Nuclear shapes and new excitations in n-rich nuclei from the spontaneous fission of ^{252}Cf

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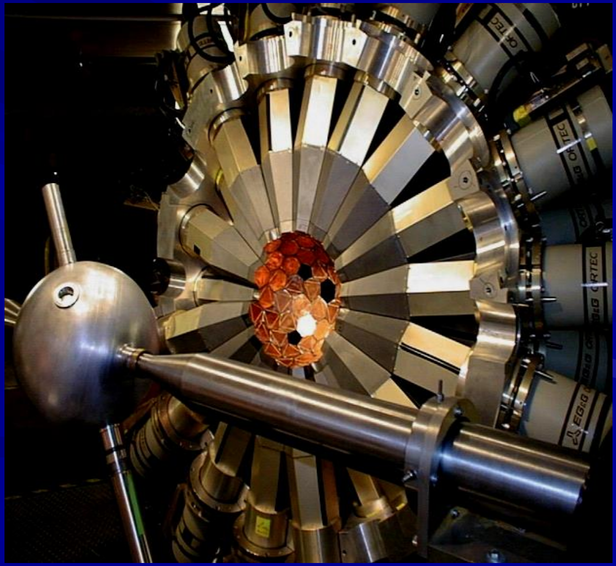
Talk at Shanghai Symposium in honor of Professor Akito Arima's 88 years birthday, Sep. 26-28, 2018, Shanghai , China



First of all, I wish to say “Happy Birthday !” to the world-well-known physicist, respected Professor Akito Arima for his great achievements in nuclear physics research and the contributions to the friendship of the Chinese and Japanese physicists !

In the 95 International Nuclear Physics Conference, August 21-26, 1995, Beijing, China, Professor Arima gave the Summary Talk for all the talks at the conference. His quit positive comments on our breakthrough in the heavy neutron region beyond the fission limit, which I reported in an invited talk at the conference, was a great encouragement and promotion to our Key Project "Synthesis and Studies of New Nuclei far from Stability". And afterwards, many more progresses were achievements in other nuclear region.

After the conference, an interview of Professor Zhou Guang-zhao with Professor Akito Arima and Mrs Arima, August 26, 1995 来今雨轩，Zhong-shan Park

95 International Nuclear Physics Conference, August 21-26, 1995, Beijing, China

25 new nuclides have been synthesized and studied in IMP, Lanzhou, China

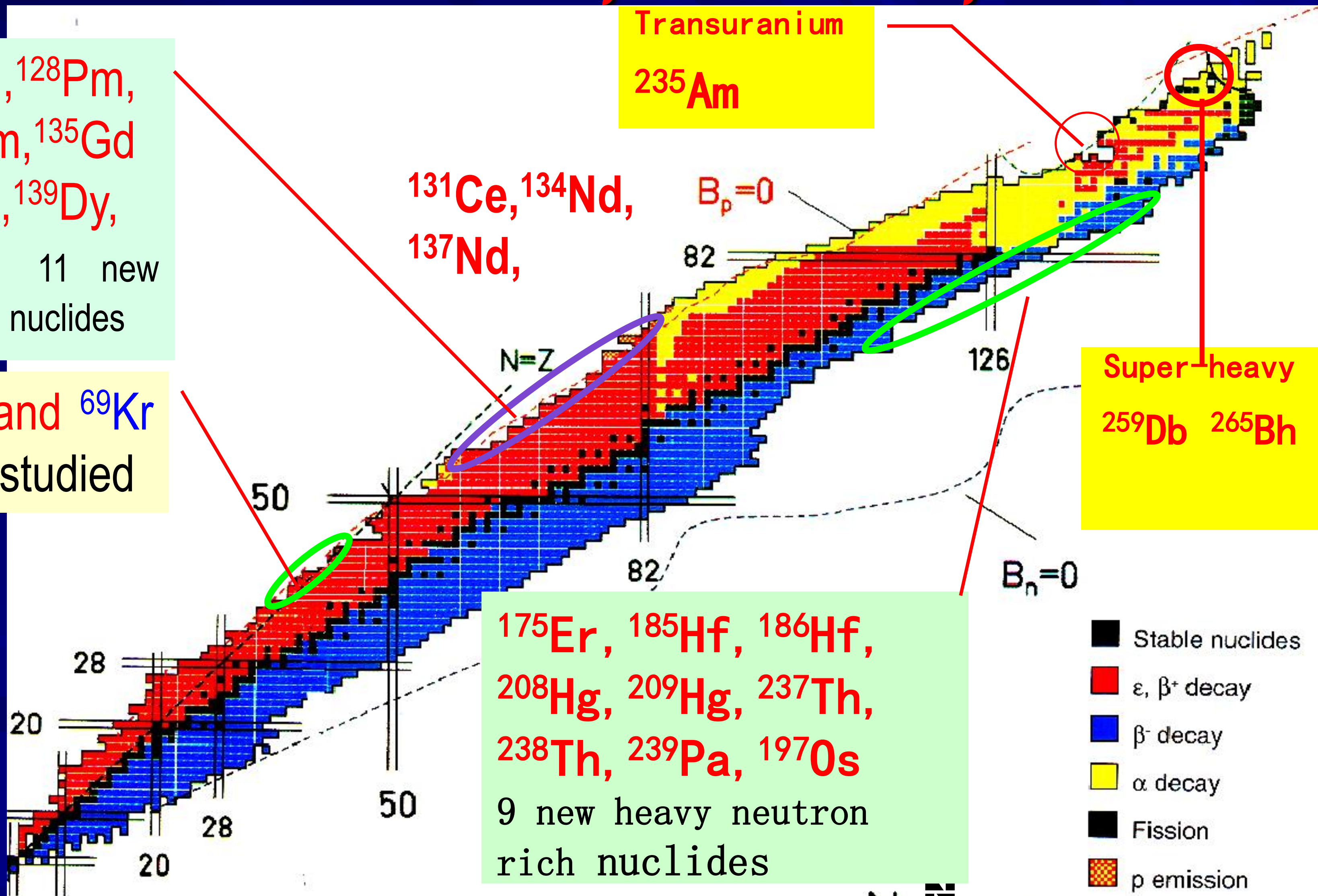
^{121}Ce, ^{125}Nd, ^{128}Pm, ^{129}Pm, ^{129}Sm, ^{135}Gd ^{137}Gd, ^{139}Tb, ^{139}Dy, ^{142}Ho, ^{149}Yb 11 new proton-drip line nuclides

^{25}P, ^{65}Se and ^{69}Kr have been studied

Transuranium

^{235}Am

^{131}Ce, ^{134}Nd, ^{137}Nd,



Super-heavy

^{259}Db ^{265}Bh

^{175}Er, ^{185}Hf, ^{186}Hf, ^{208}Hg, ^{209}Hg, ^{237}Th, ^{238}Th, ^{239}Pa, ^{197}Os

9 new heavy neutron rich nuclides

1. Introduction

1.1 Brief introduction of the nuclear shapes

- ***Nuclear shapes – one of the most fundamental properties of nucleus***
- ***Nuclear shapes are governed by the interplay of :***

  - ***Macroscopic, liquid-drop like properties of the nuclear matter,***
  - ***Microscopic shell effects,***
  - ***Valence nucleon driving , Structural effect, E_{exc}, and angular momentum.***

Spherical — deformed shapes

Reflection – symmetric *Prolate / Oblate*

Reflection – asymmetric *Octupole (pear)*

Axially – symmetric to

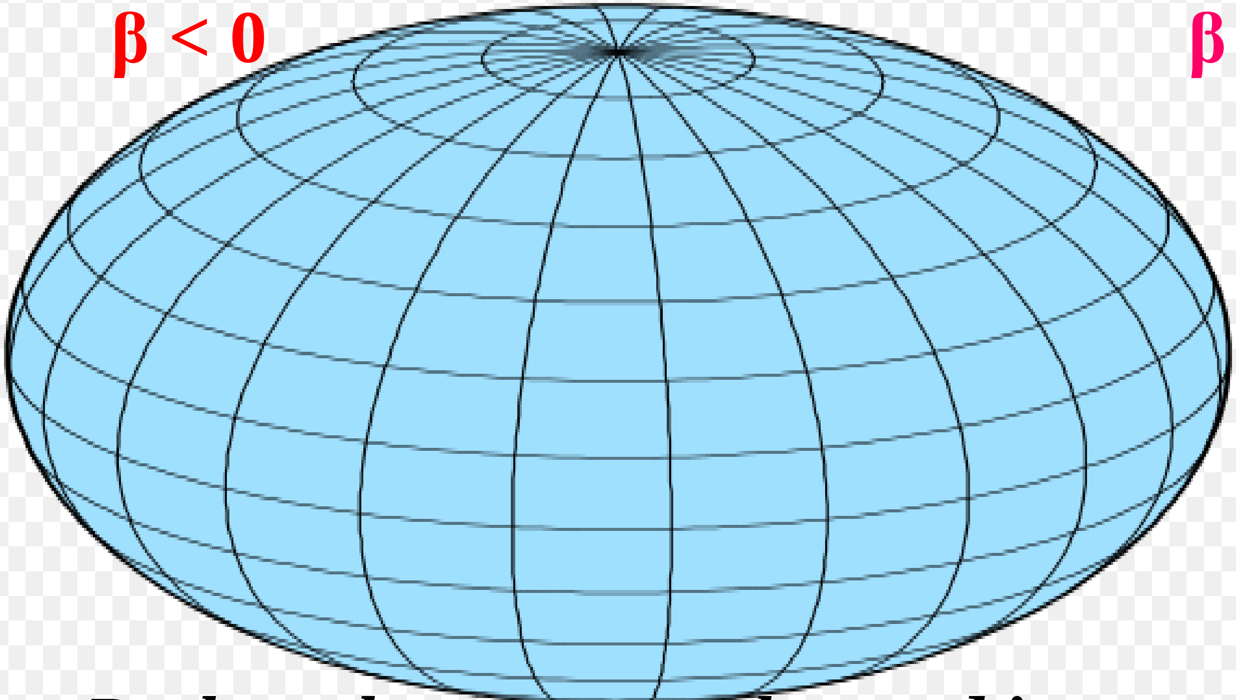
Axially – asymmetric *Triaxial deformation*

Quadrupole, *Reflection – Symmetric Shapes*

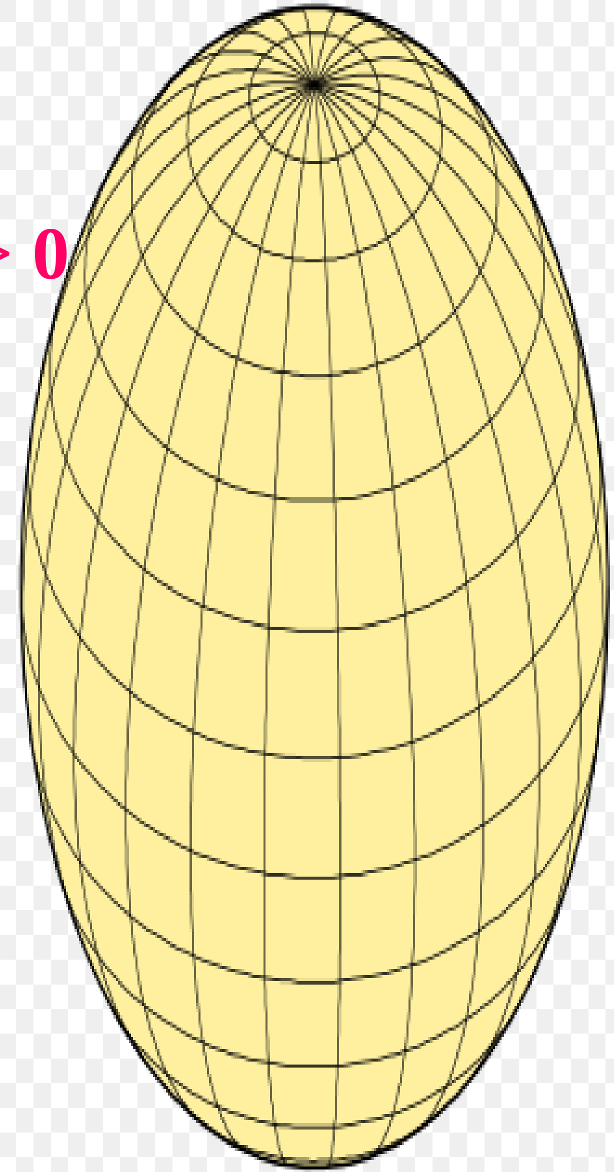
Oblate **Prolate**

A dominance of oblate ground-state shapes just below the N=82, N=126, and Z=82 shell closures.

$\beta < 0$

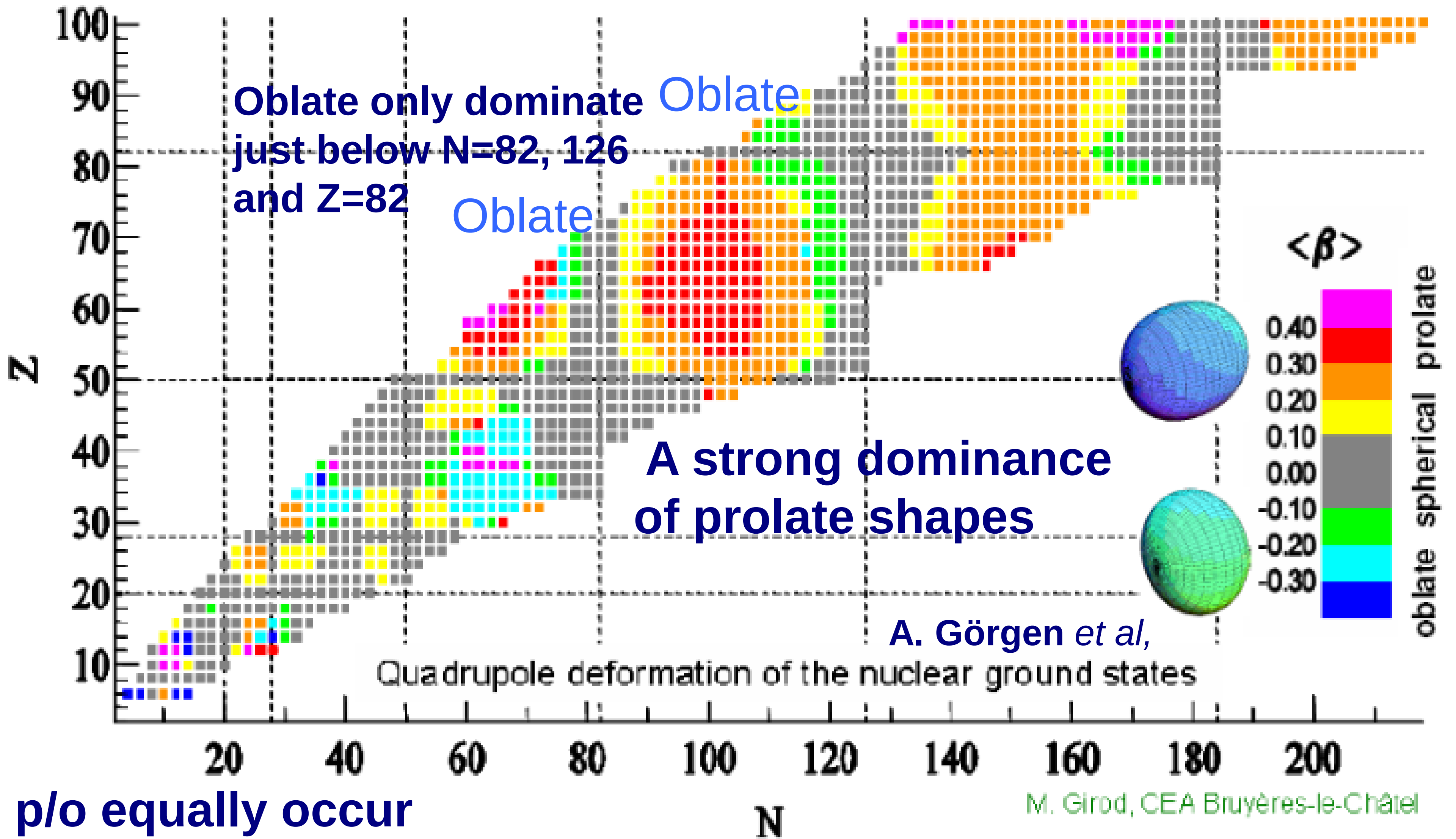


$\beta > 0$



Prolate shapes were observed in rare earth and actinide nuclei, and then found to take 86% of all the nuclides.

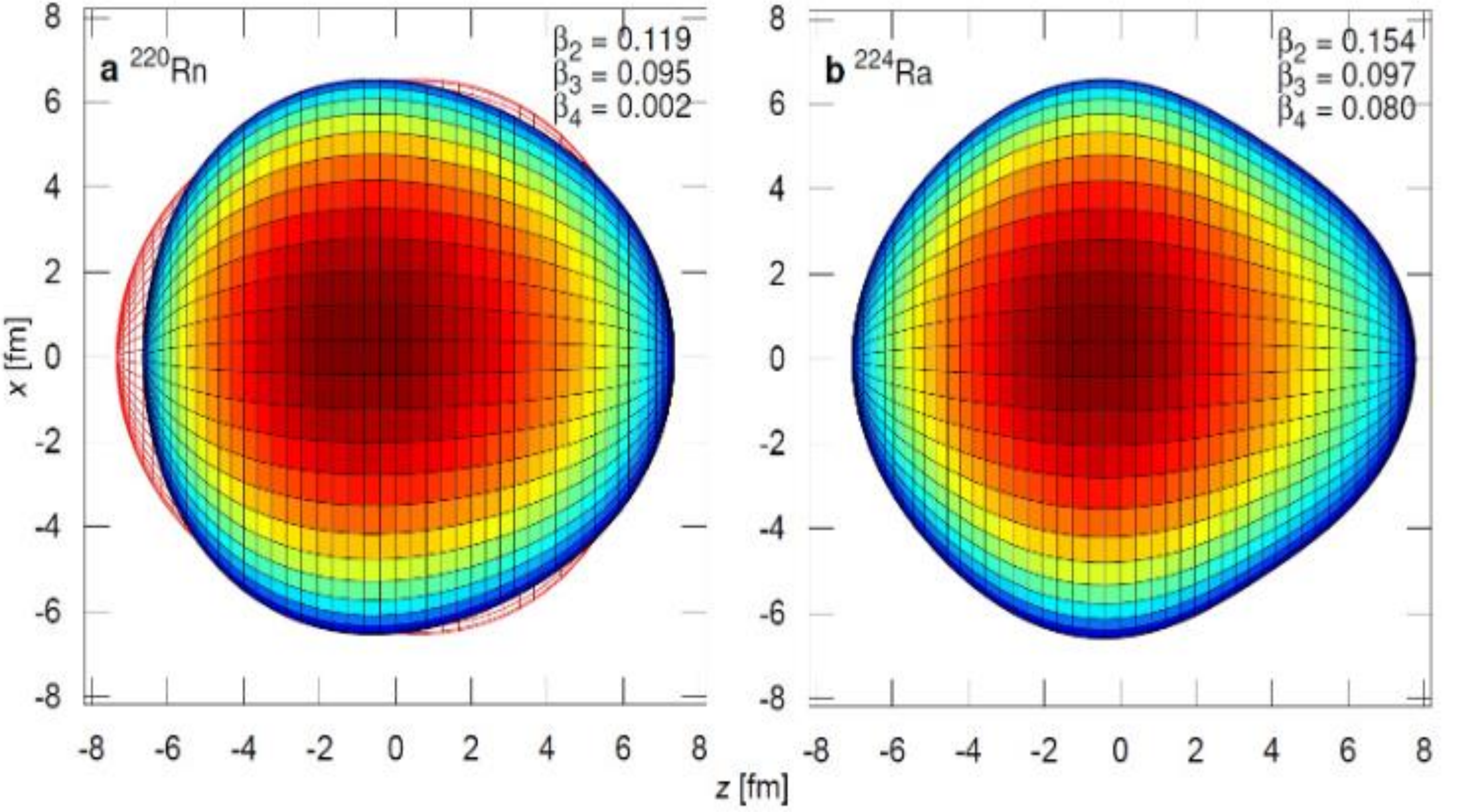
Nuclear chart showing the ground - state shapes predicted by a Hartree – Fock - Bogolyubov (HFB) calculation with the Gogny D1S effective interaction.



p/o equally occur

Reflection – asymmetric, Octupole shapes

L.P. Gaffney et al., Nature 497, 199(2013)



An island of stable octupole deformed nuclei around Z = 56 and N = 88 was predicted by theoretical calculations in the deformed shell model，where the separation of center-of-charge and center-of-mass manifests itself by E1 transition linking the opposite-parity levels.

