Study Of Nuclei at High Angular Momentum – Day 3

Some Current Topics In High-Spin Studies

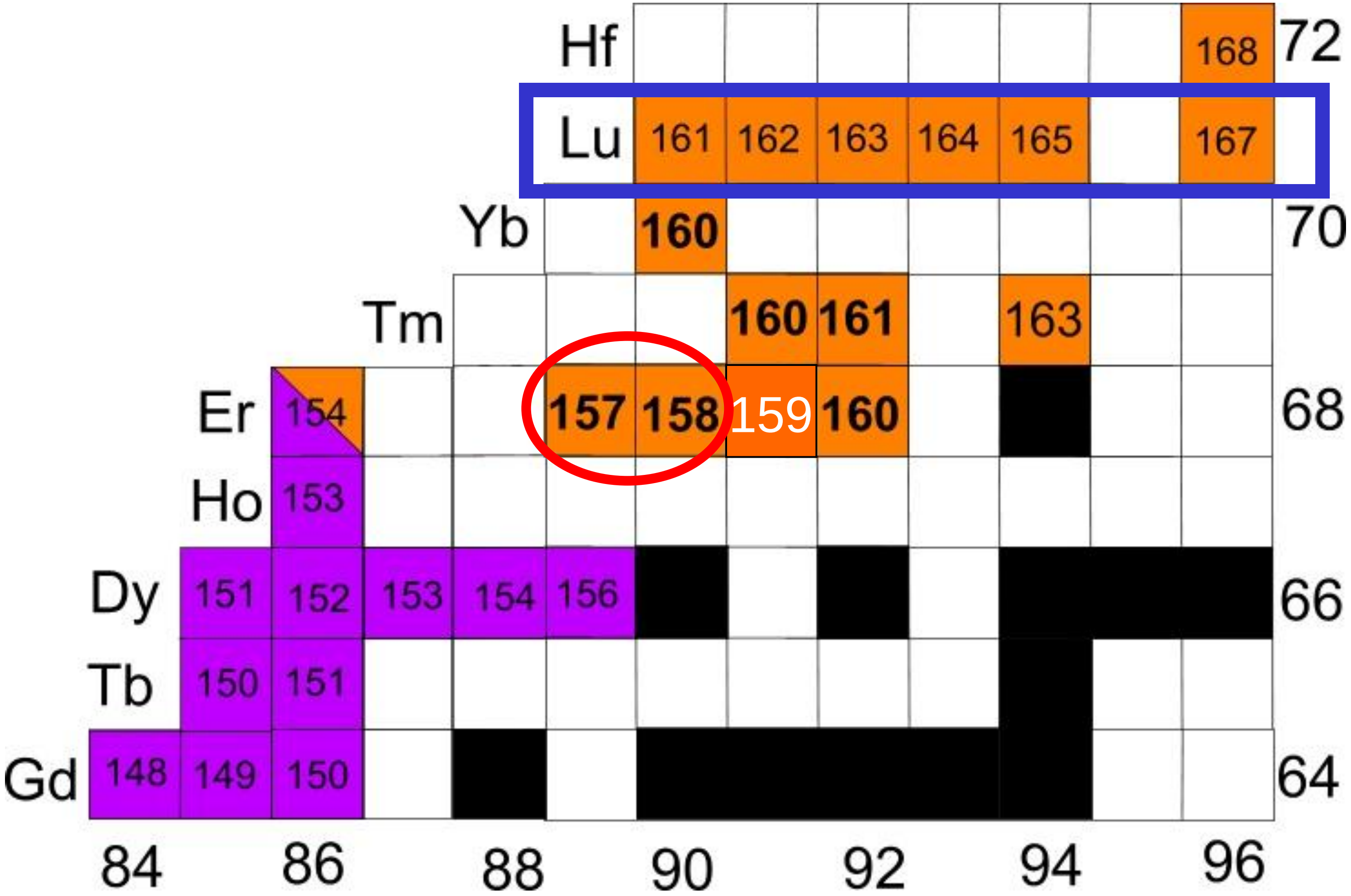
1) Re-emergence of Collectivity at High Spin
2) A New “Spin” on Octopole Collectivity
3) High Spinners can study Neutron Rich Nuclei too!

Michael P. Carpenter
Nuclear Physics School, Goa, India
Nov. 9-17, 2011

Re-Emergence of Collectivity at High Spin

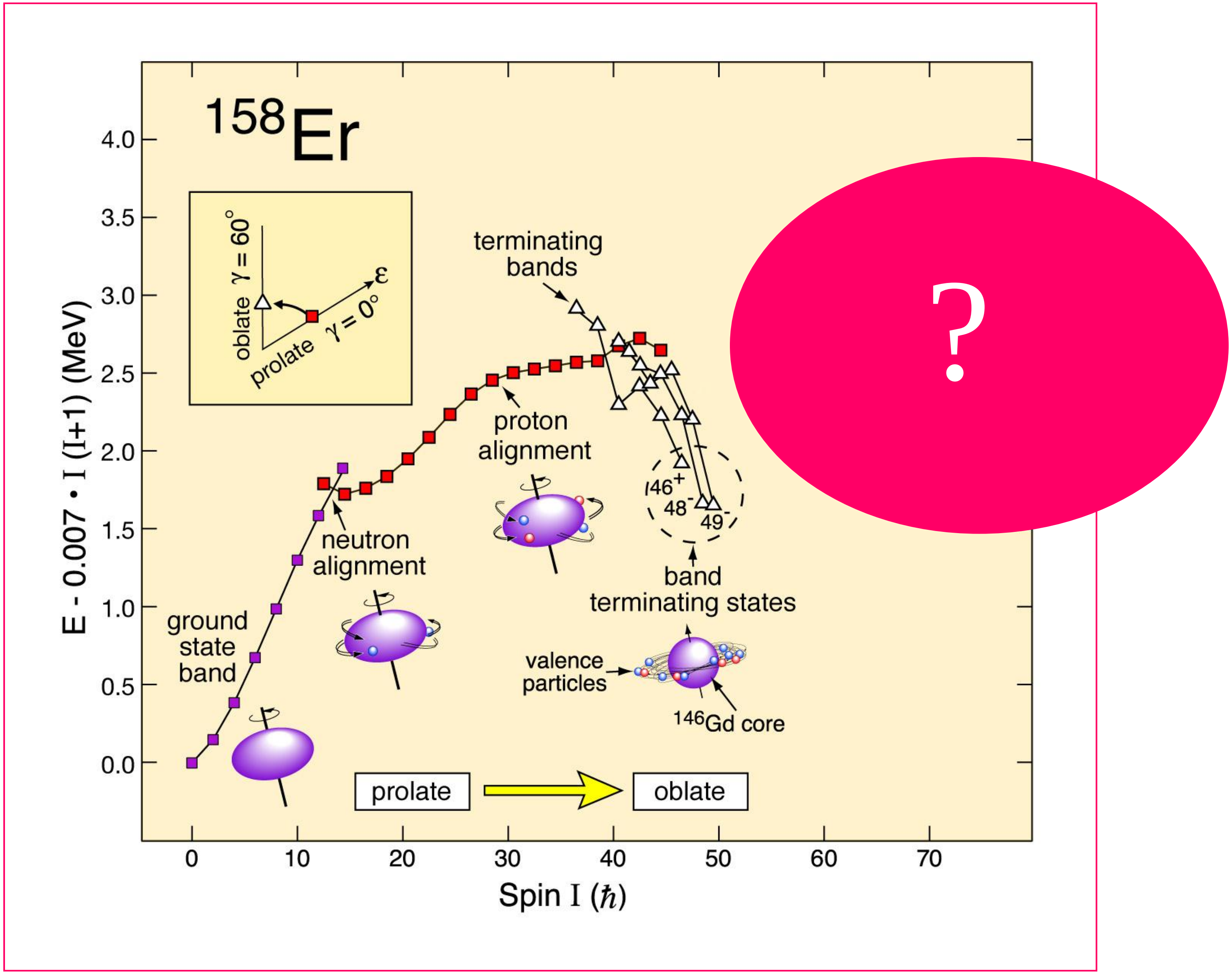
Nuclei at the highest spins: Beyond band termination

Triaxial strongly
Deformed (TSD)



Superdeformed (SD)

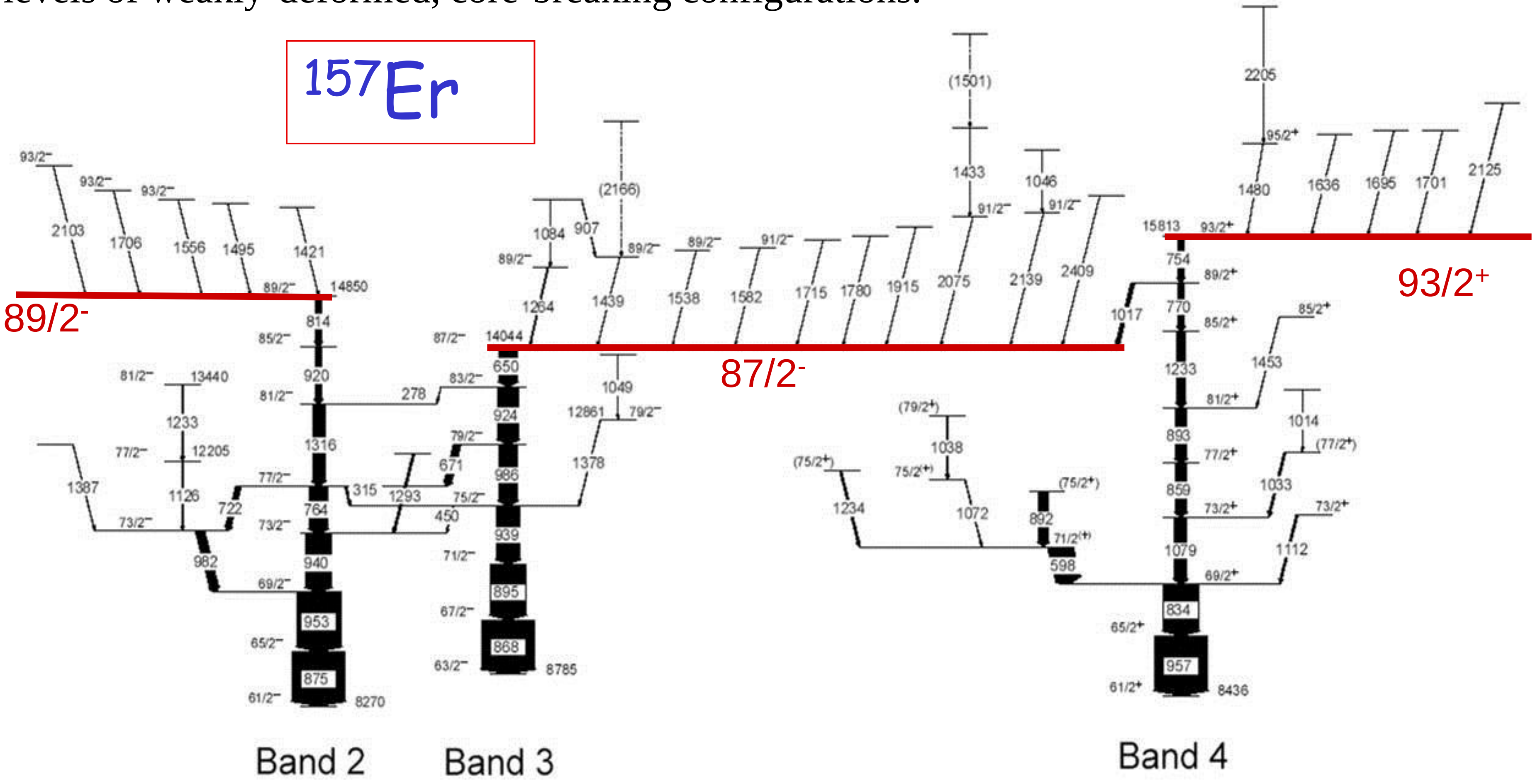
Mid-90's: From collective rotation to band termination



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

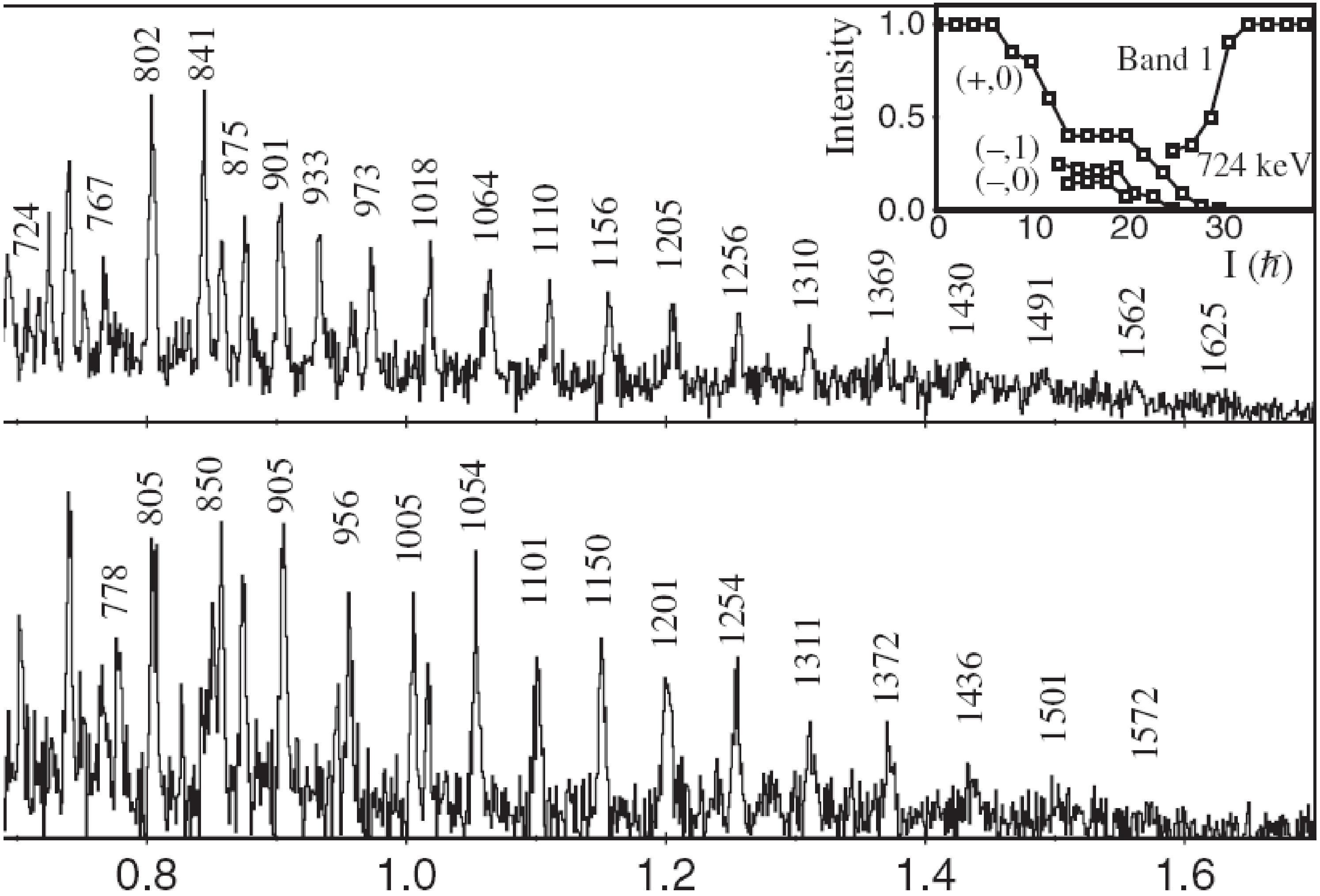
Mid-2000's: Feeding of the terminating states

