

Boundaries of the $N=90$ QPT and Evolution of Deformation in Rare Earth Nuclei



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Volker Werner

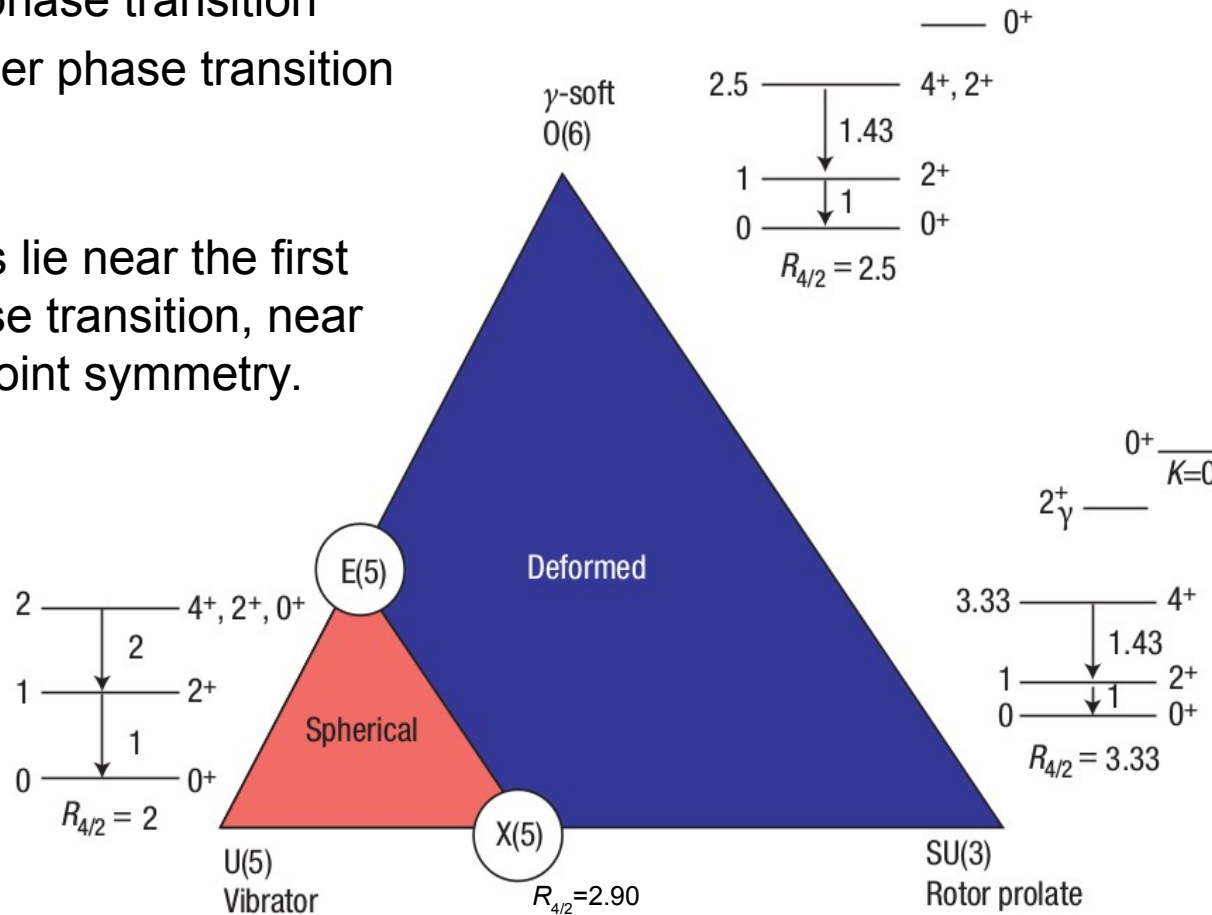
**Institut für Kernphysik, TU Darmstadt
AG Pietralla**

Symmetry triangle – Phase transitions

X(5): first order phase transition

E(5): second order phase transition

All N=90 isotones lie near the first order shape phase transition, near the X(5) critical point symmetry.