W. Nazarewicz et al., Nucl. Phys. A429, 269 (1984).

W. Nazarewicz et al., Nucl. Phys. A441, 420 (1985).

G.A. Leander et al., Phys. Lett. B152, 284 (1985).

R. Piepenbring, Z. Phys. A322, 495 (1985).

For the nuclear quantum system, spontaneous symmetry breaking that arises from deformation will in general lower its energy. This 'nuclear Jahn-Teller effect' [1] is illustrated by considering a simple nuclear Hamiltonian representing nuclear vibrations, written as (see [2] and references therein)

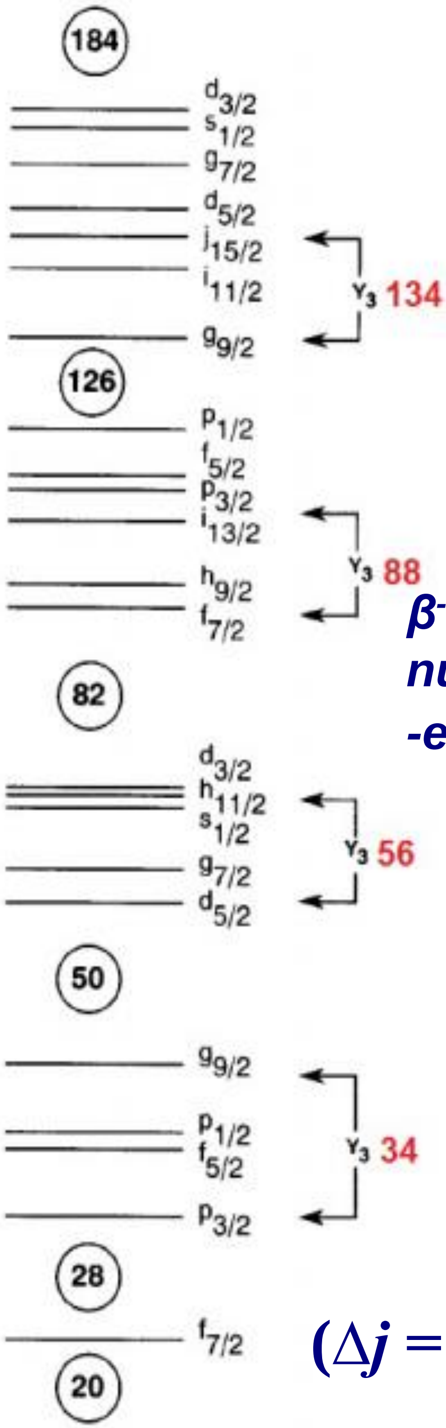
P.A. Butner, J. Phys. G: Nucl. Part. Phys. 43 (2016) 073002

$$H = \sum_j e_j c_j^+ c_{j'} - \frac{1}{2} \sum_\lambda \kappa_\lambda \sum_{\mu=-\lambda}^{+\lambda} Q_{\lambda\mu}^+ \cdot Q_{\lambda\mu} + H_{\text{pair}} \quad (1)$$

Spherical SM **Collective motion term** **Pairing Hamiltonian**

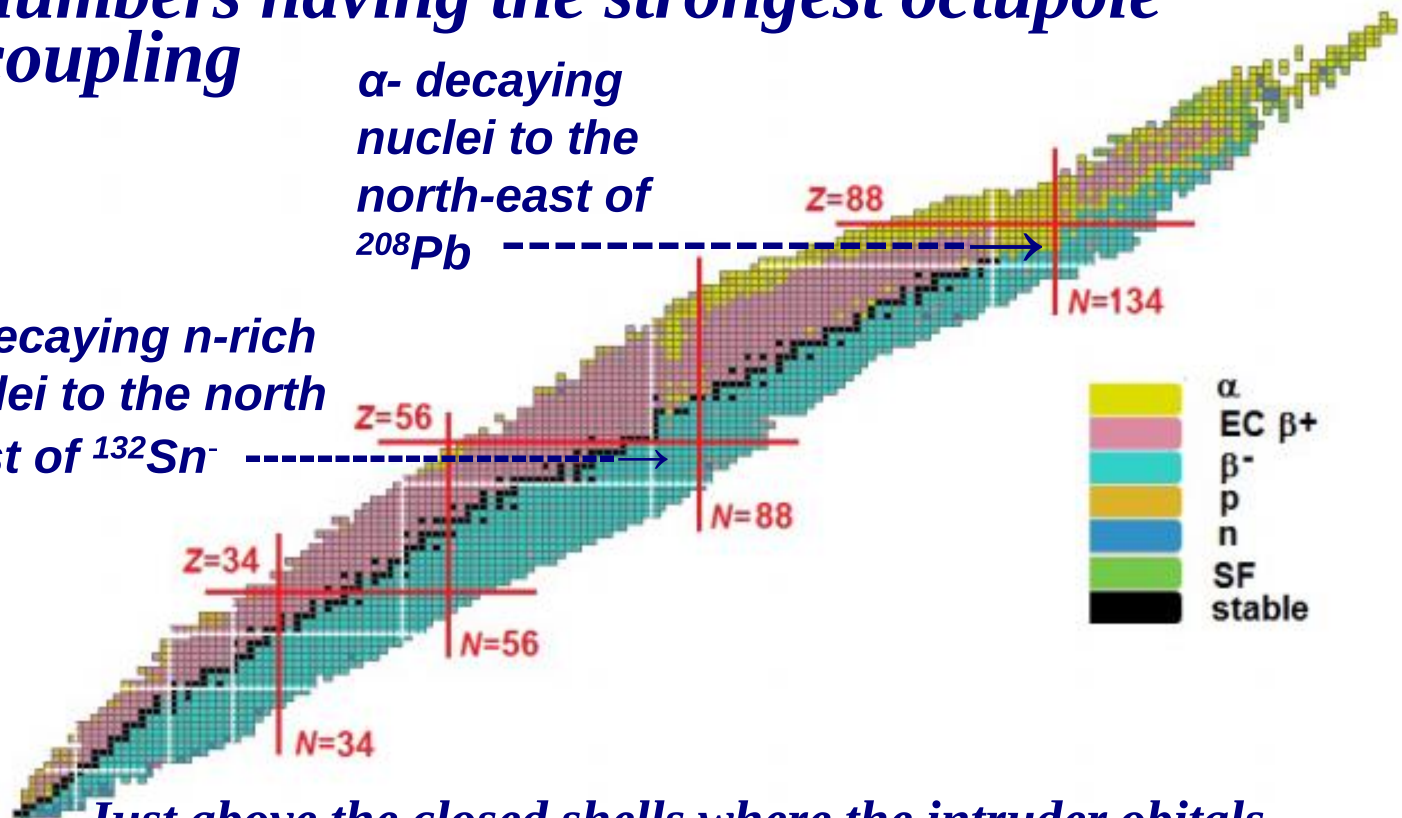
In this expression the first term is the spherical shell-model potential, the second term represents the long-range multipole-multipole force generating the collective motion, and H_{pair} is the pairing Hamiltonian; j stands for the set of quantum numbers (n, ℓ, j). Spherical symmetry will be removed for $\lambda = 2$ quadrupole-quadrupole interactions, and most nuclei are quadrupole deformed in their lowest energy state. For some combinations of Z and N the nucleus can further lower its energy through octupole-octupole interactions, and the nucleus no longer retains reflection symmetry . In a mean-field description of the nucleus, octupole correlations depend on the matrix elements of the spherical harmonic Y_3^0 between single particle states with $\Delta j = \Delta \ell = 3$ and the spacing between them. The left hand side of figure 1 shows that the proton number

Spherical single particle levels showing the most important octupole couplings , and proton and neutron numbers having the strongest octupole coupling



α- decaying nuclei to the north-east of ^{208}Pb

β^- decaying n-rich nuclei to the north -east of $^{132}Sn^-$



Just above the closed shells where the intruder obitals (N, ℓ, j) interact with the (N-1, ℓ-3, j-3) normal-parity states through octupoles components in Hamiltonian

$(\Delta j = \Delta \ell = 3)$

P.A. Butner, J. Phys. G: Nucl. Part. Phys. 43 (2016) 073002

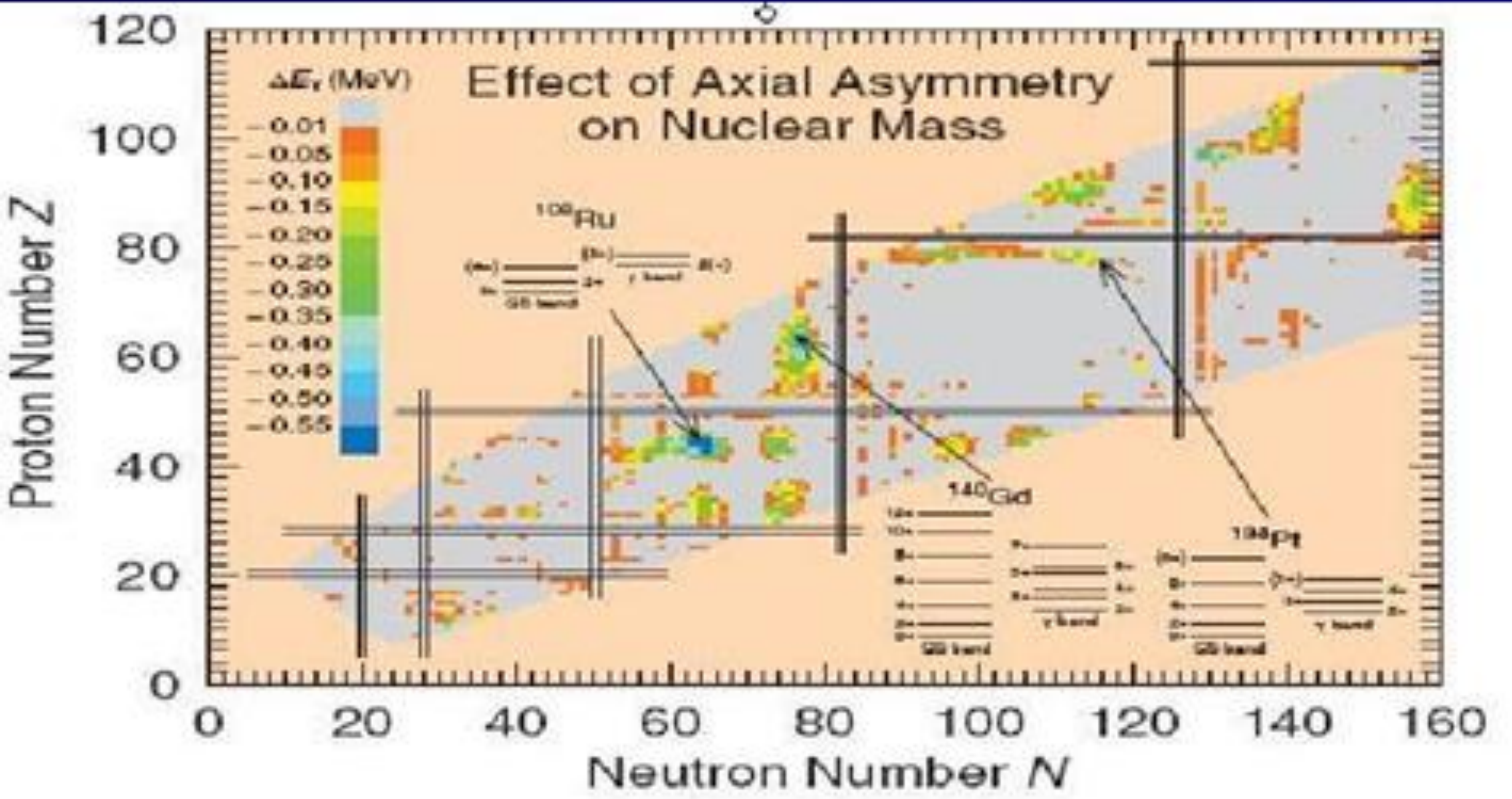
Nucleus had first of all long been thought to be axially-symmetric !

However, triaxial shapes were predicted and studied. (e.g. J. Aystoet al. Nucl. Phys. A515, 365(1990)). S. Frauendorf and Jie Meng suggested that chiral doubling can be associated with angular momenta in triaxial nuclei − a dynamic nature.

S. Frauendorf and J. Meng,
Nucl. Phys. A617, 131(1997)

Global search for triaxiality by Möller et al. Largest lowering of E_{gs} centered around ^{108}Ru with an energy gain of 0.67 MeV

P. Möller et al. PRL 97, 162502 (2006)



Chiral symmetry breaking

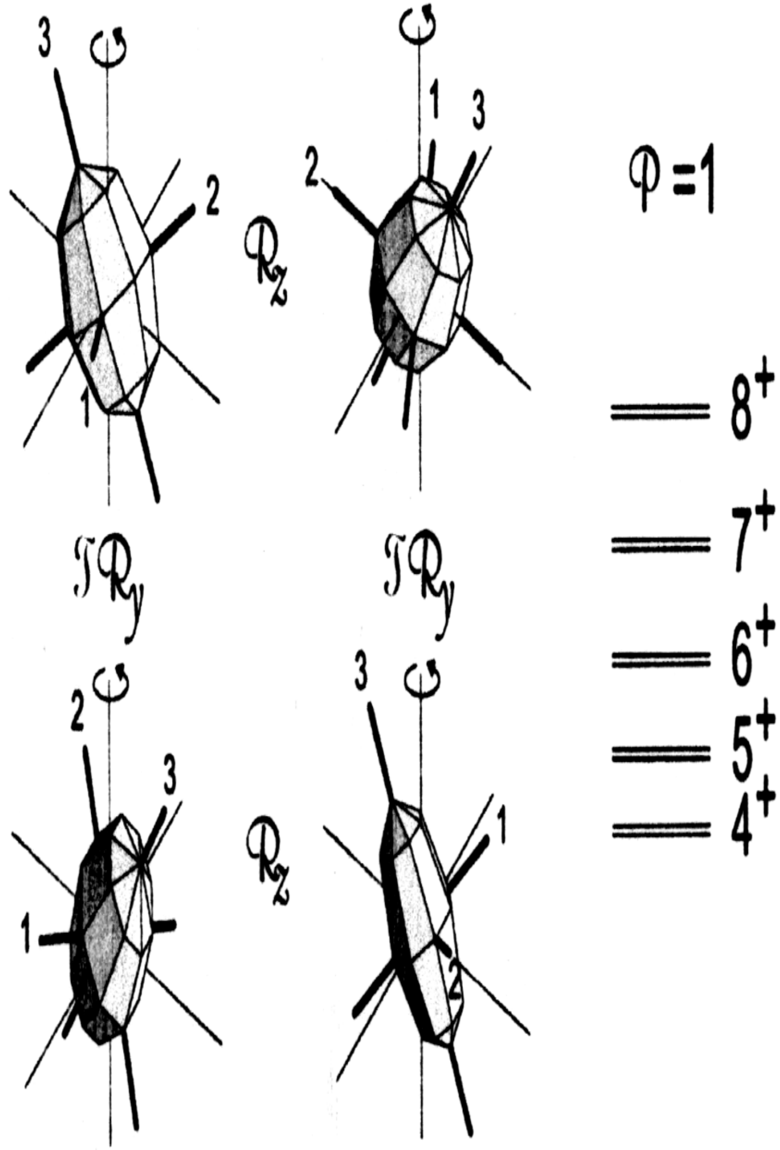
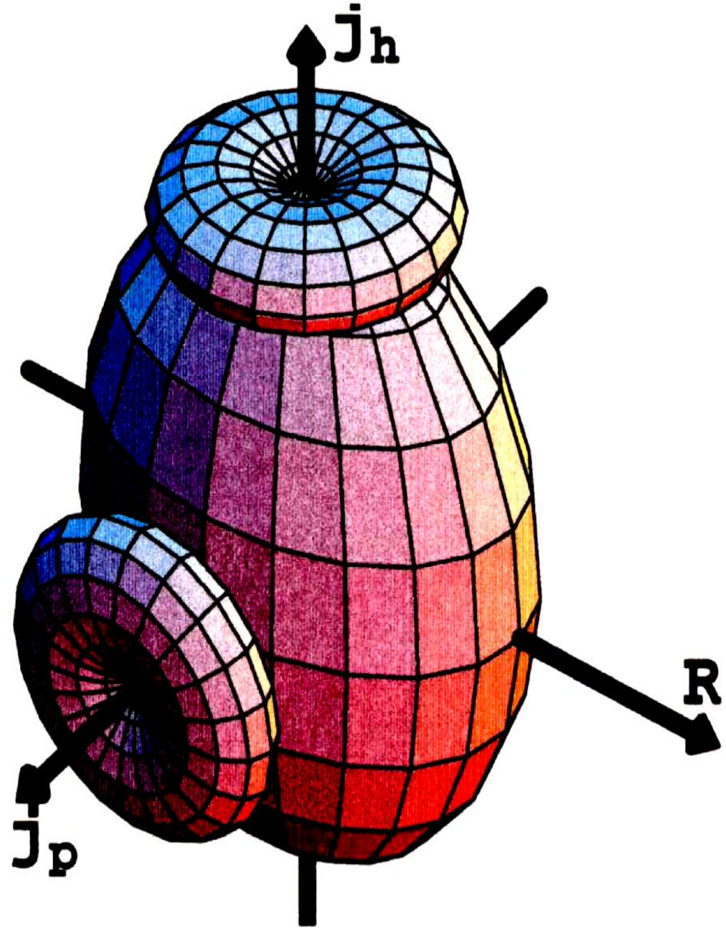


Figure 12. Graphic Illustrating a Nucleus with Chiral Bands [6]

A triaxial chiral rotor



Axially-asymmetric shape:
Triaxial deformation

S. Frauendorf *et al.*

How chiral symmetry breaking can occur?

For an odd-odd triaxial nucleus

A high j particle aligns along the short axis, a high j hole aligns along the long axis, and the rotational angular momentum aligns along the intermediate axis, j_p, j_h and R vectors couple to each other in r- or l-handed way

For an odd-A triaxial nucleus

Two high j particles align with the short axis

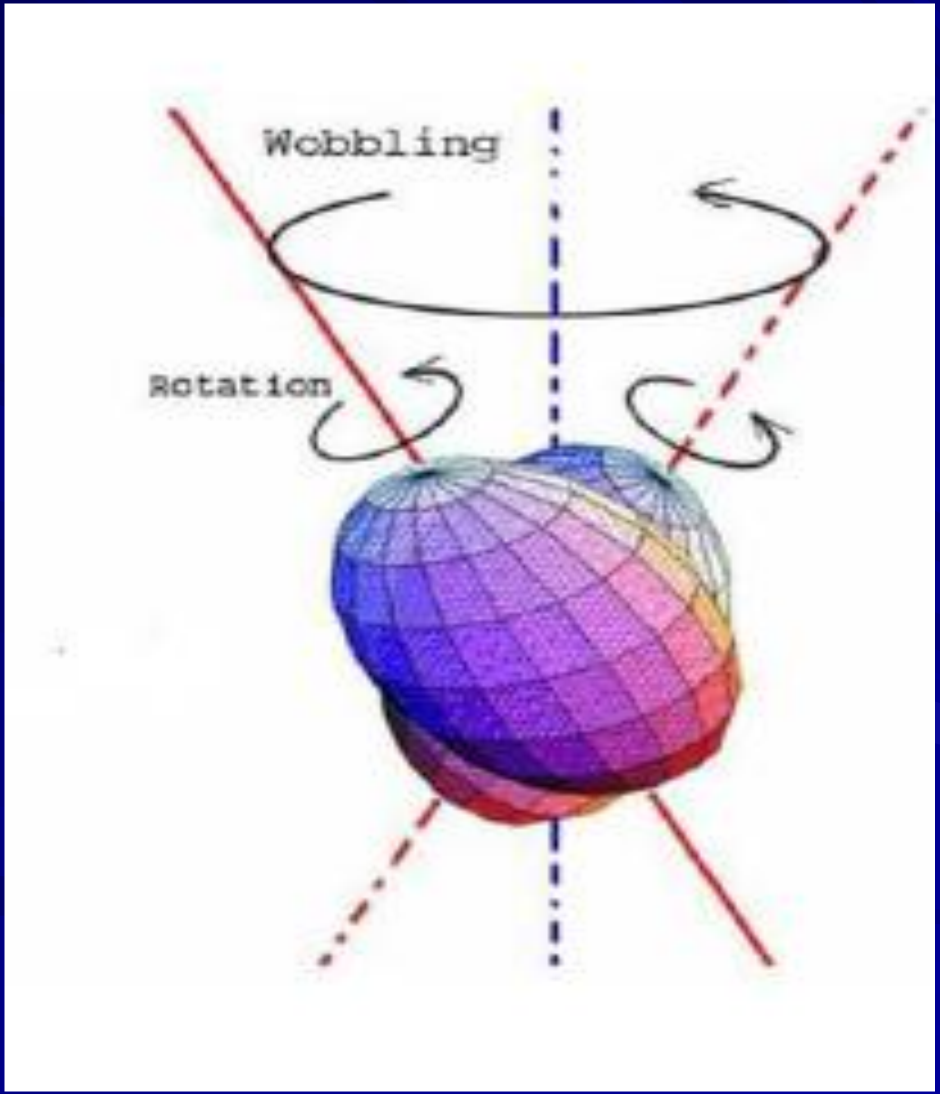
For a even-even triaxial nucleus

A low-lying collective mode in the orientation degree of freedom, i.e. a soft chiral vibration, a slow motion of the J relative to the three-axial nuclear shape between left-handed and right-handed geometries.