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

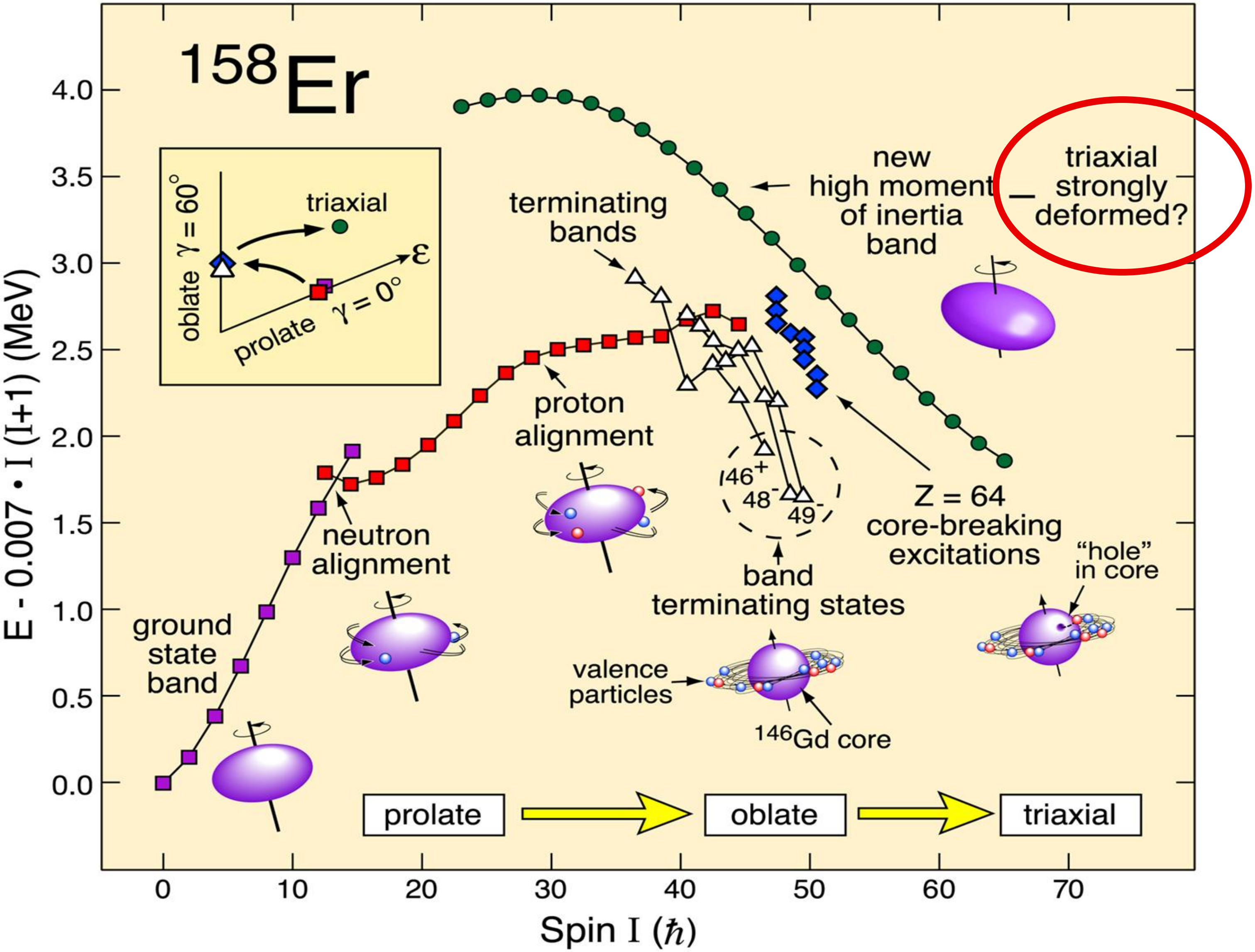


^{158}Er

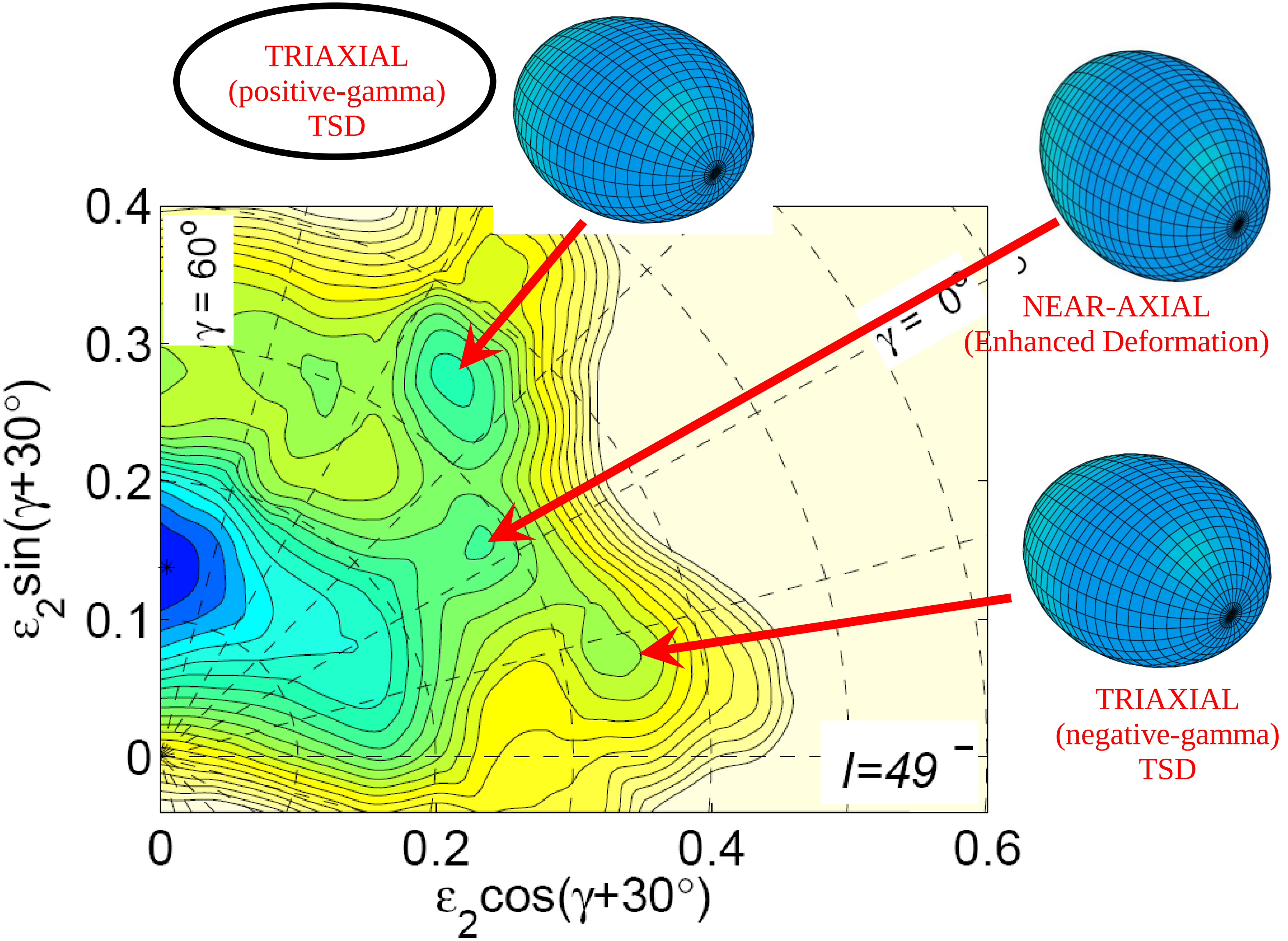
^{157}Er

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

2007: Return to collectivity



2011: What deformation?

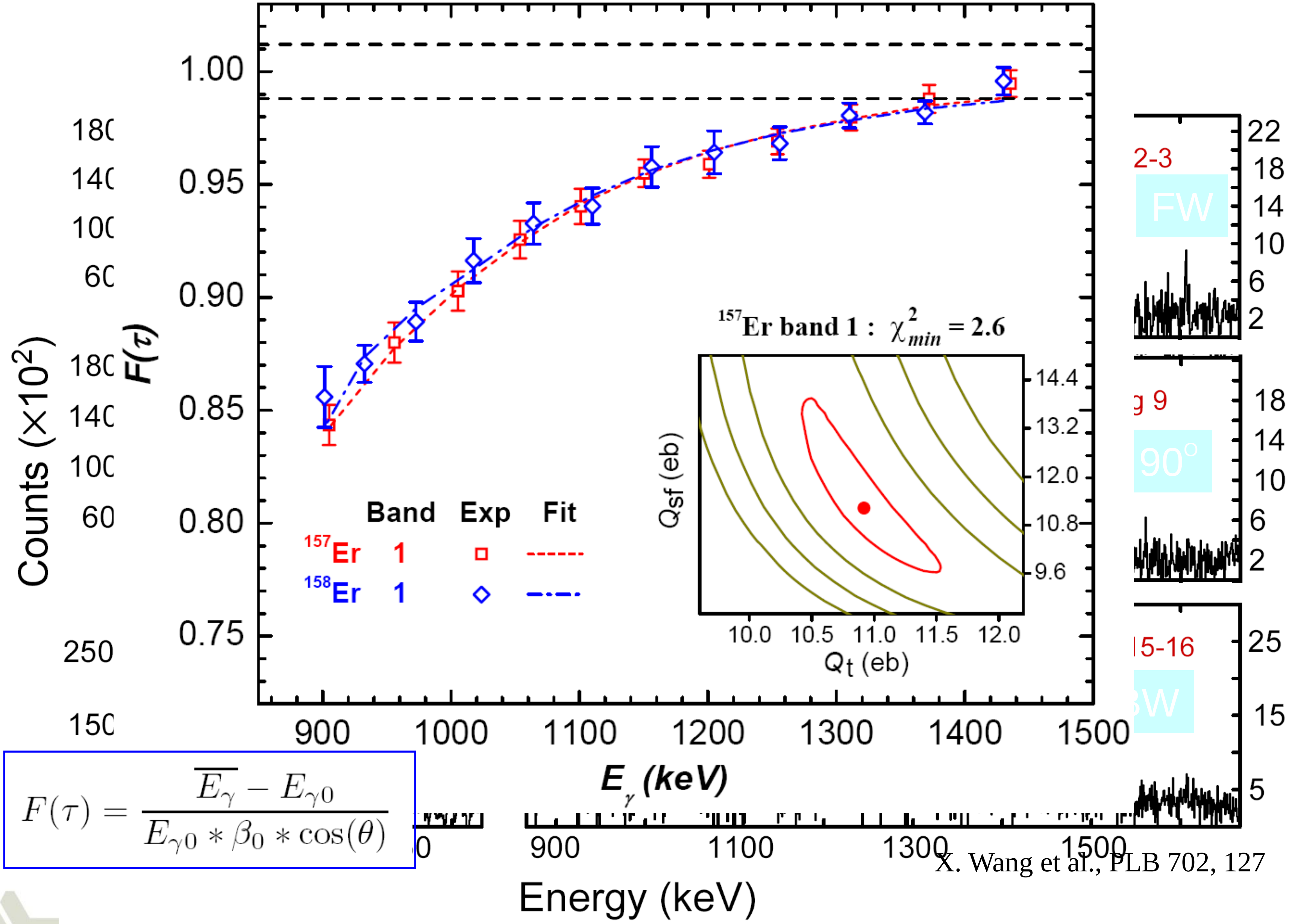


TRIAXIAL
(positive-gamma)
TSD

NEAR-AXIAL
(Enhanced Deformation)

TRIAXIAL
(negative-gamma)
TSD

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

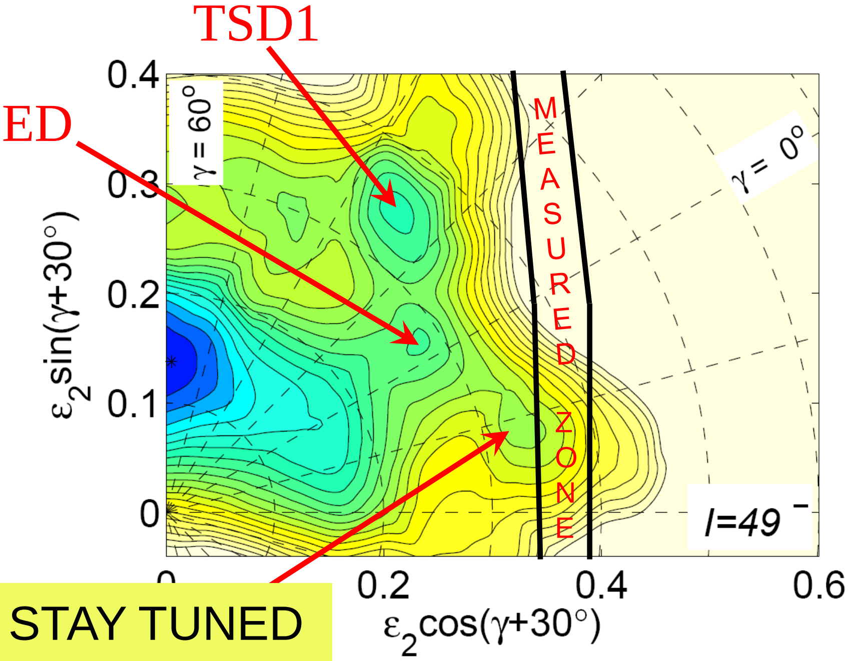
Theory vs Experiment

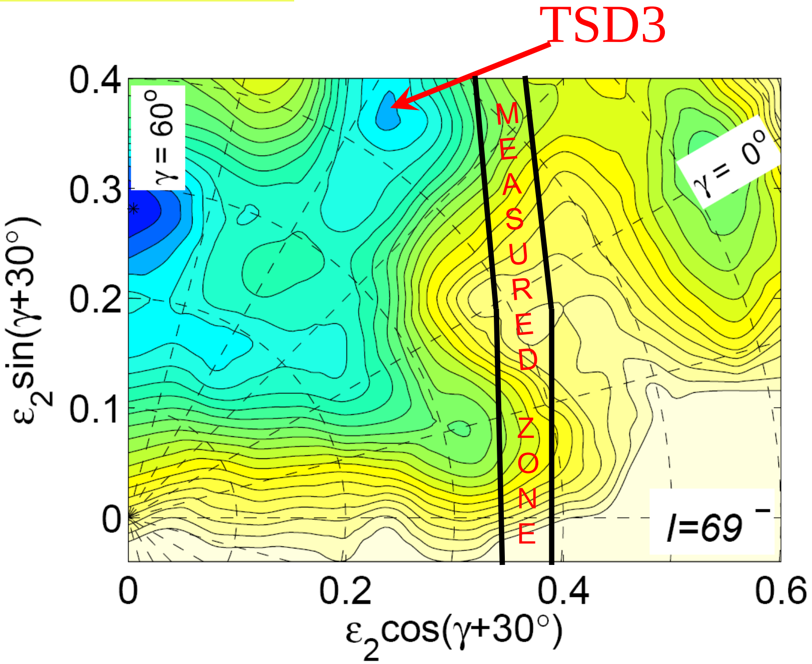
	MEASURED (band 1s)	CALCULATED			
		TSD1	TSD2	TSD3	ED
Q_t (*eb*)	^{158}Er: **11.7** (+0.7, -0.6) ^{157}Er: **10.9** (+0.6, -0.5)	6.0 – 7.2	10 – 11.2	8 – 9.2	6.7 – 7.9

THEORY NEEDS WORK→ STAY TUNED

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

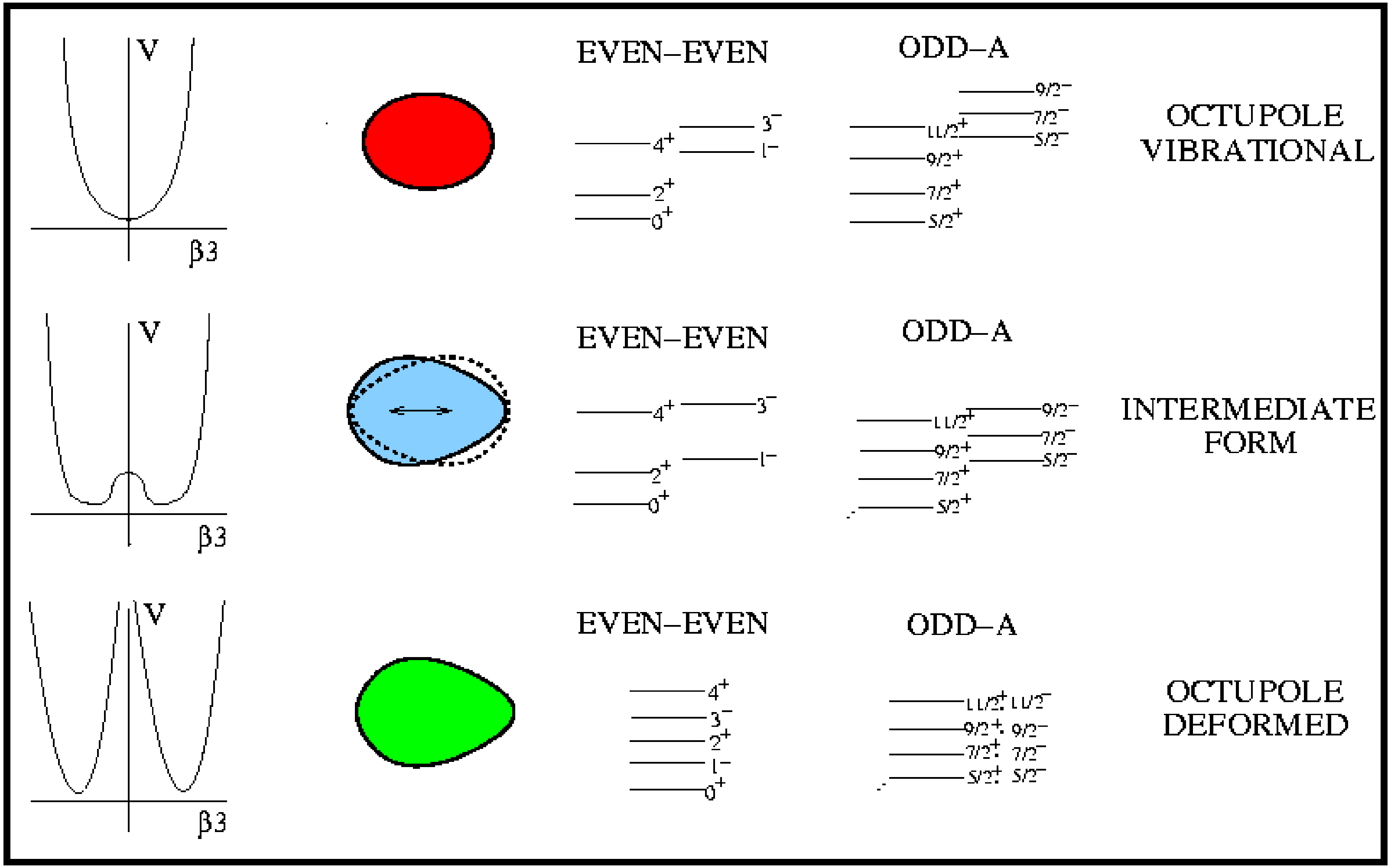
Q_t is transitional quadrupole moment; Q_0 is intrinsic quadrupole moment;
ε_4 is set to be 0 here; Z is proton number;
A is mass number.