R. F. Casten, Review Article, Nature physics, Vol 2 (2006)

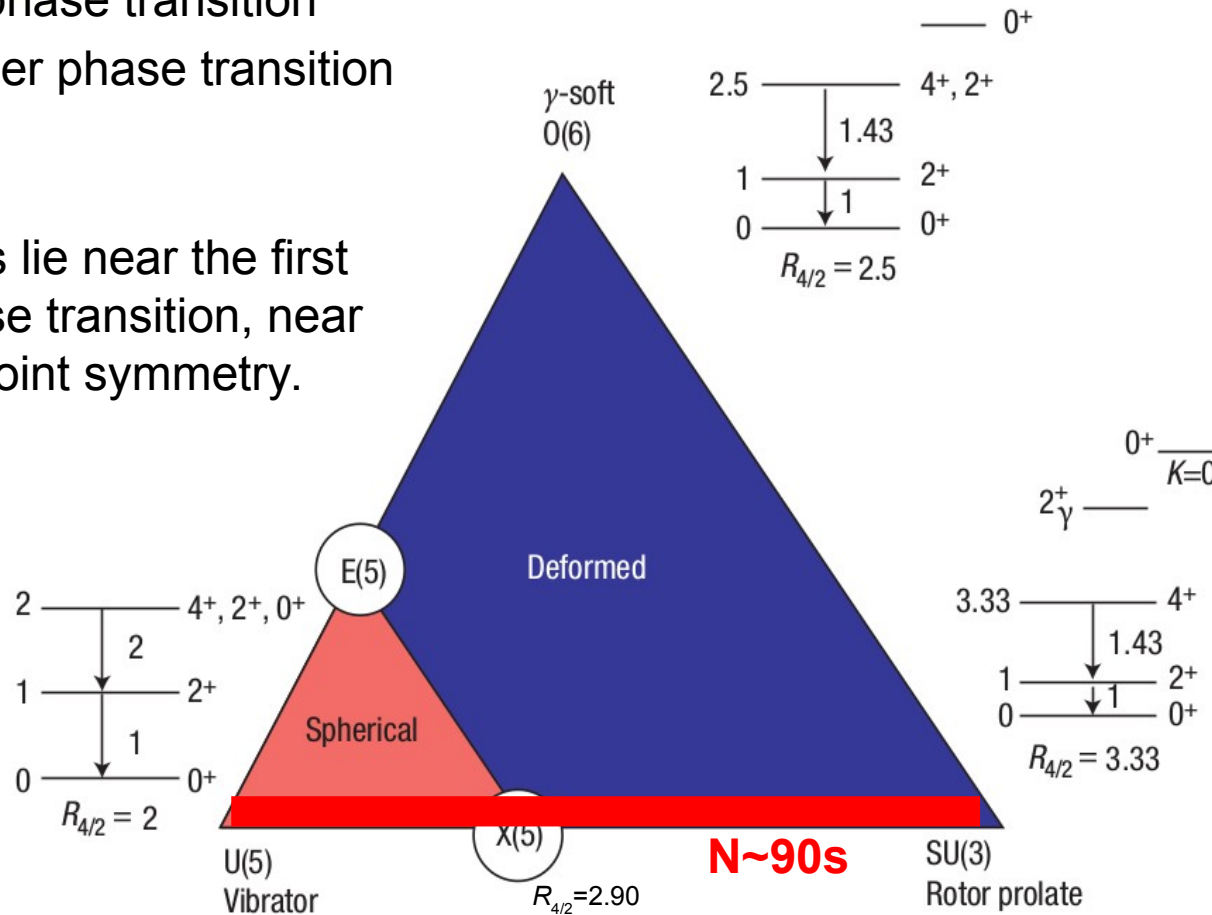
F. Iachello, Phys. Rev. Lett., 85, 3580–3583 (2000) ; 87, 052502-1–052502-4 (2001)