Fingerprints of Chiral doublets

- ***Energy degeneracy of the partner levels in doublets;***
- ***Similar electromagnetic properties such as similar B(E2)/B(M1) ratios of the partner levels in doublets – similar structure;***
- ***Nearly constant signature splitting with spins and equal value for partner levels***

Wobbling motions in triaxial nuclei



A revolving motion

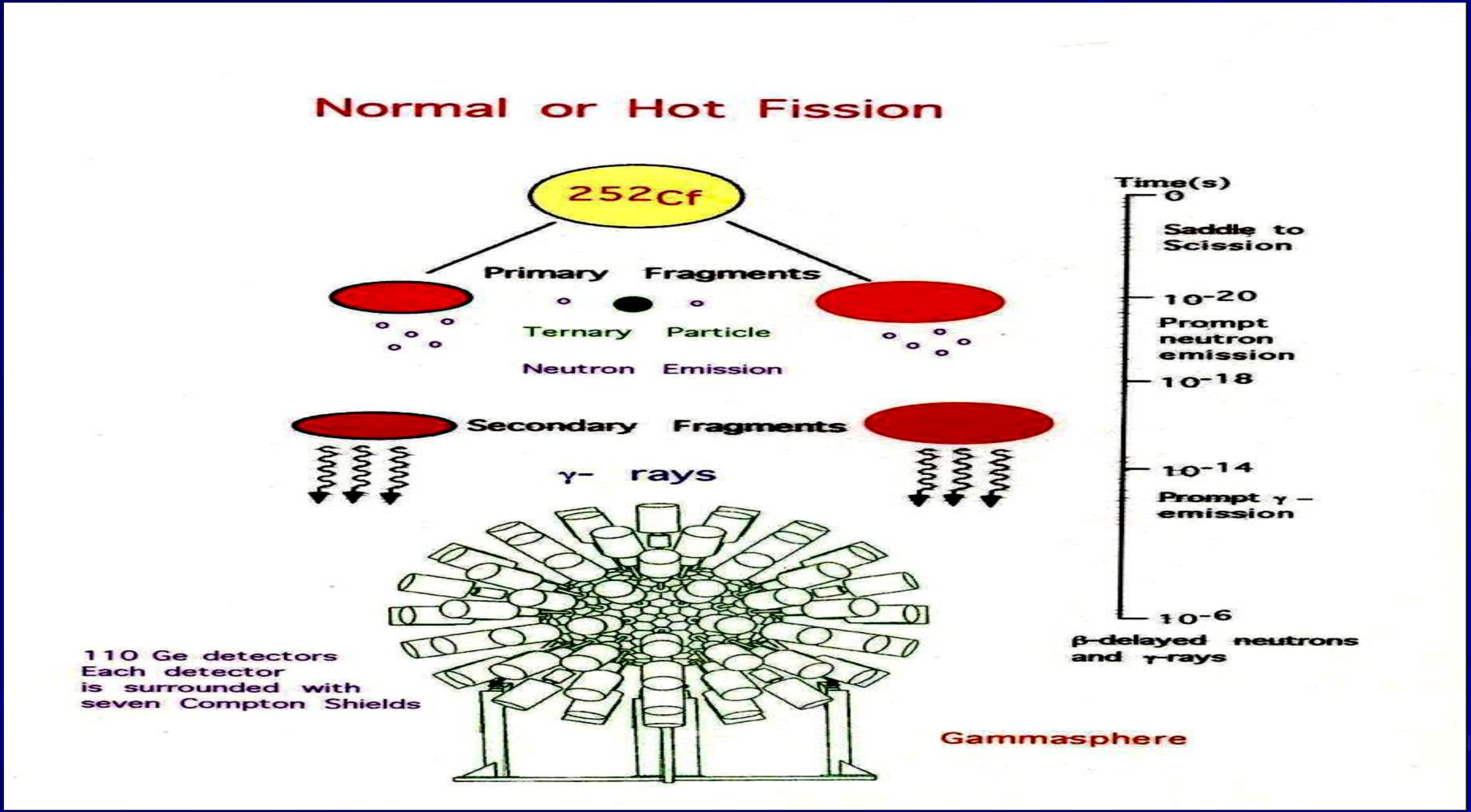
J.H. Hamilton *et al.*, Nucl. Phys. A 834, 28c(2010)

- ***Fingerprint of the wobbling*** *: α = 0 wobbling (even-spin member of the γ band) is above the α = 1 wobbling*
- *Onset of wobbling was identified in ^{112}Ru and its N=68 isotone ^{114}Pd*
- *Wobbling motion was also identified in ^{114}Ru and ^{116}Pd*

1.2 Experimental Details – the "gold mine" developed by J.H. Hamilton and collaborators

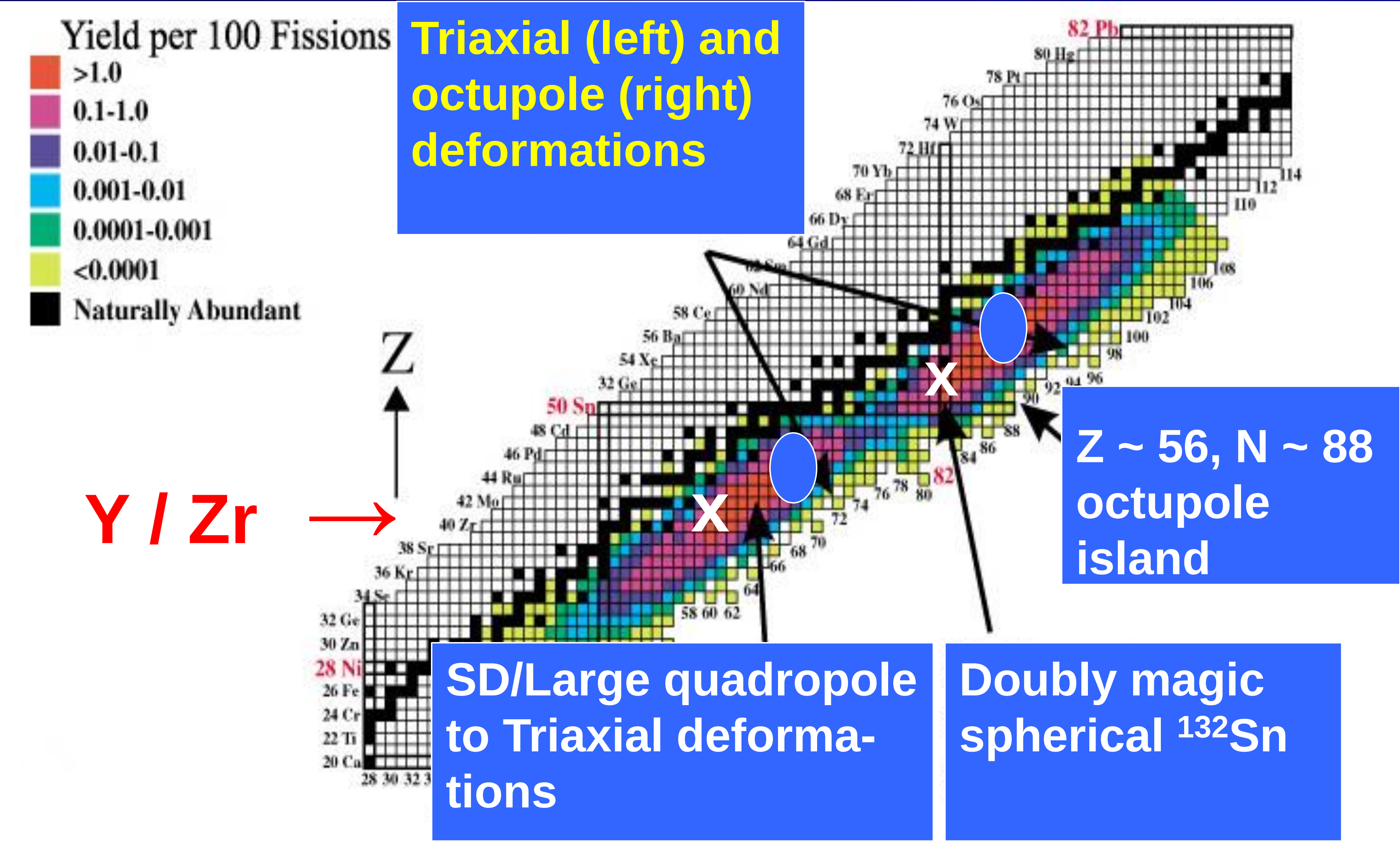
- *Fission source : ^{252}Cf*
- *Strength : 62 μCi*
- *Sandwiched between two Fe foils of thickness 10 mg/cm^2 and mounted in a 3-inch-diameter plastic ball*
- *Detectors : Gammasphere with 102 Compton-suppressed Ge detectors*
- *5.7x10^{11} triple- and higher-fold, and 1.9 x10^{11} 4d - and higher-fold coincidence events with 1μs time window accumulated*

The "gold mine" for exploring in neutron-rich nuclei is productive over 25 years !



Around 150 neutron – rich nuclei have been produced and studied with fission of ^{252}Cf at Gammasphere

2. The systematic studies of nuclear shapes of the neutron -rich nuclear by means of fission gamma spectroscopy



3. *Systematic studies of octupole shapes (pear shapes) and octupole correlation, paying a close attention to D_0*

In a reflection-asymmetric nuclear mean field, an electric dipole moment D_0 occurs as a difference of the interference terms between quadrupole Y_{20} and octupole Y_{30} shape vibrations for protons and that for neutrons.

Octupole deformations/correlations studied in :

Y.X. Luo *et al*. Nucl. Phys. Rev. Vol.27, No. 3, 229(2010); No. 4, 363(2010)

^{139,140,141,142}Xe (Z=54, N=85-88)

^{139,140,141,142,143,145}Cs (Z=55, N=84-88, 90)

^{141,142,143,144,145,146,147,148}Ba (Z=56, N=85-92)

^{142,143,144,145,146,147}La (Z=57, N=85-90)

^{144,146,148}Ce (Z=58, N=86, 88, 90)

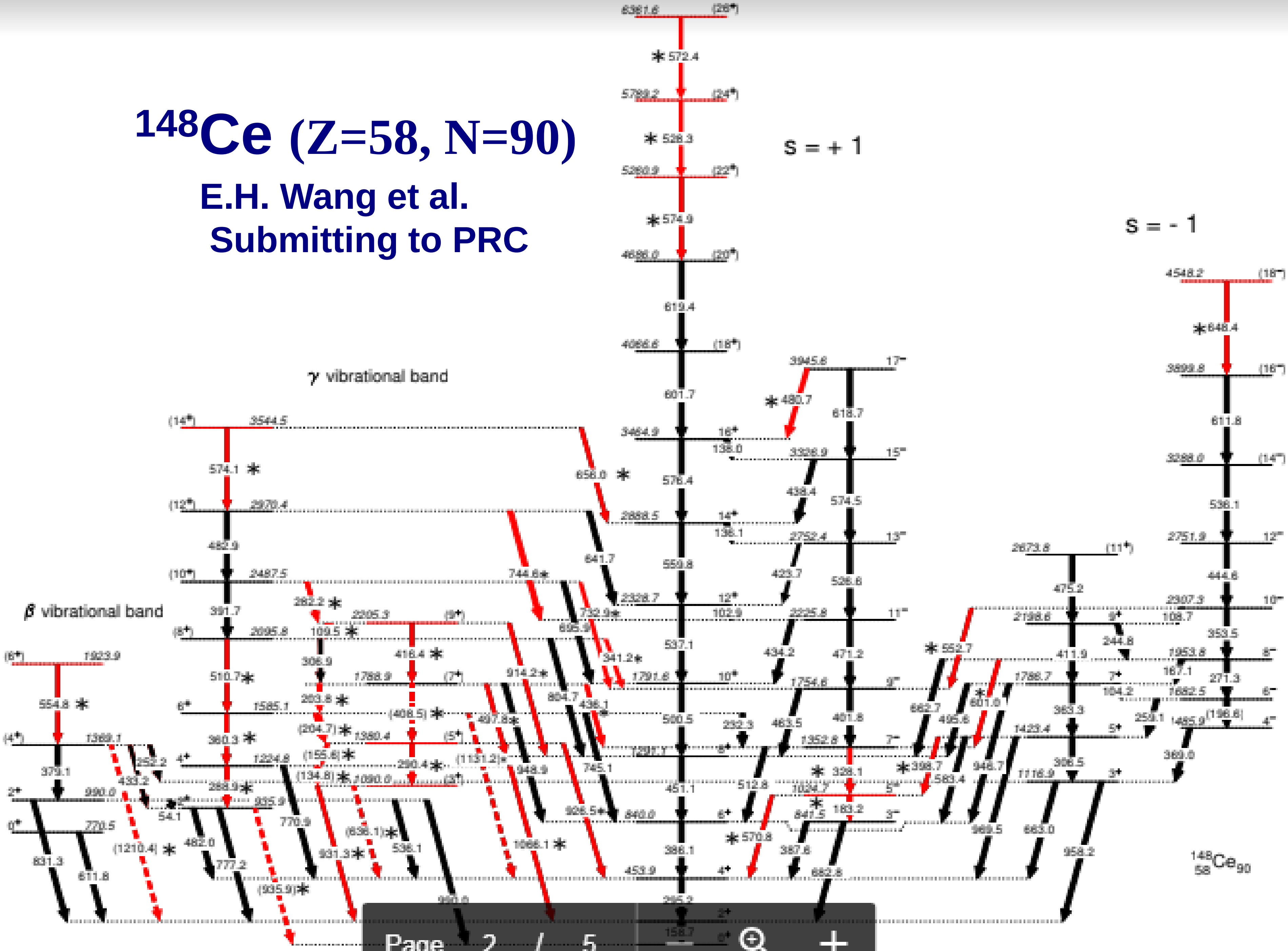
^{146,148,150}Nd (Z=60, N=86, 88, 90)

^{148,150,152}Sm (Z=62, N=86, 88, 90)

33 nuclei in total (Z=54-62, N=84-90)

^{148}Ce (Z=58, N=90)