A New “Spin” On Octupole Collectivity

Octupole Collectivity

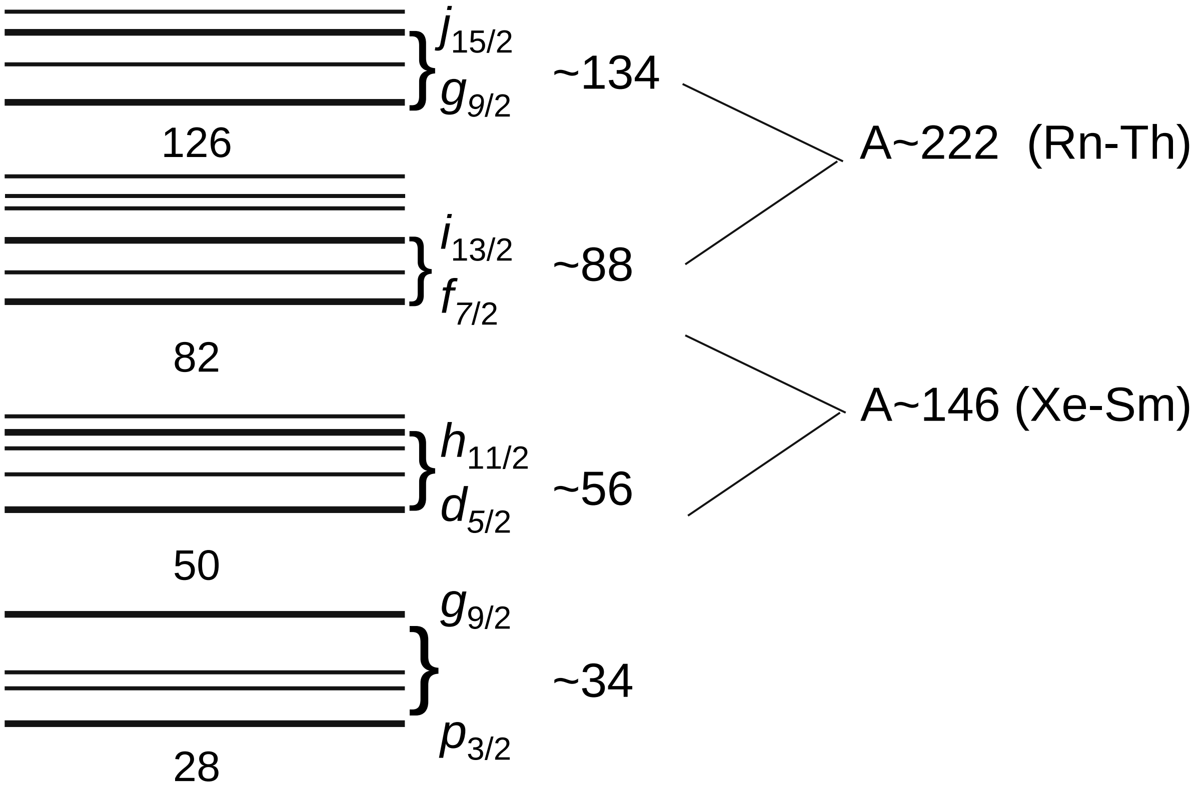


I. Ahmad & P. A. Butler, Annu. Rev. Nucl. Part. Sci. **43**, 71 (1993).

P. A. Butler and W. Nazarewicz, Rev. Mod. Phy. **68**, 349 (1996).

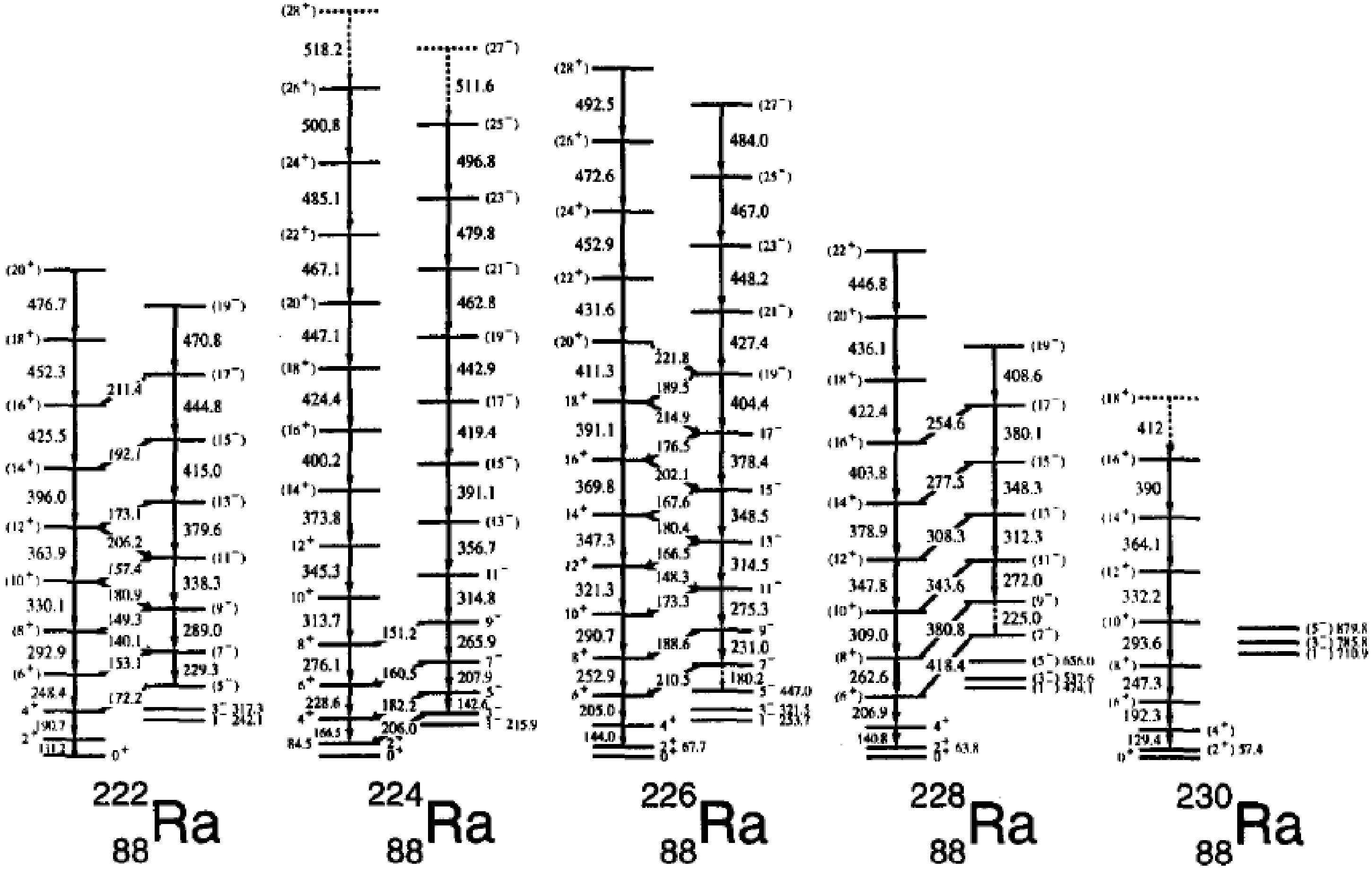
Where to find enhanced octupole collectivity

Long-range interactions between single particle states with $\Delta j = \Delta l = 3$;



Difficult regions to study experimentally

Multi-Nucleon Transfer: $^{136}Xe + ^{232}Th$ (Gammasphere)



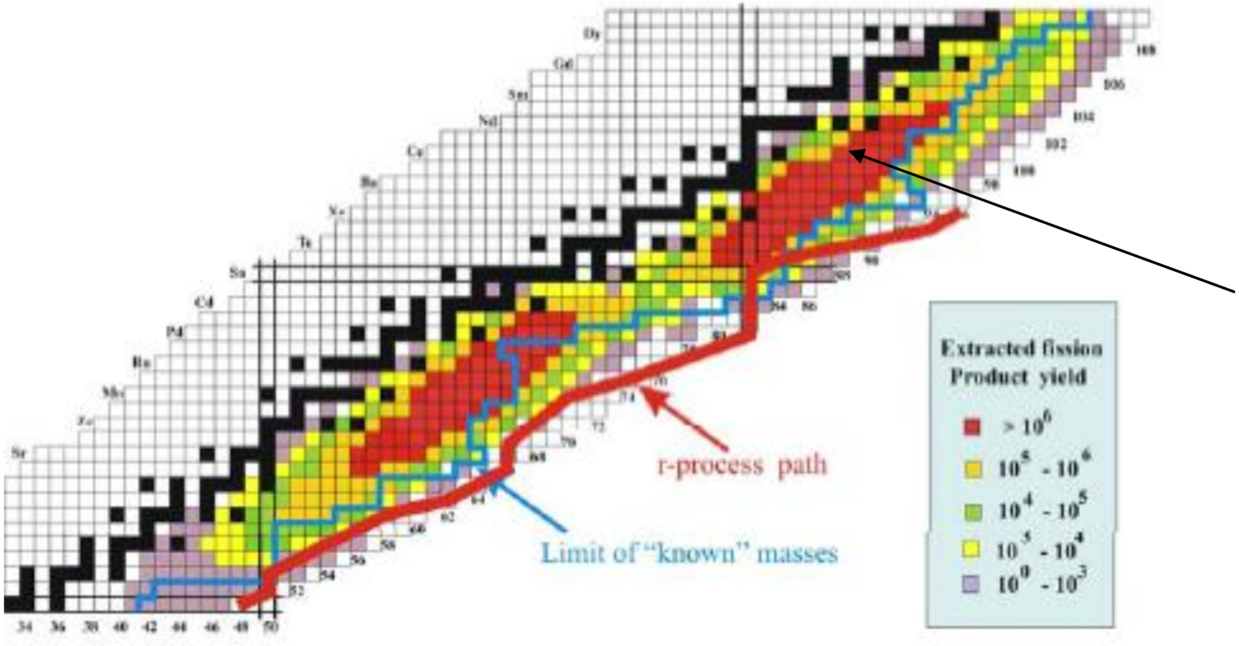
In addition, $^{226,228,230,232,234}Th$

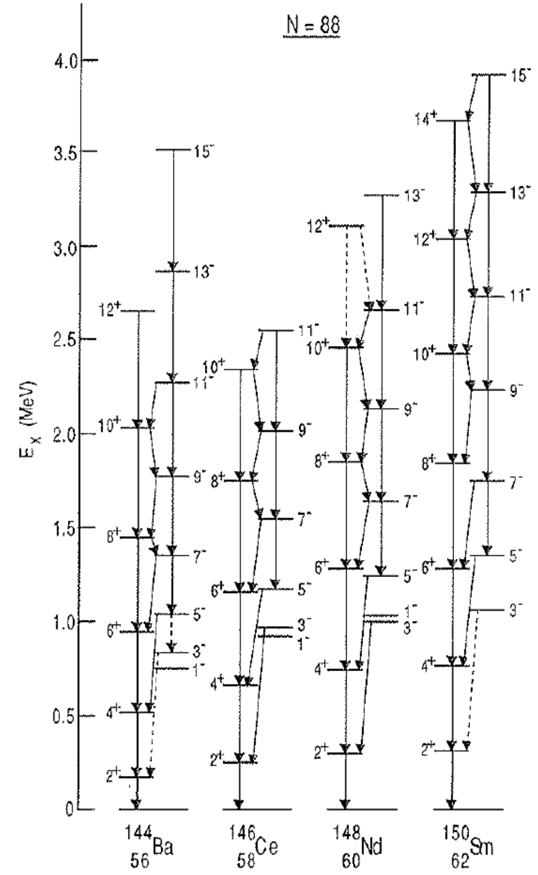
J.F.C. Cocks et at., Nuc. Phys. A 645 (1999) 61

A~146 Region (Ba, Ce, Nd, Sm)

^{252}Cf spontaneous fission yield

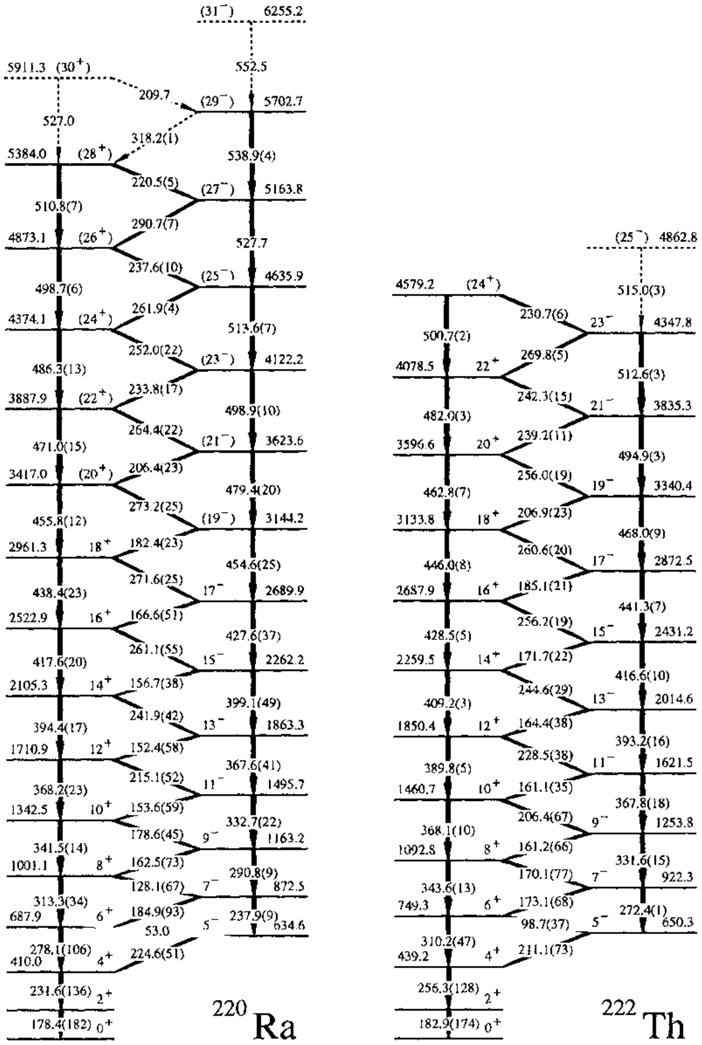
$T_{1/2}$=2.6 a   3+% fission branch



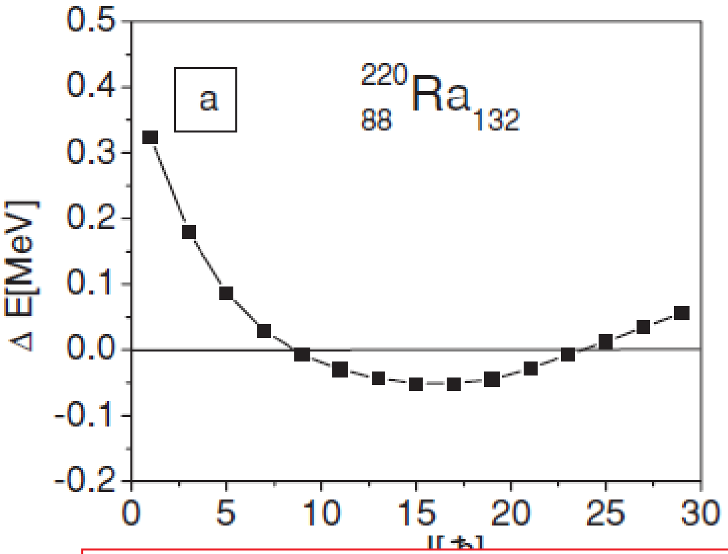


- Neutron rich region, excited states populated by spontaneous fission.
- CARIBU at ANL will provide reaccelerated beams of neutron-rich Ba isotopes for Coulomb excitation studies.