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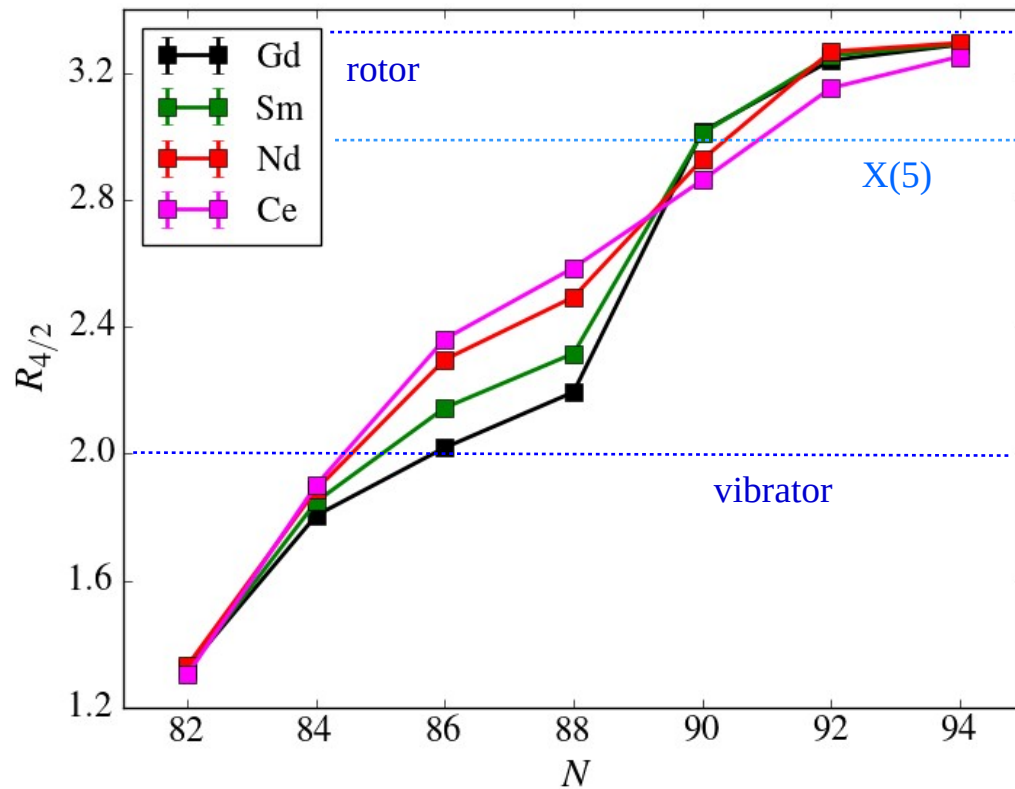
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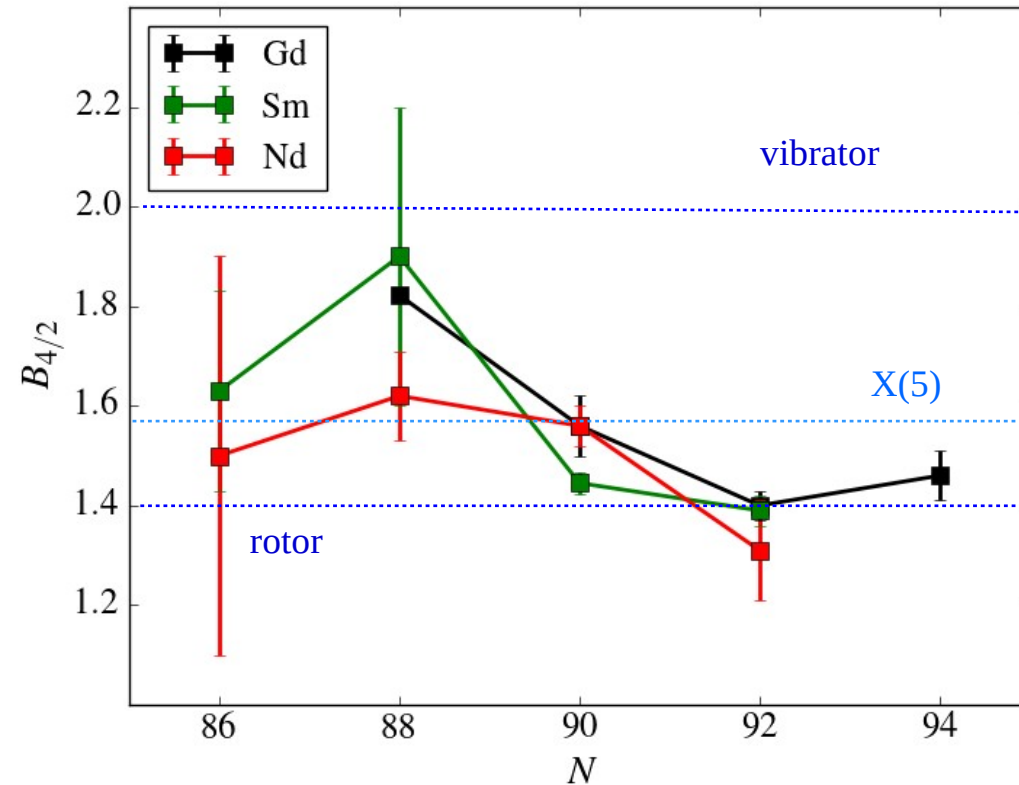
R. F. Casten, Review Article, Nature physics, Vol 2 (2006)