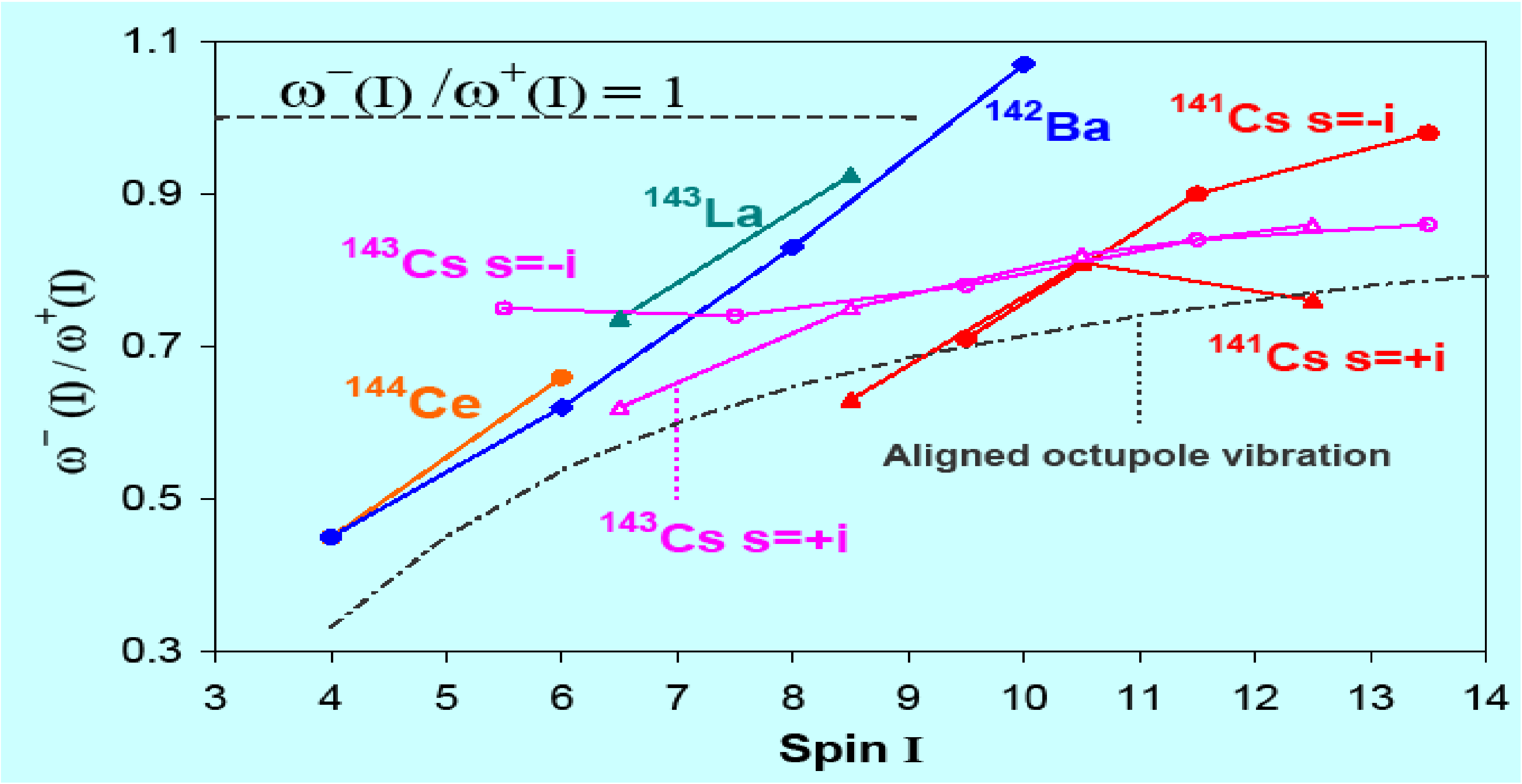
E.H. Wang et al.
Submitting to PRC



Rotational frequency ratio $\omega^-(I)/\omega^+(I)$

$$\omega^-(I)/\omega^+(I) = 2\,[E(I+1)^- - E(I-1)^-]\,/\,[E(I+2)^+ - E(I-2)^+]$$

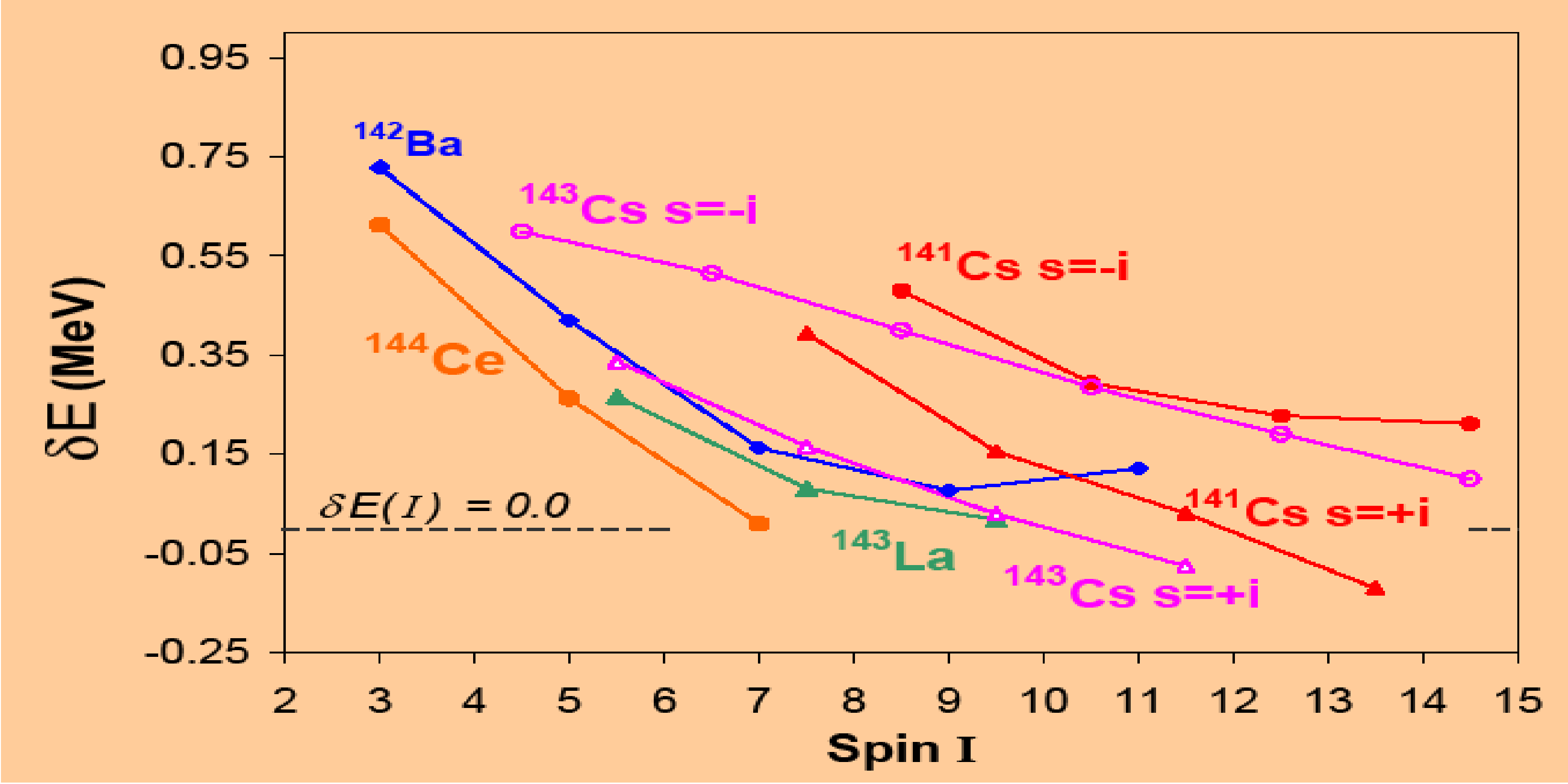
Showing octupole deformation or octupole vibration



Energy displacement $\delta E(I)$

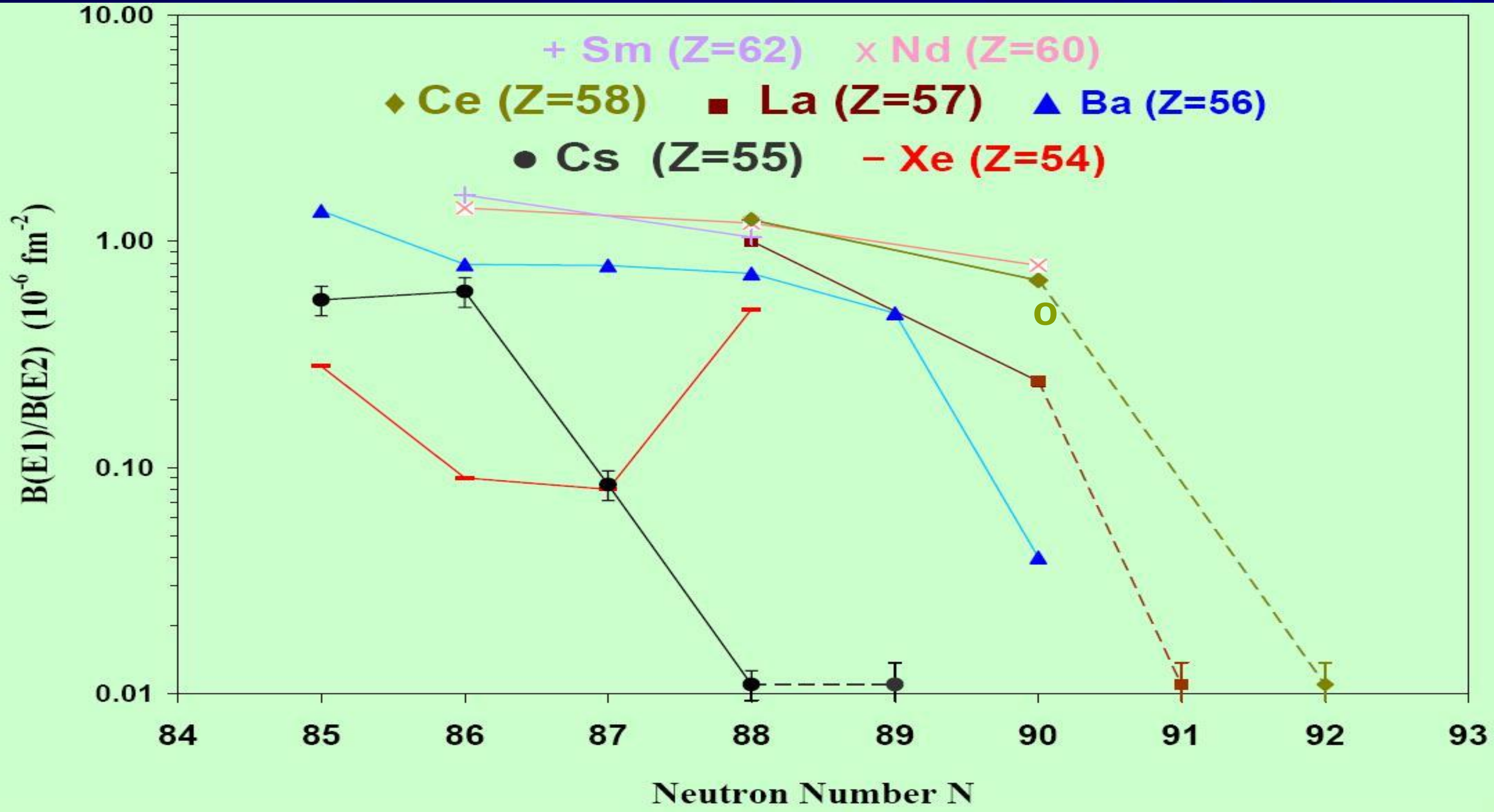
$$\delta E(I) = E(I^-) - [(I+1)E(I-1)^+ + IE(I+1)^+] / (2I+1)$$

Showing stability of the octupole excitations



B(E1)/B(E2)

B(E1)/B(E2)=0.771[Eγ(E2)⁵Iγ(E1)]/[Eγ(E1)³Iγ(E2)](10⁻⁶fm⁻²)

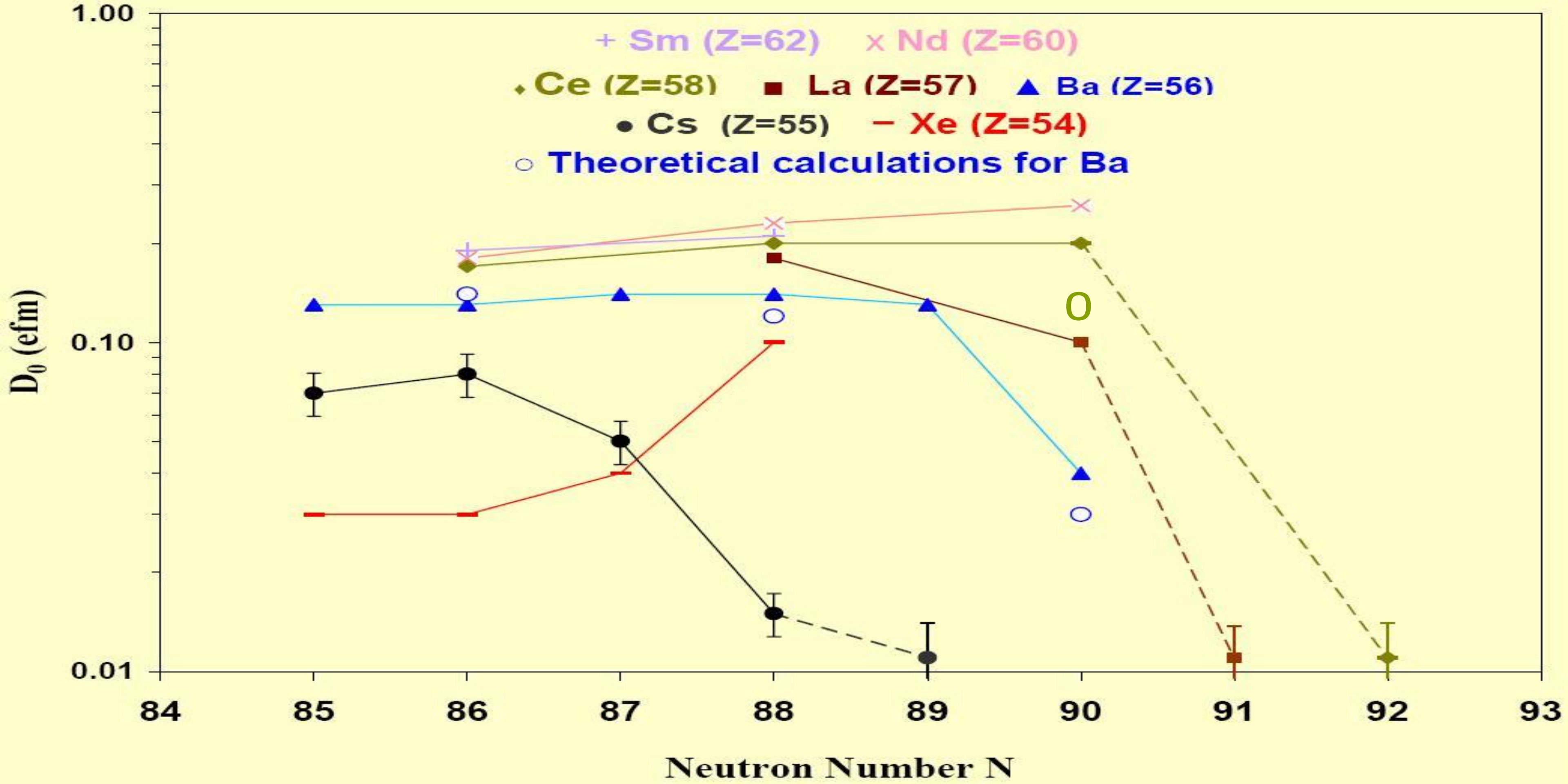


Electric dipole moments D_0

$D_0 = [5B(E1)/16B(E2)]^{1/2} \times Q_0$ (efm)

D_0 *increasing with increasing Z*

D_0 *decreasing with increasing N*



Reflection-asymmetric mean field shell-correction theory

P. Butler and W. Nazarewicz, Nucl. Phys. A533, 249 (1990)

W. Nazarewicz, S.L. Tabor Phys. Rev. C45, 2226(1992) (with cranking)

$$D_1 = D_1^{LD} + D_1^{shell}$$

Negligible macroscopic (droplet) term D_1^{LD}, due to the cancellation between the "reorientation" and the neutron-skin terms.

For an isotonic chain D_1^{shell} increases towards Z=64.

For an isotopic sequence D_1^{shell} decreases with N.

For ^{146}Ba very small shell-correction term D_1^{shell}, due to the cancellation between contributions from protons and neutrons,

So, …

- ***Well developed octupole deformations or correlations have been identified around neutron-rich Z=56 and N=88 as predicted, and stability/excitation modes studied.***
- ***An increasing D_0 with increasing Z, and a dramatic drop of D_0 with increasing neutron number identified in the region.***
- ***This drop of D_0 can be accounted for by the Reflection-asymmetric mean field shell-correction theory.***

4. *Prolate/oblate – triaxial region*

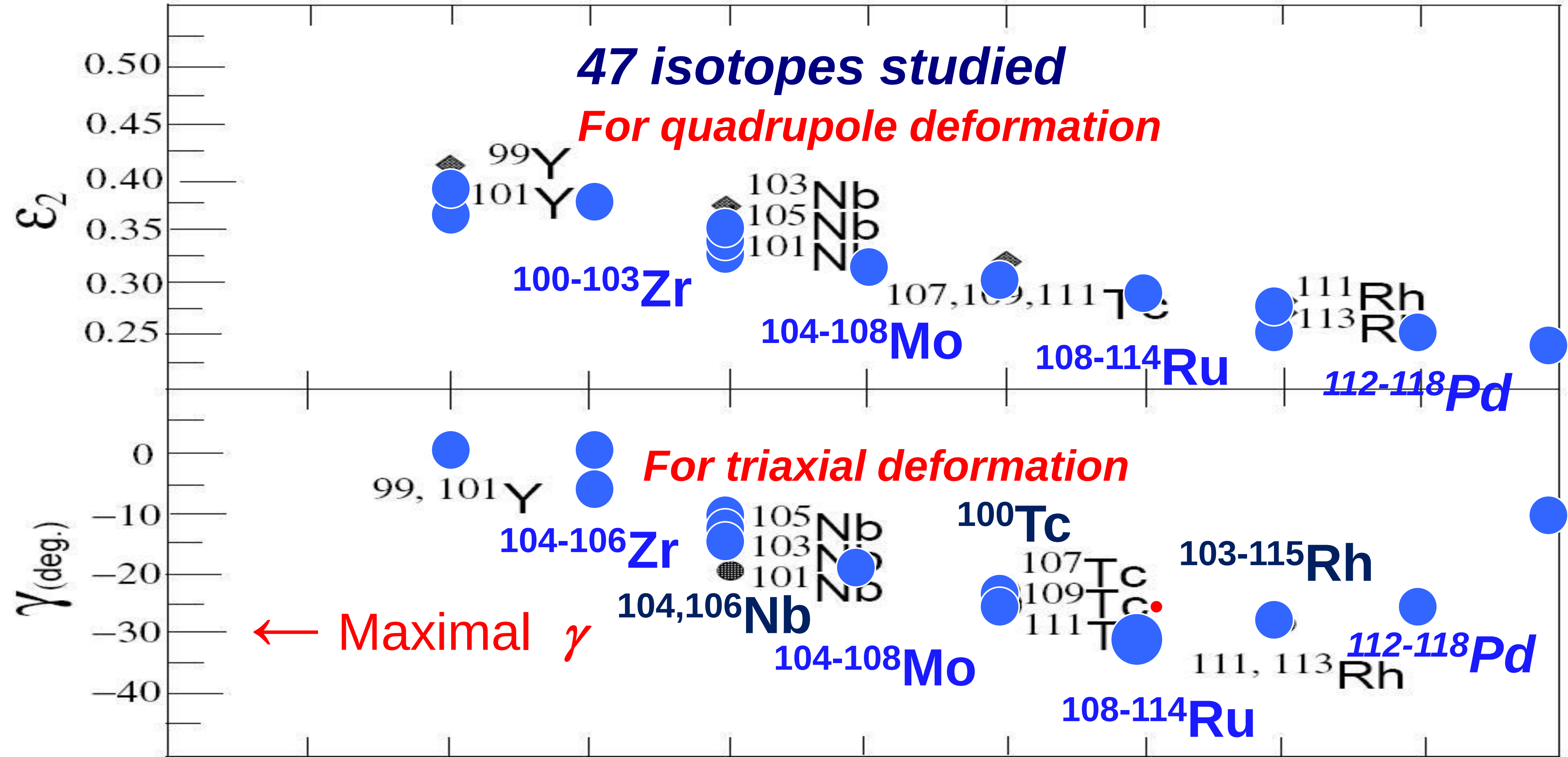
Z = 41 – 48, A ~ 100 – 126, n - rich nuclei

Intermediate between the strongly deformed Sr (Z=38), Y (Z=39) and Zr (Z=40) and the spherical doubly magic ^{132}Sn. 47 nuclei in total studied!

Fermi level relative to the high-j subshell, $\nu h_{11/2}$, $\pi g_{9/2}$ — at bottom, middle, to upper half of the shells, favoring triaxial prolate, through large triaxial deformations, to triaxial oblate, very good opportunities for studying shape transition and new excitations with regard to triaxial deformation.

*Y.X. Luo et al., Nucl. Phys. **A 825**, 1 (2009)*
*Y.X. Luo et al., Phys. Rev. **C74**, 024308(2006);*
*Y.X. Luo et al., J. Phys. **G31**, 1303(2005);*
*Y.X. Luo et al., Phys. Rev. **C70**, 044310(2004);*
*Y.X. Luo et al., Phys. Rev. **C69**, 024315(2004);*
*Y.X. Luo et al., Phys. Rev. **C89**, 044326(2014);*
Y.X. Luo et al., Nucl. Phys. A919, 67(2013);
M. Caprio, Phys. Rev. C83, 064309(2011);

One particle plus triaxial rotor model, PES and PSM Models



The region below Ru ($Z \leq 44$)

Y (Z=39) and Zr (Z=40) of A < 104, axially-symmetric

with large $\varepsilon_2 \sim 0.40$; onset of triaxiality in ^{104,106}Zr

↓

Nb (Z=41) with small and coexisting triaxiality,

transitional behavior ↓ $\gamma \sim 2^0 – 15^0$

Mo (Z=42) with large triaxiality , rigid rotors, $\gamma \sim 20^0$

↓

Tc (Z=43) with large triaxiality, $\gamma \sim -22^0 – -26^0$

↓

Ru (Z=44) Maximum triaxiality, rigid rotor, $\gamma \sim -30^0$

The region beyond Ru (Z ≥ 44)

Ru (Z=44)and Rh (Z=45) with maximum/near maximum triaxiality, $\gamma \sim -30^0$, -28^0, rigid triaxial rotors

↓

Pd (Z=46) with less pronounced triaxiality, $\gamma \sim -41^0$ in ^{114}Pd, a minimum energy gain 0.32 MeV, in contrast to 0.67 MeV in Ru

