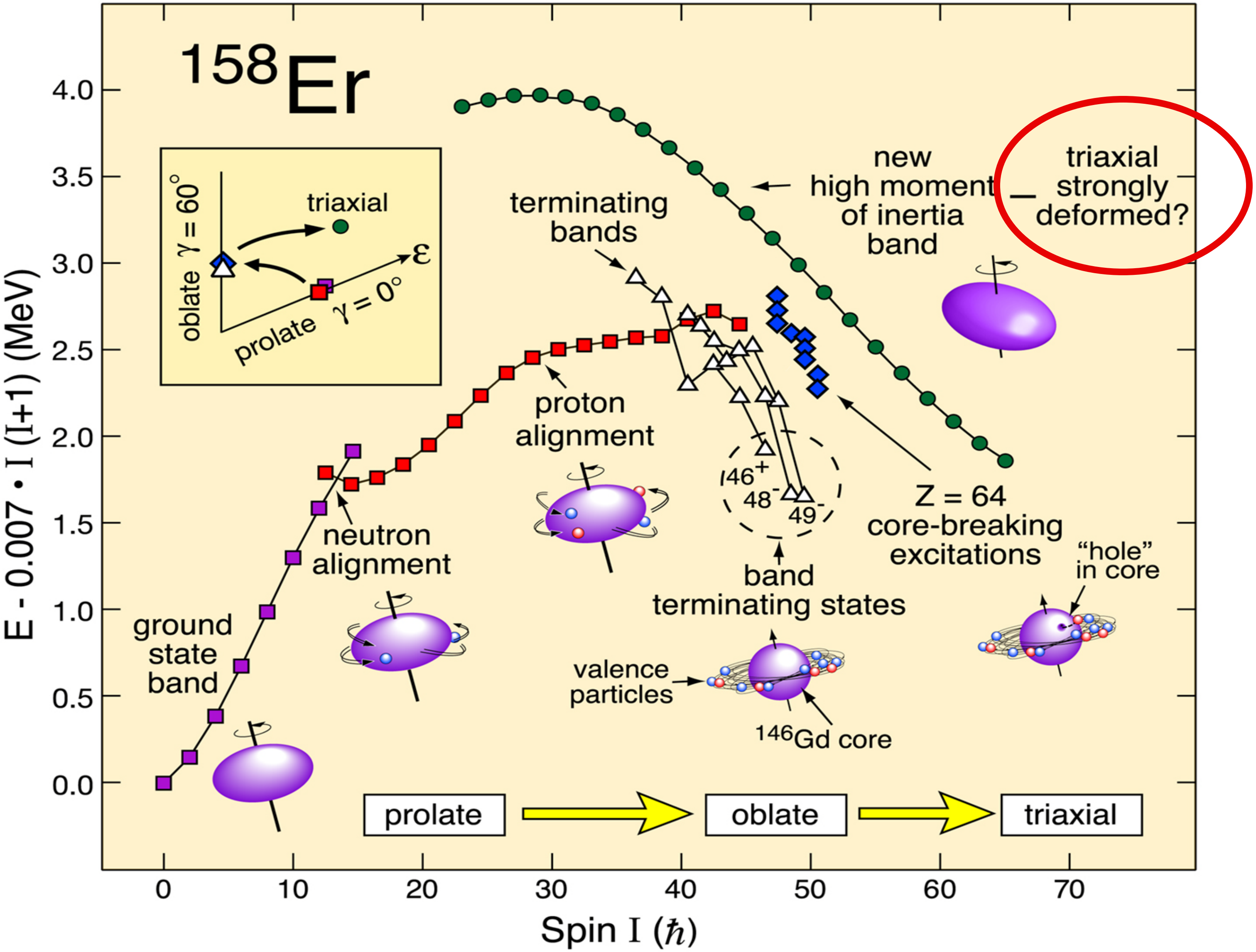


^{158}Er

^{157}Er

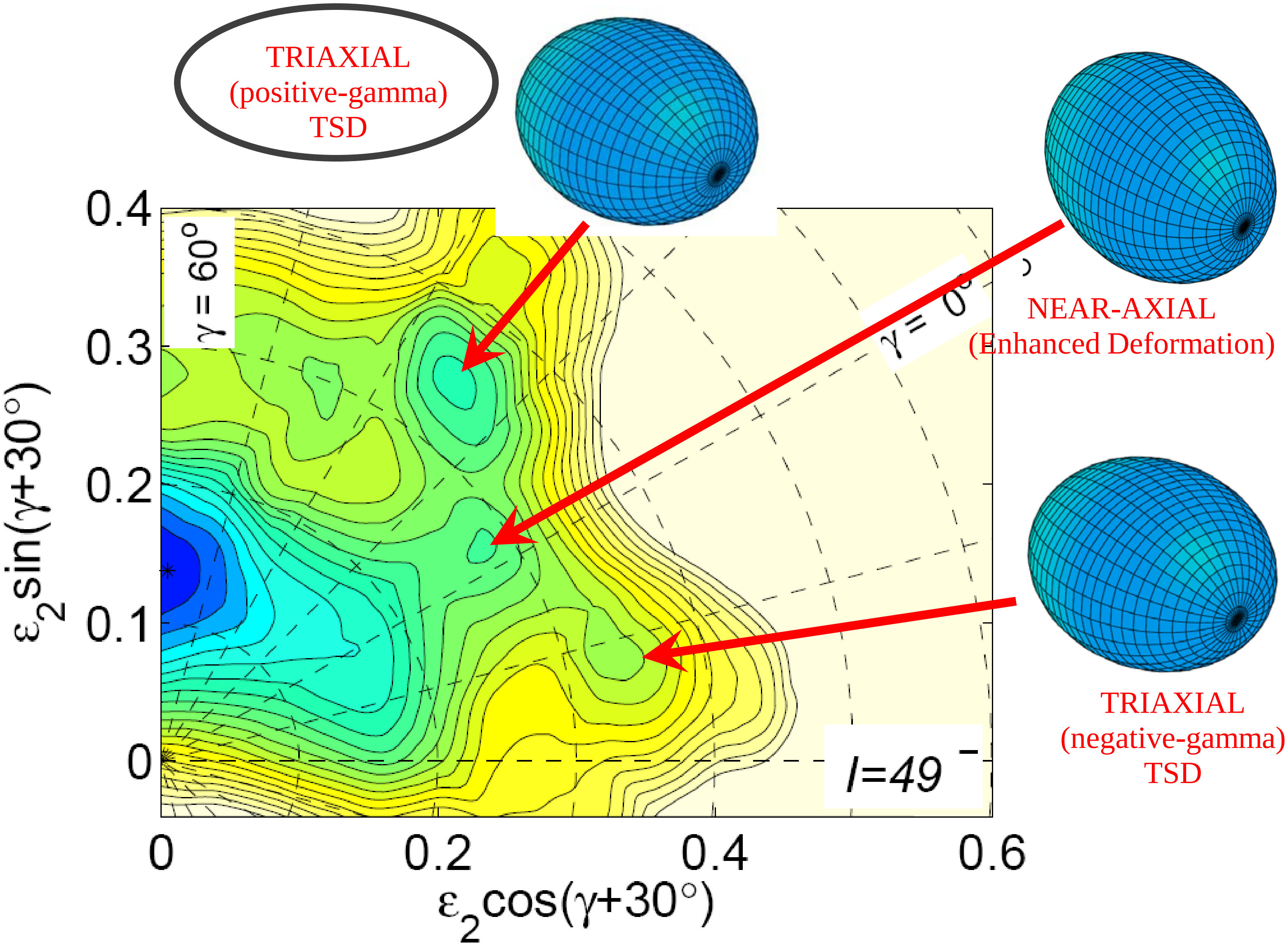
E.S. Paul et al., PRL 98, 012501(2007)

2007: Return to collectivity

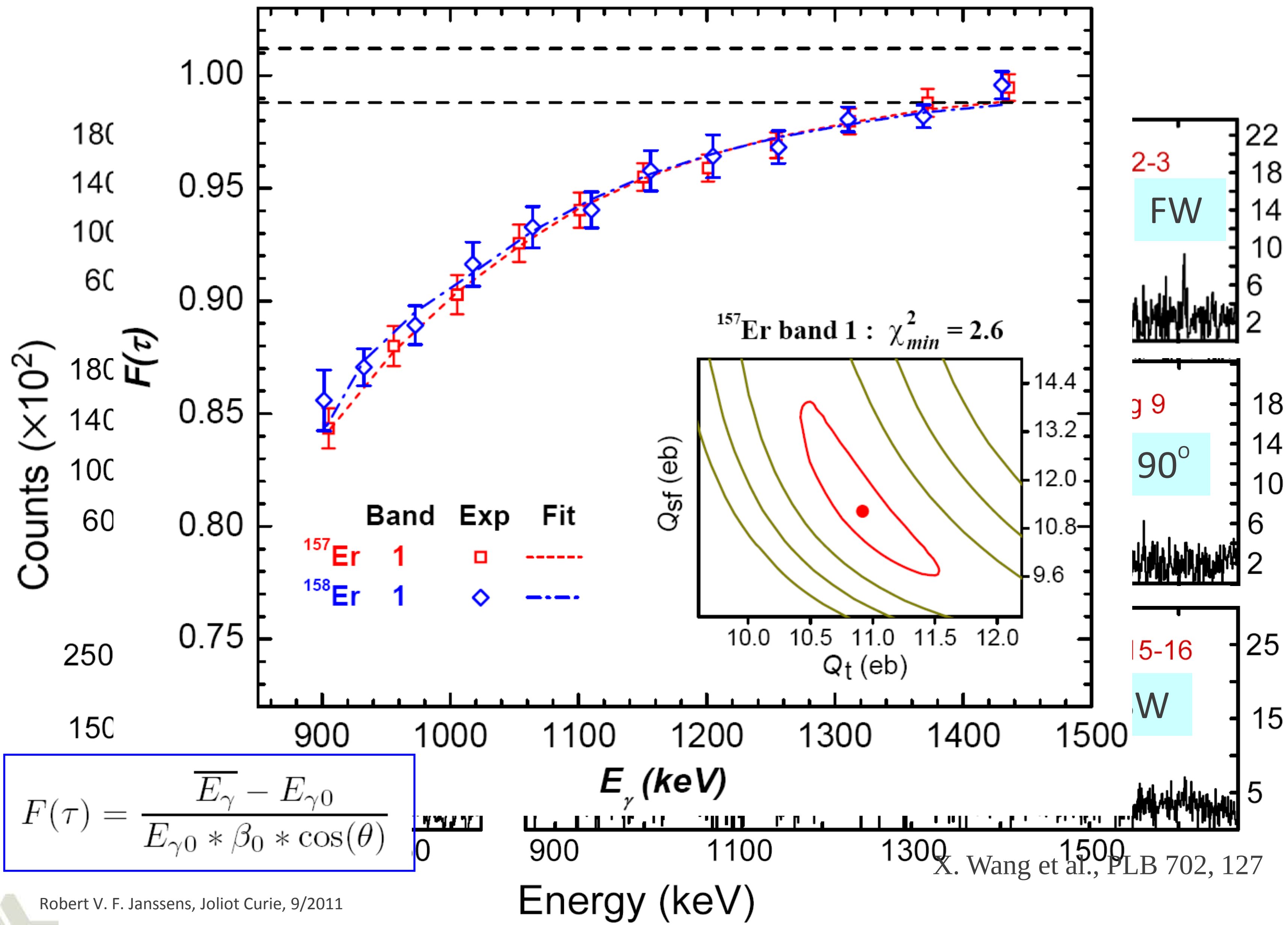


E.S. Paul et al., PRL 98, 012501 (2007)

2011: What deformation?