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Systematics around N=90



$$R_{4/2} = E(4^+_{1}) / E(2^+_{1})$$

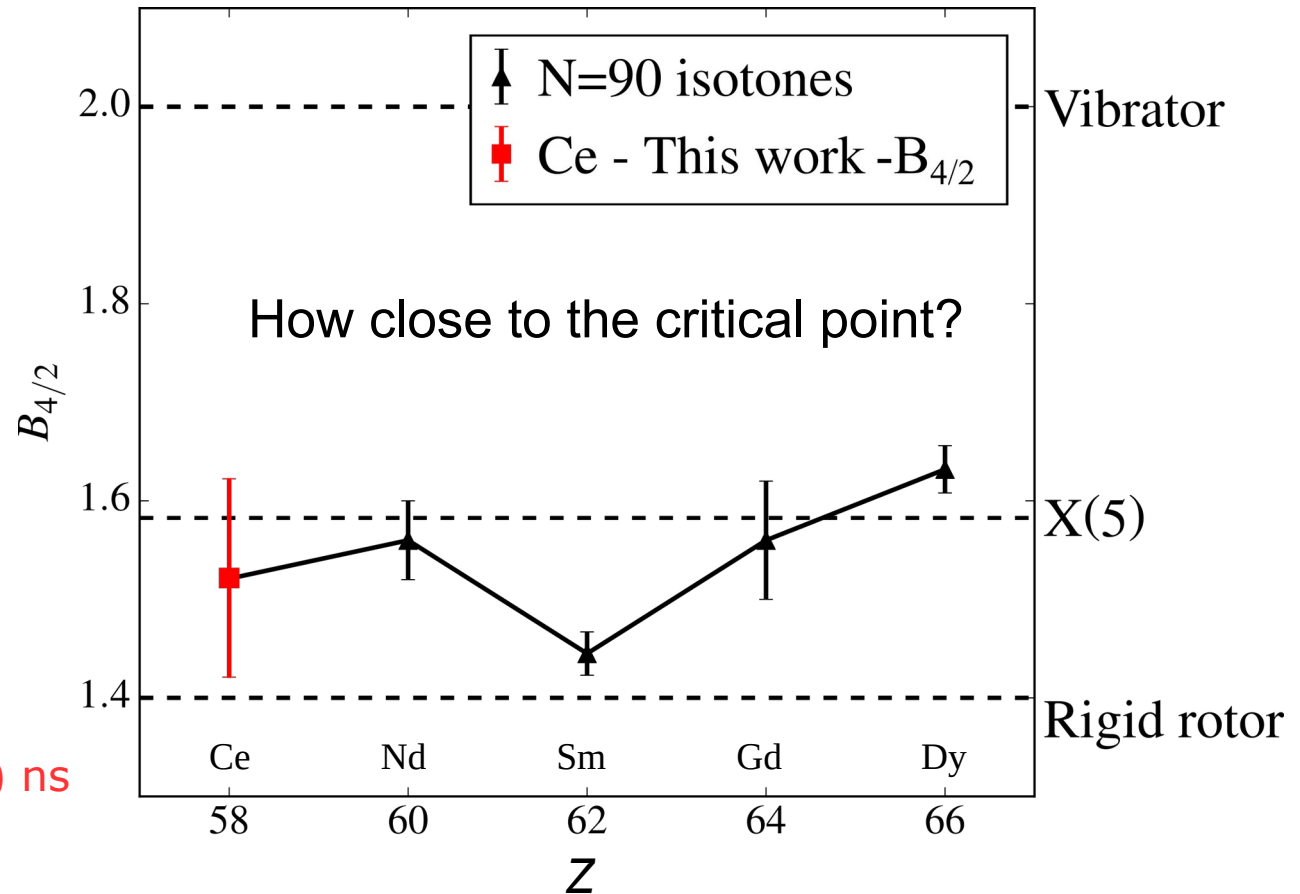