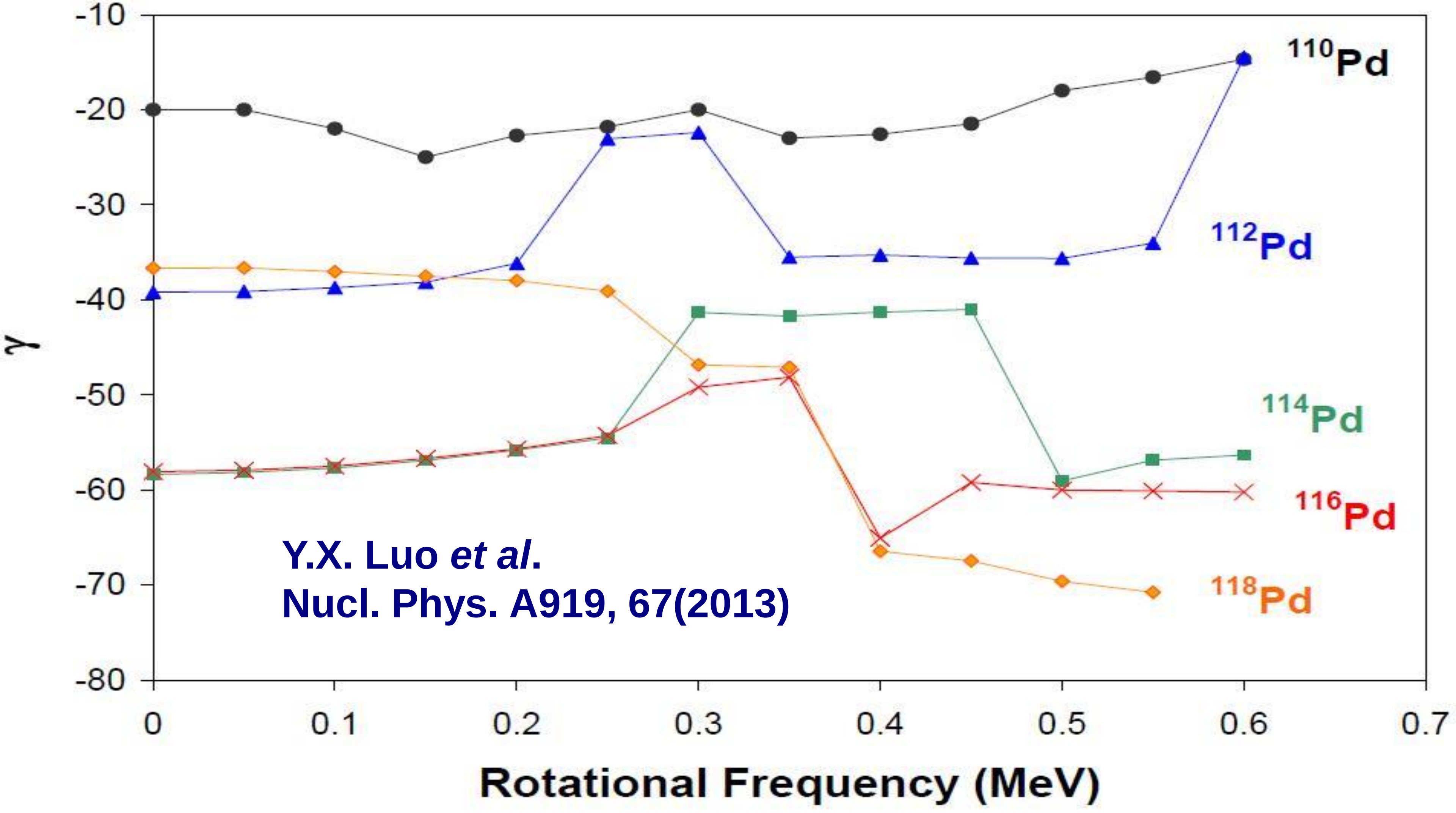
↓

Ag (Z=47) with softness towards triaxiality , rich structure

↓

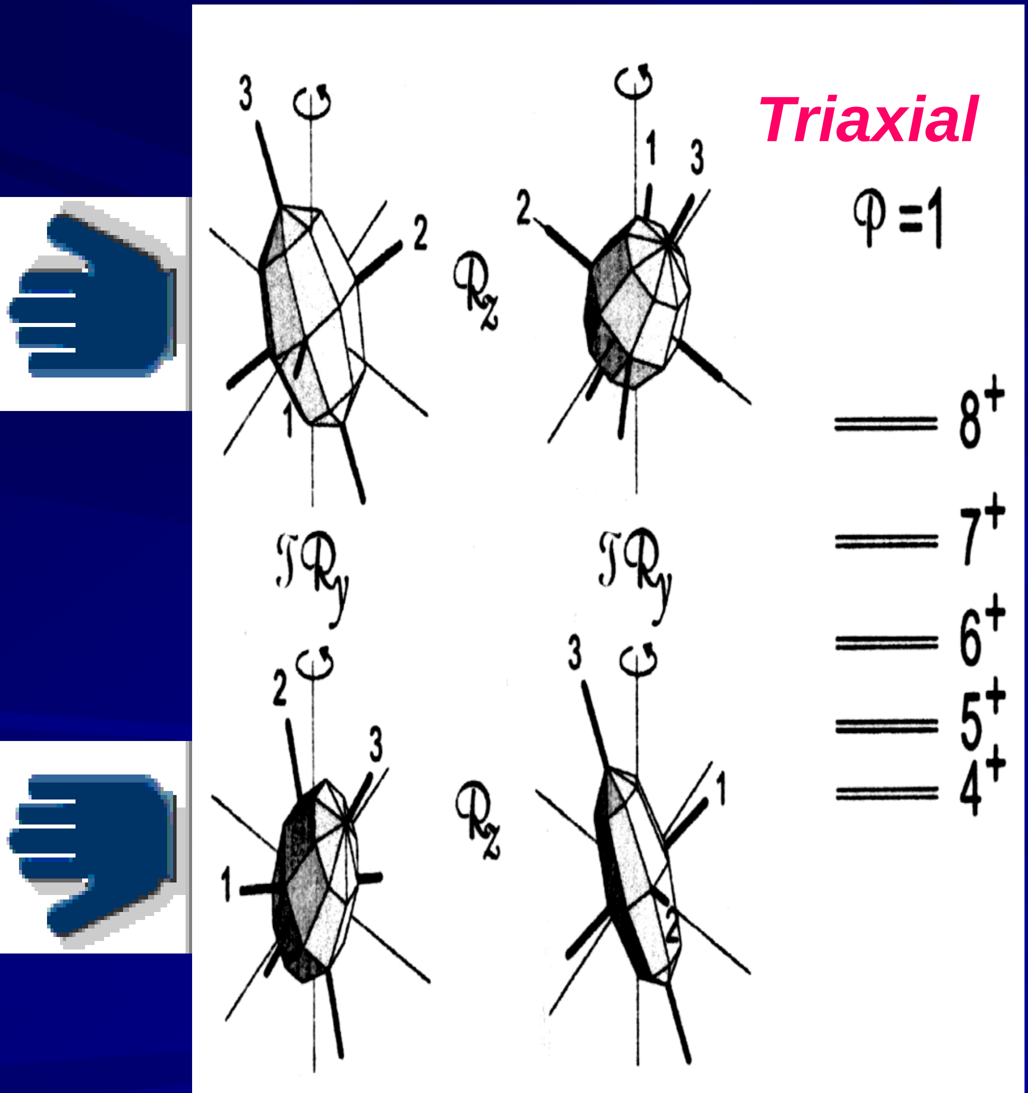
Cd (Z=48) quasi-particle couplings, vibrations, onset of collectivity, quasi-rotations, soft triaxiality $\gamma \sim -10^0$

Shape evolution with regard to triaxial deformations, changing with Z, N and rotations. The γ values corresponding to the minimum in the contour plots of the TRS for Pd.

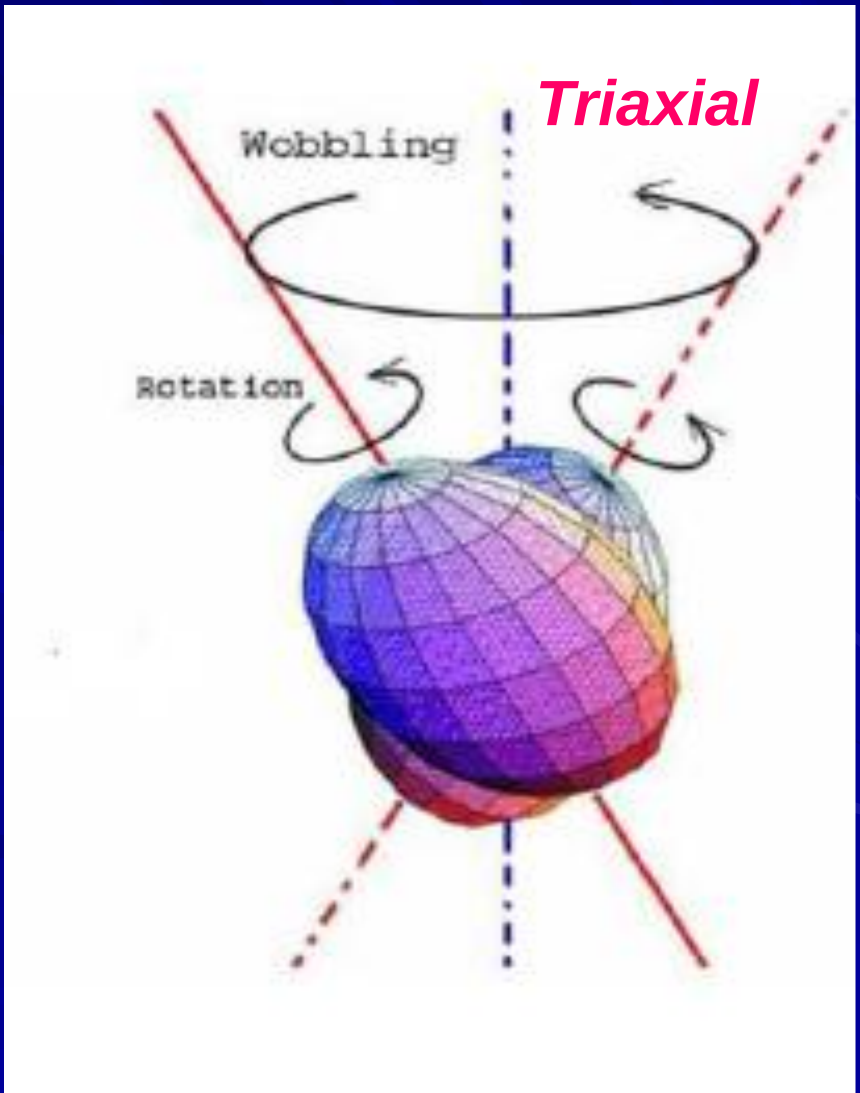


5. New excitations based on triaxial deformations

Chiral symmetry breaking



Wobbling motions



5.1 Chiral symmetry breaking identified in: (10 chiral, 4 disturbed)

^{104,106,108}Mo (Z=42)

^{100}Tc (Z=43)

^{110,112}Ru, (Z=44)

^{108}Ru (disturbed) (Z=44)

$^{103-106}$Rh (Z=45)

^{112,114,116}Pd (disturbed) (Z=46)

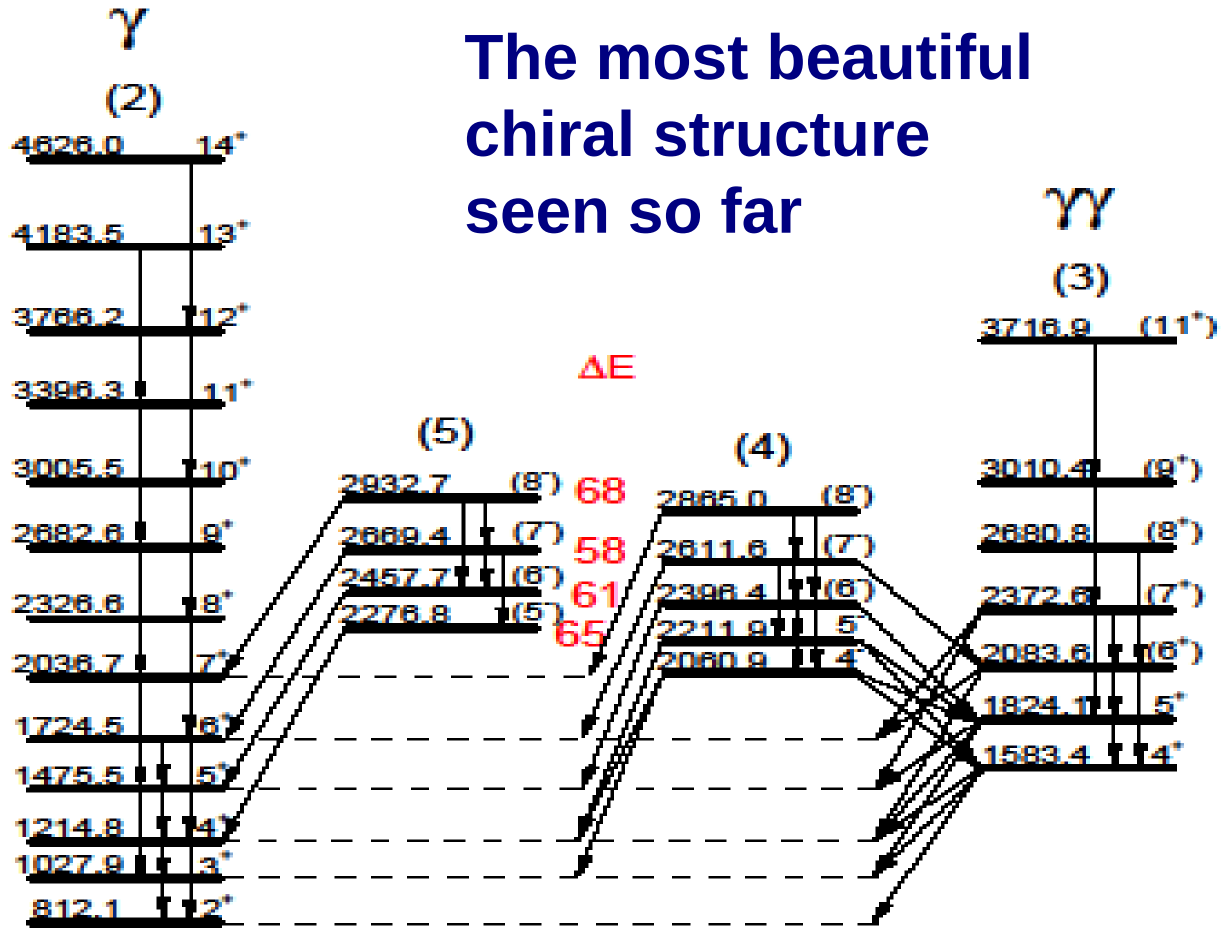
e.g. Y.X. Luo *et al*. Nucl. Phys. A919, 67(2013);
B. Musangu *et al.* Submitting to PRC.

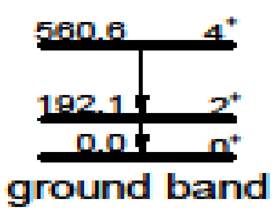
New excitation – chiral symmetry breaking

^{104}Mo

B. Musangu et al.
Submitting PRC

The most beautiful chiral structure seen so far





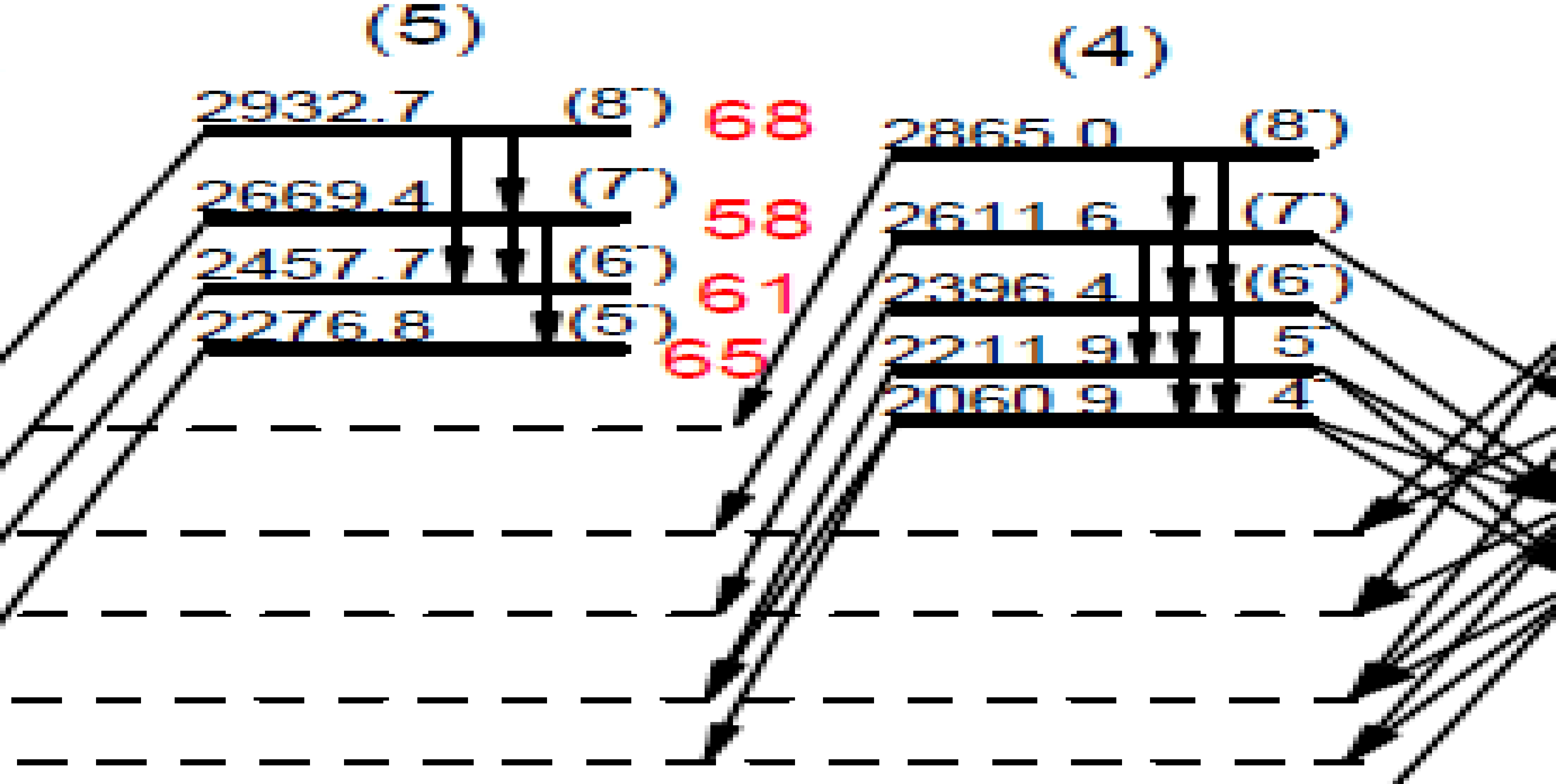
The most recent results for the studies of triaxial deformations