2011: Doppler Shift (DSAM) Measurement

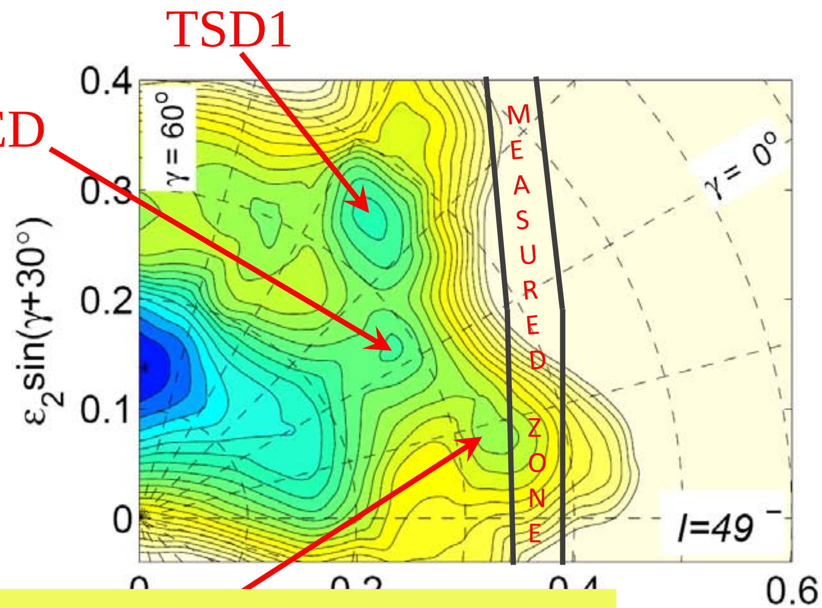


$$F(\tau) = \frac{\overline{E_\gamma} - E_{\gamma 0}}{E_{\gamma 0} * \beta_0 * \cos(\theta)}$$

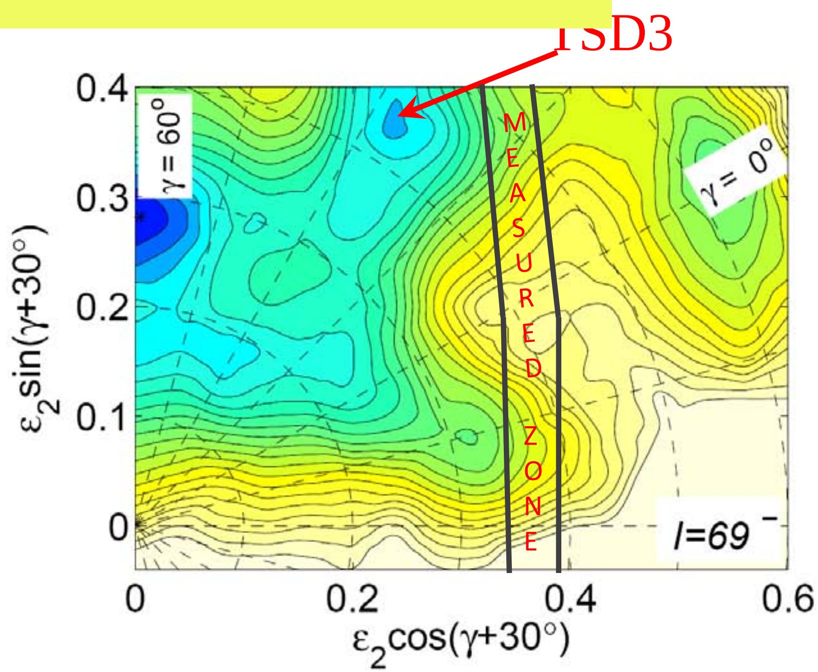
X. Wang et al., PLB 702, 127

Theory vs Experiment

	MEASURED (band 1s)	CALCULATED			
		TSD1	TSD2	TSD3	ED
Q_t (*eb*)	^{158}Er: **11.7** (+0.7, -0.6) ^{157}Er: **10.9** (+0.6, -0.5)	6.0 – 7.2	10 – 11.2	8 – 9.2	6.7 – 7.9



THEORY NEEDS WORK→ STAY TUNED



$Q_t = Q_0 * \cos(\gamma+30^\circ)/\cos(30^\circ)$;
$Q_0 = [\varepsilon_2*(1+\varepsilon_2/2)+25/33*\varepsilon_4^2-\varepsilon_2*\varepsilon_4]*[4/5*(1.2)^2*Z*A^{(2/3)}]/100$;

Q_t is transitional quadrupole moment; Q_0 is intrinsic quadrupole moment;
ε_4 is set to be 0 here; Z is proton number; A is mass number.

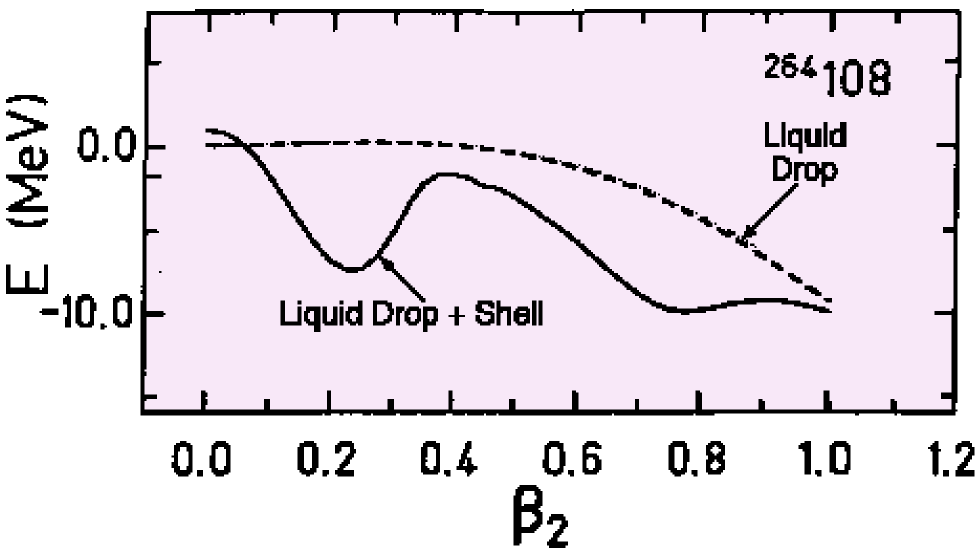
X. Wang et al., PLB 702, 127

→ ***Structure of Exotic Nuclei***

→ The Heaviest Nuclei

→ Changes in Shell Structure in Neutron-Rich Nuclei

Heavy Shell-Stabilized Nuclei

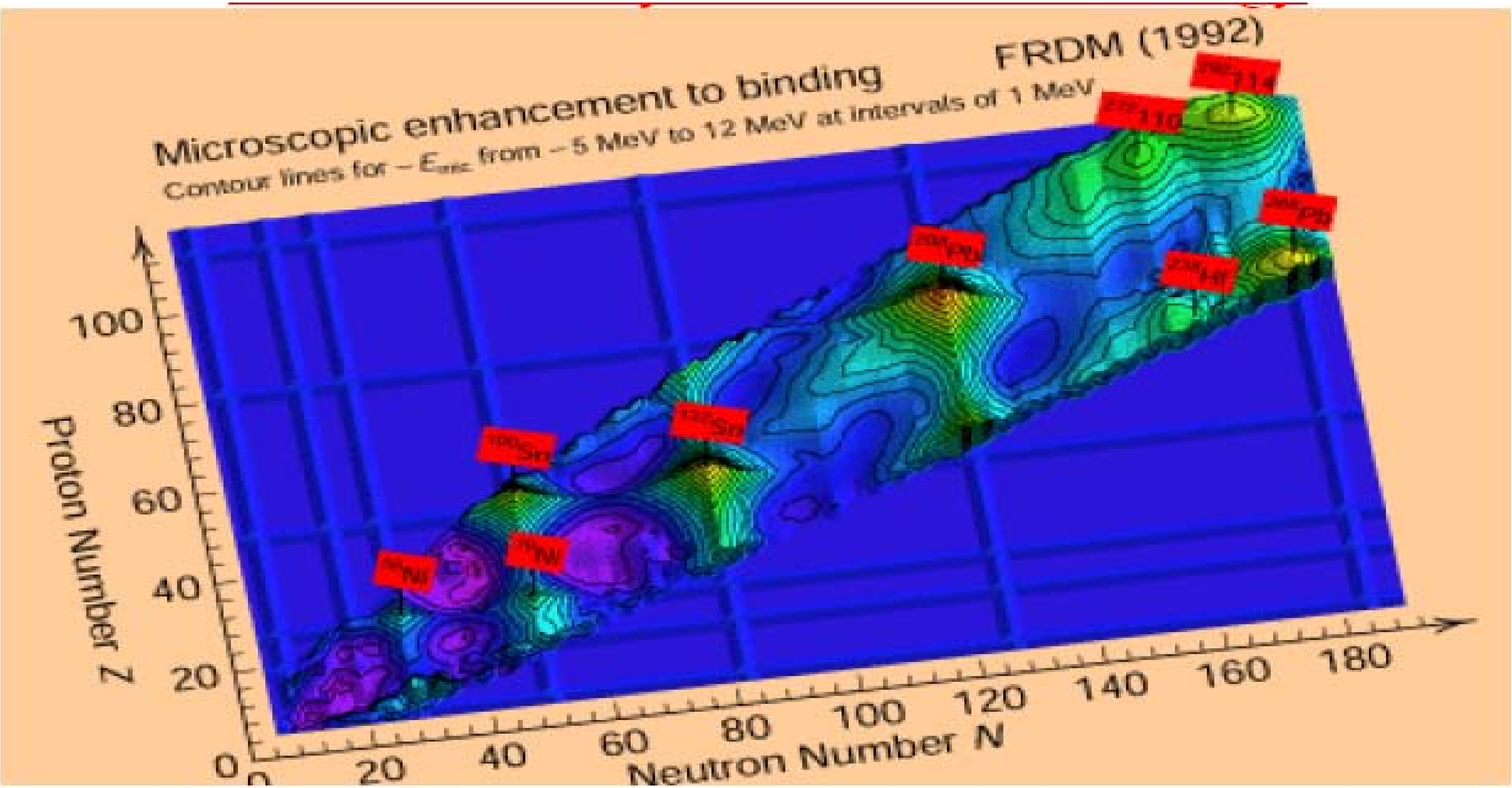


Heaviest nuclei: **at the limits of Coulomb stability**; would fission instantaneously, but

shell-correction energy lowers the ground state, thereby creating a **barrier against fission.**

Superheavy nuclei: delicate balance between **nuclear attraction** and **Coulomb repulsion.**

Calculated Shell Correction for the Heaviest Nuclei: Stability is all from shell energy