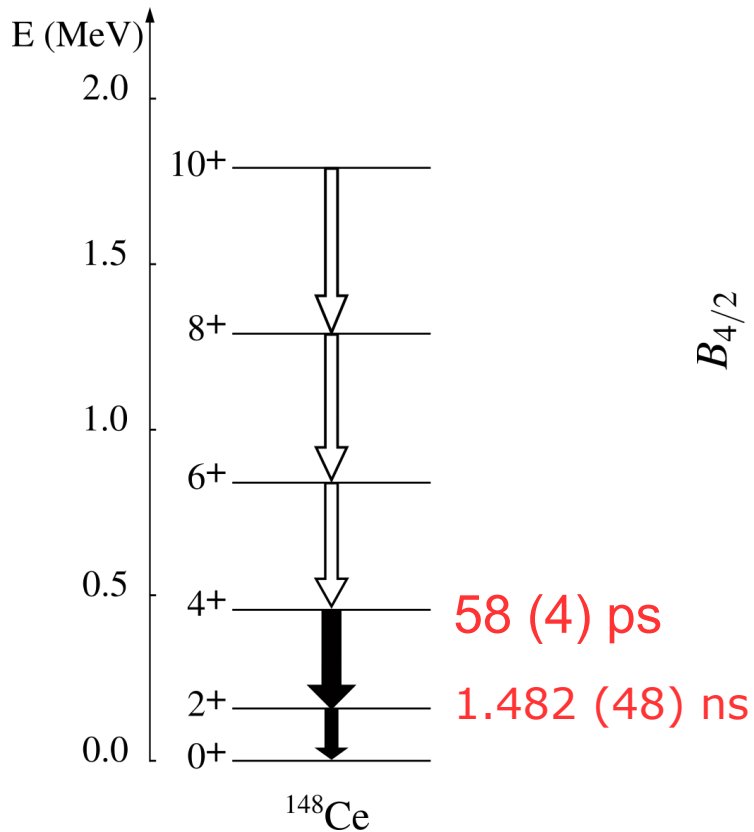


$$B_{4/2} = B(E2; 4^+_{1} \rightarrow 2^+_{1}) / B(E2; 2^+_{1} \rightarrow 0^+_{1})$$