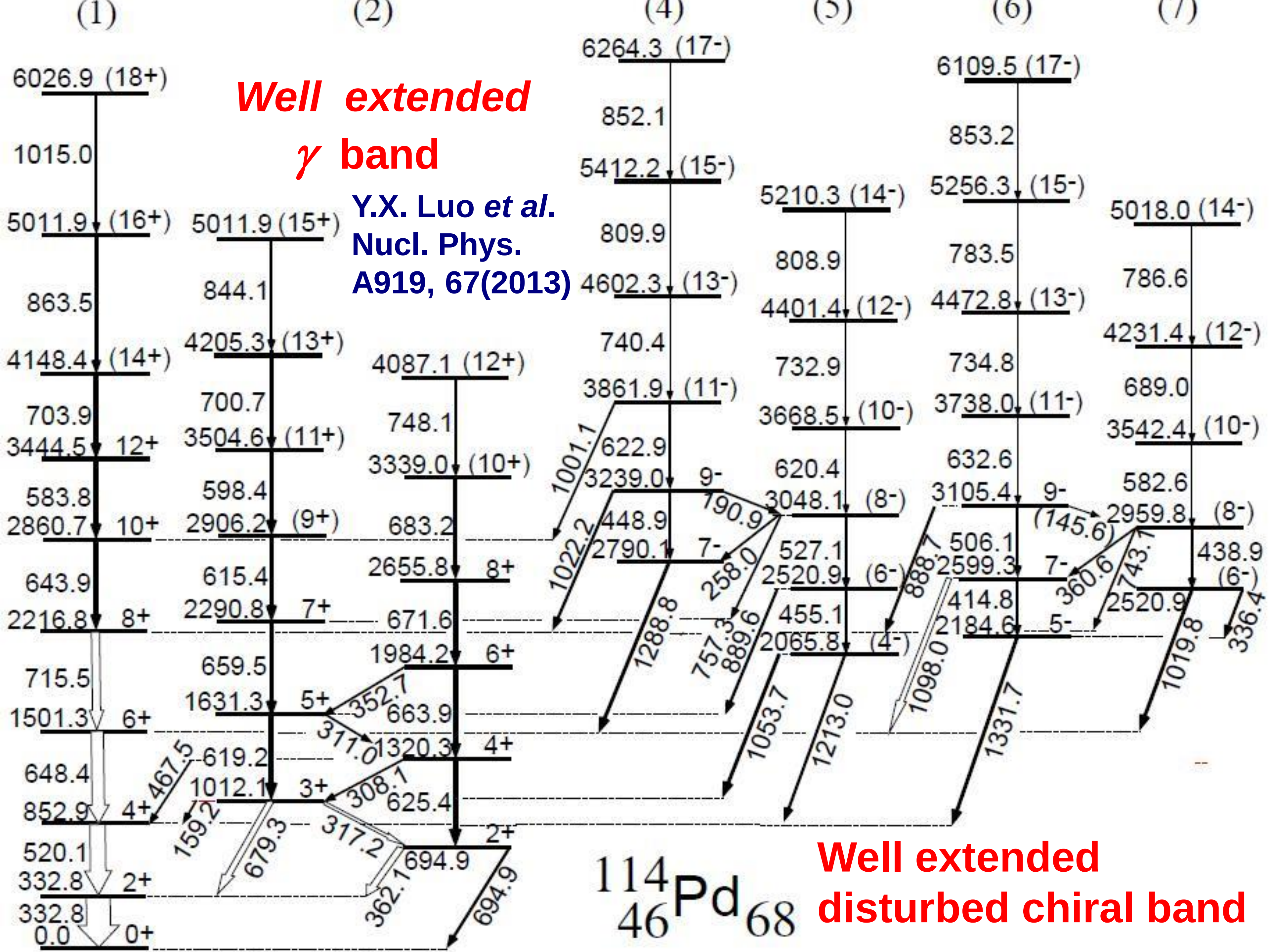
Chiral doublet bands in ^{104}Mo

Weak population

Rich decay-out paths

B. Musangu *et al.*
Submitting Phys. Rev. C



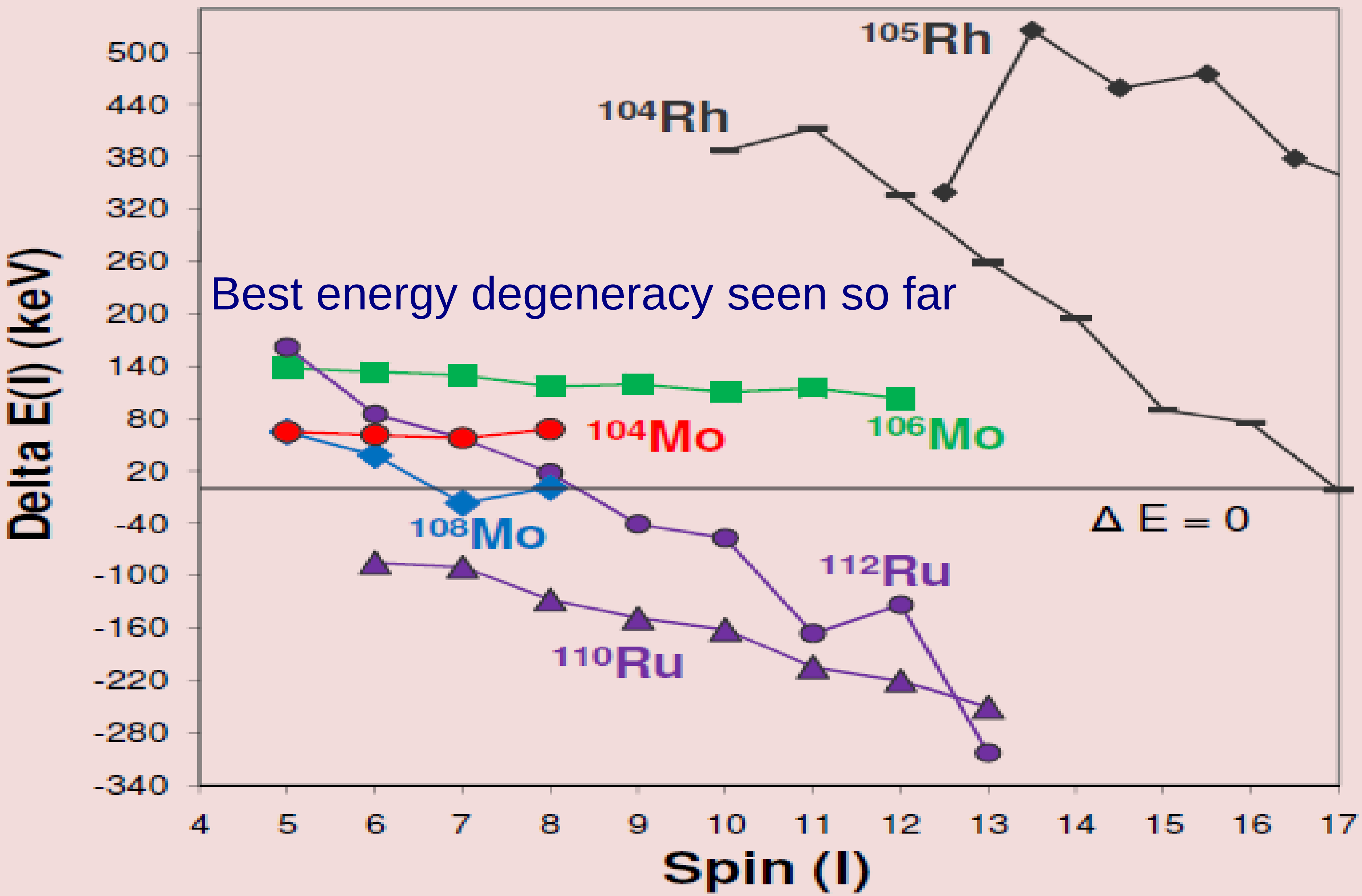


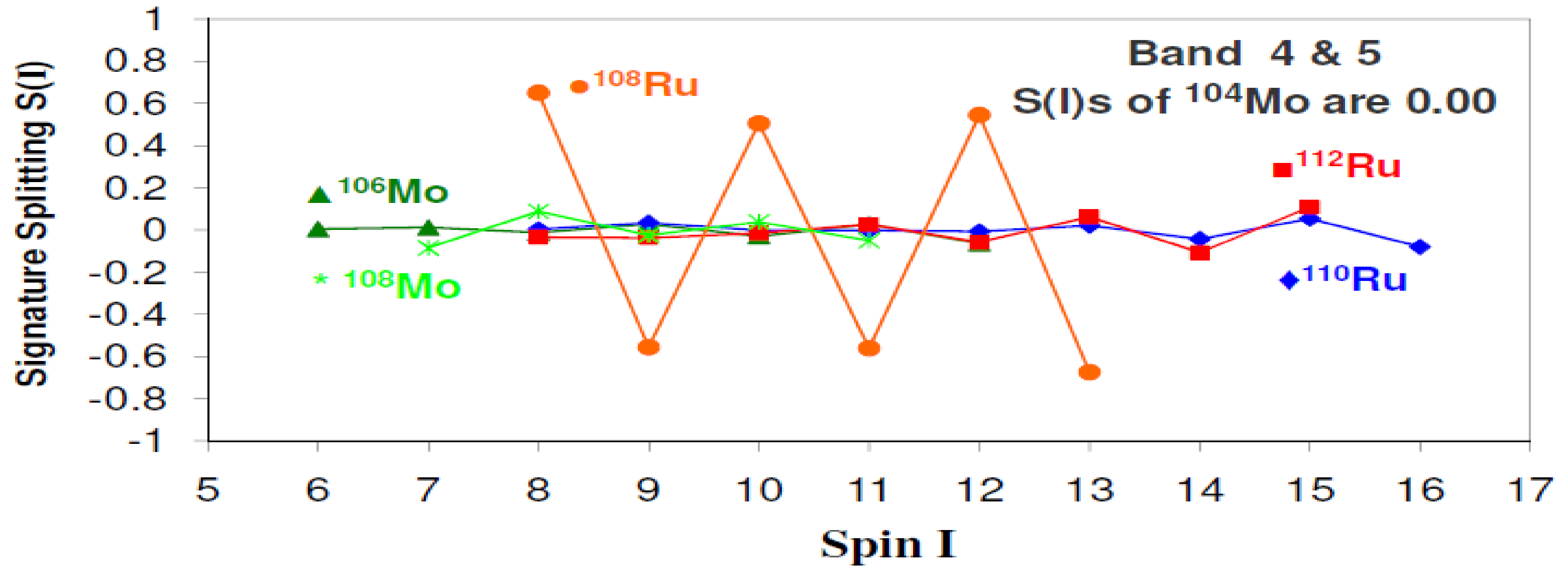
Well extended γ band

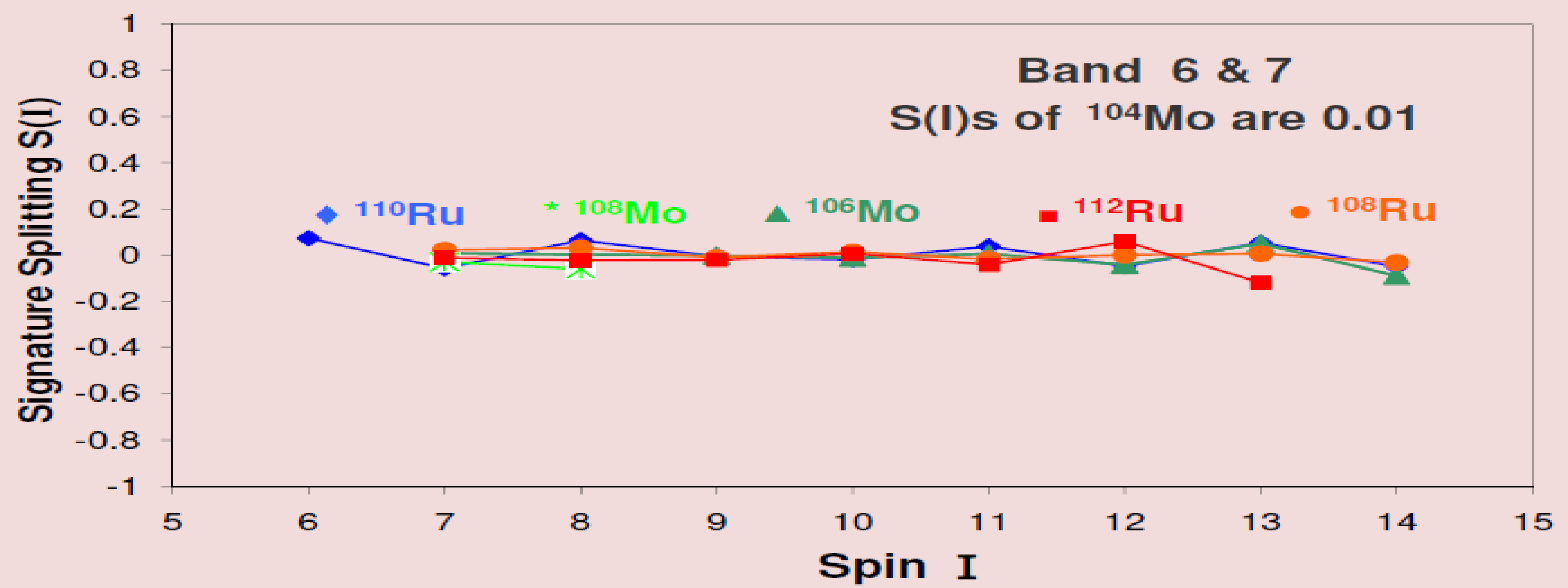
Y.X. Luo *et al*. Nucl. Phys. A919, 67(2013)

Well extended disturbed chiral band

Energy differences of partner levels




Band 4 & 5
S(I)s of 104Mo are 0.00
108Ru
106Mo
112Ru
108Mo
110Ru
Signature Splitting S(I)
Spin I


Band 6 & 7
S(I)s of 104Mo are 0.01
110Ru
108Mo
106Mo
112Ru
108Ru
Signature Splitting S(I)
Spin I

Evolutions of chiral structure

For Z=44 (Ru) isotopic chain,

from disturbed chiral to chiral

from N=64 to N=66,68

For N=66, 68 isotonic chains,

from chiral to disturbed chiral

from Z=44 (Ru) to Z=46 (Pd)

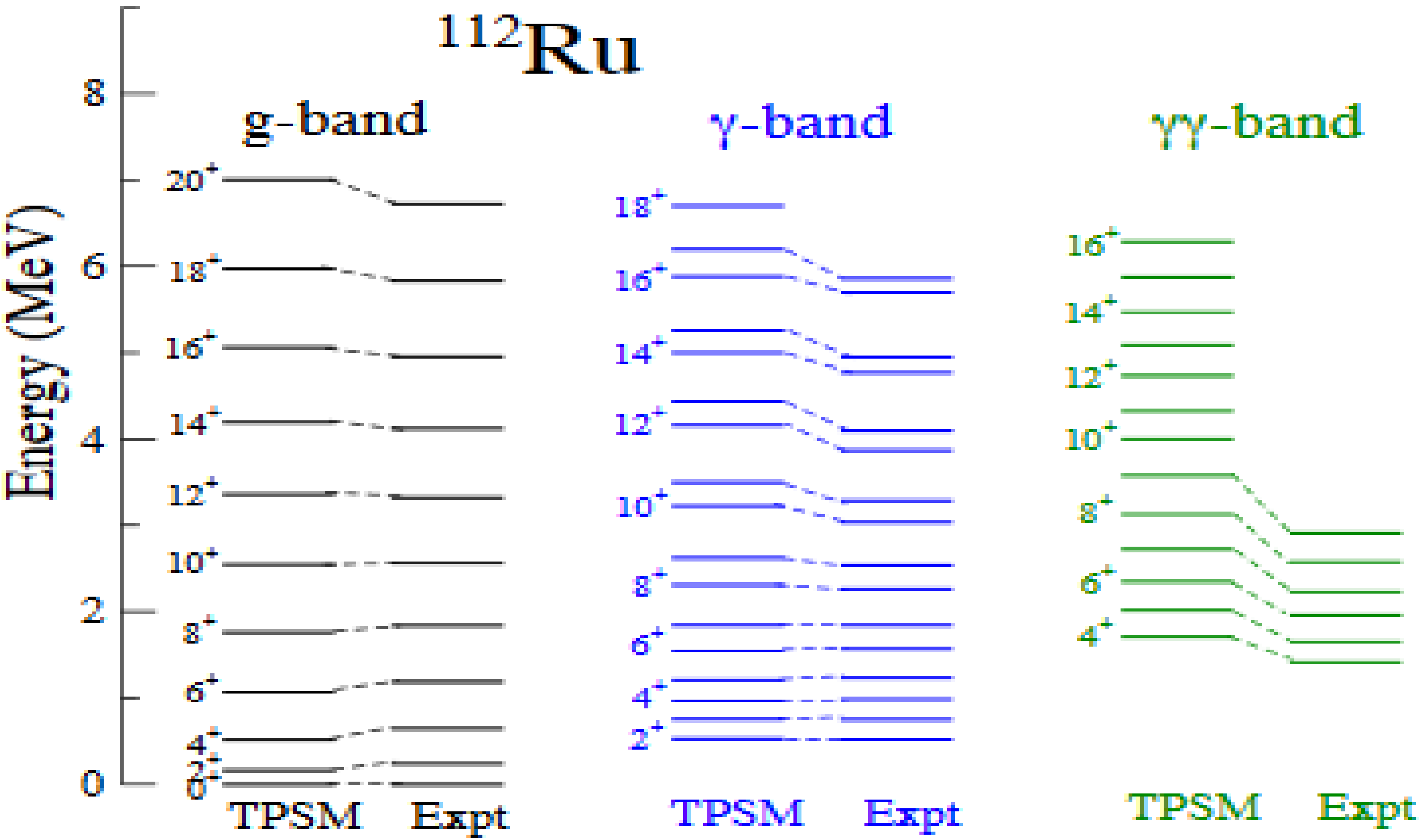
The TPSM basis employed in this study consists of 0-q.p. vacuum, two-proton, two-neutron, and the four-q.p. configurations [45]. The q.p. basis chosen is adequate to describe high-spin states up to angular momentum $I \sim 20$. In the present analysis we shall, therefore, restrict our discussion to this spin regime. As in the earlier TPSM calculations, we use the pairing plus quadrupole-quadrupole Hamiltonian [33, 47]: **C.L Zhang *et al.***

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_{\mu} \hat{Q}^{\dagger}_{\mu}\hat{Q}_{\mu} - G_M \hat{P}^{\dagger}\hat{P} - G_Q \sum_{\mu} \hat{P}^{\dagger}_{\mu}\hat{P}_{\mu}, \quad (1)$$

where $\hat{H}_0$ is the single-particle spherical Nilsson Hamiltonian, χ is the strength of the quadrupole-quadrupole force related in a self-consistent way to deformation of the q.p. basis, and G_M and G_Q are the strengths of the monopole and quadrupole pairing terms, respectively. The configuration space employed corresponds to three principal oscillator shells $\mathcal{N}_{\rm osc}$: $\nu[3,4,5]$ and $\pi[2,3,4]$. The pairing strengths have been parametrized as in Refs. [32, 48] in terms of two constants G_1 and G_2. In this work, we choose $G_1 = 16.22\,\mathrm{MeV}$ and $G_2 = 22.68\,\mathrm{MeV}$; with these pairing strengths we approximately reproduce the experimental odd-even mass differences in this region. The quadrupole pairing strength G_Q is assumed to be proportional to G_M, and the proportionality constant was set to 0.18 [32, 48]. The single-particle basis is that of the deformed Nilsson Hamiltonian parametrized in terms of axial (ε) and triaxial (ε') deformations related to the standard Bohr triaxiality parameter γ by $\gamma = \arctan(\varepsilon'/\varepsilon)$.

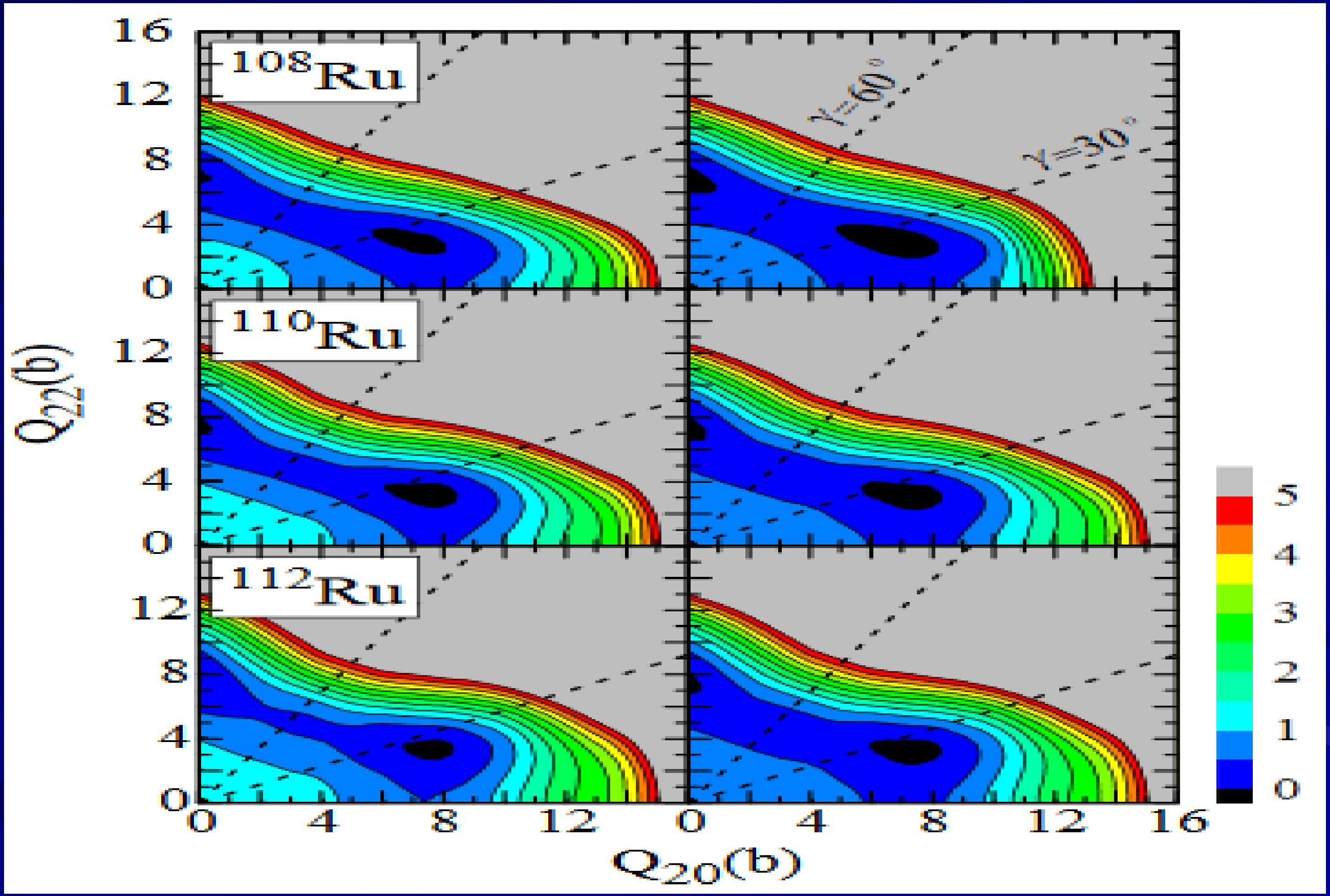
Band structure reproduced by the TPSM calculations

C.L Zhang et al.