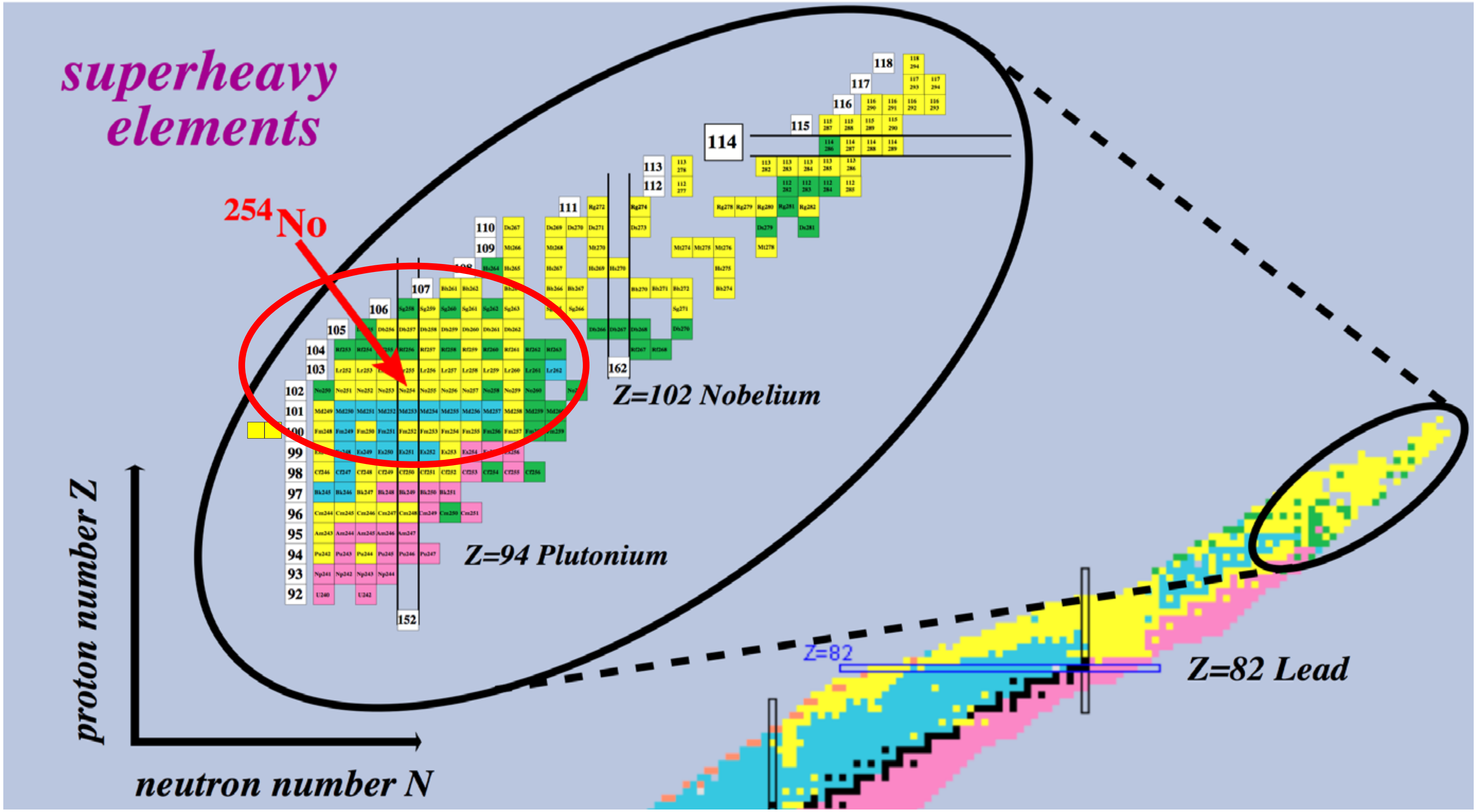


Heavy shell-stabilized nuclei

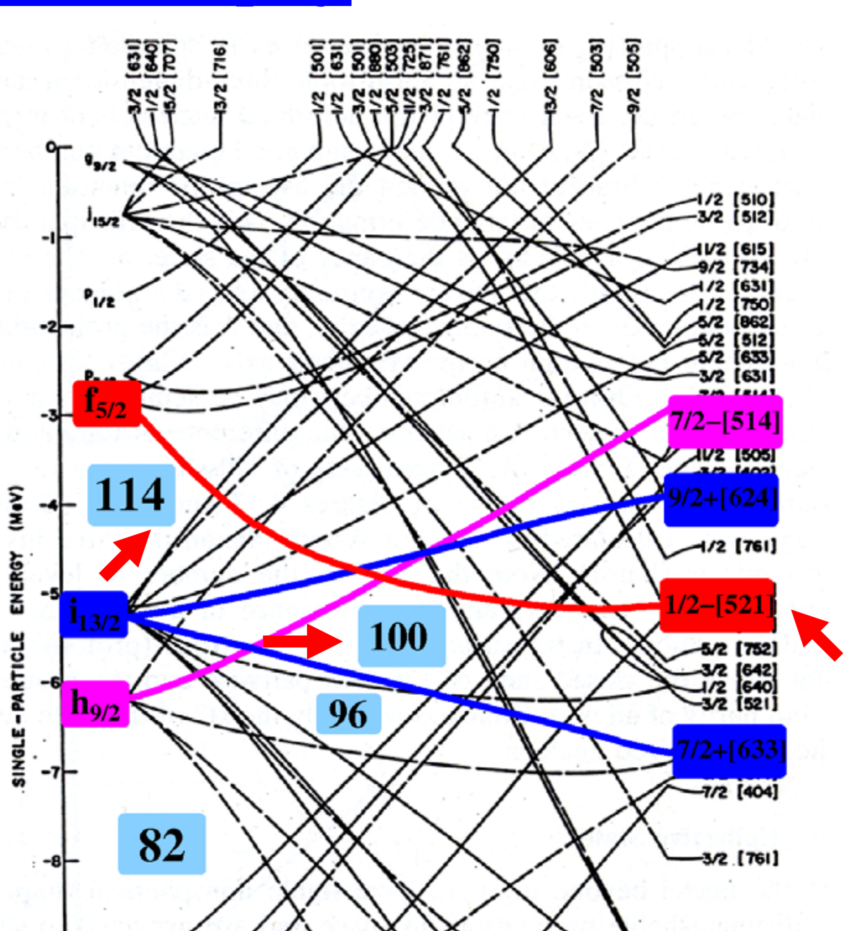
- Opportunities to study nuclei at the limits of Charge, Spin and Excitation Energy.
- What are the limits?
- Are shell-stabilized nuclei different from lighter (normal) nuclei?

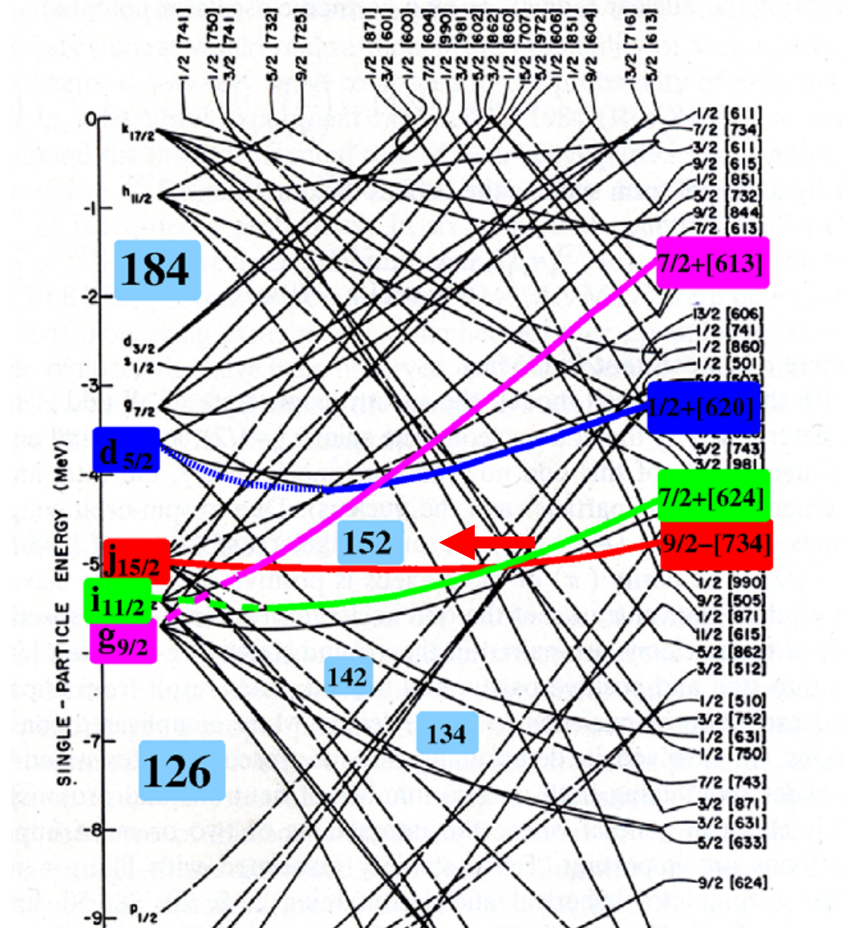
Approach:

Check validity of theory by establishing structure for Z>100 rather than through production of ever heavier nuclei



Orbitals at play





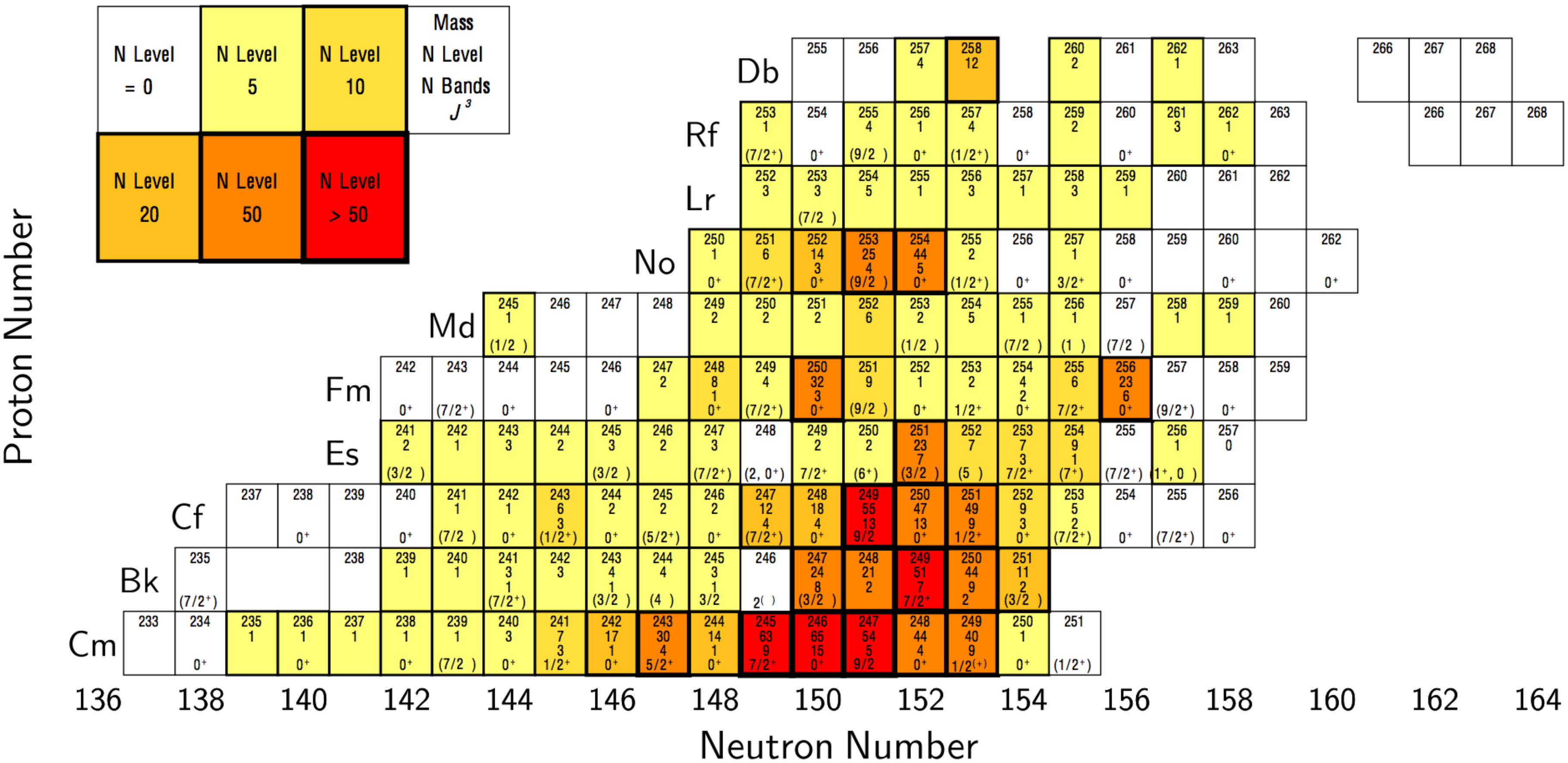
→ **Opportunity to check single particle energies**

→ **Opportunity to verify presence & role of deformation (& importance of associated shell gaps**

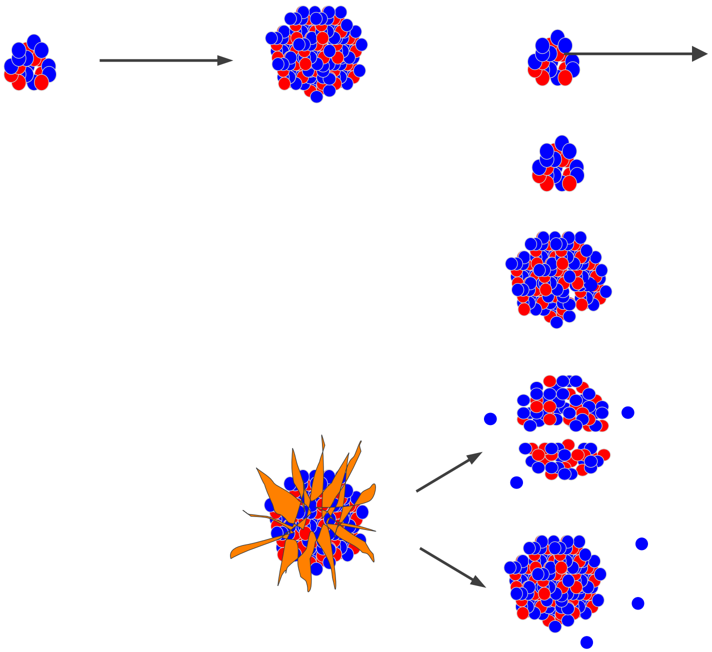
→ **Opportunity to examine role of orbitals located above the Z=114 shell gap at sphericity**

Motivation: There is MUCH work to do

R. Herzberg and P. Greenlees, Progress in Part. and Nucl. Phys. 61 (2008) 674



Production : fusion-evaporation reaction → Challenge



Unreacted beam
Scattered beam

Transfer : beamlike

Transfer : targetlike
Coulex

σ > 1 barn

Fusion - Fission

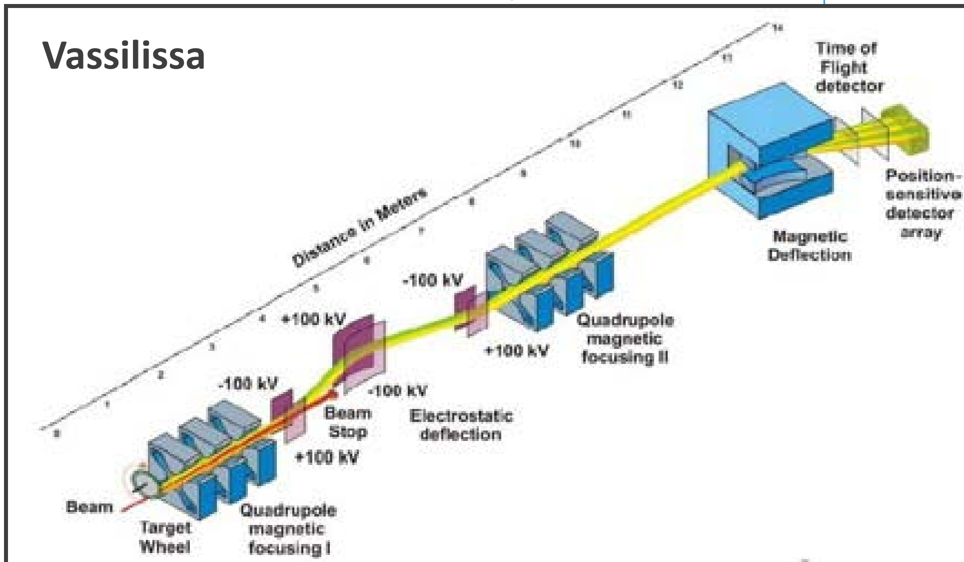
Survival of nucleus of interest : σ ~ 1-1000 nb

For , I_{BEAM} = 1 pμA, σ = 100 nb, A_{target} ~ 200
=> < 2 ER/s per mg/cm^2

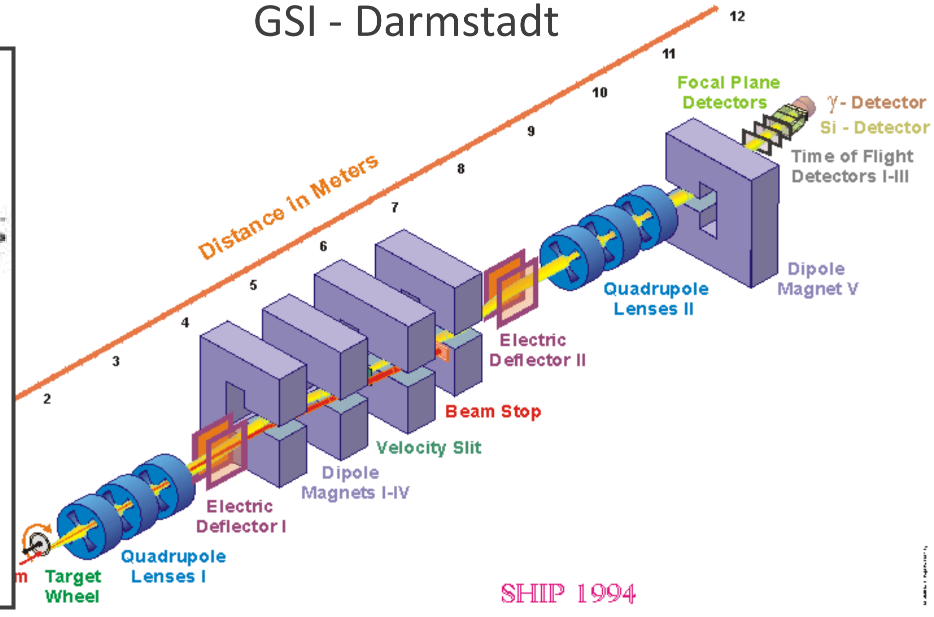
⇨ Need to find & select the needle in the hay stack !