Slide from P. Koseoglou

^{148}Ce $B_{4/2}$ ratio

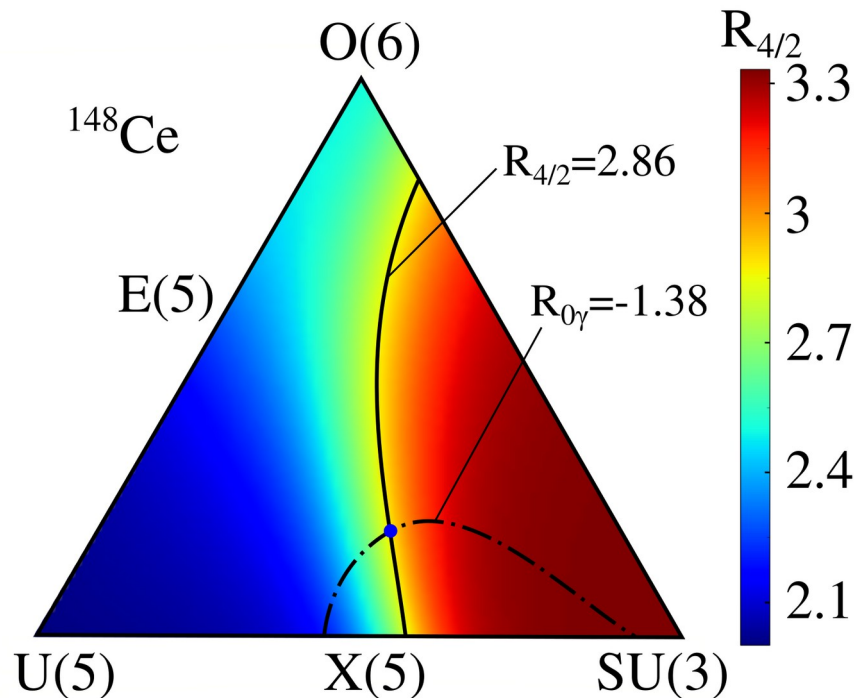
$$B_{4/2} = 1.53 (12)$$



P. Koseoglou et al. Phys. Rev. C 101, 014303 (2020)

EXILL data

^{148}Ce in IBM symmetry triangle



The orthogonal crossing of constant contours of basic observables can place a nucleus in the triangle.

$$R_{4/2} = E(4_1^+) / E(2_1^+)$$

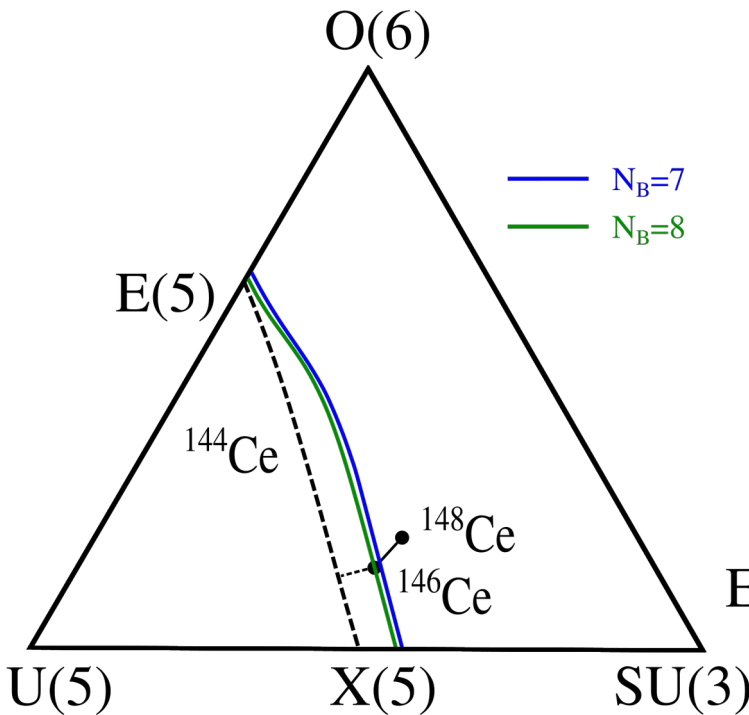
$$R_{0\gamma} = \frac{E(0_2^+) - E(2_\gamma^+)}{E(2_1^+)}$$

W.-T. Chou, N.V. Zamfir and R.F. Casten, Phys. Rev. C 56, 829 (1997)