PES in CHFB + UNDE0 model calculations.

Standard paring **Paring increased by 5%**



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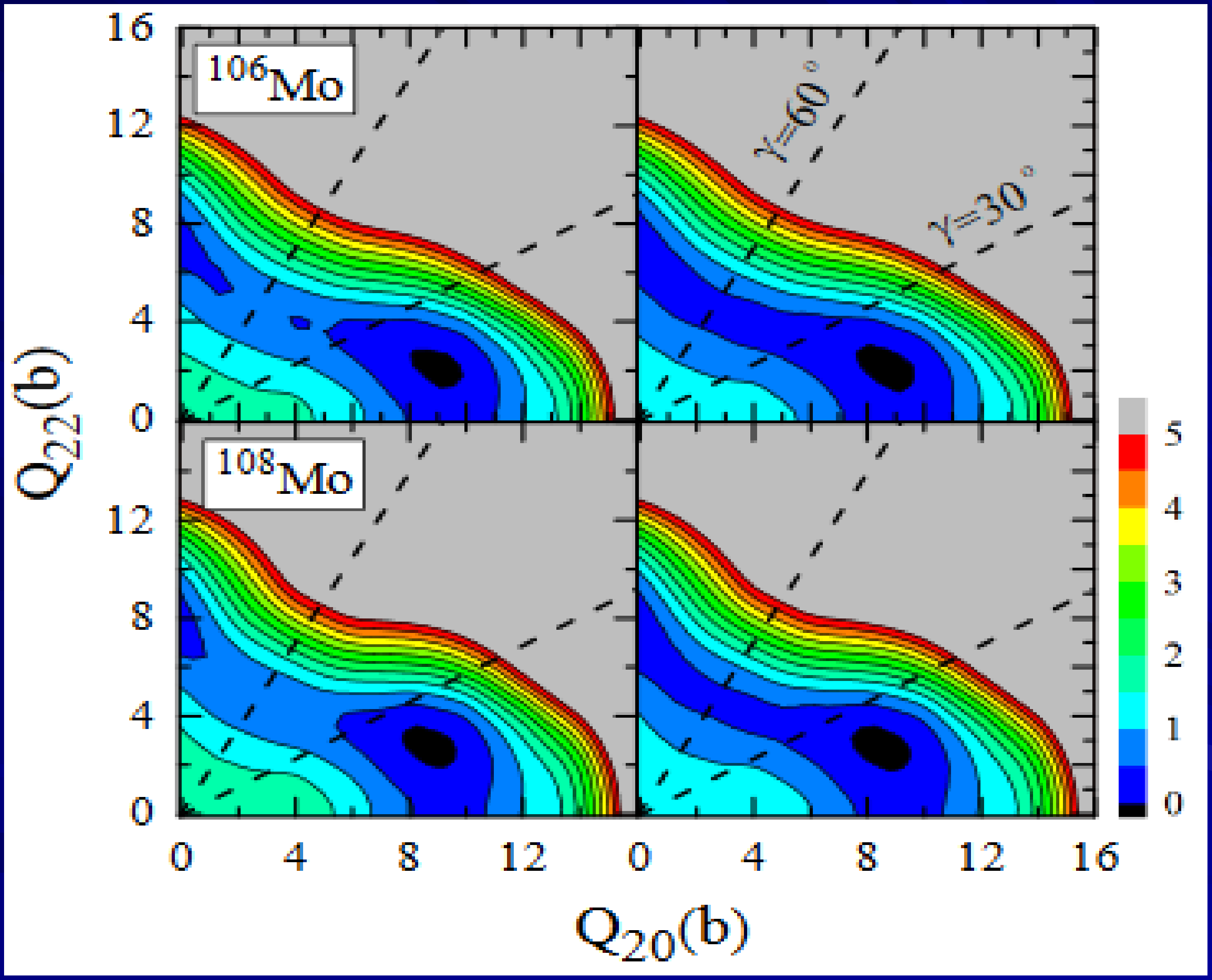
PES in CHFB + UNDE0 model calculations.

Standard paring **Paring increased by 5%**



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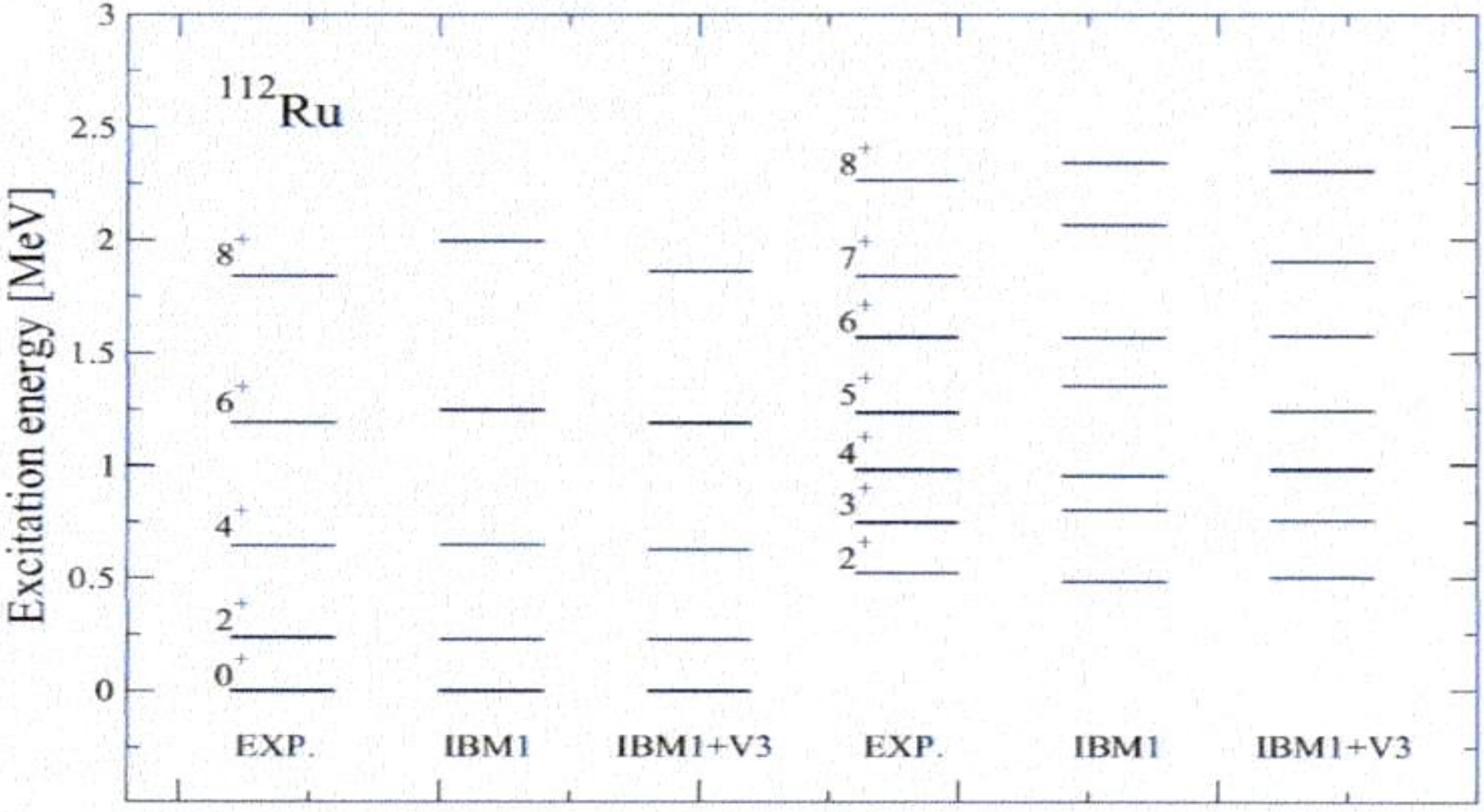
Our calculations, Stefanescu et al. Nucl. Phys. ***789****, 125(2007)*



Even at low spin the staggering is best fit by rigid triaxial rotor model IBM1+V3 (including three body terms) and more definitely at high I.

Our calculations, Stefanescu et al. Nucl. Phys. ***789****, 125(2007)*

Can also reproduce with IBM1 model to E_{exc}, B(E2) and signature splittings of the ground-band and one-phonon gamma band of ^{108}Ru

↓

suggesting it as a Gamma soft SU(6) nucleus

↓

Gamma softness disturbing the chiral symmetry breaking in the nucleus

(also observed in ^{106}Ag (P. Joshi et al. PRL, 98,102501(2007))

So, the IBM models can reproduce the differences between ^{110,112}Ru (chiral) and ^{108}Ru (disturbed chiral). IBM are nowdays still playing remarkable role in the interpretations for nuclear structure.

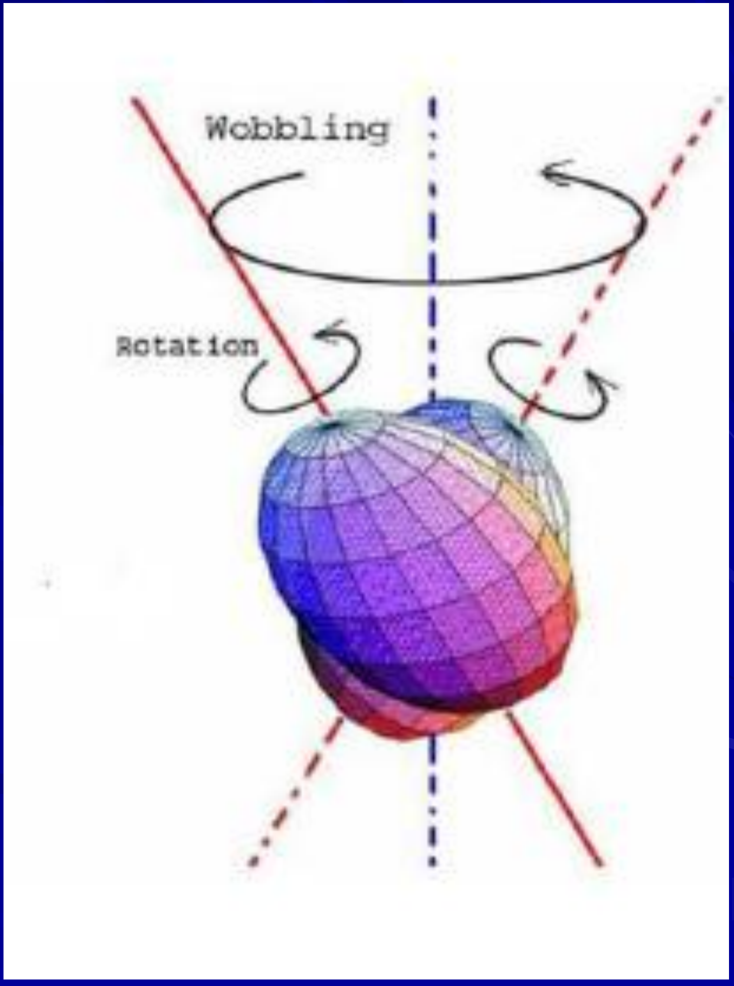
5.2 Onset and evolutions of triaxial wobbling motions in Ru and Pd

Wobbling Motion

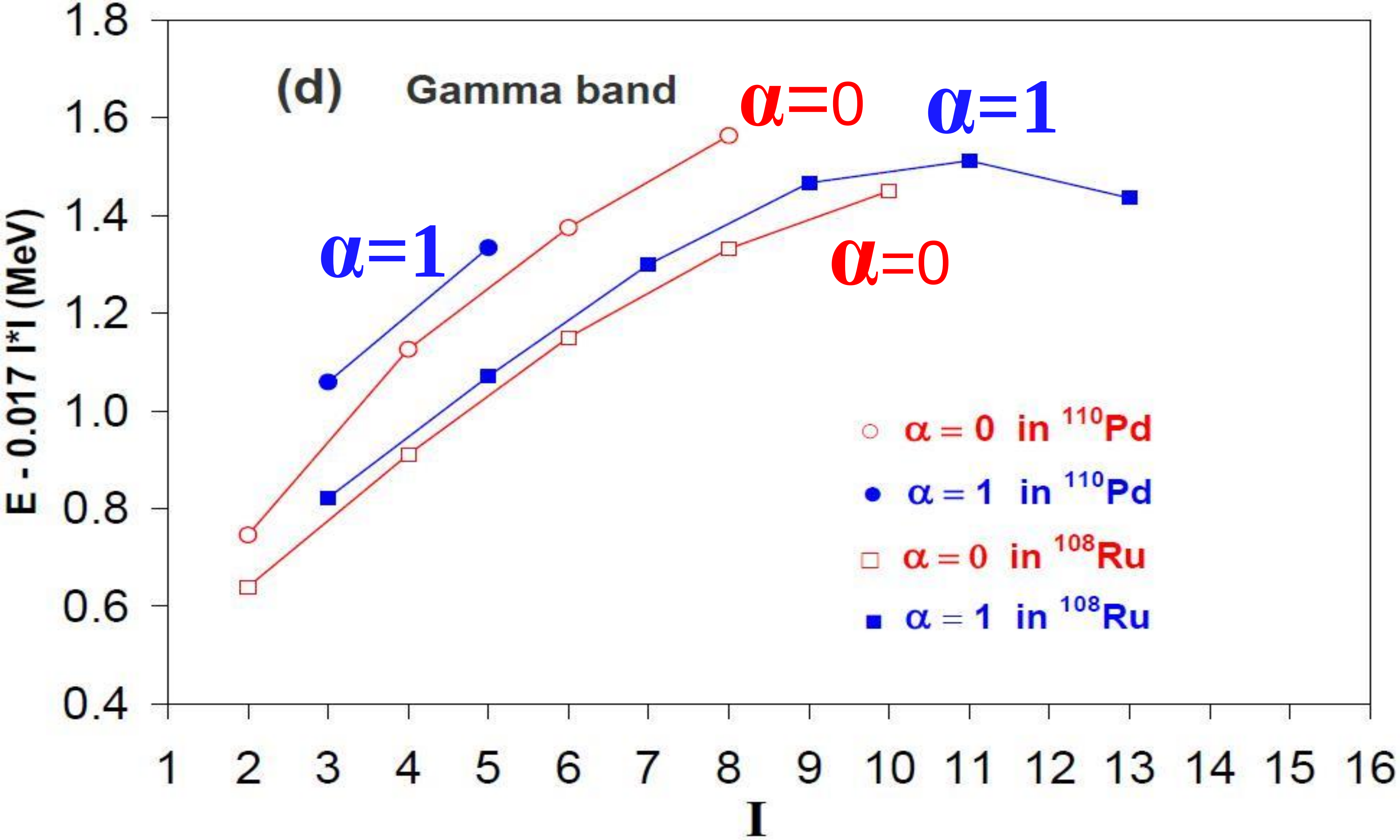
A revolving motion of J about an axis of the triaxial nucleus

seen in ^{161,163,165,167}Lu and ^{167}Ta at high spin

S. W. Ødegård, et al., Phys. Rev. Lett. 86, 5866(2001); G. Schőnwaβer et al, Phys. Lett, B552, 9(2003); P. Bringel et al., Eur. Phys. J. A24, 167(2005); H. Amro et al., Phys. Lett. B553, 197(2003); D. J. Hartley et al, Phys. Rev. C80, 041304(R)(2009); C83, 064307(2011)