In-flight separation

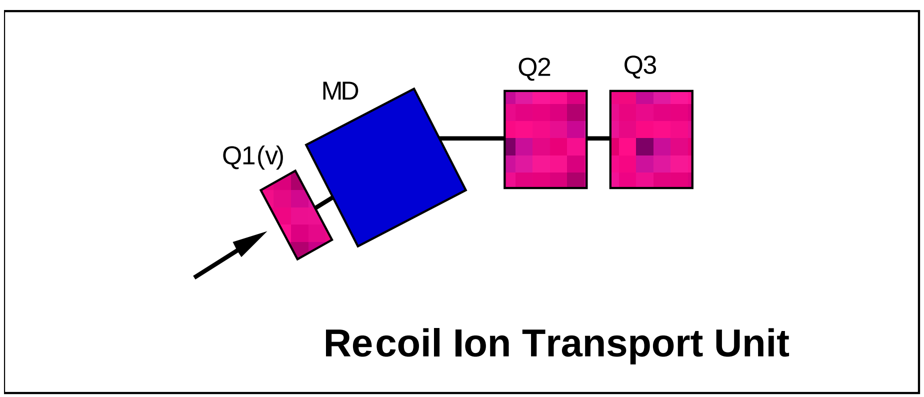
FLNR - JINR, Dubna



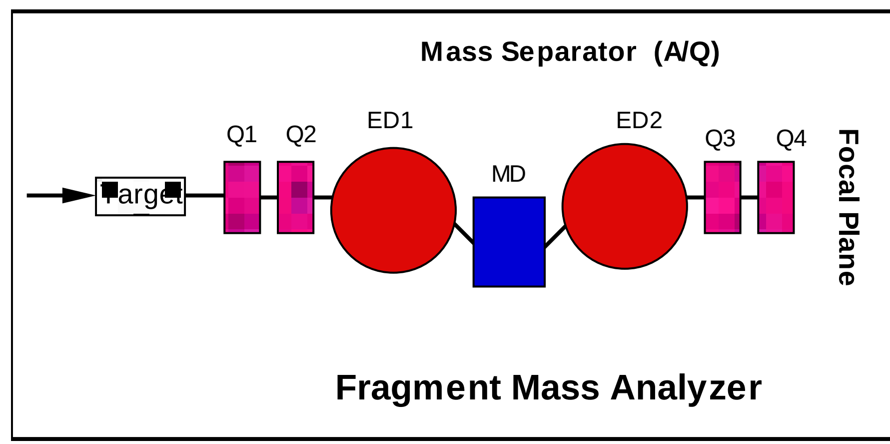
GSI - Darmstadt



University of Jyväskylä, Finland



Argonne National Laboratory
Argonne Tandem Linear Accelerator System (ATLAS)



other gas-filled devices: BGS, TASCA

First data in the region: ^{254}No

Reaction:

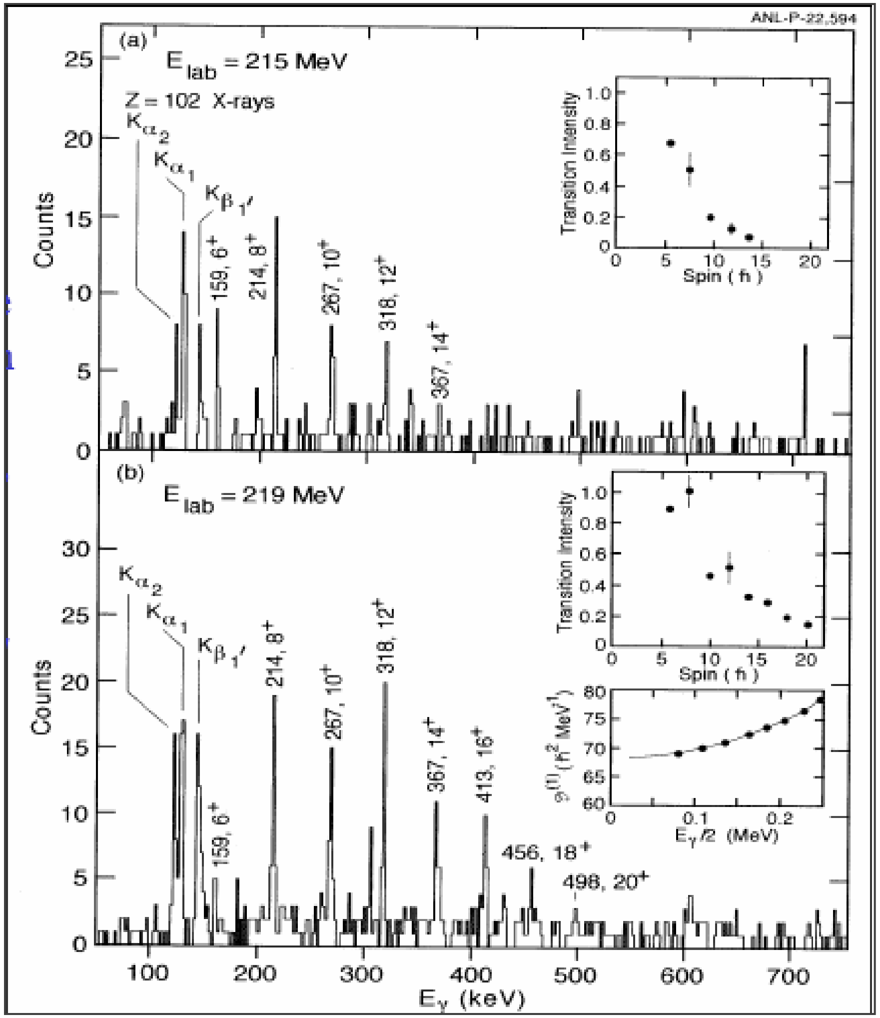
$^{48}Ca + ^{208}Pb$

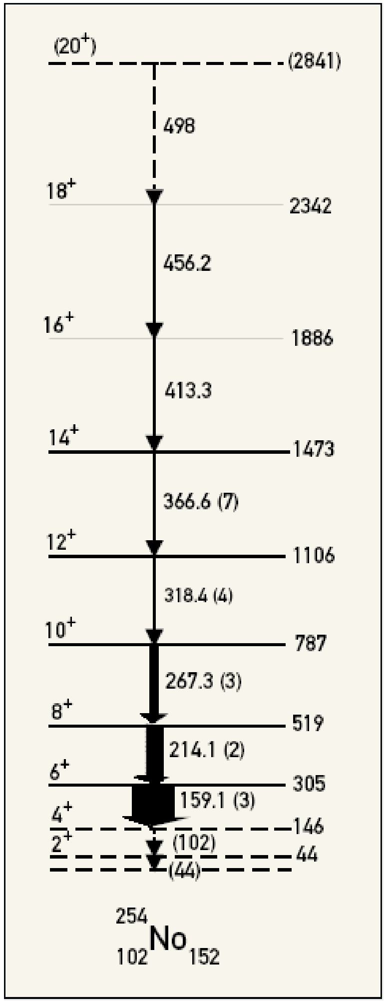
First Observations:

From γ-ray energies →

Deformation β_2 ~ 0.27

Largest shell effects correspond to a deformed nucleus as predicted by theory

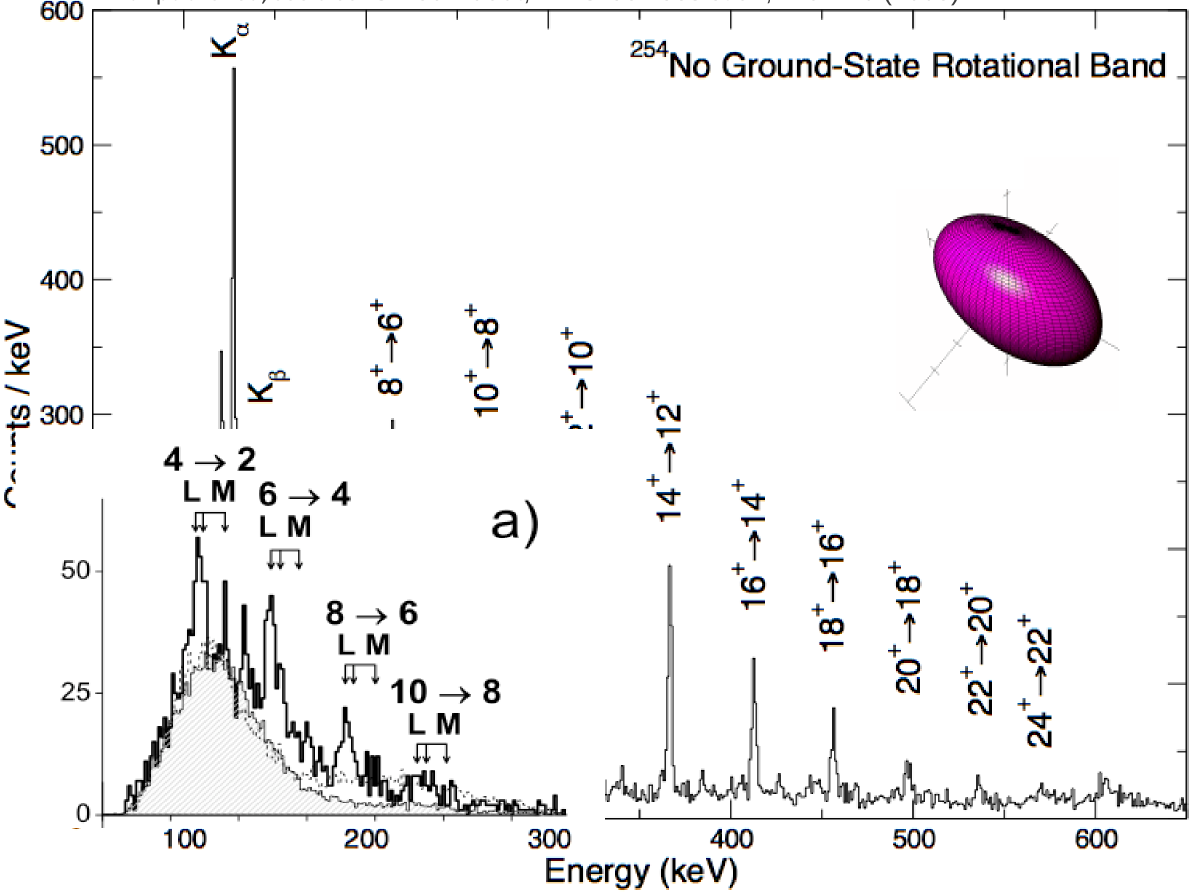


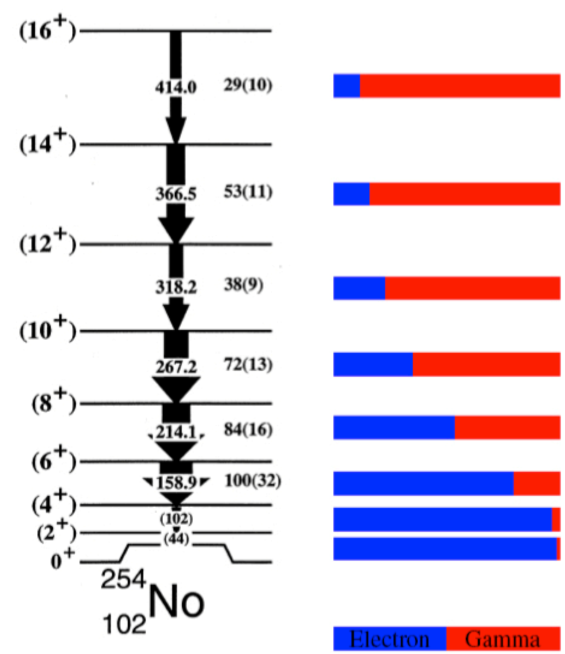


P. Reiter et al., Phys. Rev. Lett. 82 (1999) 509

^{254}No: Present Status

unpublished, see also: S.Eeckhaudt,P.T.Greenlees et al.,EPJA 26 (2005) 227



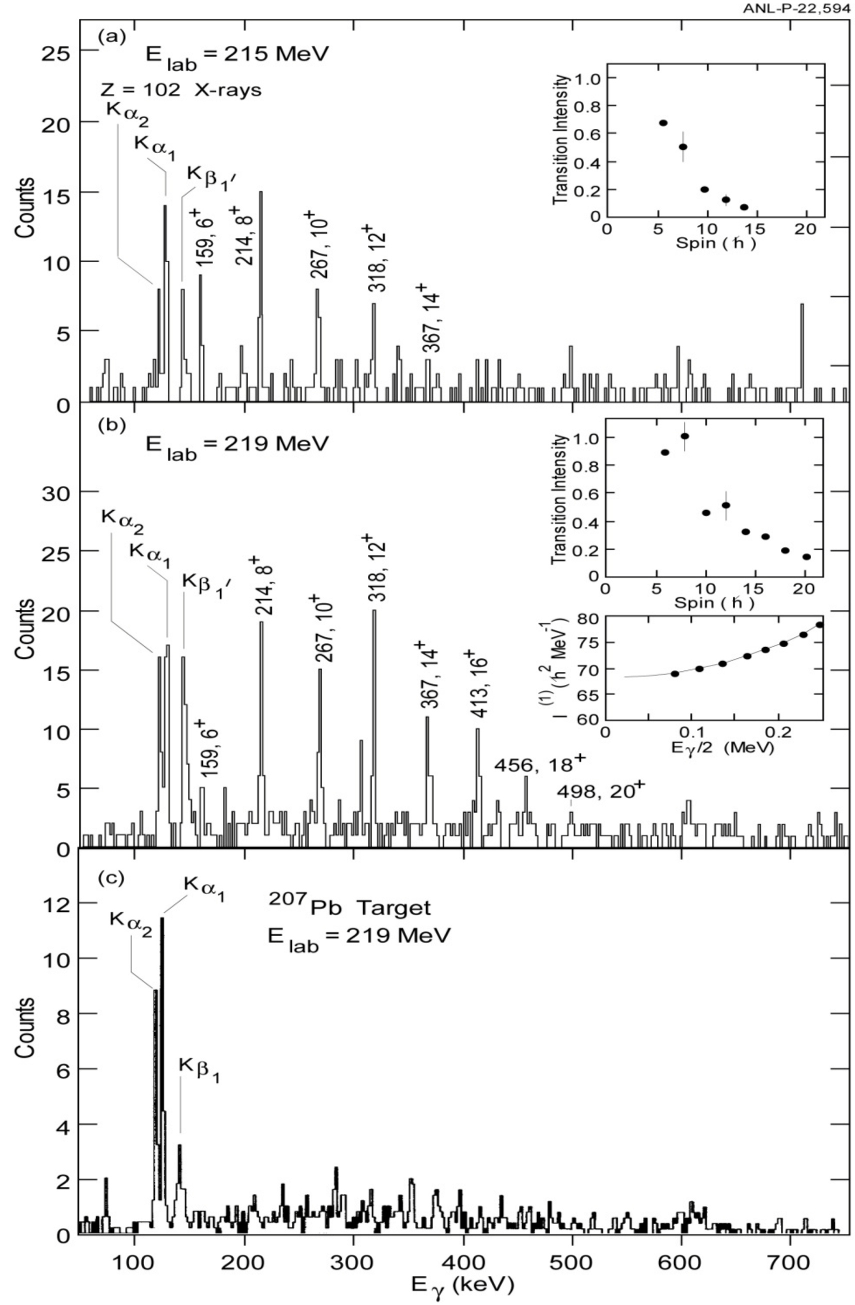


P.A. Butler et al. Phys. Rev. Lett. 89 (2002) 202501

^{253}No: the Challenge of odd nuclei

^{48}Ca + ^{208}Pb

σ_{fusion} ~ 1 μb



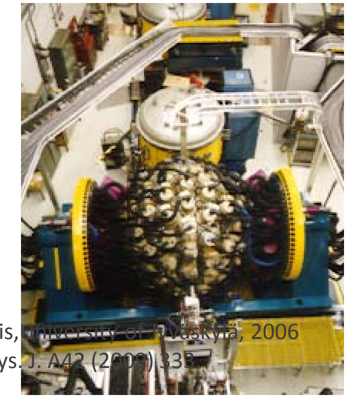
^{48}Ca + ^{207}Pb

σ_{fusion} ~ 300 nb

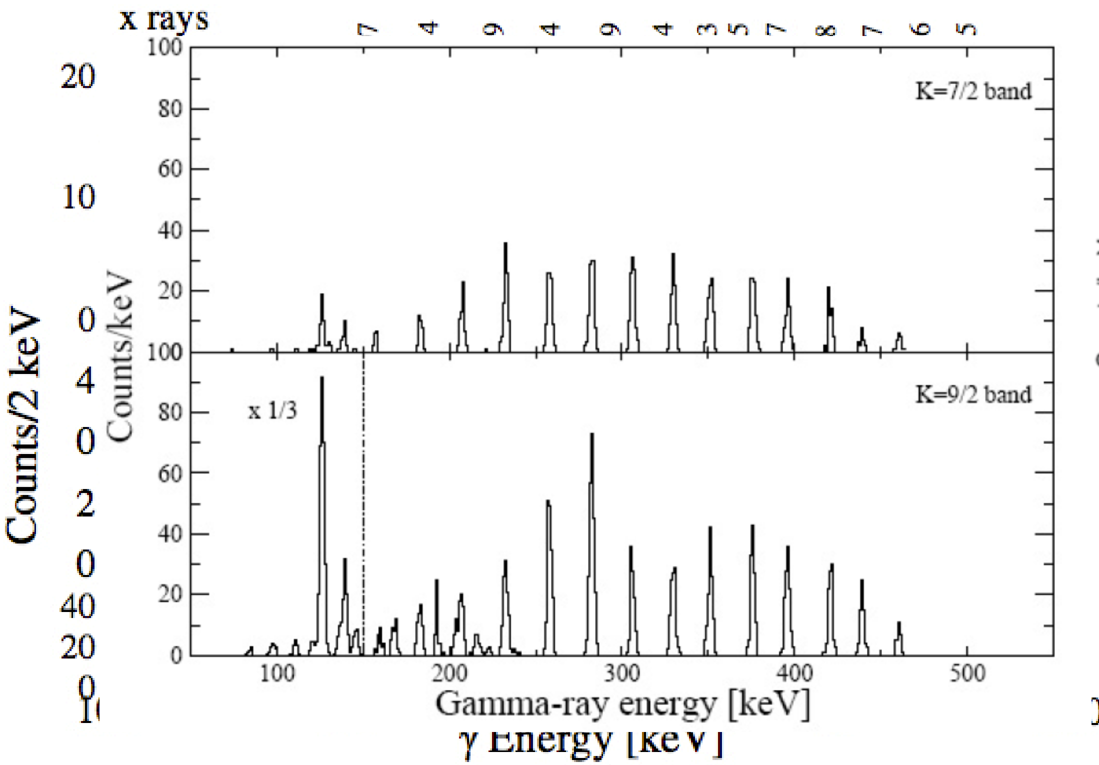
^{253}No: Observation of an excited band ?

^{207}Pb(^{48}Ca,2n)^{253}No,

σ = 300 nb, E=219 MeV



Sarah Eeckhaudt, PhD thesis, University of Jyväskylä, 2006
R.D.Herzberg, et al.,Eur.Phys. J. A42 (2009) 333



P. Reiter et al. Phys. Rev. Lett. 95, 032501 (2005)

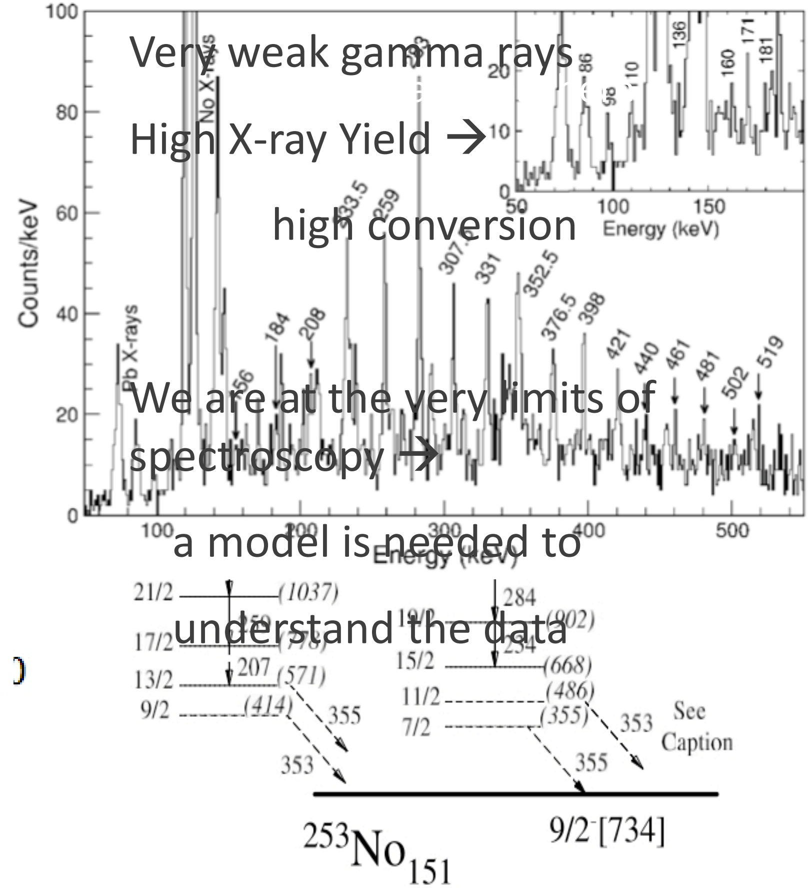
Very weak gamma rays

High X-ray Yield →

high conversion

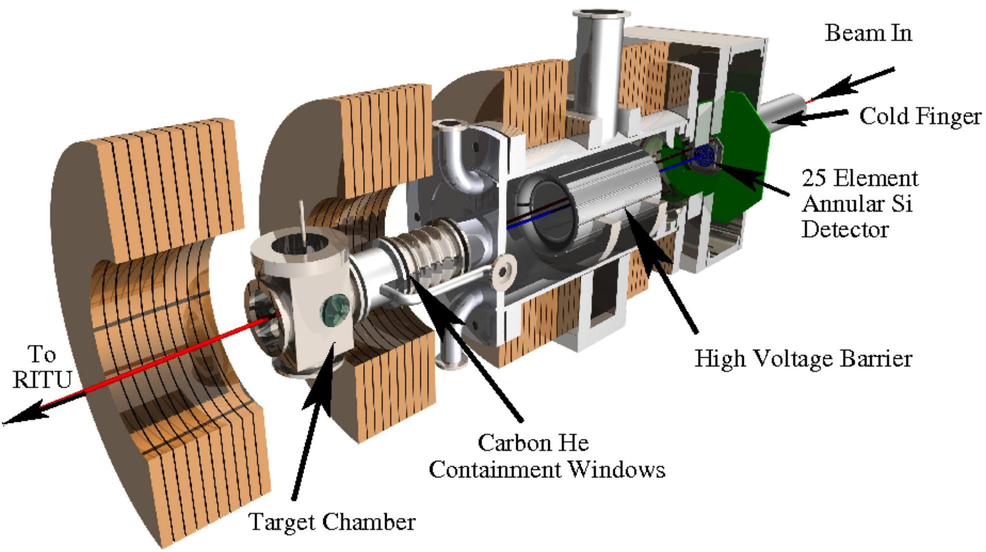
We are at the very limits of spectroscopy →

a model is needed to understand the data

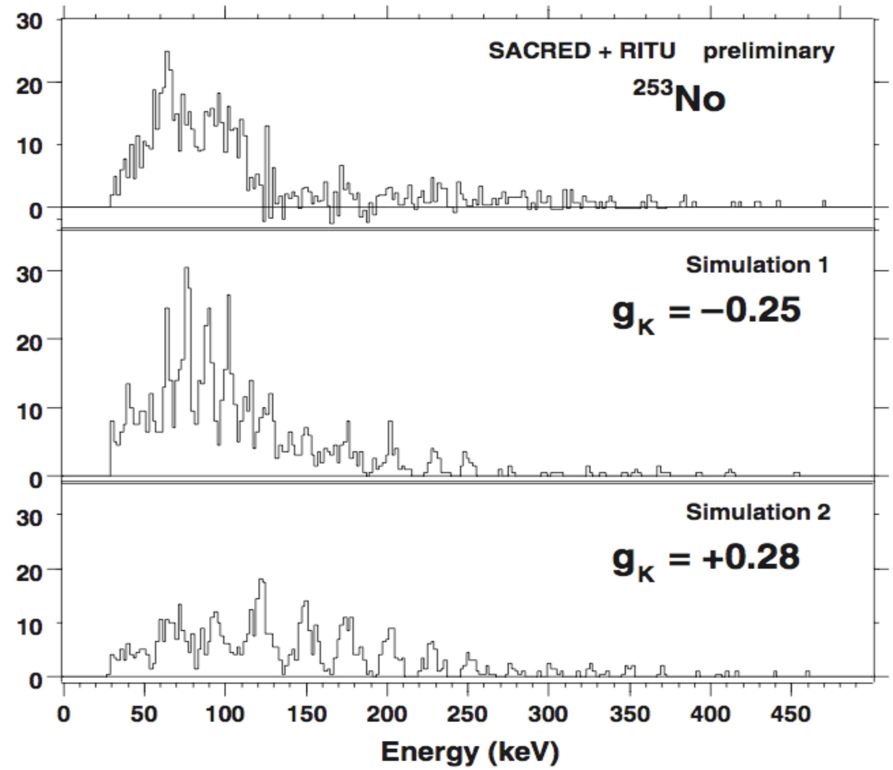


^{253}No: Observation of the groundstate band ?