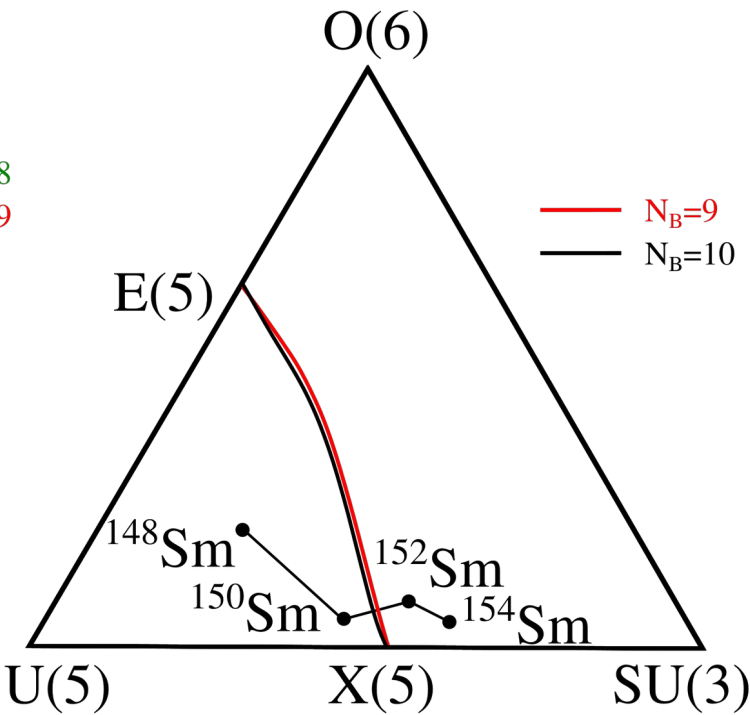
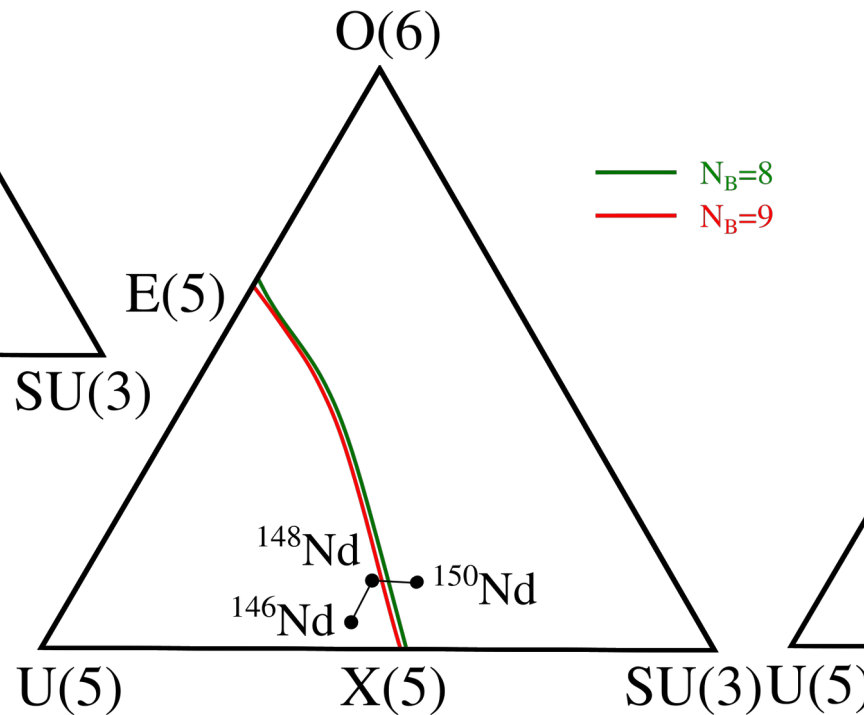
E. A. McCutchan and R.F. Casten, Phys. Rev. C 74, 0.57302 (2006)

Slide from P. Koseoglou

Isotopic chains in the symmetry triangle



- In all isotopic chains the PT-line is between the $N=88$ and $N=90$ isotopes.
- ^{148}Ce on the deformed side.
- Ce isotopic chain shows higher axial asymmetry.