Rotation appears to stabilize static octupole shape



J. Smith *et al.,* Phys. Rev. Lett. 75 (1995) 1050.



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

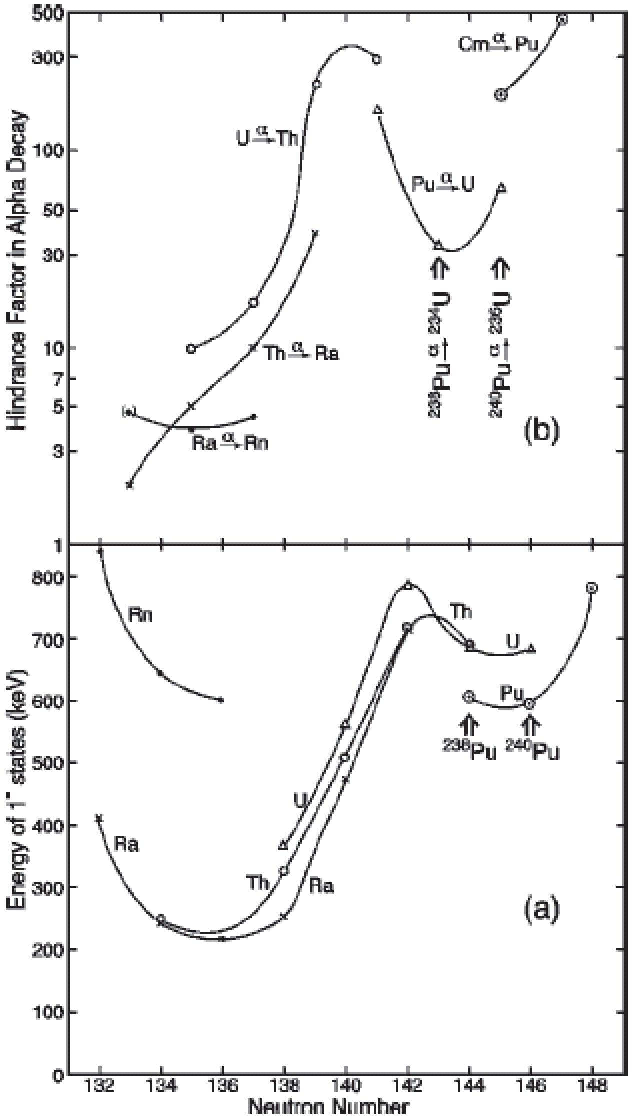
Large Dipole Moments

$D_0 \sim [B(E1)/\langle I_i 010|I_f 0\rangle]^{1/2}$

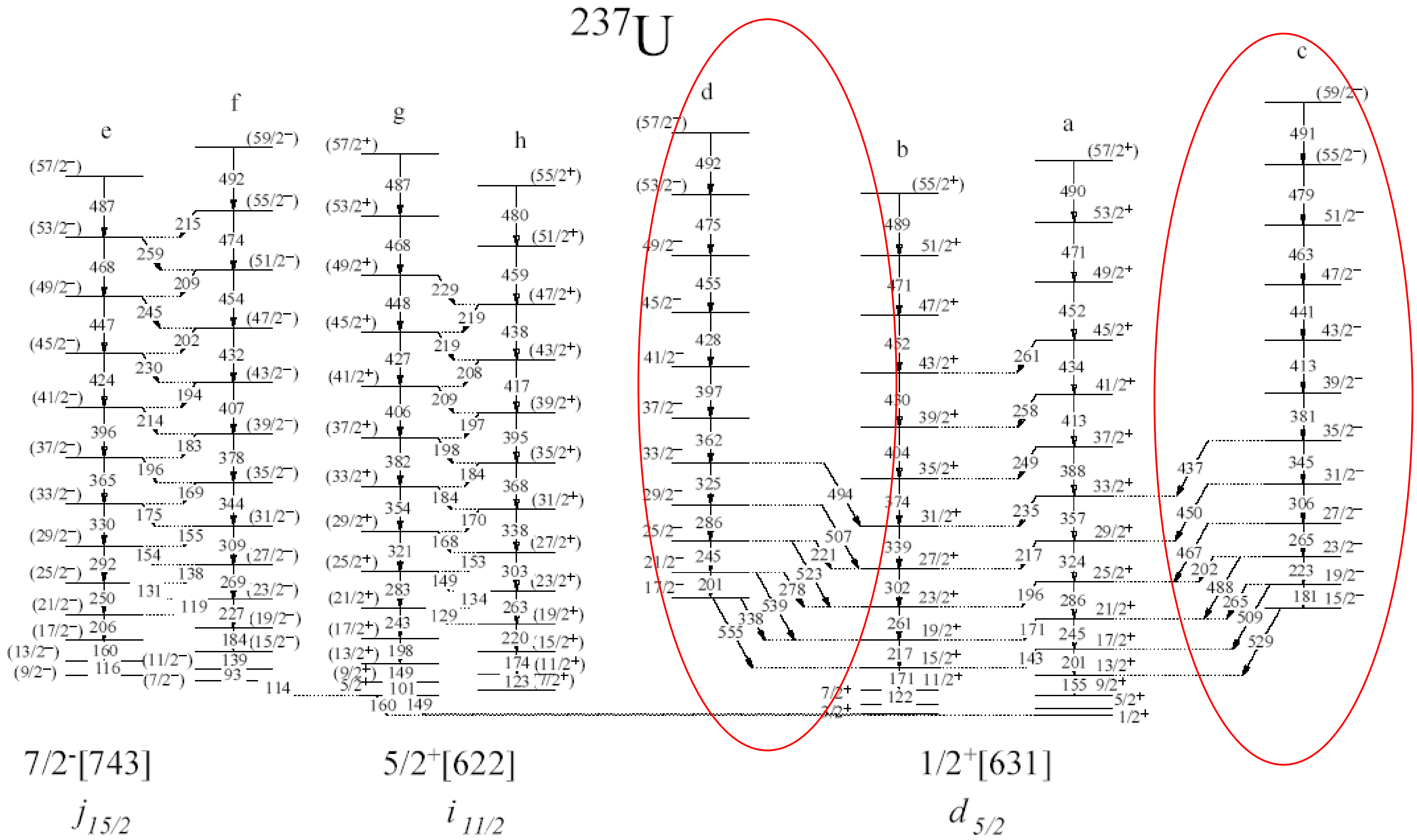
where

$D_0 > 0.2$ eb-fm

Octupole Rotation: signatures



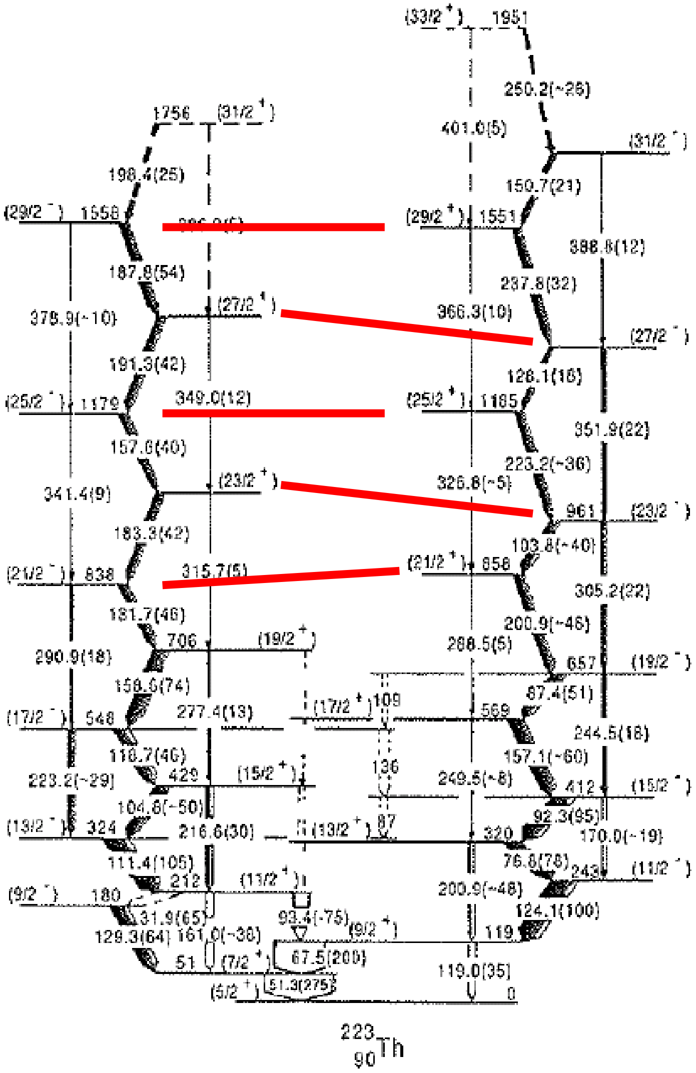
Odd-A Nuclei Exhibit Evidence of Octupole Collectivity



Octupole phonon coupled to quasiparticle

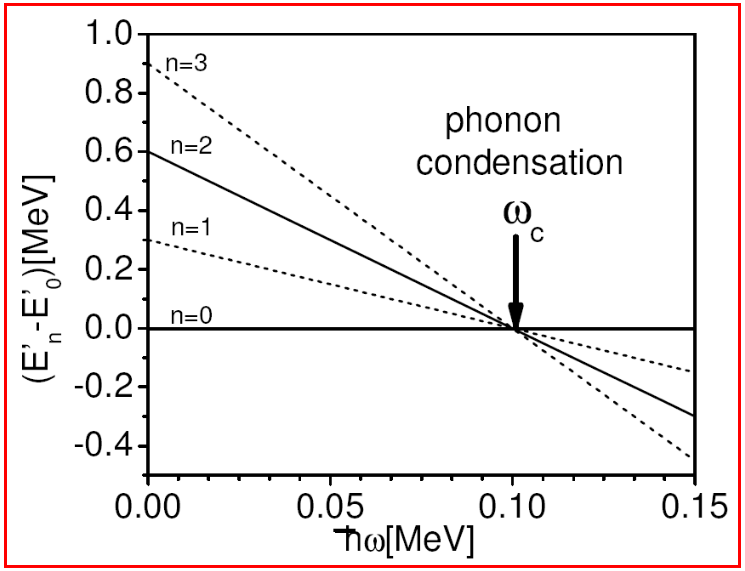
S. Zhu *et al.*, Phys. Lett. B618, 51 (2005

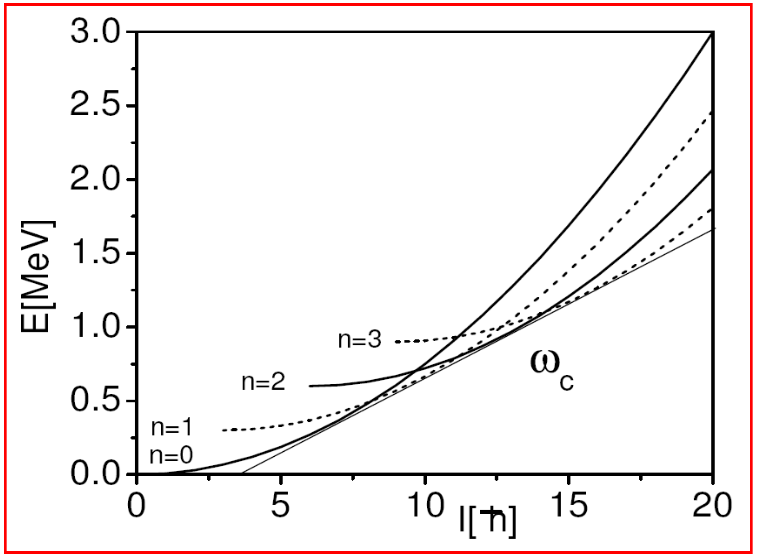
Signature of Octupole Collectivity in Odd-A Systems



Parity Doublets (Octupole deformed)

Alternative Explanation of static Octupole Deformation





Energy = Vibrational + Rotational

$$E_n = \hbar\Omega_3(n+\frac{1}{2})+\frac{1}{2}\Im\omega^2$$

Lowest excitation when phonon's align with rotational axis.

$$E_n'(\omega) = \hbar\Omega_3(n+\frac{1}{2})-ni\omega-\frac{1}{2}\Im\omega^2$$

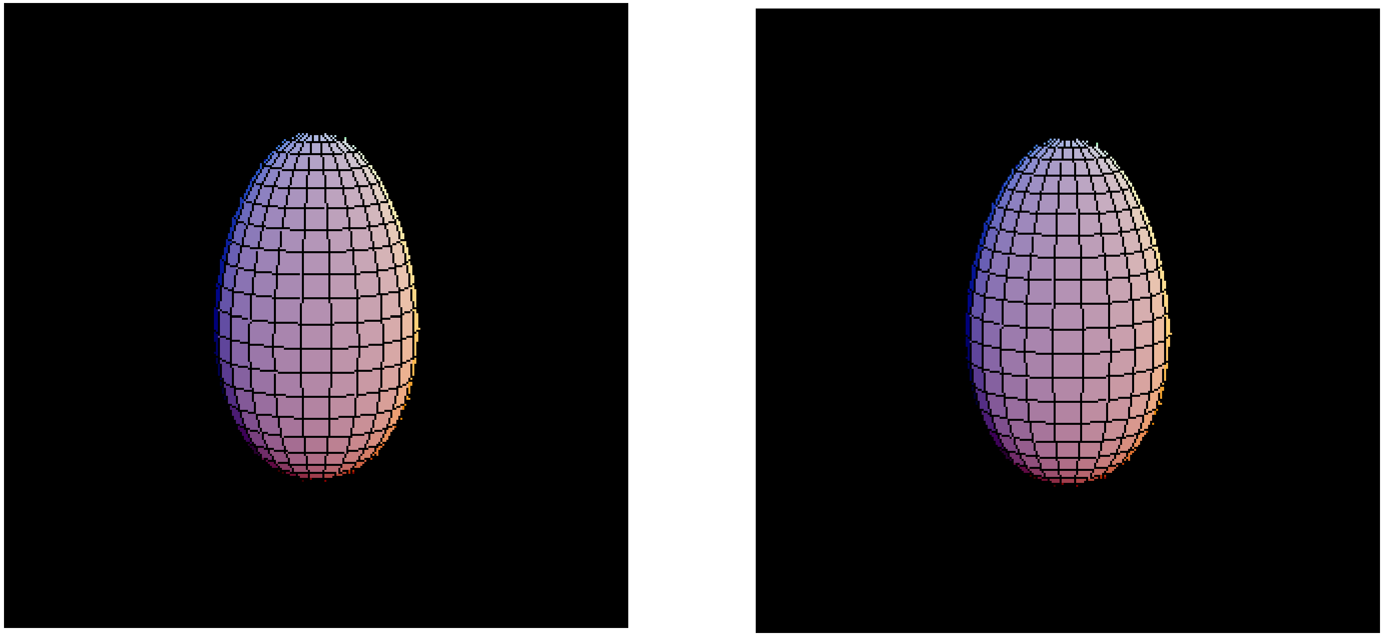
At critical frequency, ω_c, all phonon Routhians converge resulting in phonon condensation.

$$\omega_c = \Omega_3 / i$$

$$\omega_c : E_n(\omega) = E_{n+1}(\omega)$$

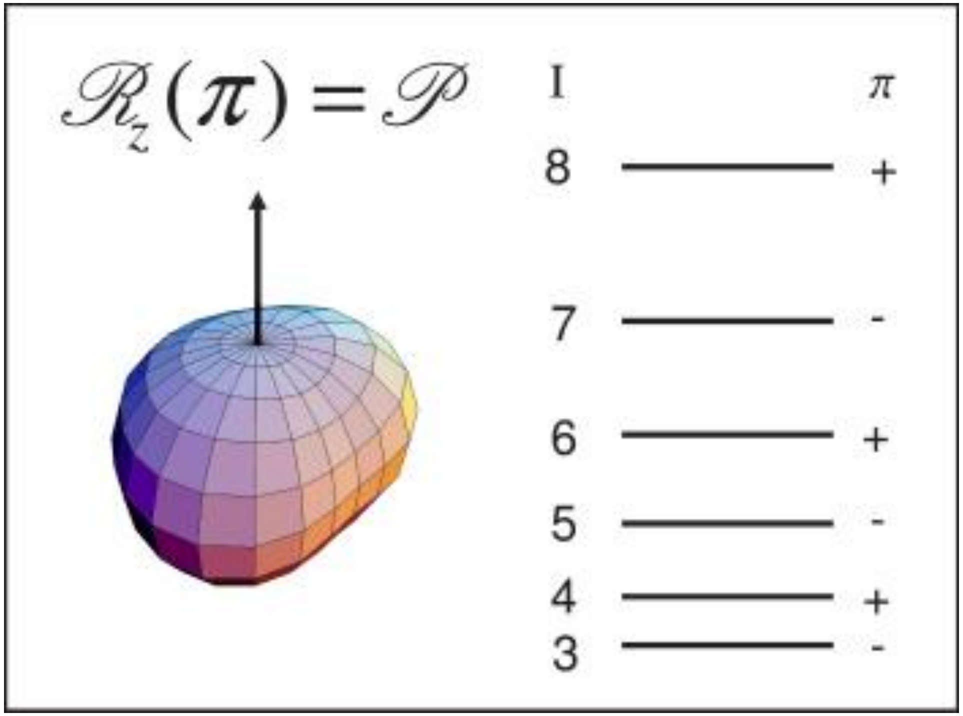
S. Frauendorf, Phys Rev. C 77 (2008) 021304(R).

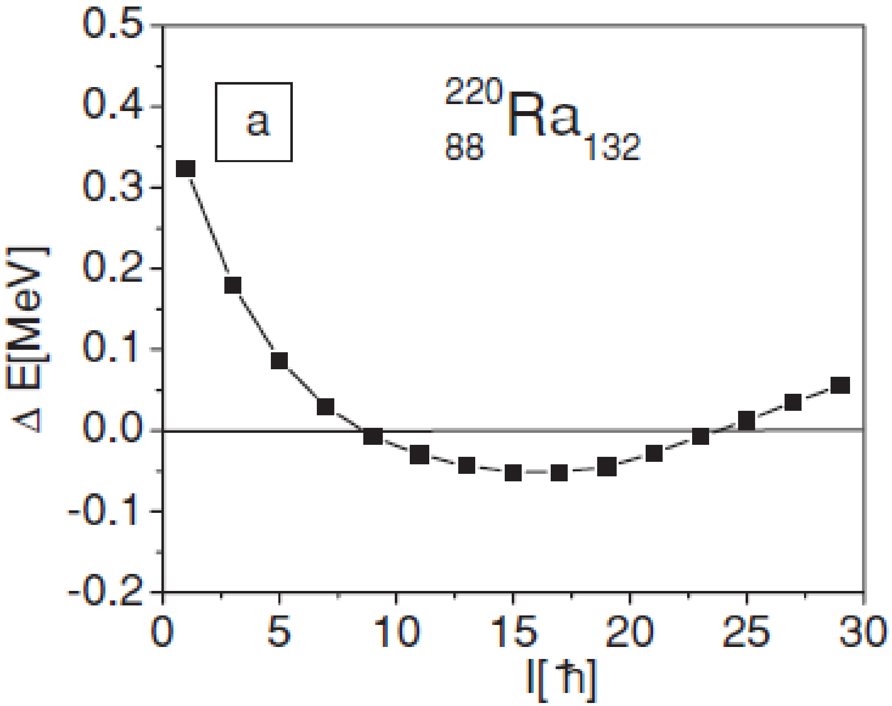
What is the Resultant Shape at Condensations



$$\omega_c = \Omega_3 / 3$$

Consequence of Anharmocities.

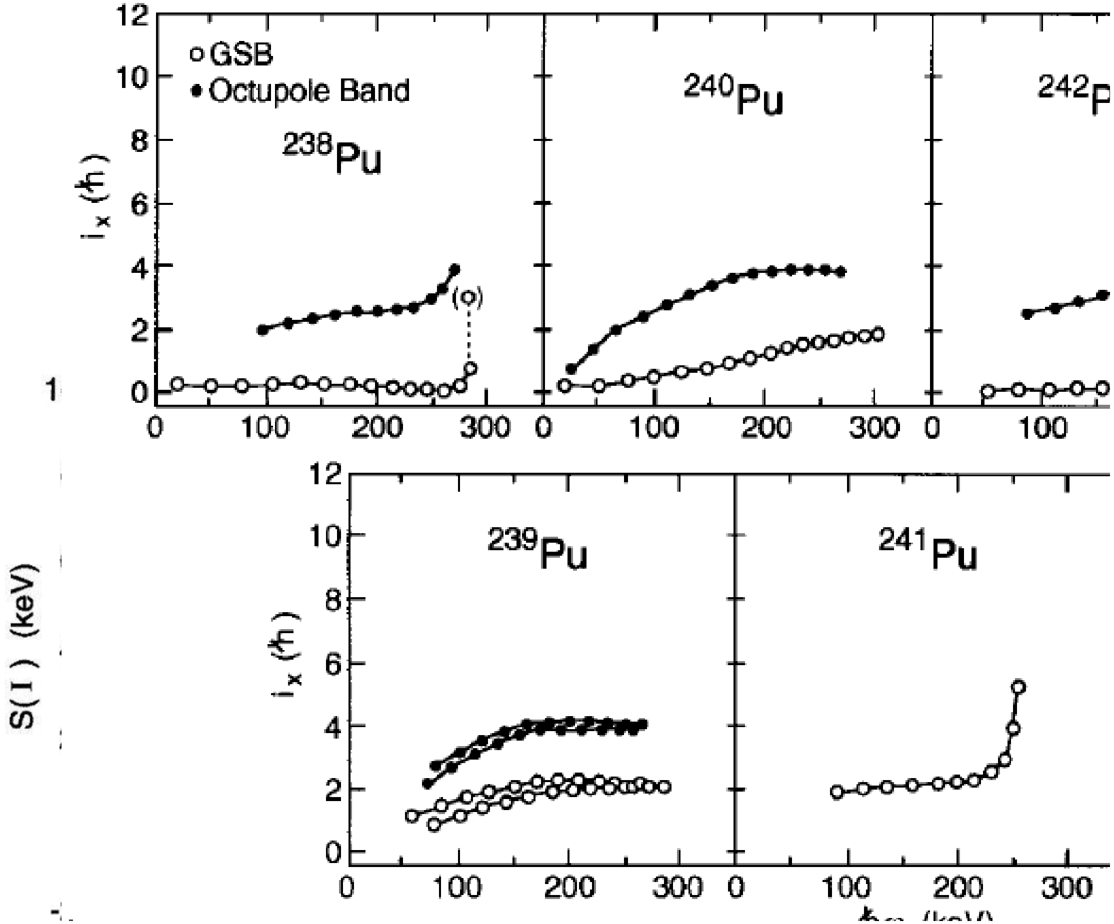


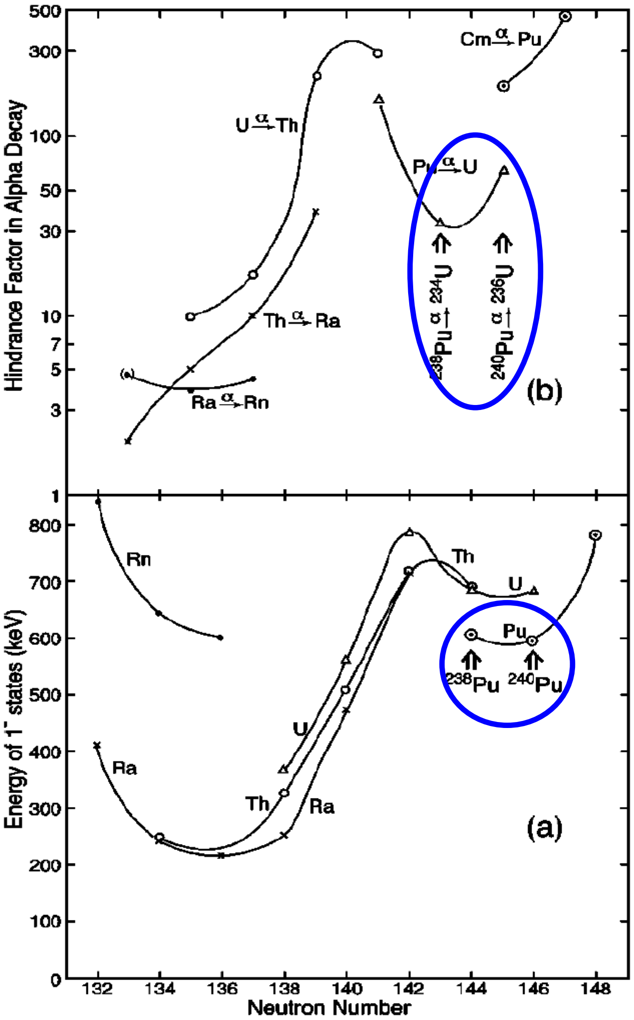


- Due to anharmocities, phonons bands will cross at different frequencies
- Phonon’s of same parity will interact.
- Resulting yrast line will have states on average which appear to be interweaved as expected for static octupole shape.