SACRED electron spectrometer



H. Kankaanpää et al., Nucl. Instr. Meth. A 534 (2004) 503
P. Butler et al., Nucl. Instr. Meth. A 381 (1996) 433



R. Herzberg et al., J. Phys. G: Nucl. Part. Phys. **30** (2004) R123

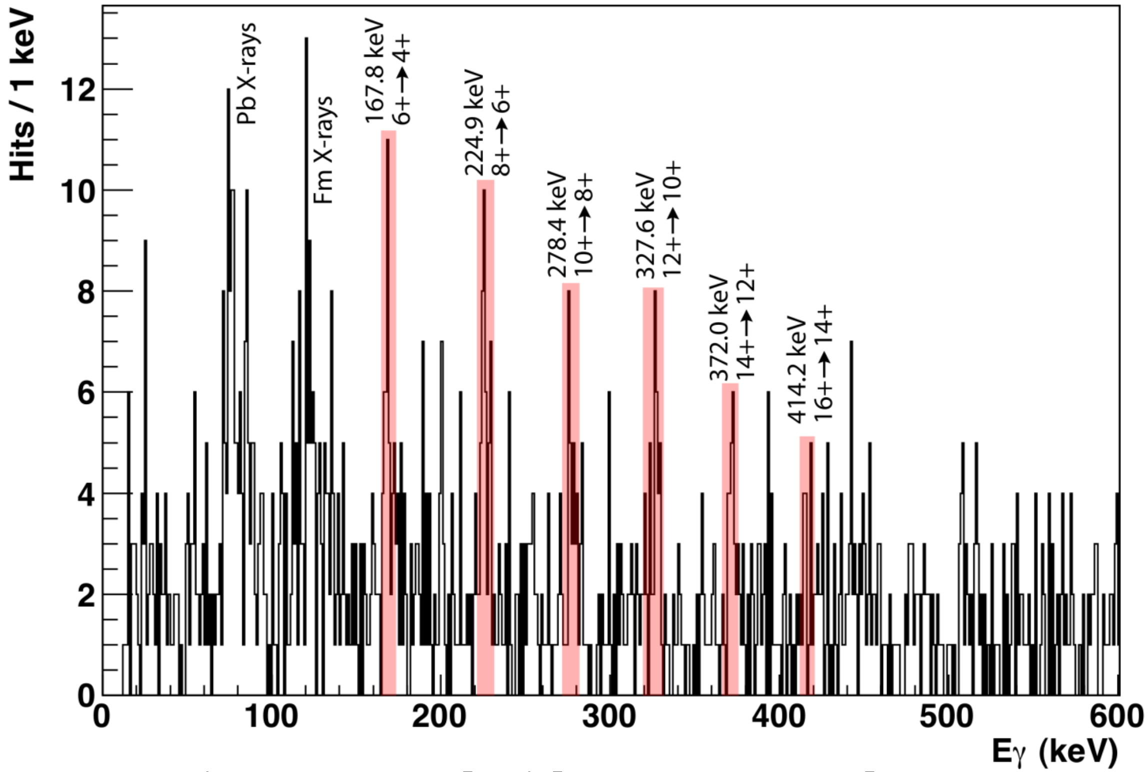
Observed band in ^{253}No is *most likely* the groundstate band

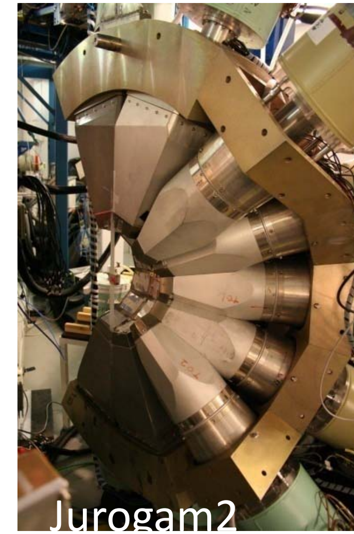
New cross section limit for in-beam spectroscopy of heavy nuclei

$^{208}Pb(^{40}Ar,2n)^{246}Fm$, $\sigma \sim 10$ nb

I_{beam} = 70 pnA ⇔ 40 kHz/detector

J. Piot et al., to be published

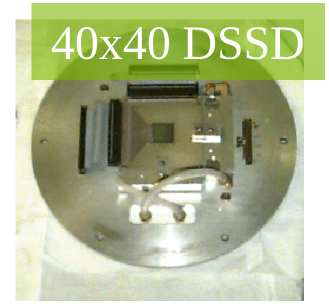


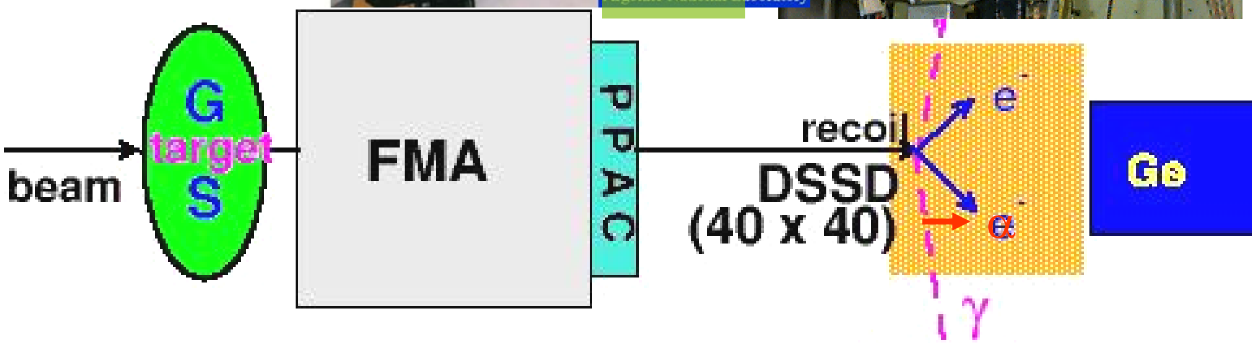


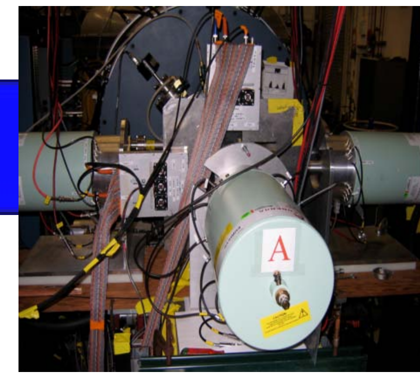
New electronics: Jurogam2 instrumented with 28 TNT2 cards
Counting rate per detector: 40 kHZ
(~200 recoils a day) → spectrum at the very limits ← Next step GRETINA + BGS at LBNL

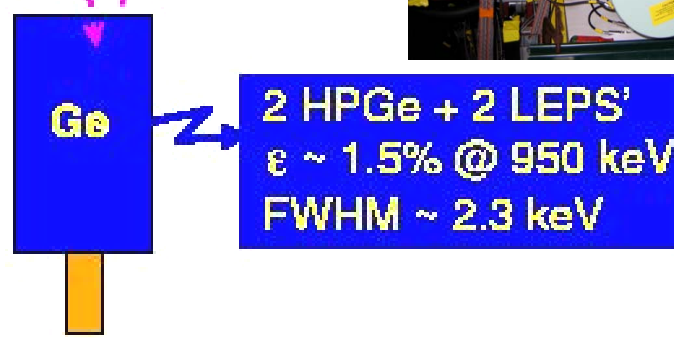
Isomer Spectroscopy: A Complementary Approach

Quasi-particle Orbitals and Energies from K-Isomers









$^{48}Ca + ^{208}Pb \rightarrow ^{254}No + 2n$

E_{beam} = 219 & 223 MeV

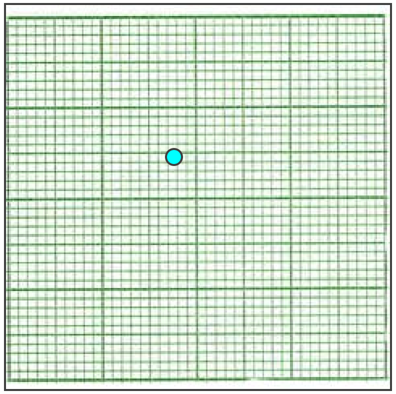
I_{beam} ~ 10 pnA

Target : ~ 0.5 mg/cm^2

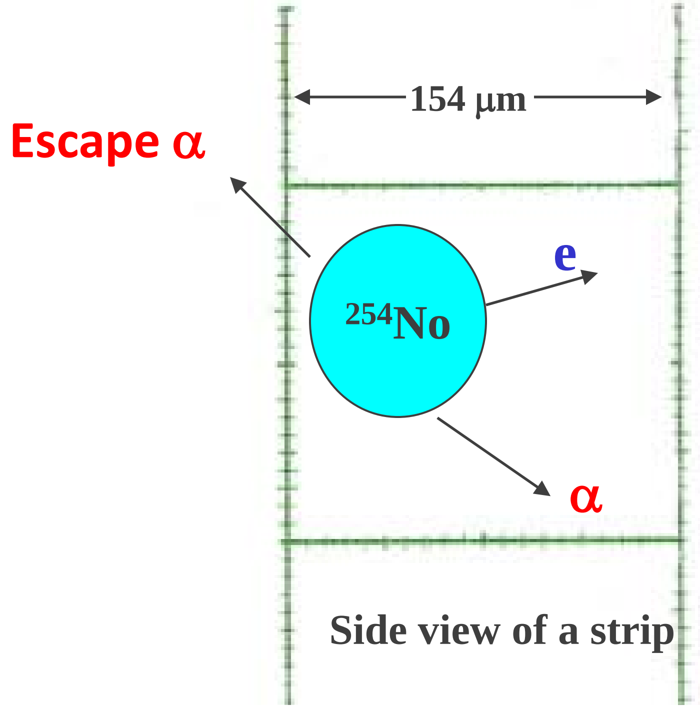
σ ~1 μb $\sigma/\sigma_{fission}$ ~ 10^{-6}