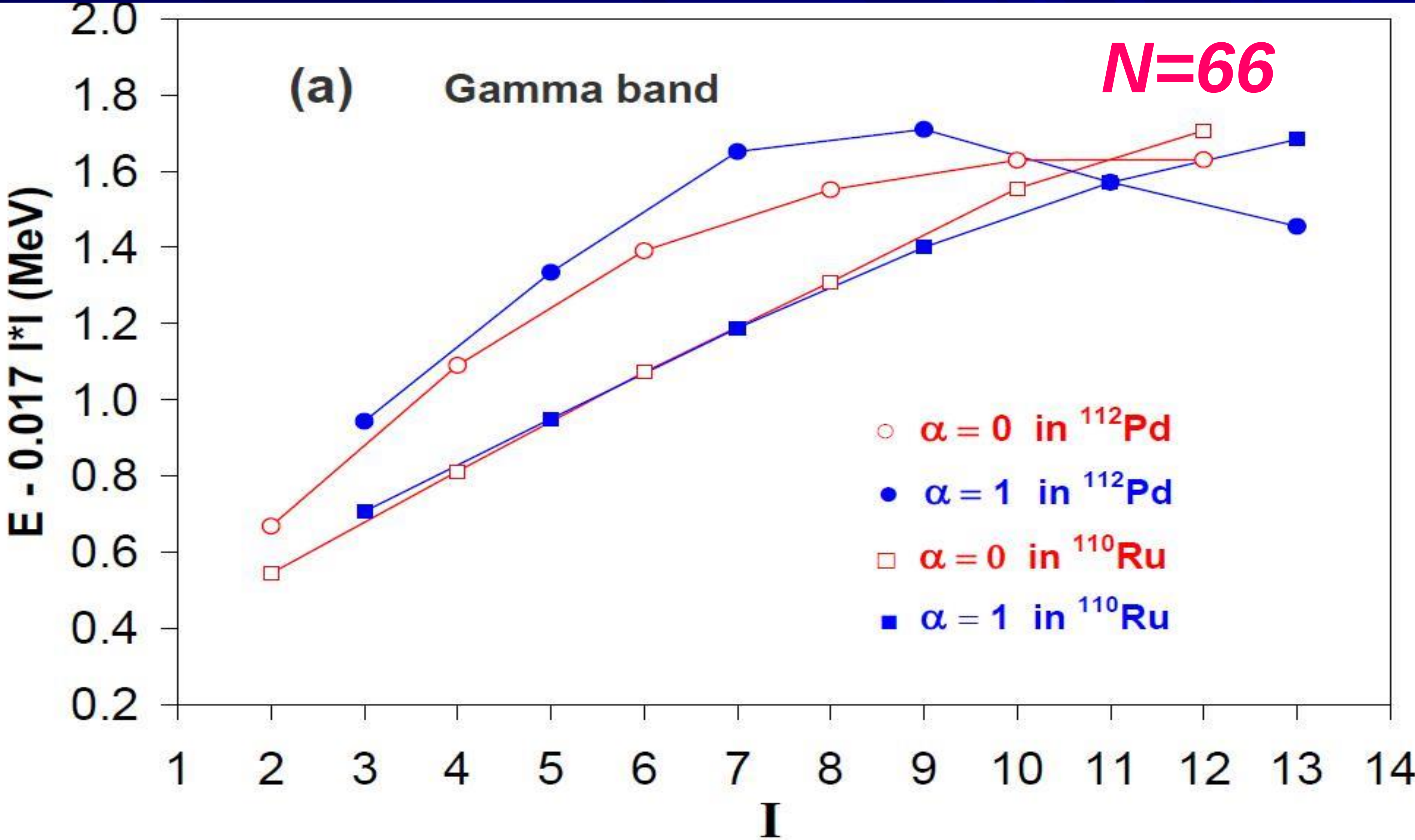


For N=64, no WM

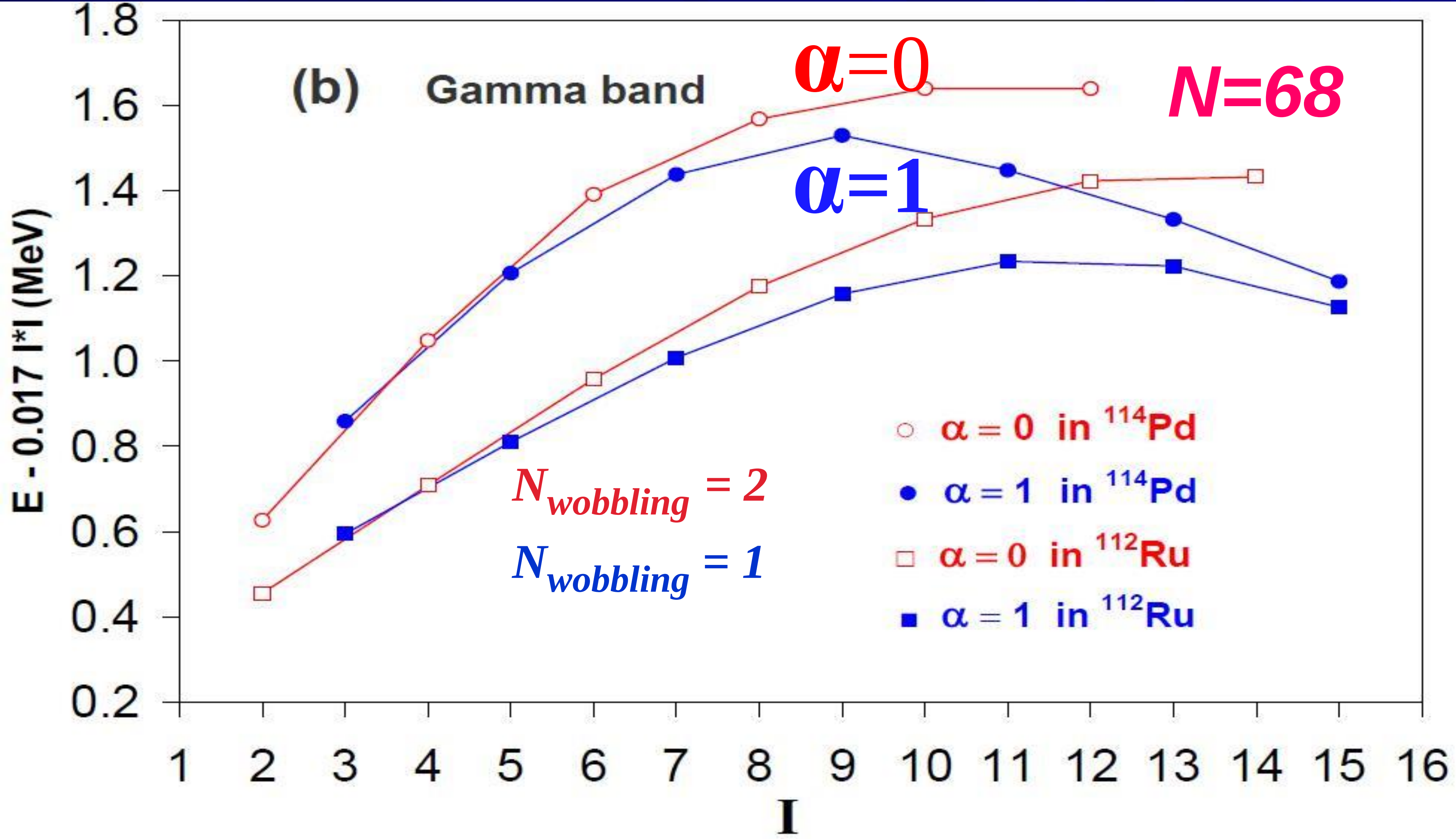


(d) Gamma band
α=0
α=1
α=1
α=0
α = 0 in 110Pd
α = 1 in 110Pd
α = 0 in 108Ru
α = 1 in 108Ru
E - 0.017 I*I (MeV)
I
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

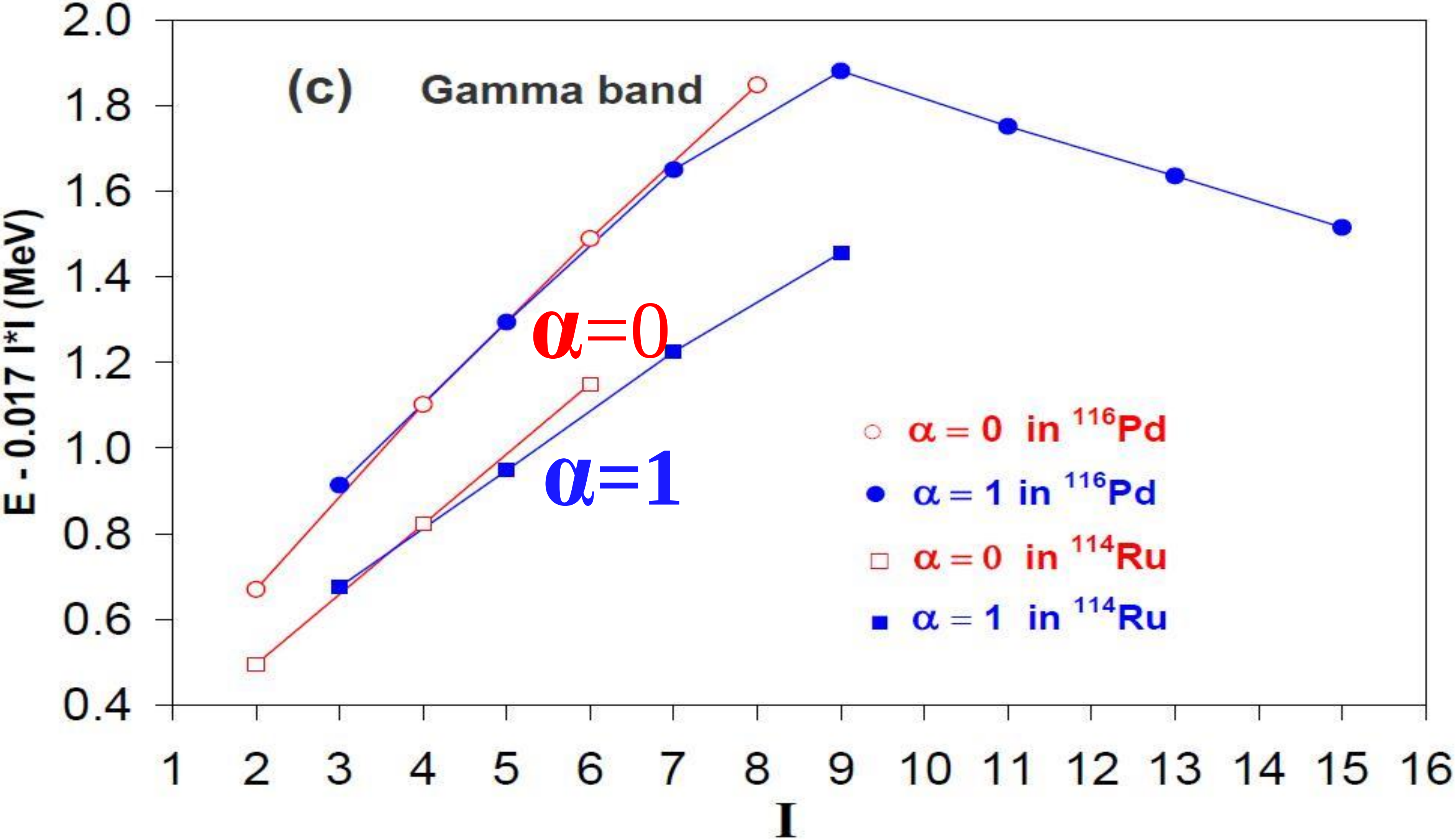
For N=66, no WM until spin 6 and 10 in ^{110}Ru and ^{112}Pd, respectively



For N=68, onset of WM at moderate spins in ^{112}Ru and ^{114}Pd, the e-e wobblers



For N=70, WM may also be seen with small staggerings in ^{114}Ru and ^{116}Pd

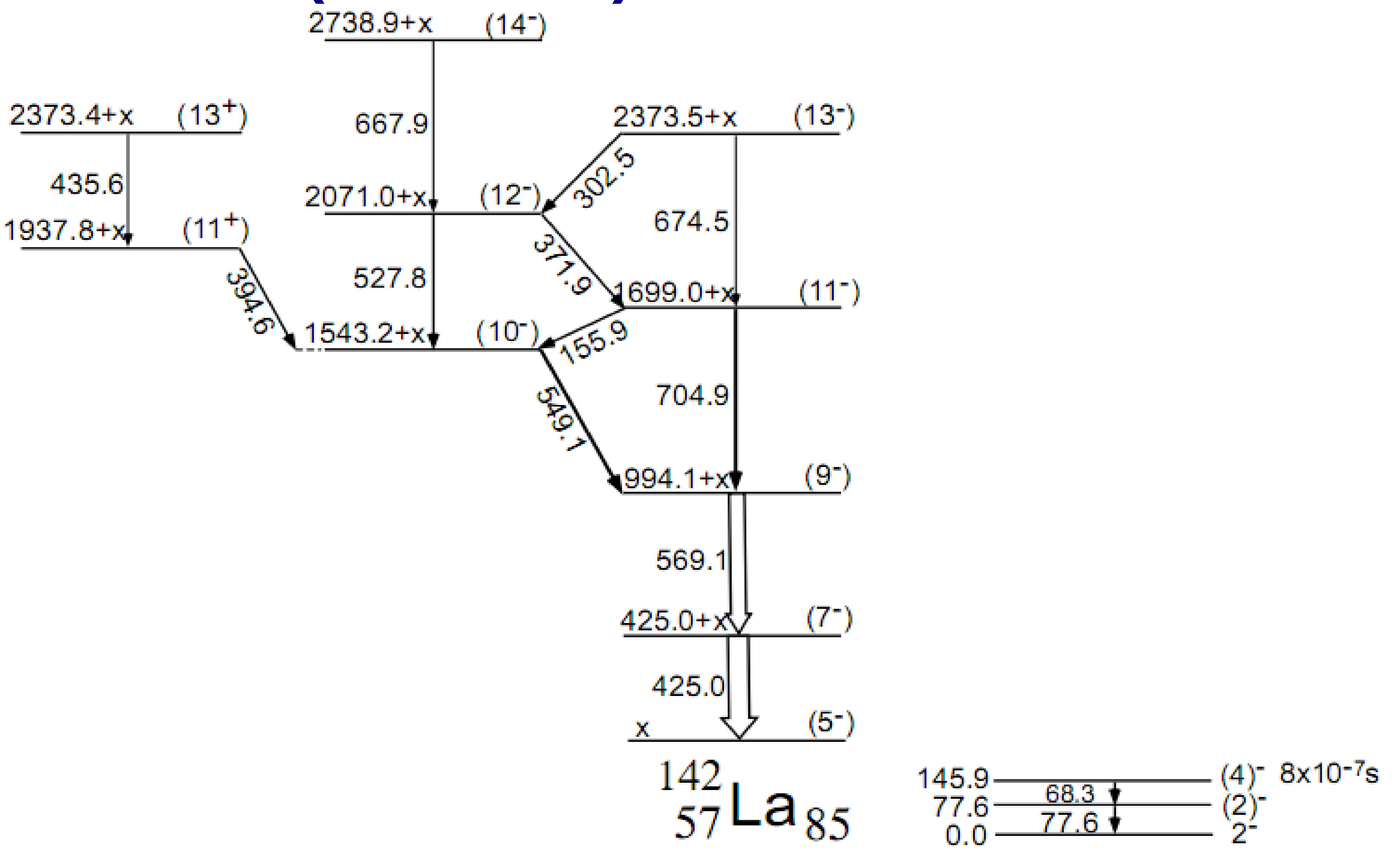


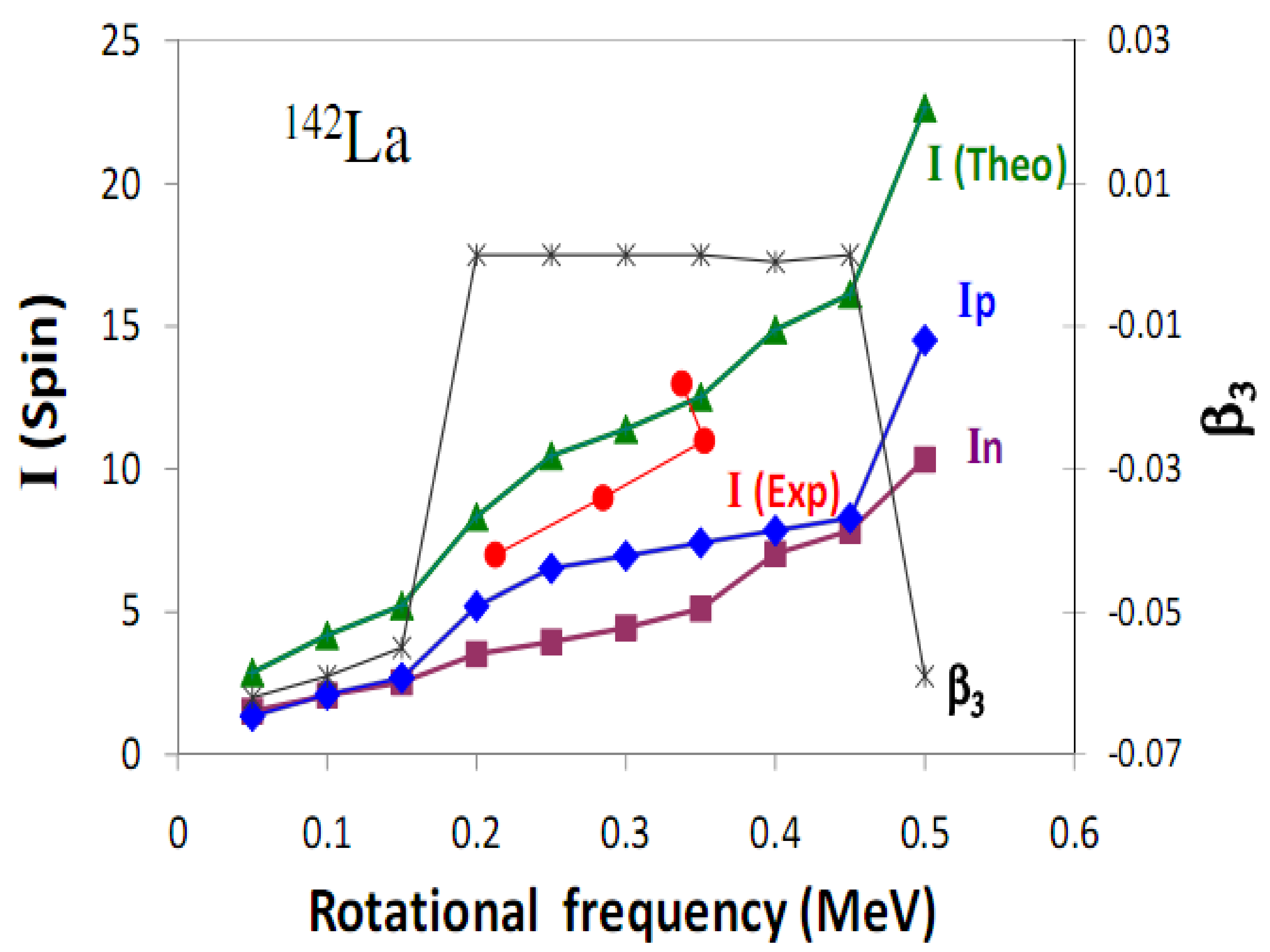
Transitions of WM in Ru (Z=44) and Pd (Z=46) isotopic chains

From No WM in N = 64 isotones, to Onset of WM in N = 68, with N=66 being transitional with regard to WM.

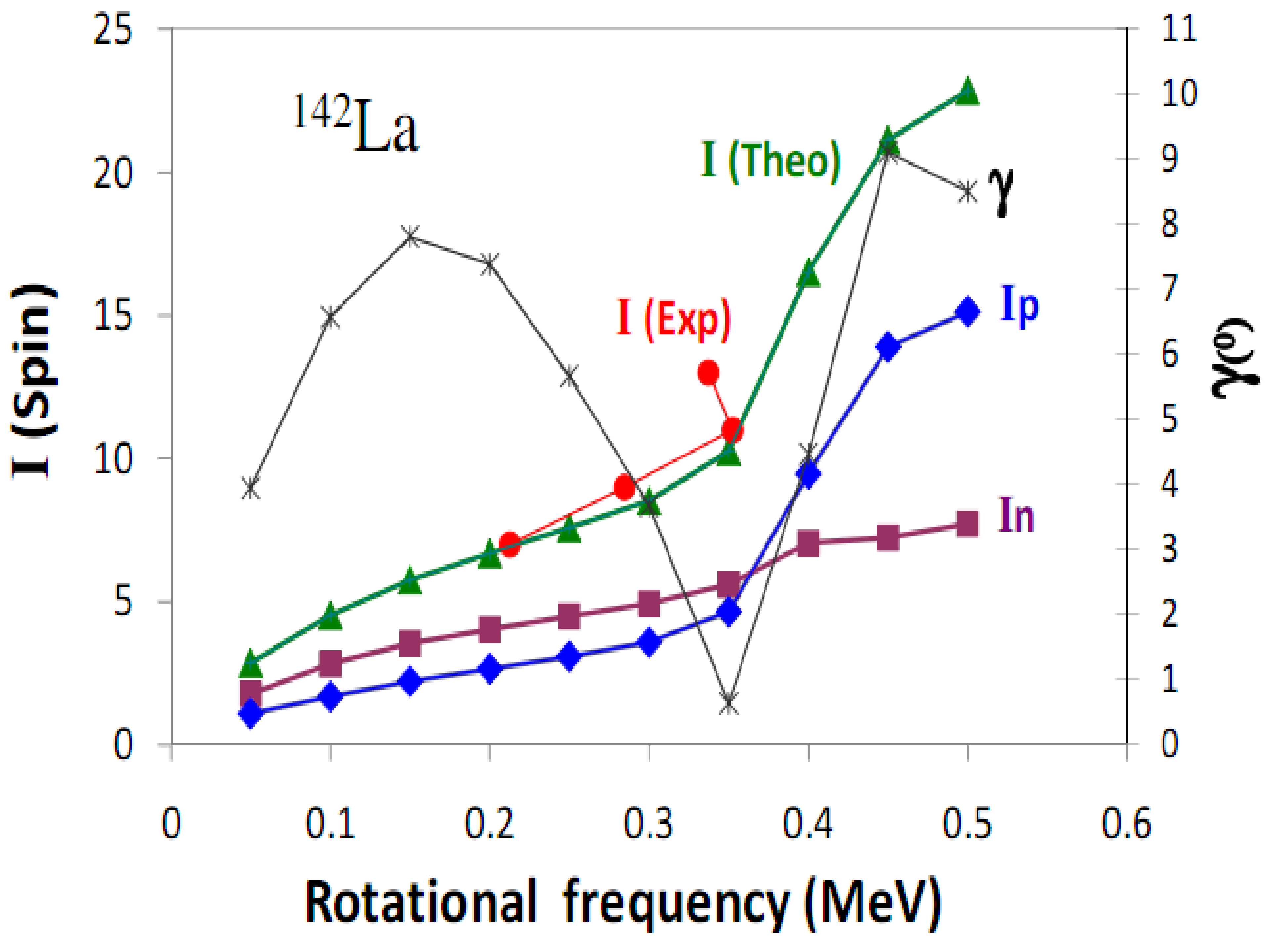
(3) (2) (1)

Octupole/triaxial deformation coexistence in ^{142}La (Z=57, N=85)





142La
I (Theo)
Ip
In
I (Exp)
β3
I (Spin)
Rotational frequency (MeV)
0
5
10
15
20
25
0.03
0.01
-0.01
-0.03
-0.05
-0.07
0
0.1
0.2
0.3
0.4
0.5
0.6



^{142}La
I (Theo)
γ
I (Exp)
Ip
In
I (Spin)
γ(°)
Rotational frequency (MeV)
0
5
10
15
20
25
0
1
2
3
4
5
6
7
8
9
10
11
0
0.1
0.2
0.3
0.4
0.5
0.6

Final Remarks

- ***Prompt fission γ spectroscopy, the “Gold mine” have made remarkable progresses in the systematic studies of nuclear shapes and new excitations for n-rich nuclei.***
- ***Octupole deformation well studied in Z~56, N~88 region.***
- ***Detailed understanding in the shape transitions and shape coexistence with regard to quadrupole / triaxial shapes achieved in the Z=41 – 48, A~100 – 126 n-rich region. Octupole/triaxial shape coexistence also suggested.***
- ***New excitations and evolutions of chiral symmetry breaking and WM have been found and studied in Mo, Ru and Pd isotopic chain, as well as in isotonic chains.***

Collaborators

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Thank you very much for your attention!