S. Frauendorf, Phys. Rev. C 77 021304(R).

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

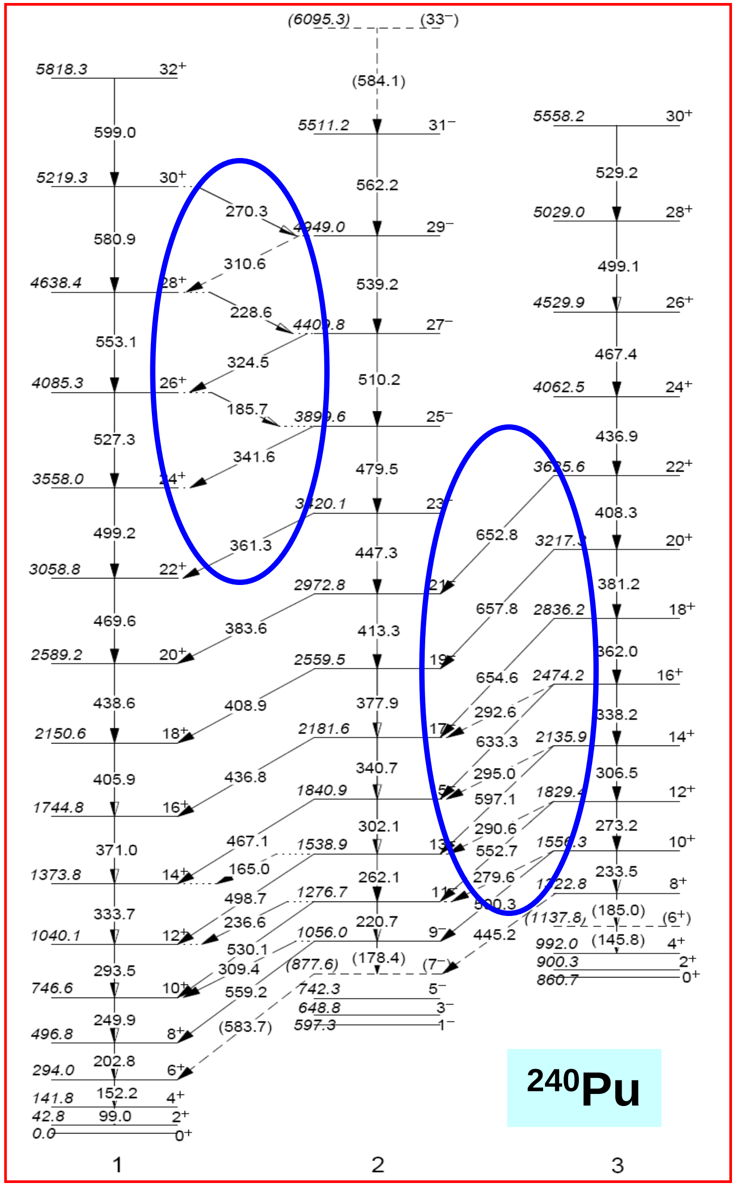
. Wiedenhöever et al., Phys. Rev. Lett. 83, 2143 (1999).
S. Zhu et al., Phys. Lett. B618, 51 (2005).
R. K. Sheline & M. A. Riley, Phys. Rev. C 61, 057301 (2000).

Can One Distinguish Between the Two Pictures?

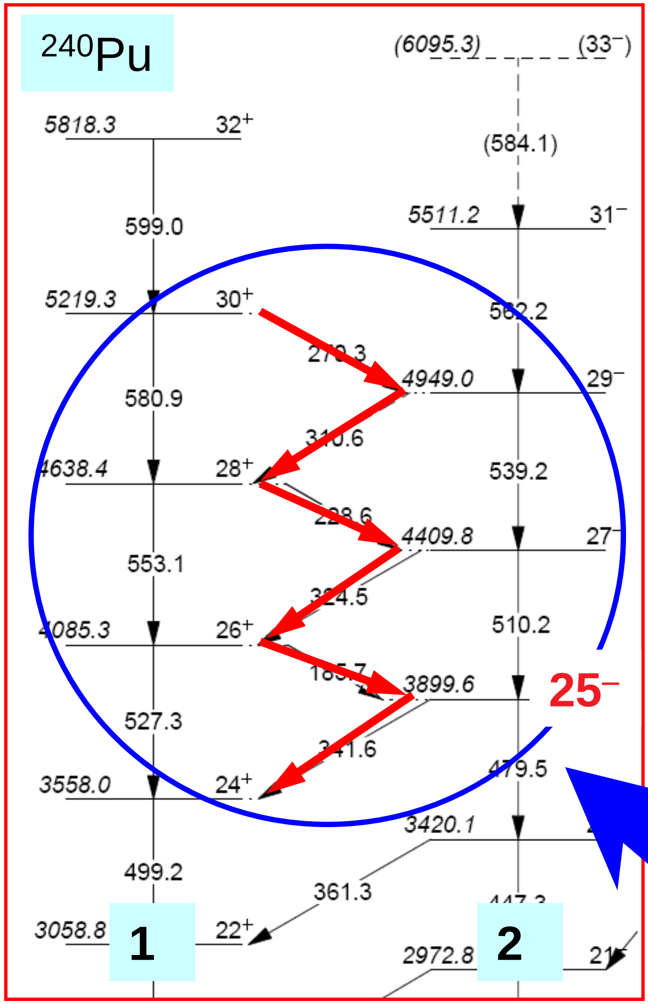
New Results on ^{240}Pu

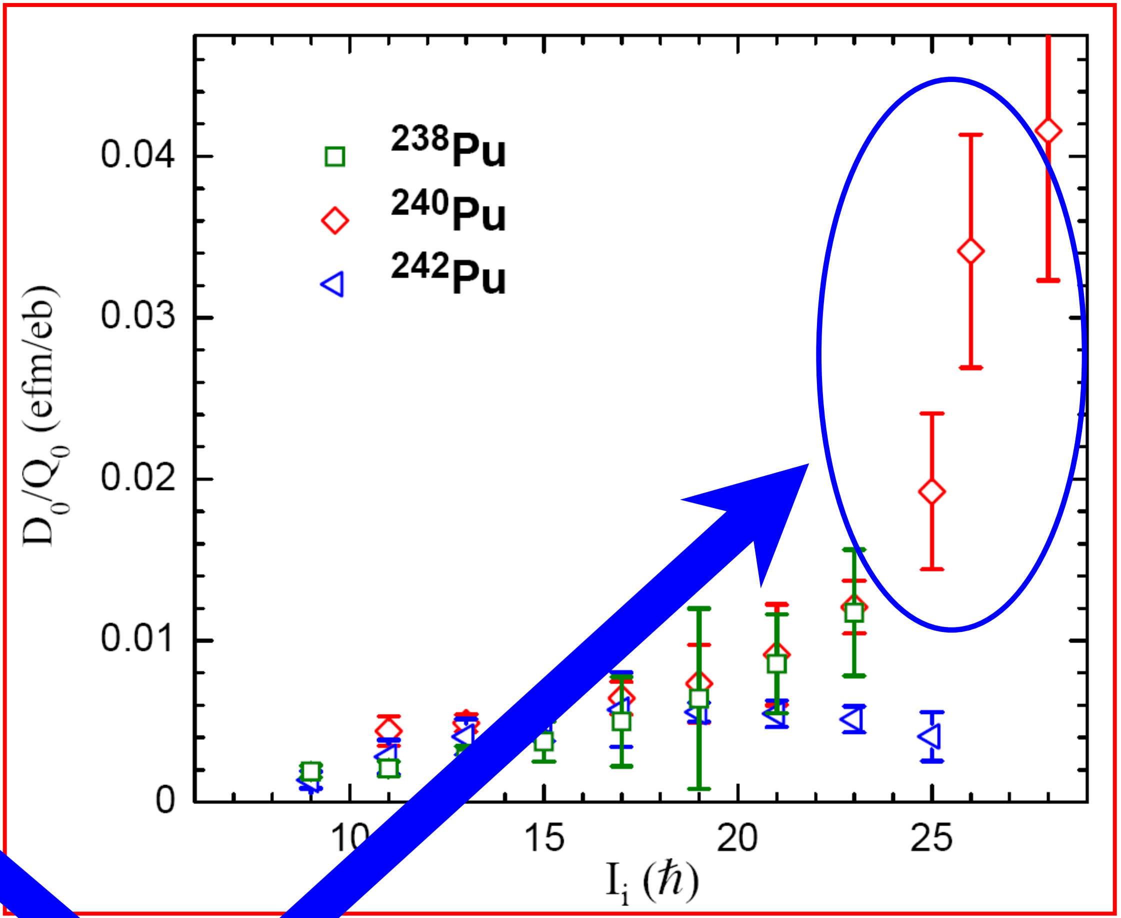
- Interleaving E1 transitions now observed between yrast (1) and octupole (2) bands.
- Positive parity band built on 0^+ state at 861 keV is observed to high-spin.
  - Competes in excitation energy with yrast band.
  - Decays exclusively to octupole band
  - Large B(E1)/B(E2) ratios: ~1×10^{-8} fm^{-2}
  - Band with these characteristics not seen before

X. Wang *et al.*, Phys. Rev. Lett. 102, 122501 (2009)



Dipole Moment at High-Spin is Large

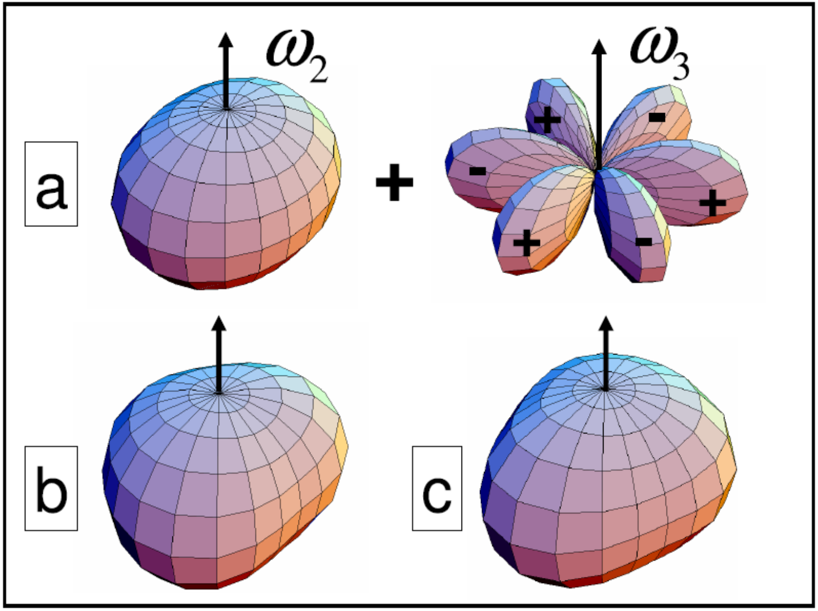




D_0 > 0.2 e fm (assuming Q_0 ~ 11eb)

X. Wang *et al.*, Phys. Rev. Lett. 102 122501 (2009)

Evidence for Octupole Condensation?

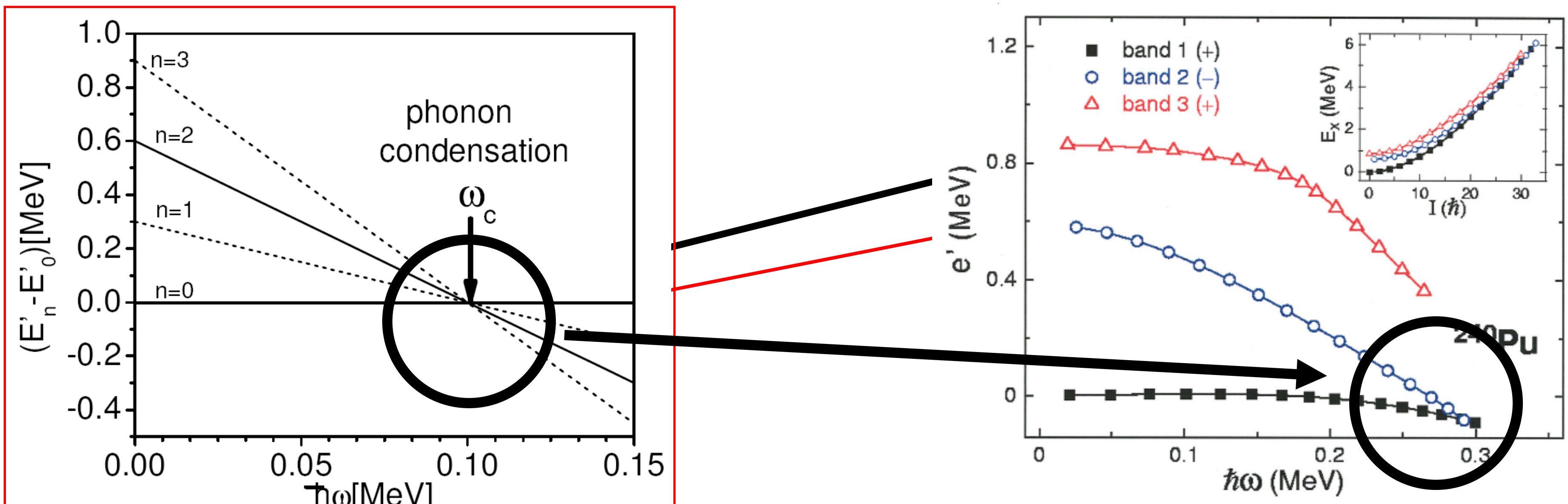


Octupole Condensation concept:

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

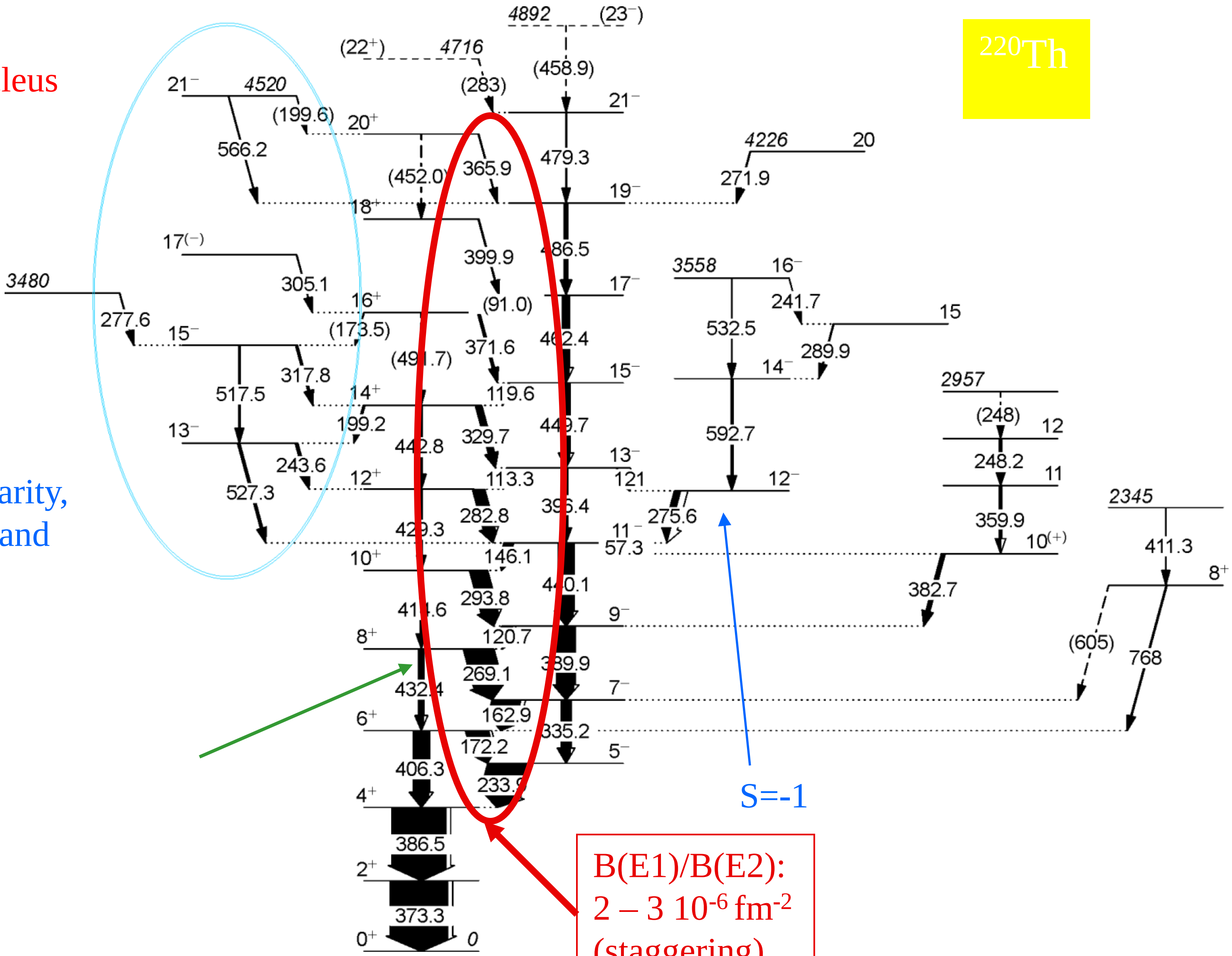
Accounts for observations, i.e., bands, energies, alignments, branching ratios etc.