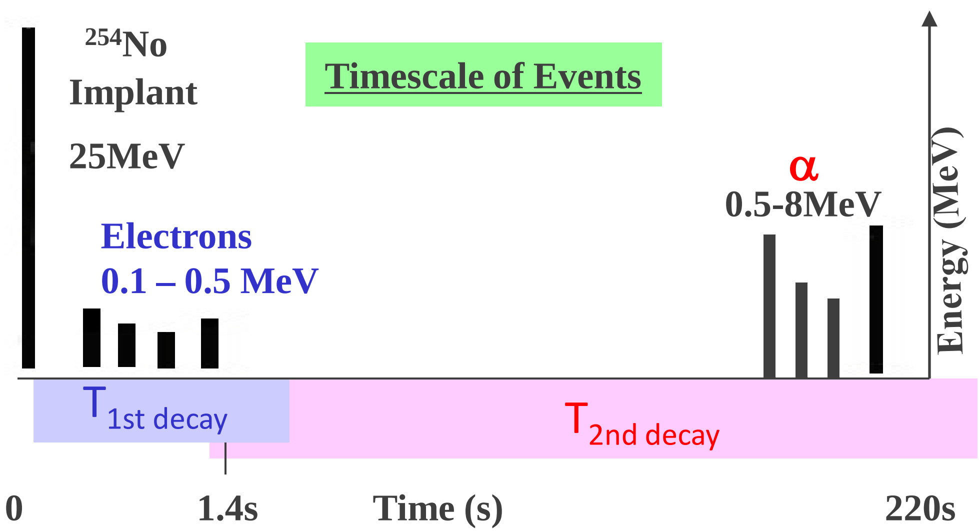
DSSD

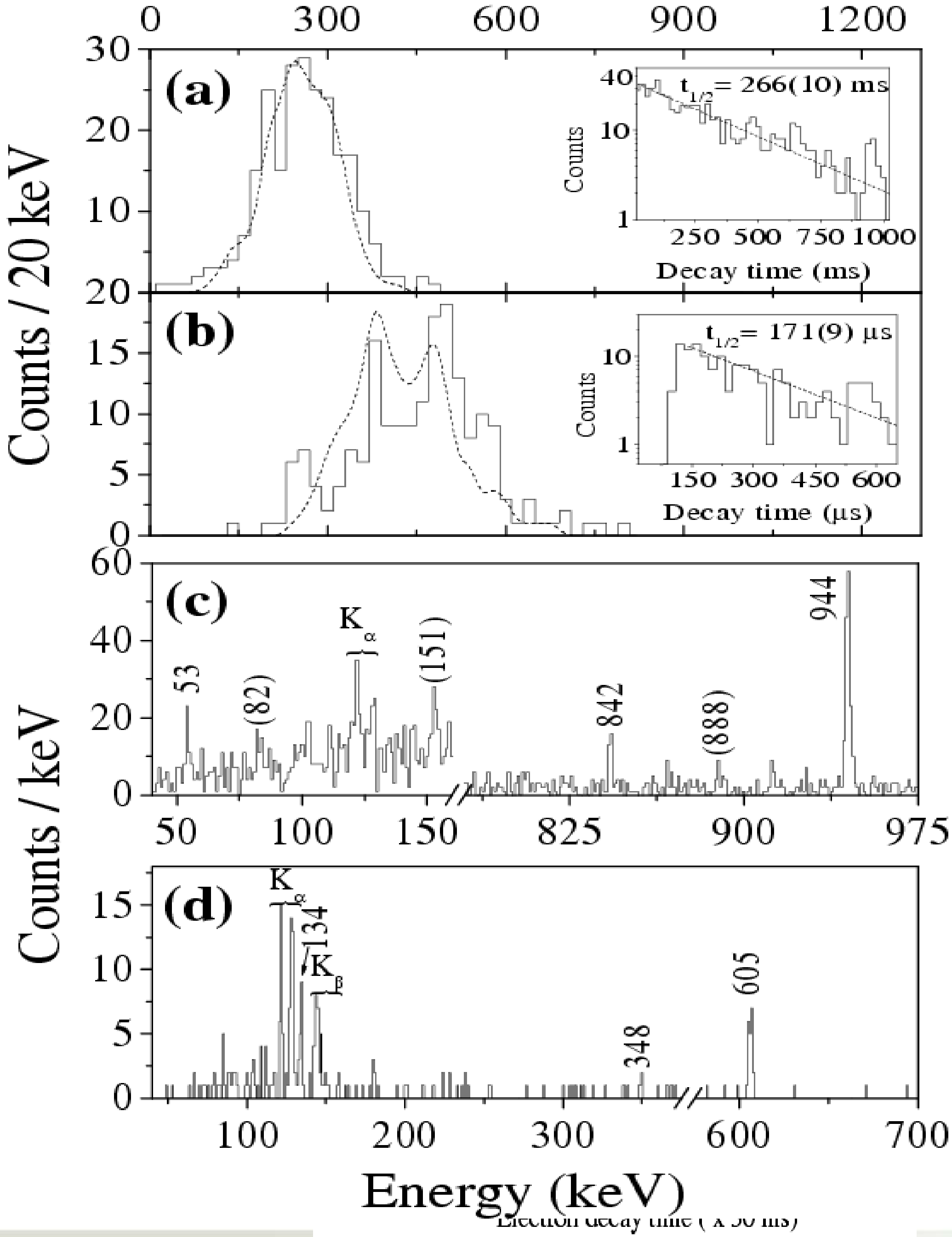
40mm X 40mm



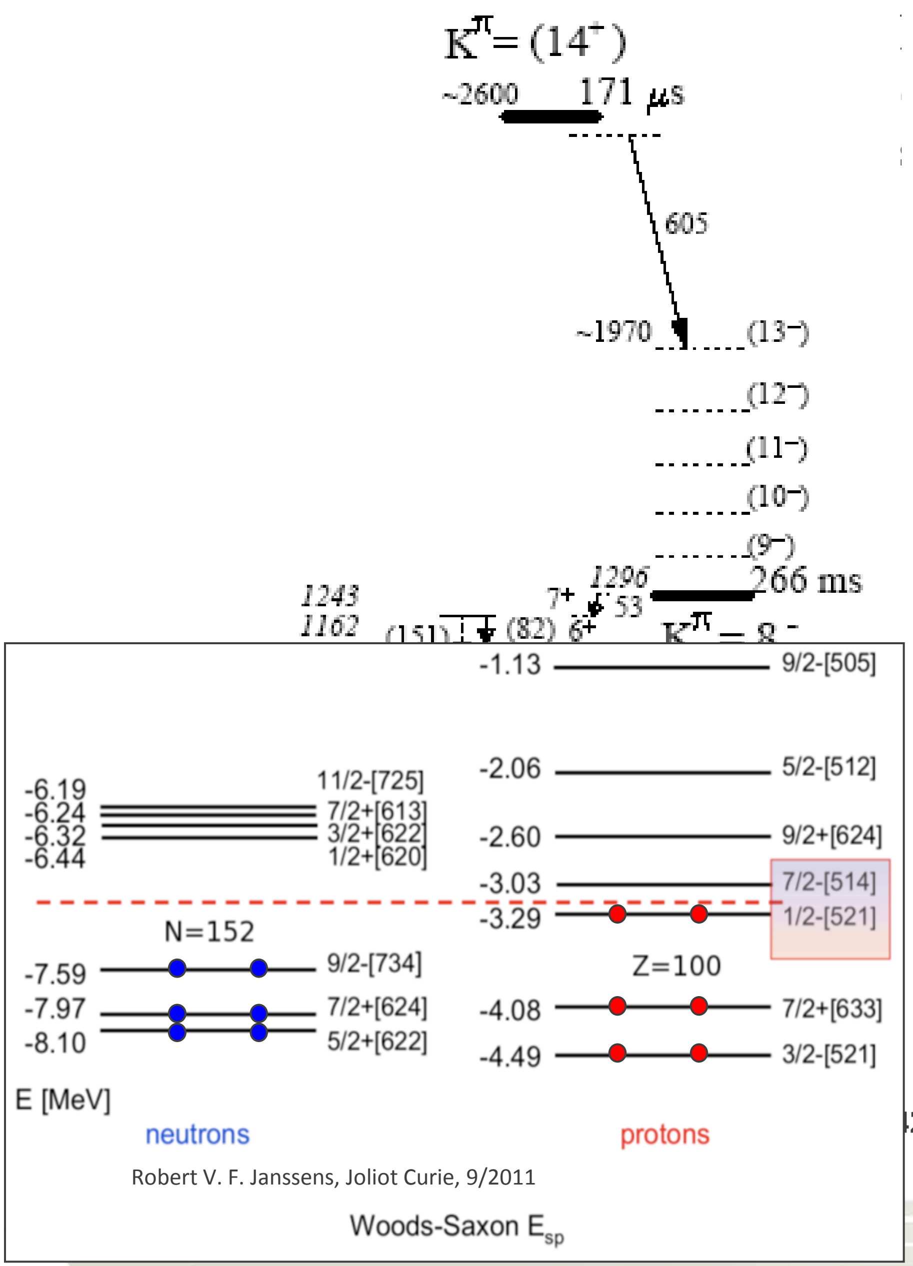
Front View of DSSD

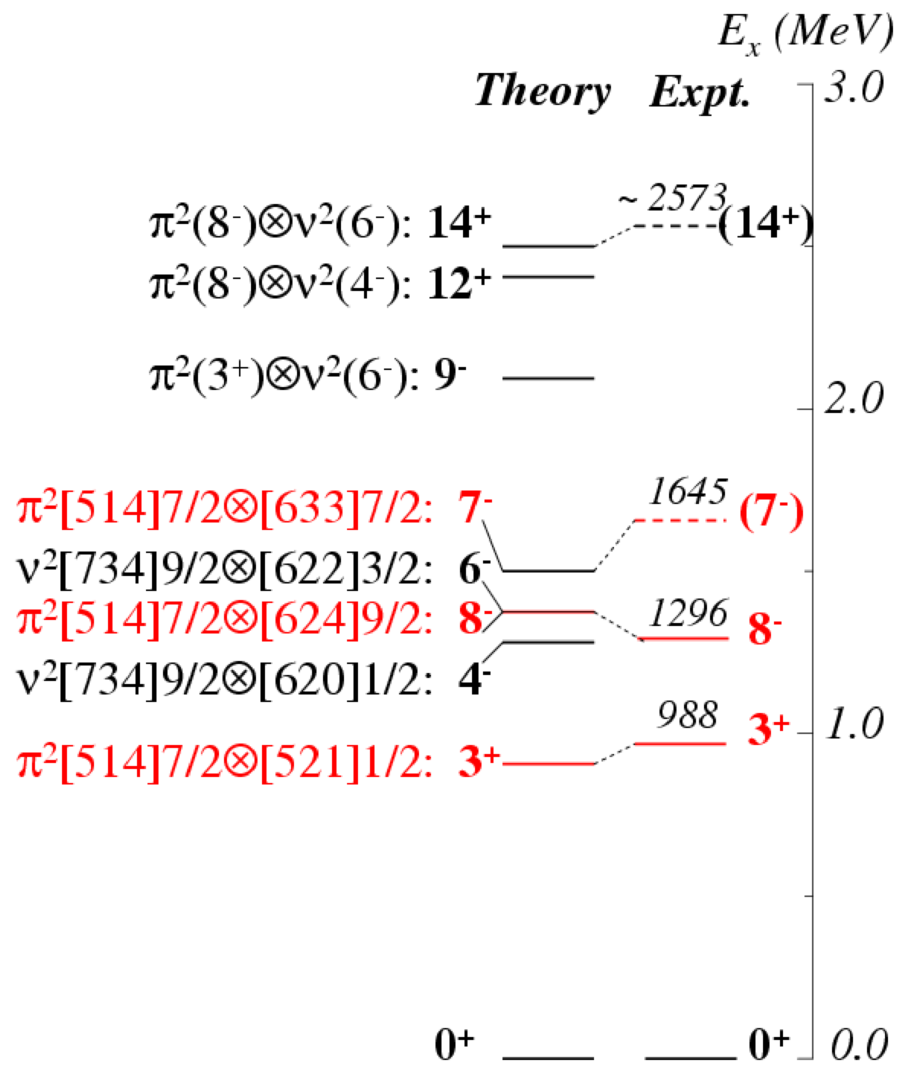





(a)
$t_{1/2}$ = 266(10) ms
Counts
Decay time (ms)
(b)
$t_{1/2}$ = 171(9) μs
Counts
Decay time (μs)
Counts / 20 keV
(c)
53
(82)
K_α
(151)
842
(888)
944
(d)
K_α
134
K_β
348
605
Counts / keV
Energy (keV)