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

Octupole Correlations: Generalization of Picture → Tidal Waves

Vibrational nucleus



^{220}Th

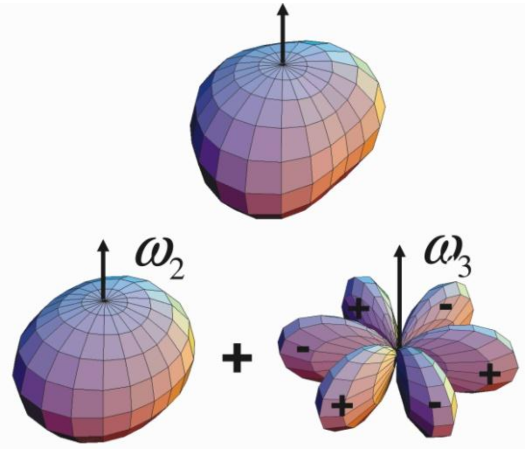
second negative-parity, odd-spin band

S=-1

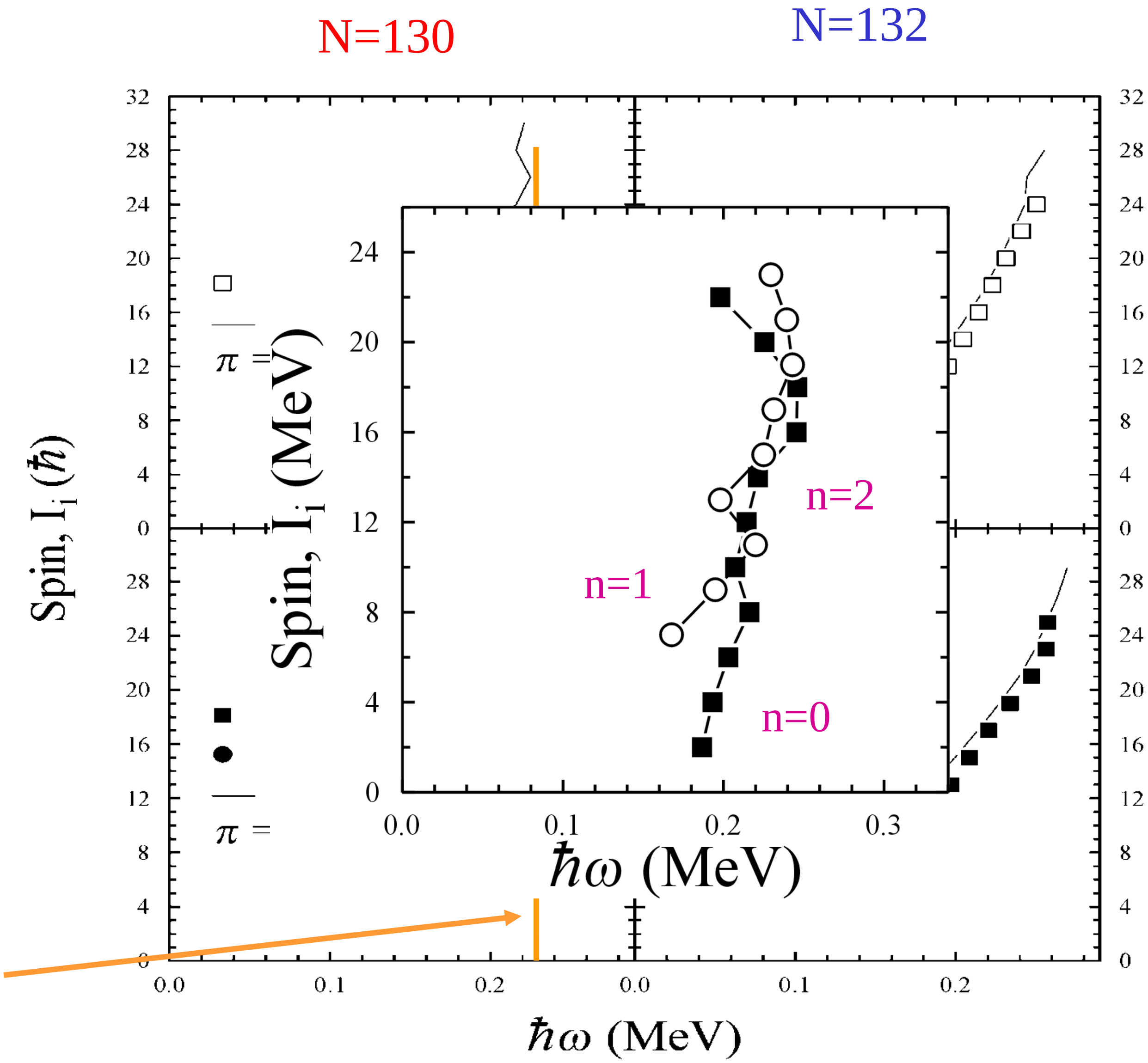
B(E1)/B(E2):
2 – 3 10^{-6} fm^{-2}
(staggering)

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$\Delta E_{\Delta I=3}$

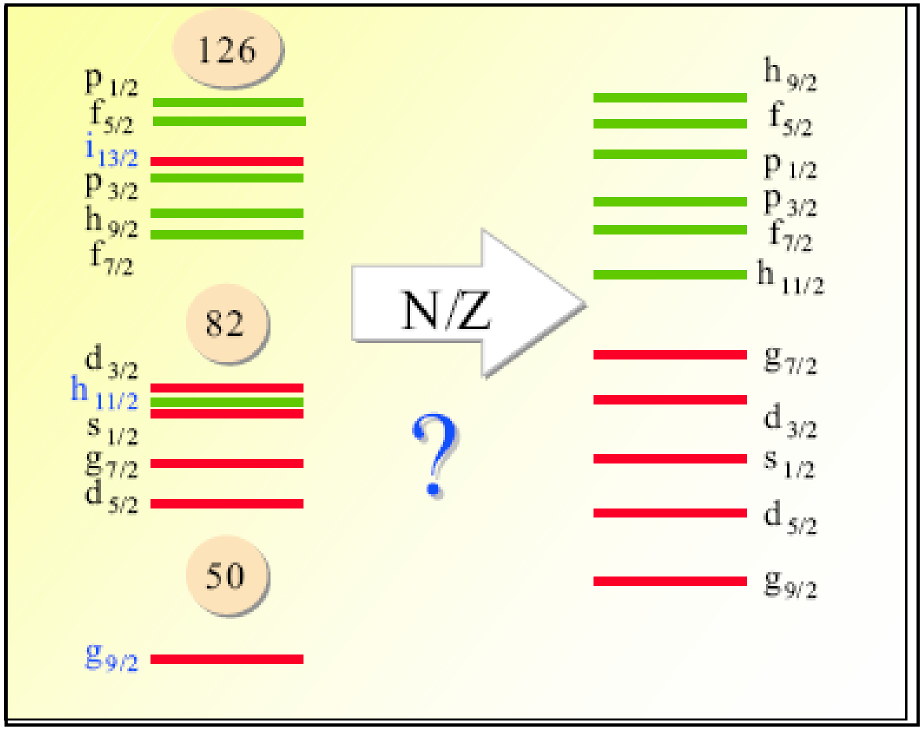


$h\omega_c$ = 0.21 MeV
(constant ω)

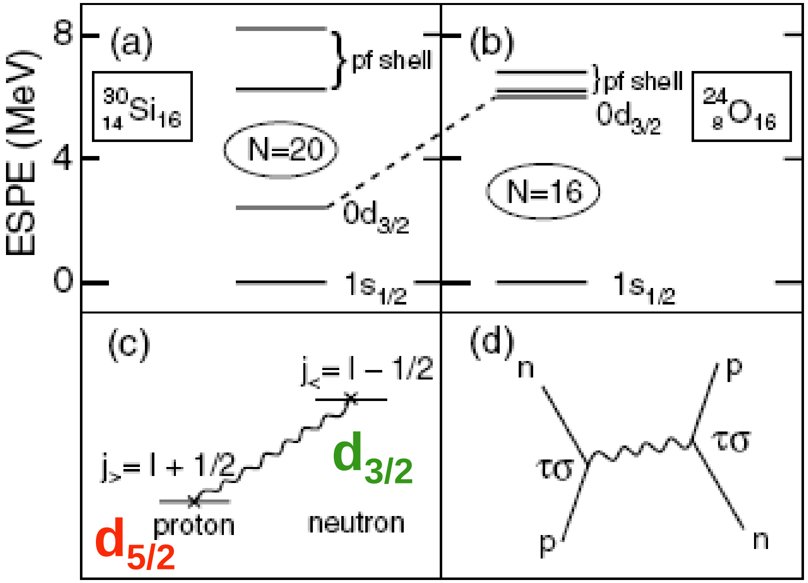
High Spinners Can Study Neutron Rich Nuclei Too!

Modification or Disappearance of Shell Gaps

T. Otsuka et al., Phys. Rev. Lett. 87 (2001), 082502.



known ***predicted***

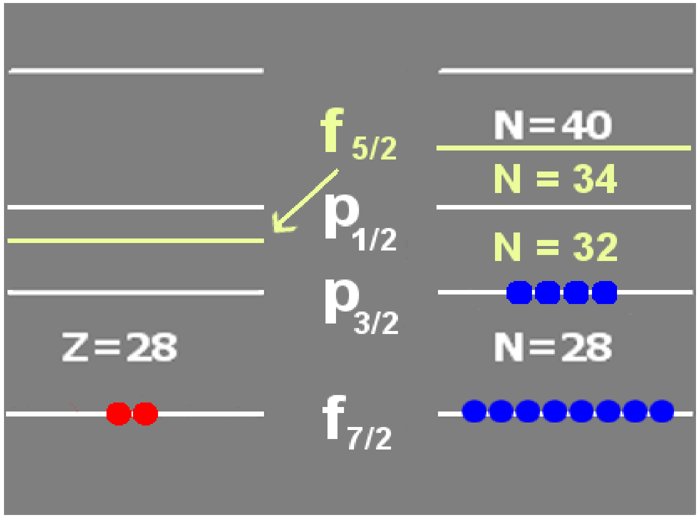


$$V_{\tau\sigma} = \tau\cdot\tau\sigma\cdot\sigma f_{\tau\sigma}(r).$$

Explains why $^{24}O_{16}$ is heaviest bound oxygen isotope and not $^{28}O_{20}$

Explains why $^{32}Mg_{20}$ is deformed and not spherical.

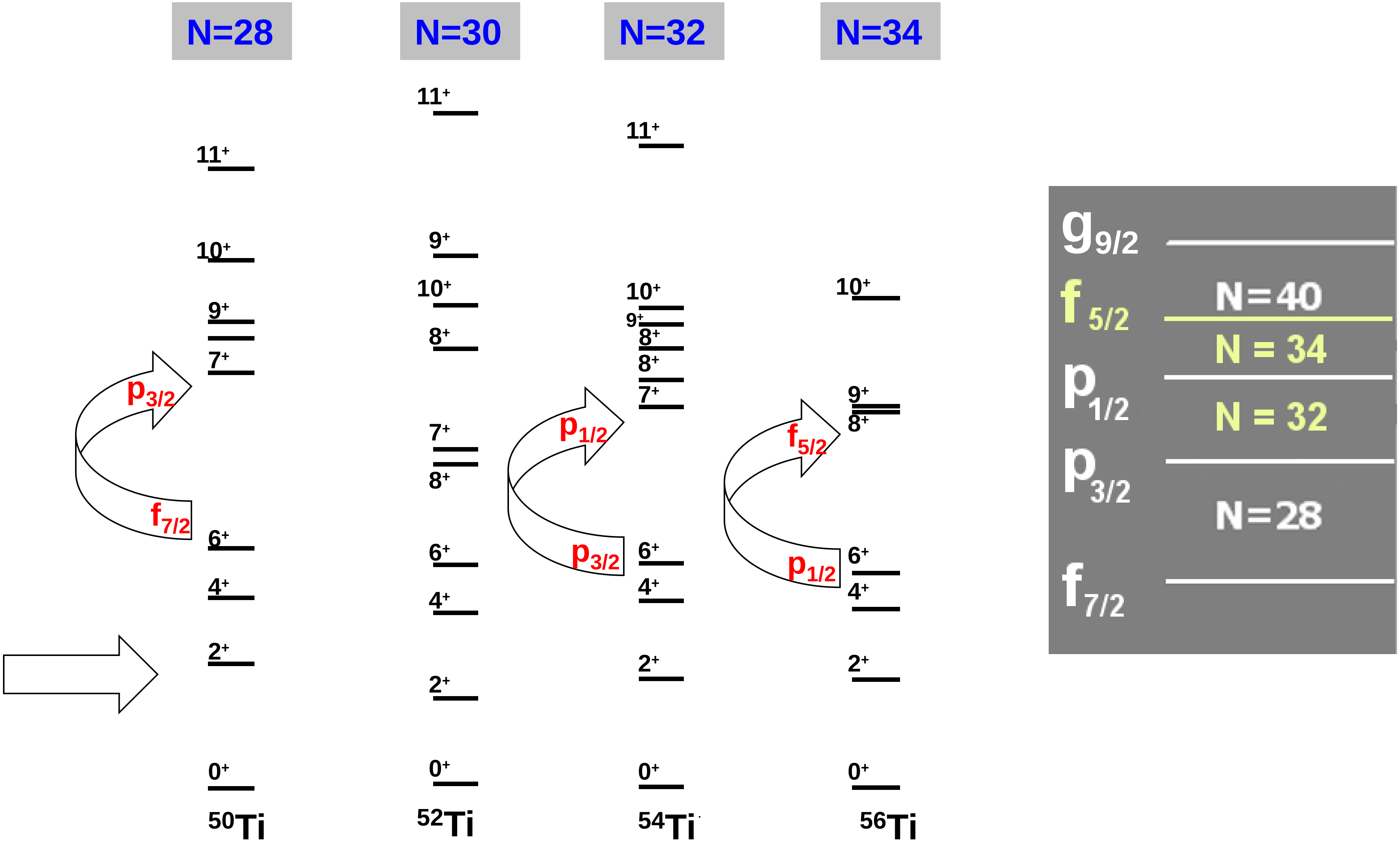
Do New Shell Gaps Develop in the f-p Shell?



Removal of protons from $f_{7/2}$ shell weakens the $\pi f_{7/2}$-$\nu f_{5/2}$ monopole interaction strength, resulting in the $\nu f_{5/2}$ orbital pushing up in energy.

Opens possibility for shell gaps at N = 32, 34.

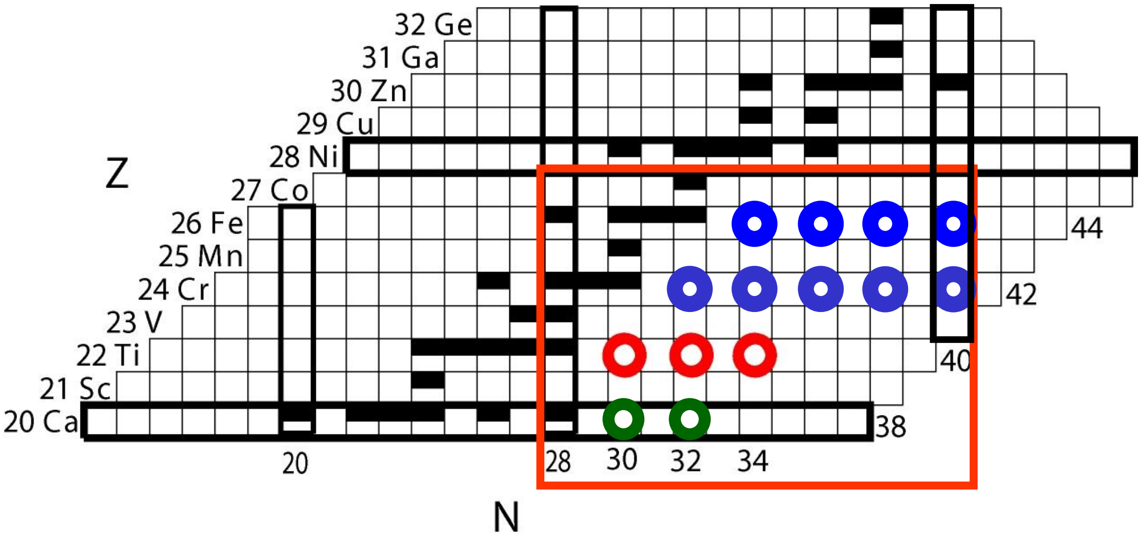
Shell Model Predictions using GXPF1 Interaction



M. Honma et al., Phys. Rev. C**65** (2002) 061301(R)

Studies of Ca-Ni Neutron Rich Isotopes:

- Collaboration began 2001 between ANL, NSCL, Krakow, Manchester, Maryland
- Data obtained at several different facilities (NSCL and ATLAS) utilizing different techniques to excite the nucleus and measure the γ decay:

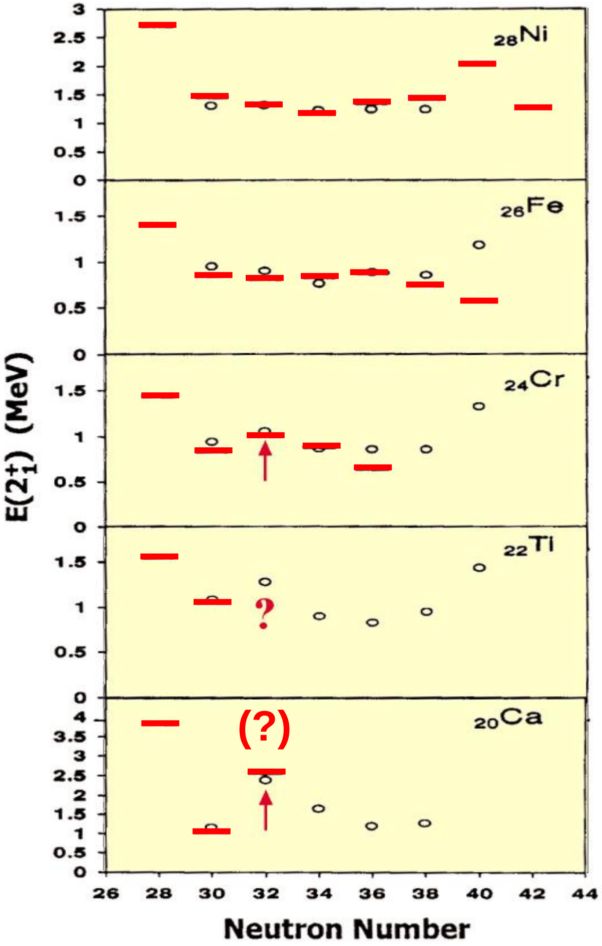


What is the evidence of new shell gaps at N=32 and 34 for Z<28.

How robust is the N=40 gap for Z<28?

Experiment Evidence for N=32 Gap (circa 2001)

J.I. Prisciandaro *et al*., PLB **501**, 17 (2001)



First Results on neutron rich ^{54}Ti (N=32):

R.V.F. Janssens *et al*., PLB 546, 22 (2002)

Before this investigation, very little known about ^{54}Ti.

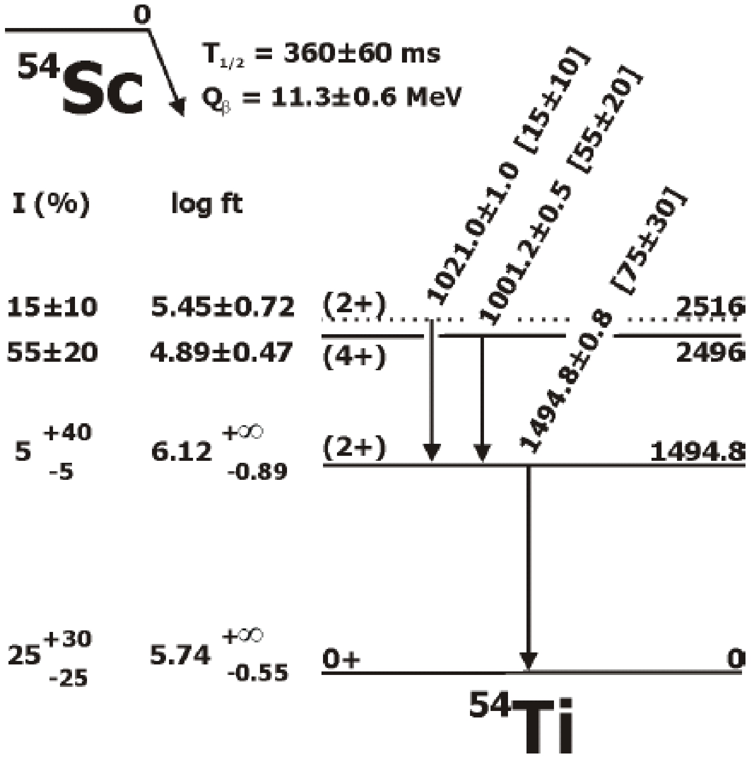
Two experiments undertaken to study properties of ^{54}Ti.

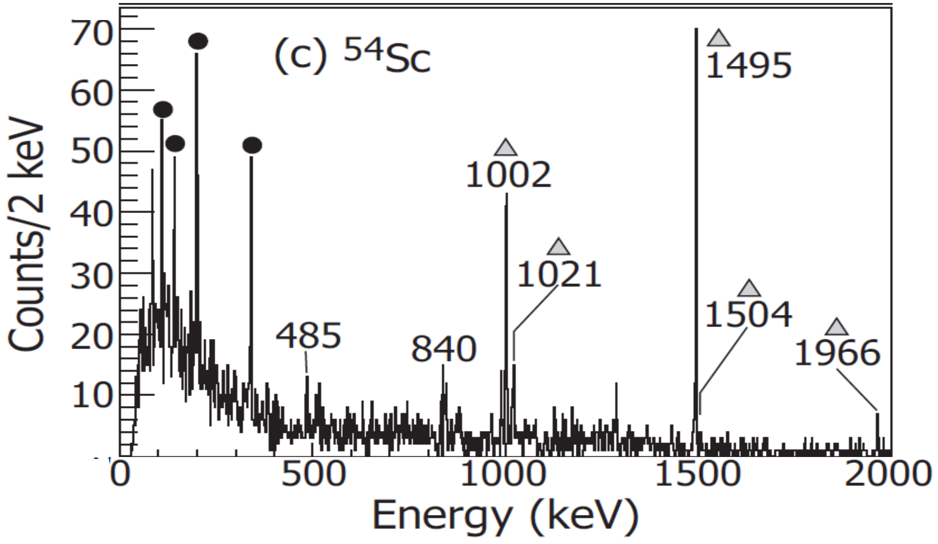
Beta decay of ^{54}Sc at NSCL *production of ^{54}Sc from fragmentation of a ^{86}Kr beam*

In-beam spectroscopy with Gammasphere utilizing the reaction ^{48}Ca + ^{208}Pb *production of ^{54}Ti via a deep inelastic reaction instead of fusion-evaporation)*

^{54}Sc b-Decay Results (NSCL)

Production rate: 0.5 ^{54}Sc/s





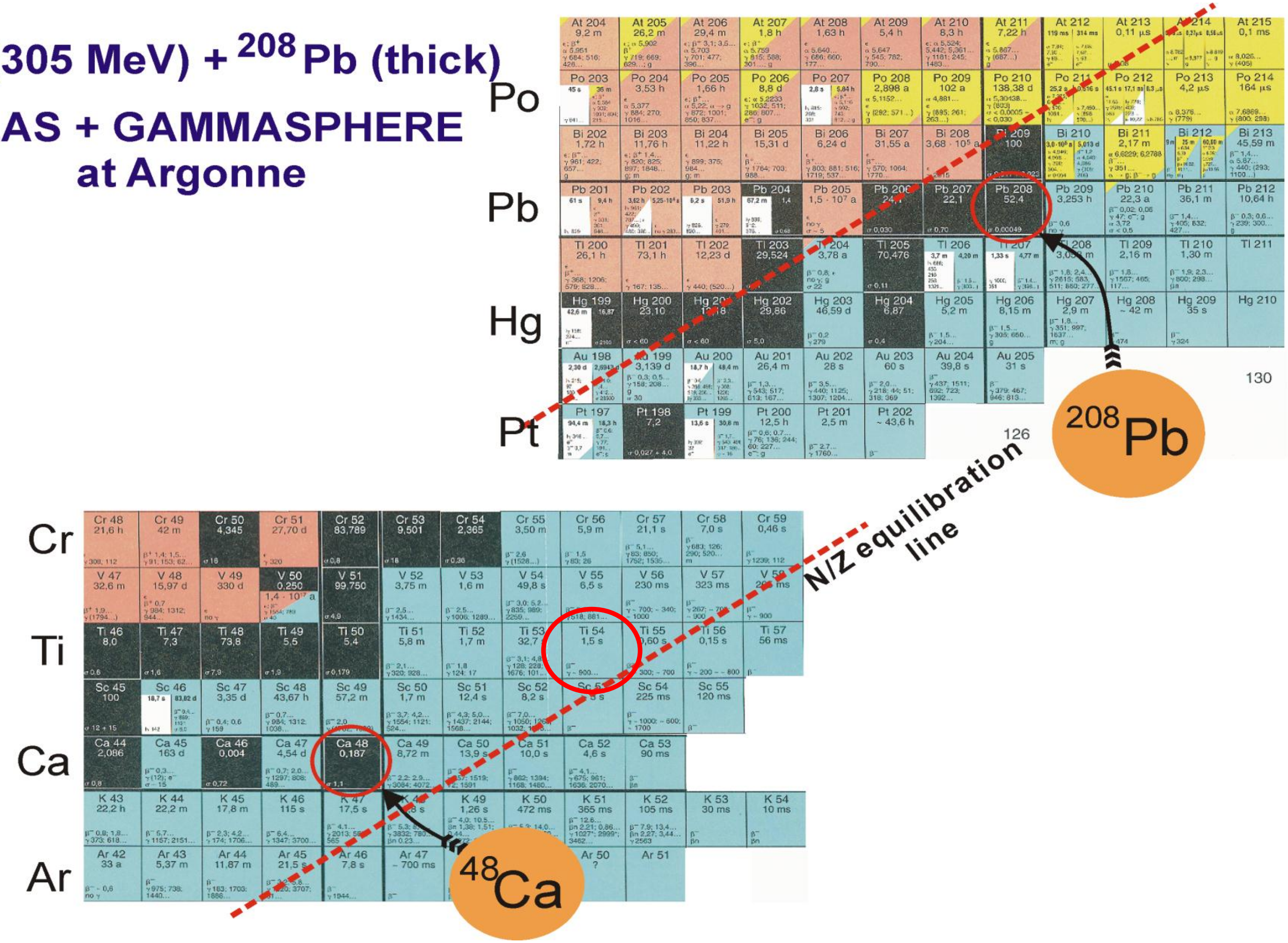
H.L. Crawford *et al.*,

Phys. Rev. C 82 (2010) 014311

Deep-inelastic data: Quest for ^{54}Ti

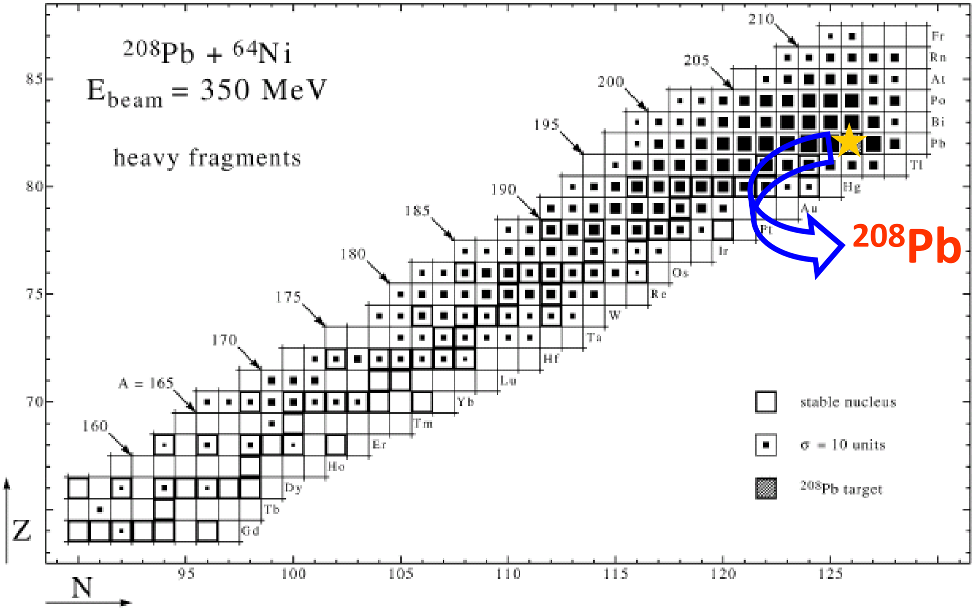
^{48}Ca (305 MeV) + ^{208}Pb (thick)

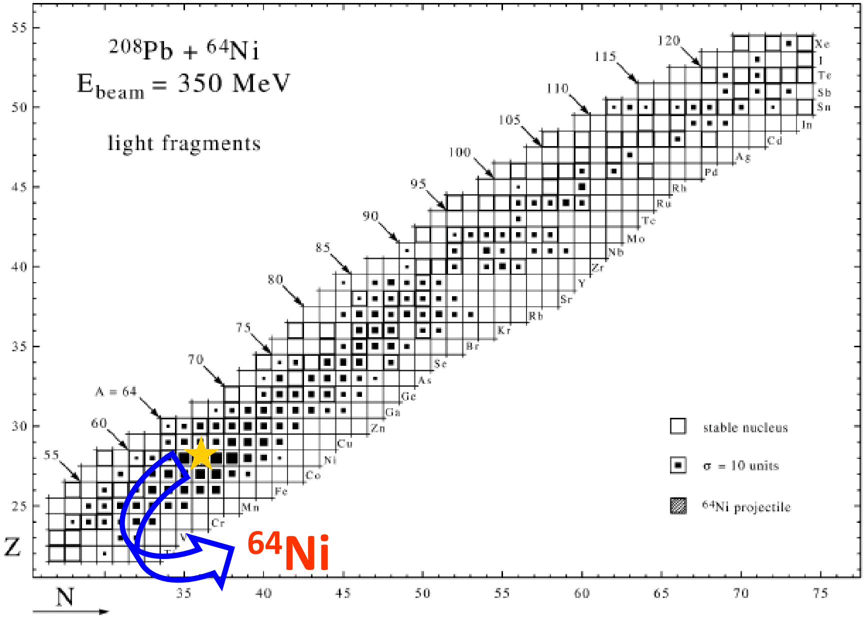
ATLAS + GAMMASPHERE
at Argonne



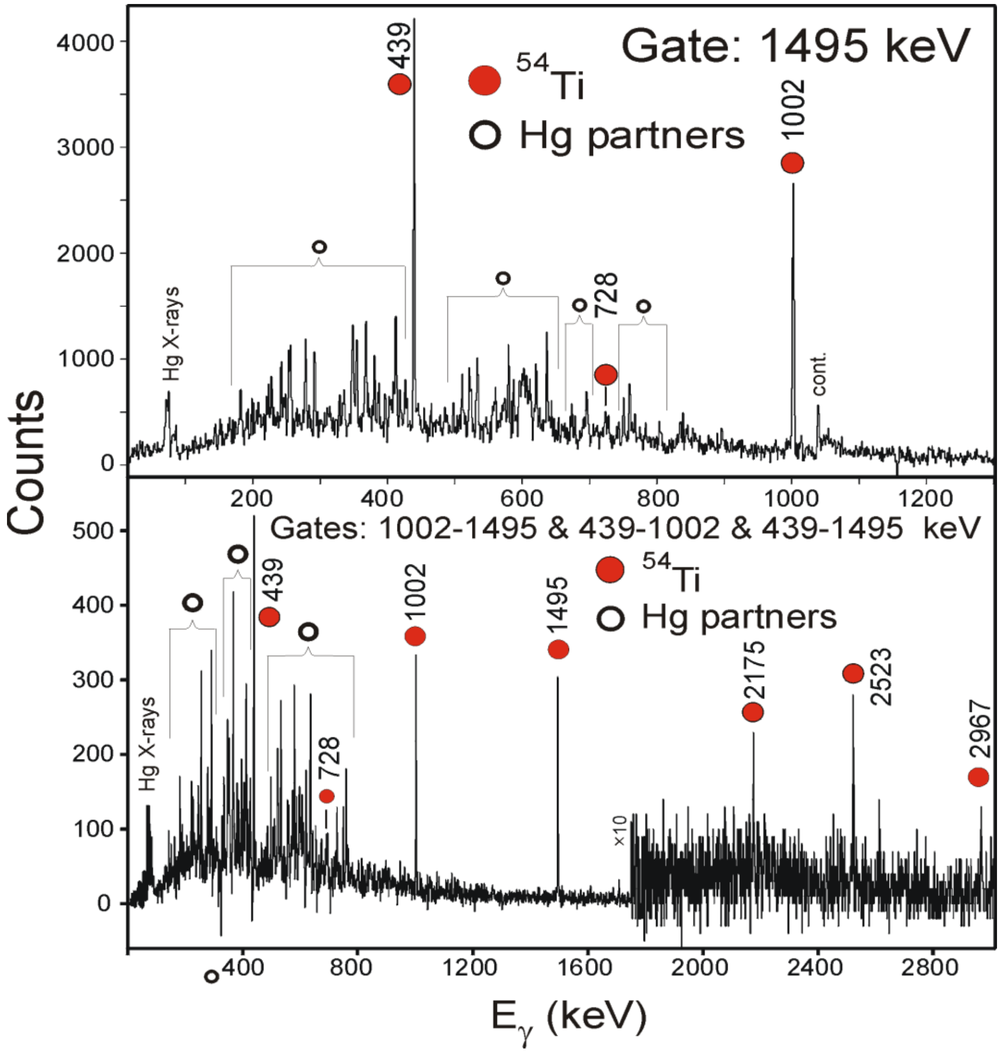
Identified Products from ^{208}Pb + ^{64}Ni @ 350 MeV

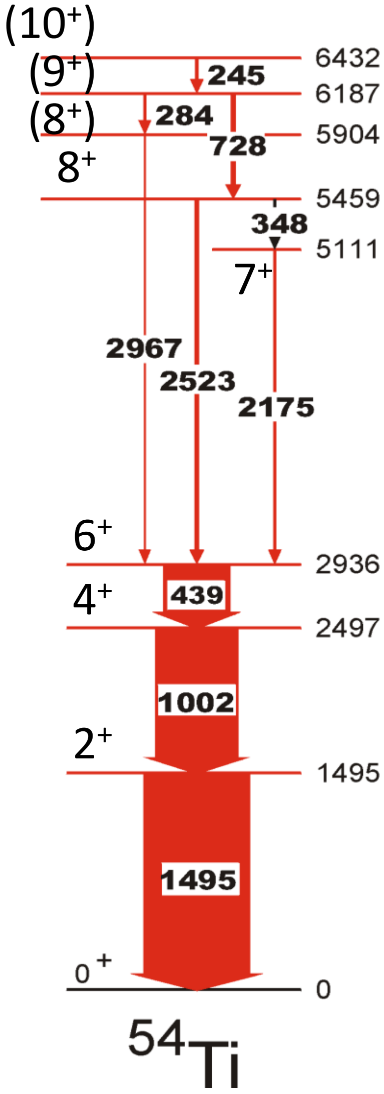
W. Królas, R. Broda, B. Fornal , T. Pawłat, H. Grawe, K.H. Maier M. Schramm, R. Schubart, Nucl. Phys. **A724** (2003) 289.