Isomer Spectroscopy: A Complementary Approach

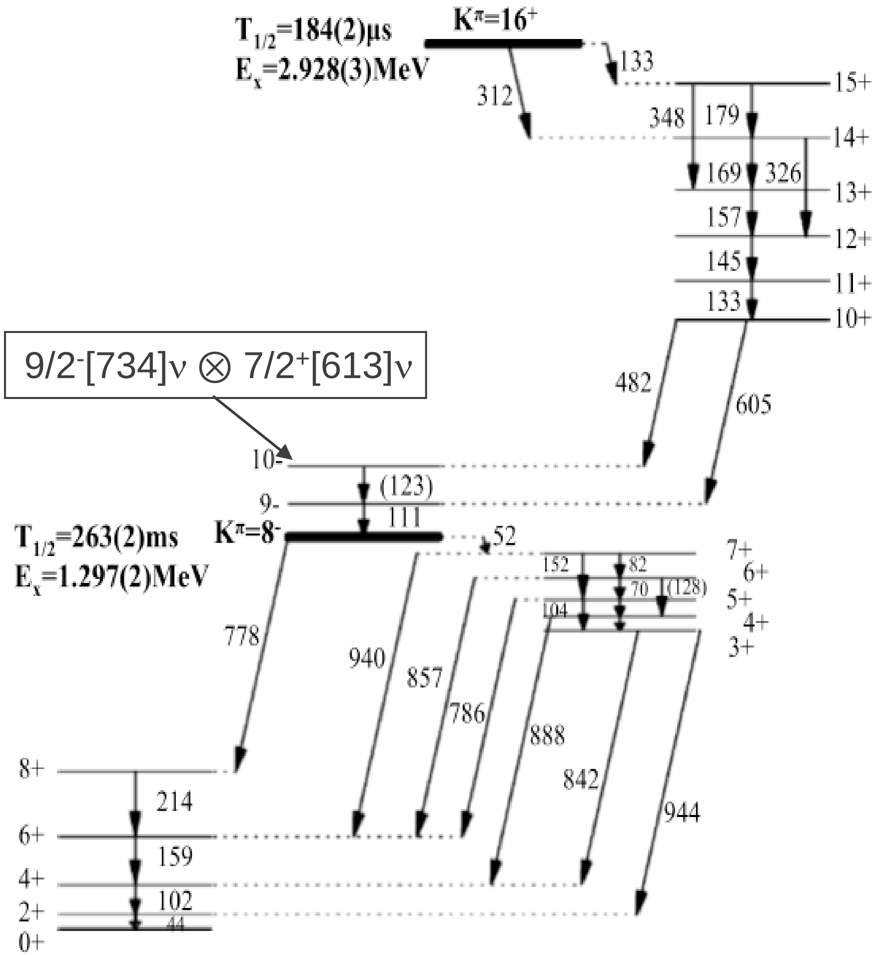




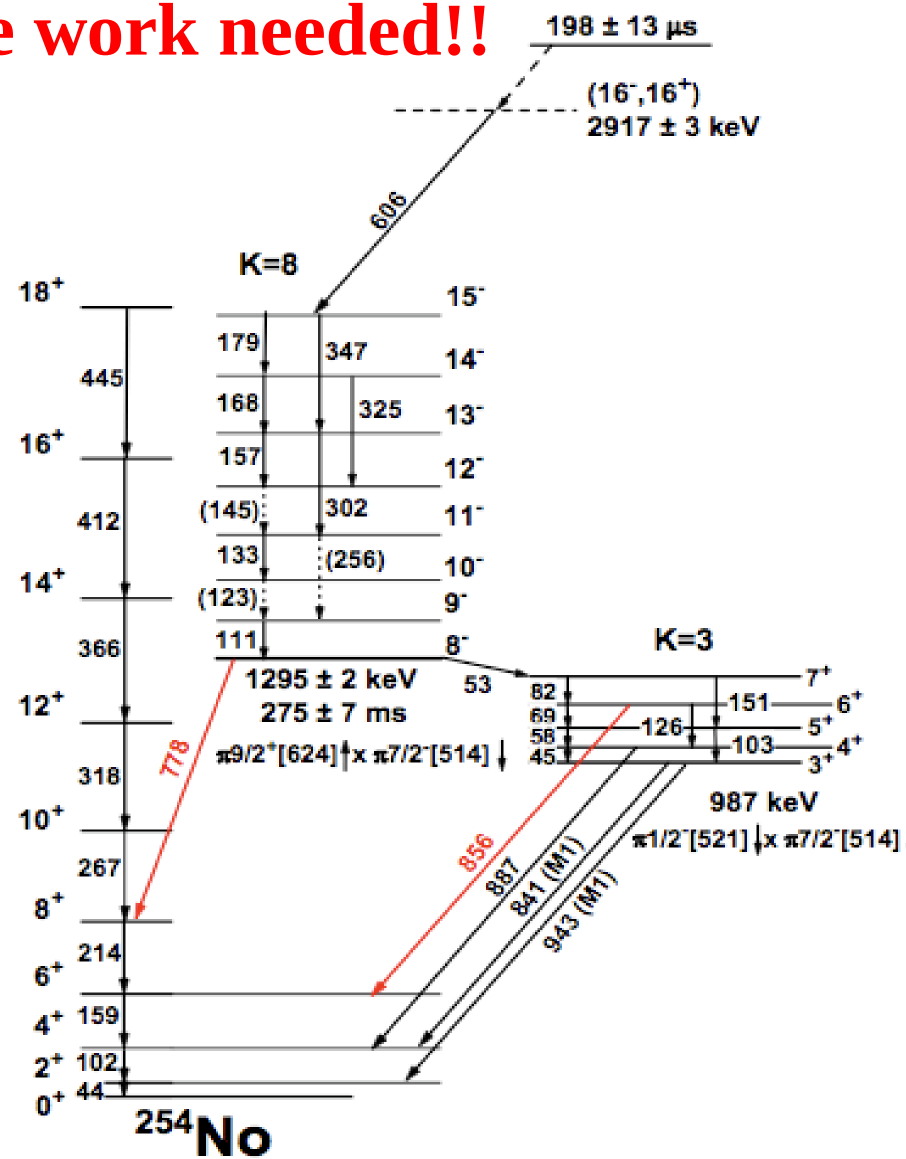
…2 (2006) 896, S. Tandel et al., Phys. Rev. Lett. 97 (2006) 082502

New data:

Clearly more work needed!!



R. Clark et al., Phys. Lett. B 690, 19 (2010)



F. Hessberger et al., Eur. Phys. J. A 43 (2010) 55

Ultimate Goal:

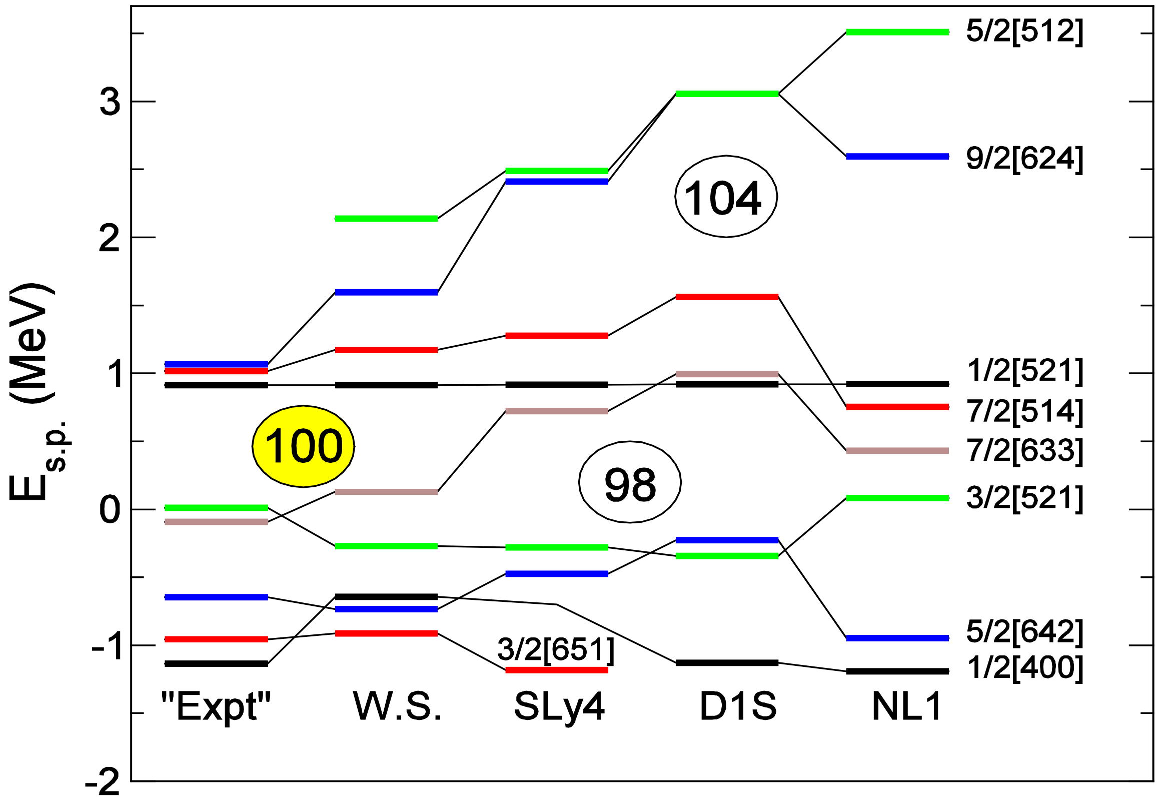
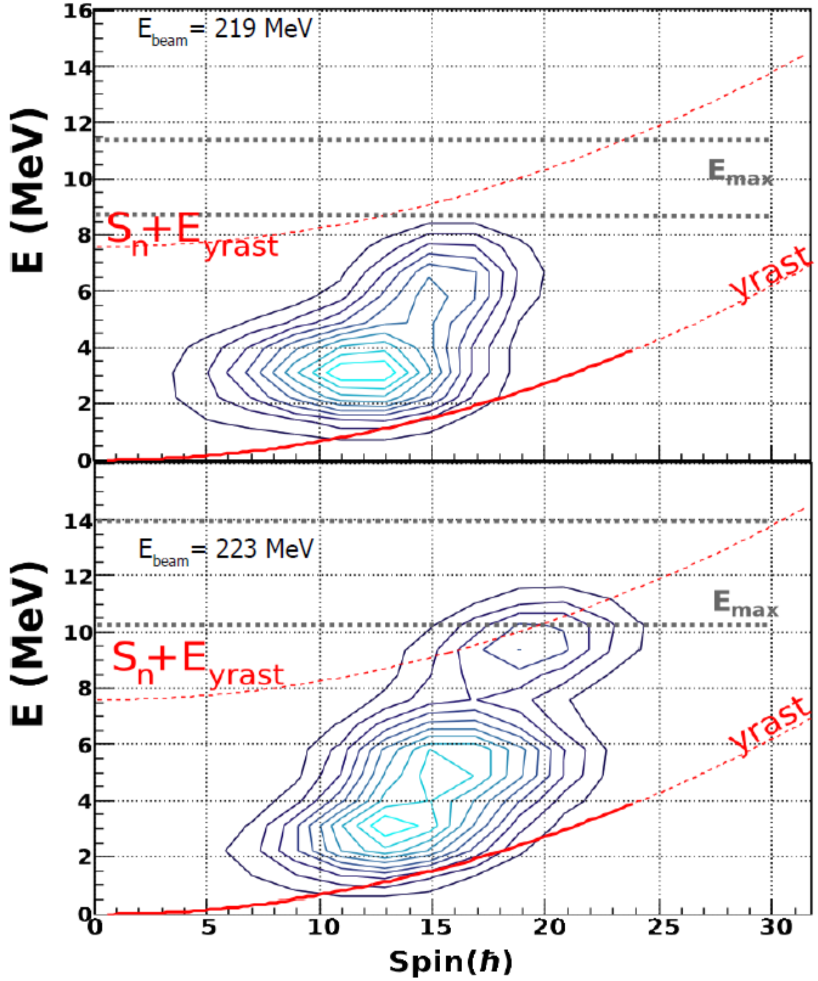
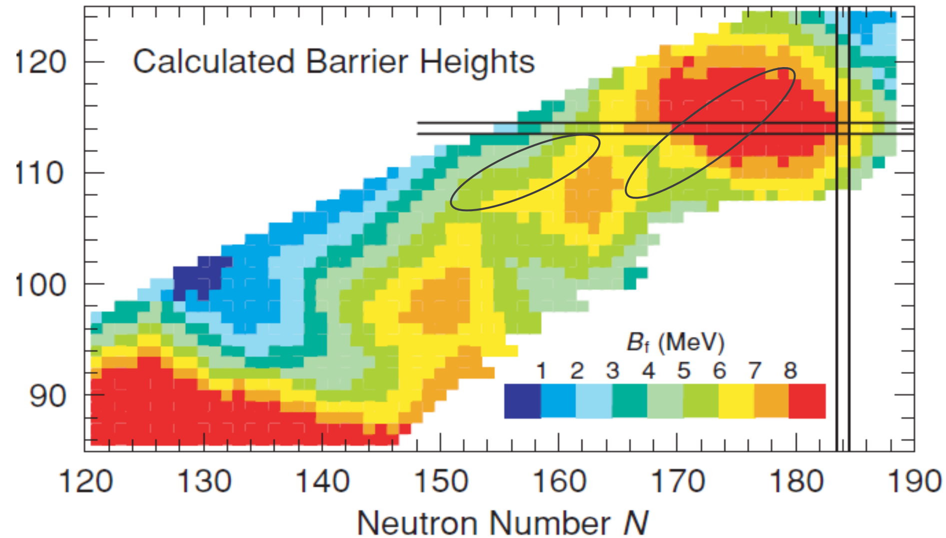


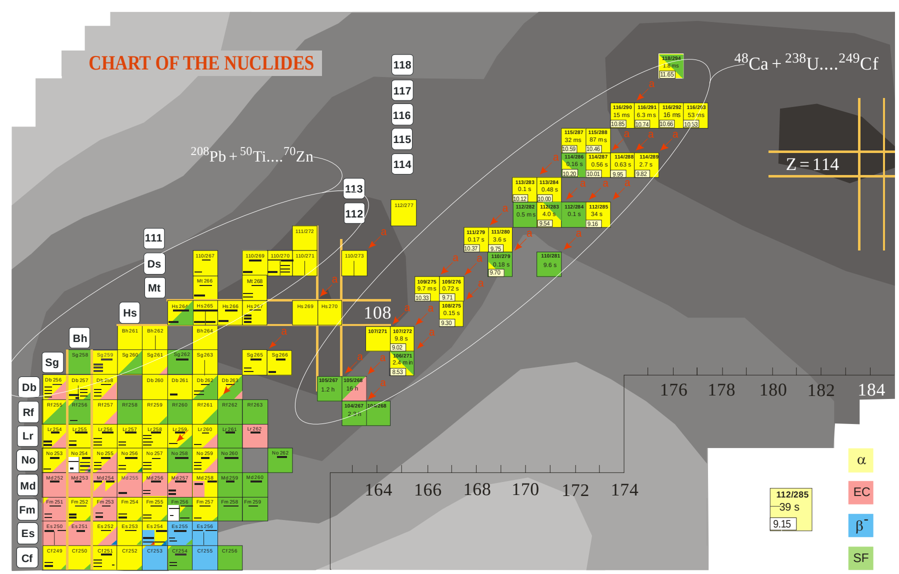
Fig. 7: Comparison between the measured one-quasi-particle single-proton energies in $^{249}Bk_{150}$ and those calculated with a Woods Saxon (W.S.) potential and density functional theories using the Skyrme (SLy4), Gogny(D1S) and NL1 interactions.

Fission Barriers at High Z and High J

With Gammasphere we can infer the fission barriers of Z > 100 nuclides and how they evolve with spin







Take Away Message:

- a lot of new and interesting data are becoming available

- there is complementarity between prompt & decay spectroscopy

- confirmation is required for in low cross-section cases

- s.p energies are thus far not well reproduced by self consistent methods

- there clearly is much to be done in both experiment & theory