^{54}Ti results from ^{48}Ca + ^{208}Pb deep inelastic reaction measured with Gammasphere

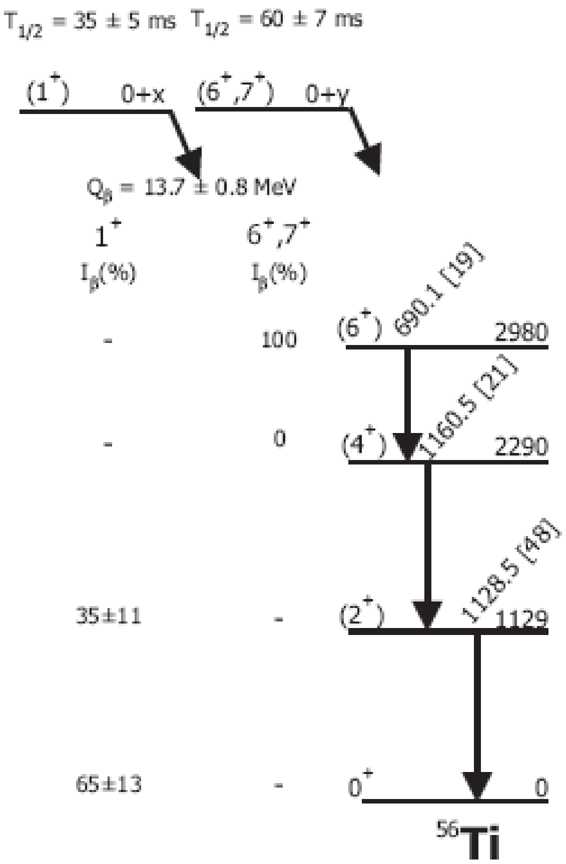




R.V.F. Janssens *et al*., PLB 546, 22 (2002)

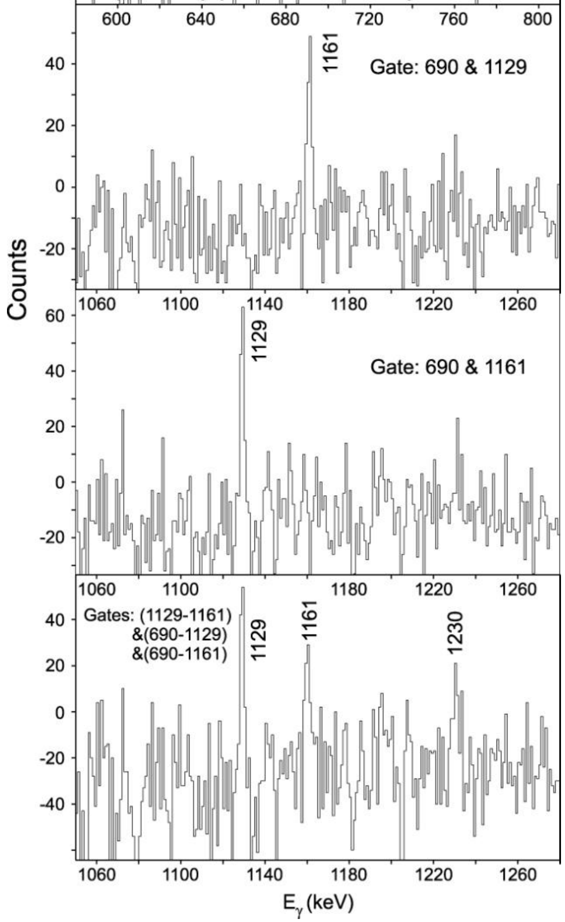
Similar set of experiments on ^{56}Ti

^{56}Sc decay at NSCL with SeGa



S. Liddick *et al.*, PRC 70, 064303 (2004)

^{48}Ca + ^{238}U @ ATLAS with Gammasphere



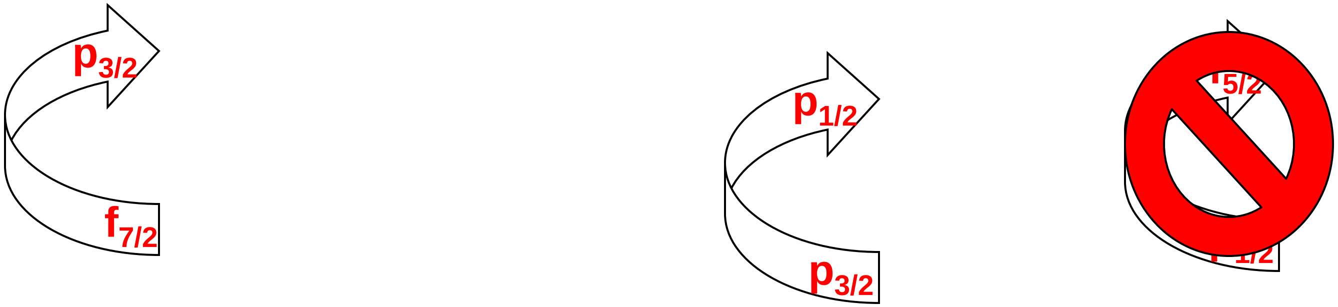
B. Fornal *et al.*, PR.C **70**, 064304 (2004)

The Ti story: N=32 shell gap, N=34 no gap.

28

32

34



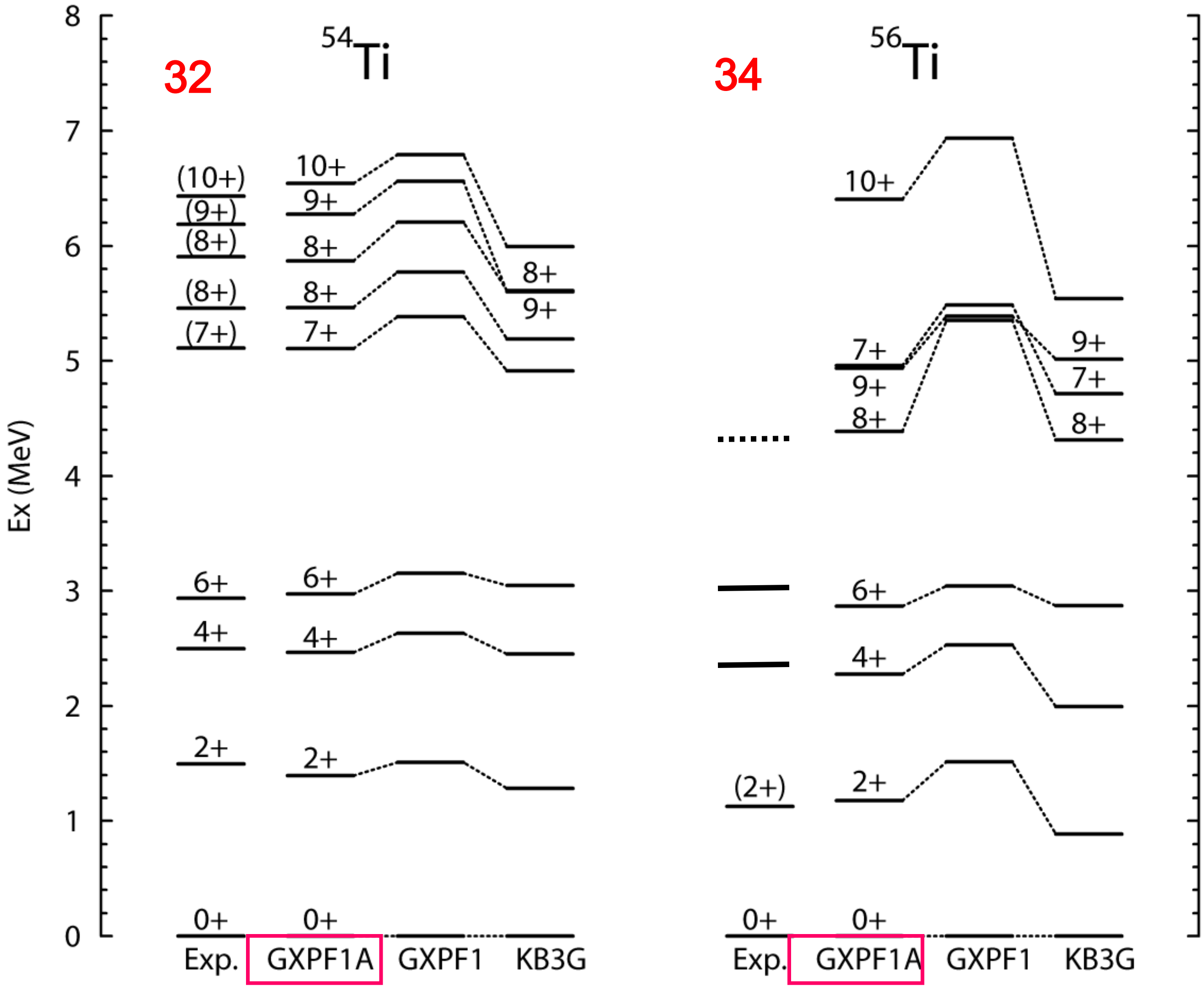
Theory Development: GXPF1A

<u>GXPF1A vs GXPF1:</u>

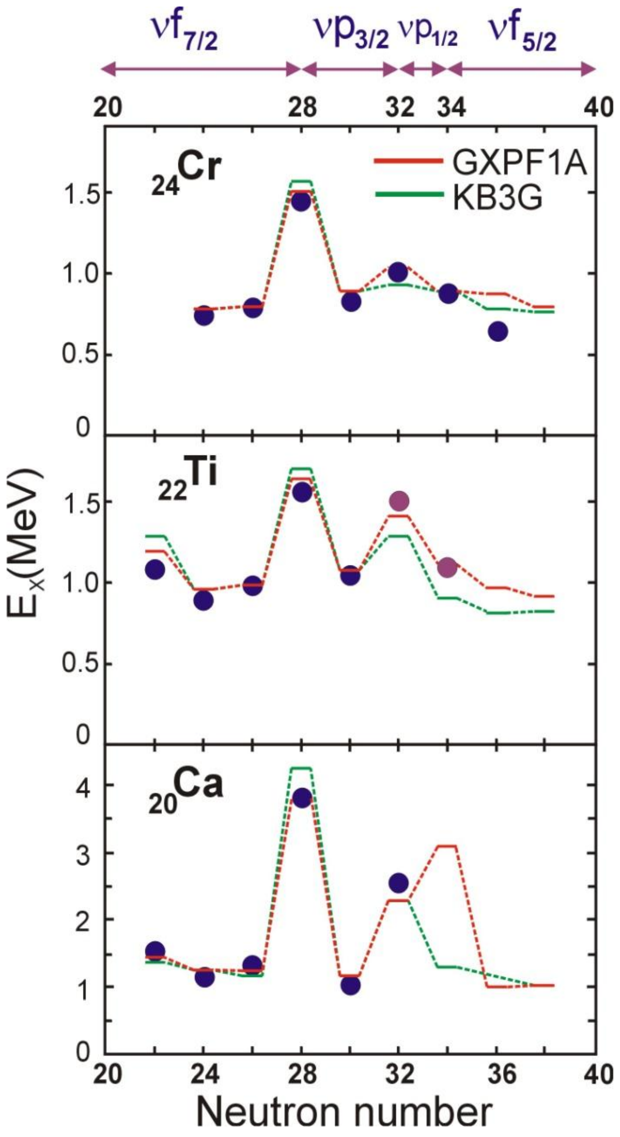
T=1 matrix elements involving ***$\nu p_{1/2}$ and $\nu f_{5/2}$ modified***

→

($\nu p_{1/2}$ - $\nu f_{5/2}$) gap reduced by ~0.5 MeV



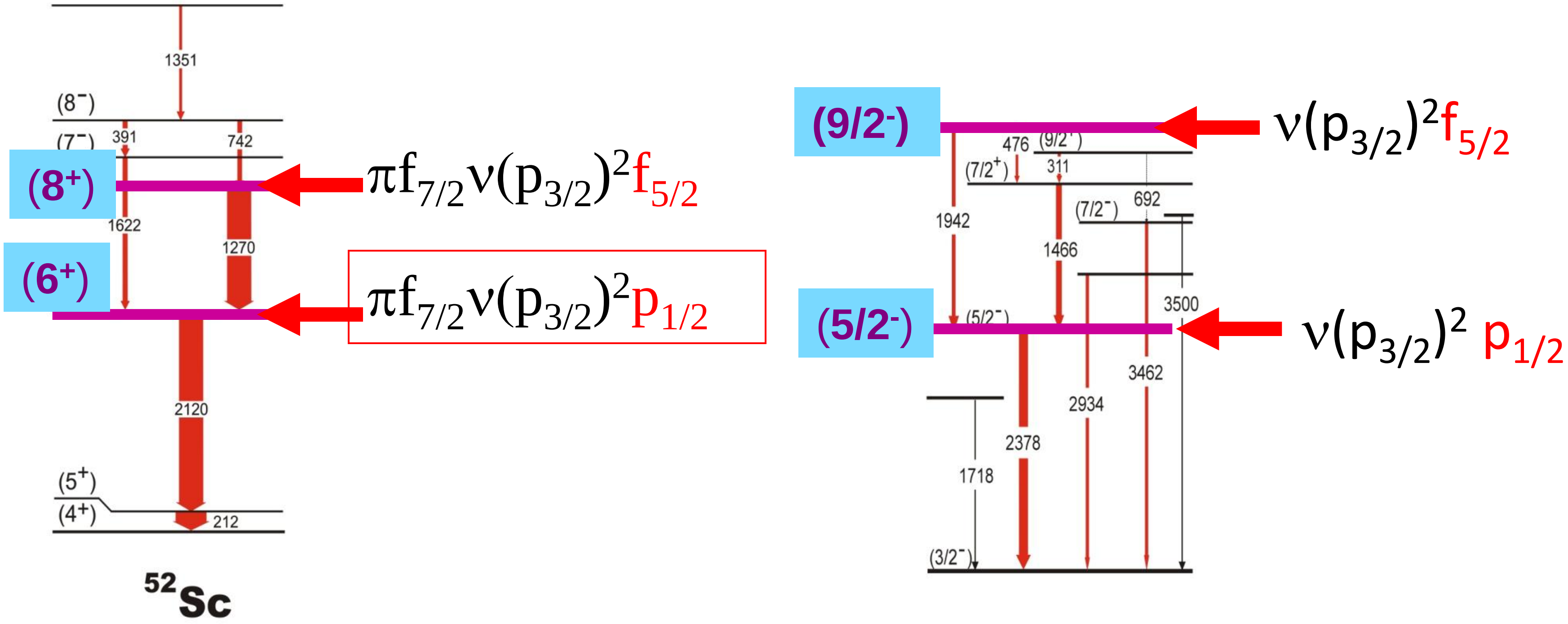
Is there a *N* = 34 gap for ^{54}Ca between $f_{5/2}$ and $p_{3/2}$?



- No evidence of shell gap at N=34 for Cr or Ti isotopes.
- Shell model calculations using GXPF1A predict sizeable shell gap for ^{54}Ca (N=34).
- Shell model calculations using KB3G interaction predict no neutron shell gap for ^{54}Ca.
- No experimental data available on ^{54}Ca excited states

Is there a N = 34 gap for ^{54}Ca between $f_{5/2}$ and $p_{3/2}$

B. Fornal *et al*., Phys. Rev. C 77, 014304 (2008)



(8^+) $\pi f_{7/2}\nu(p_{3/2})^2 f_{5/2}$

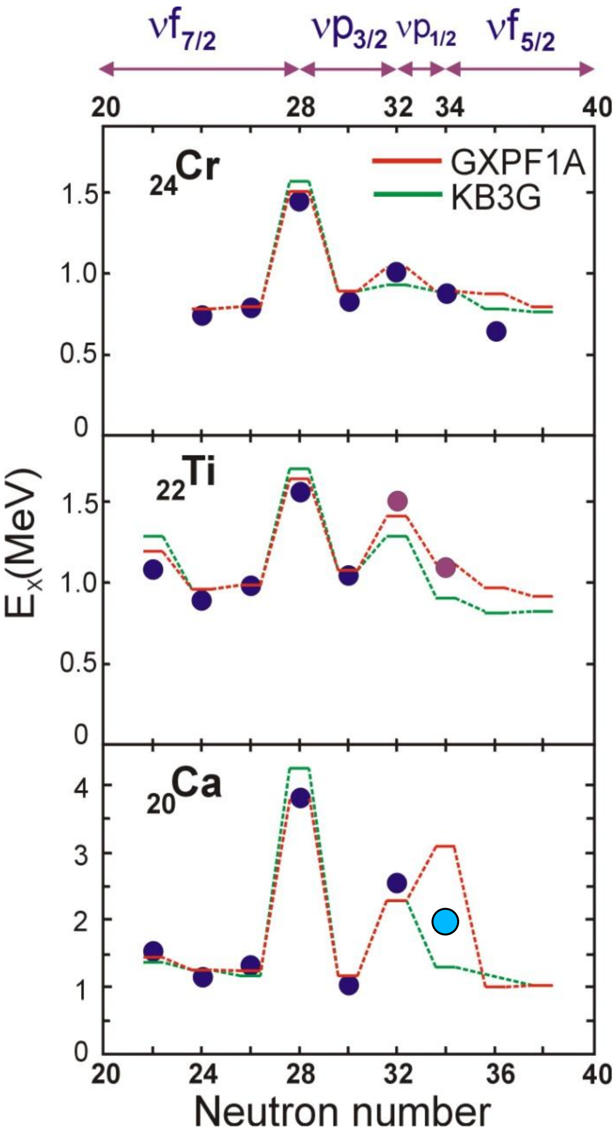
(6^+) $\pi f_{7/2}\nu(p_{3/2})^2 p_{1/2}$

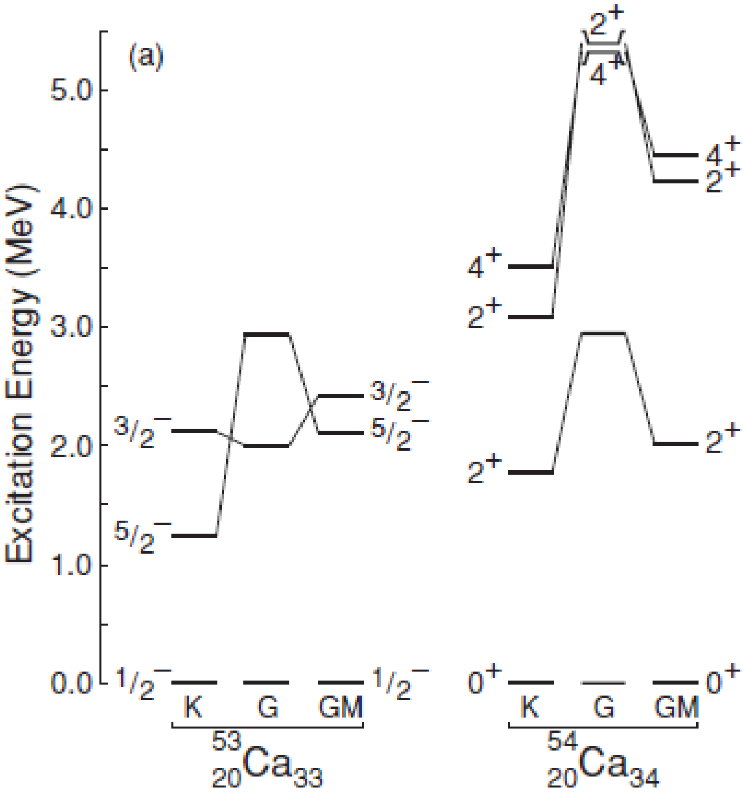
$(9/2^-)$ $\nu(p_{3/2})^2 f_{5/2}$

$(5/2^-)$ $\nu(p_{3/2})^2 p_{1/2}$

See also M. Rejmund *et al.*, Phys. Rev. C **76** (2007) 021304(R)

Is there a *N* = 34 gap for ^{54}Ca between $f_{5/2}$ and $p_{3/2}$?





K = KB3GM G=GXPF1A GM=modified GXPF1A

M. Rejmund *et al.*, Phys. Rev. C **76** (2007) 021304(R)

Thank You For Your Attention
and
Good Luck With You Thesis Work