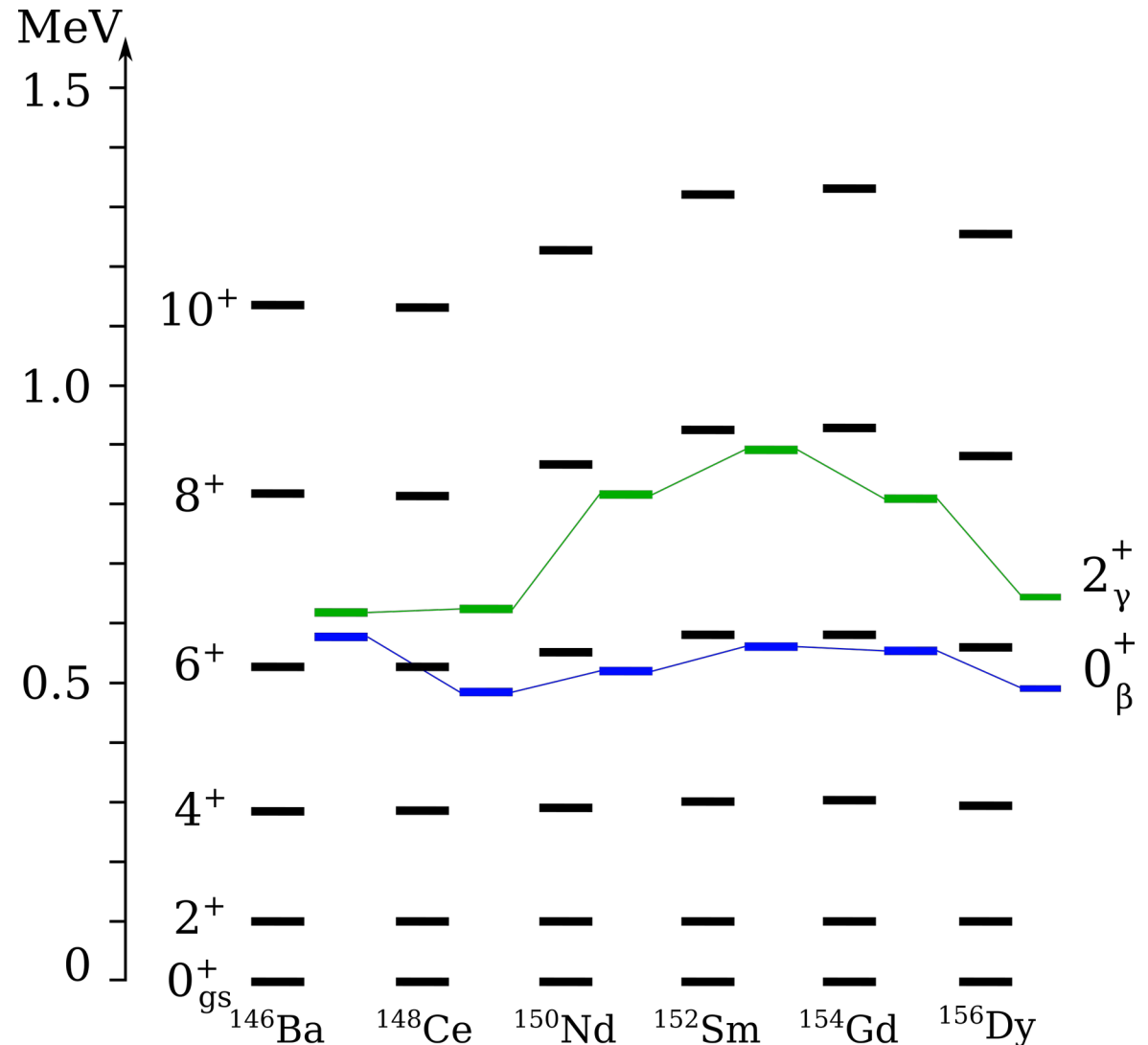


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N=90 isotones – axial asymmetry



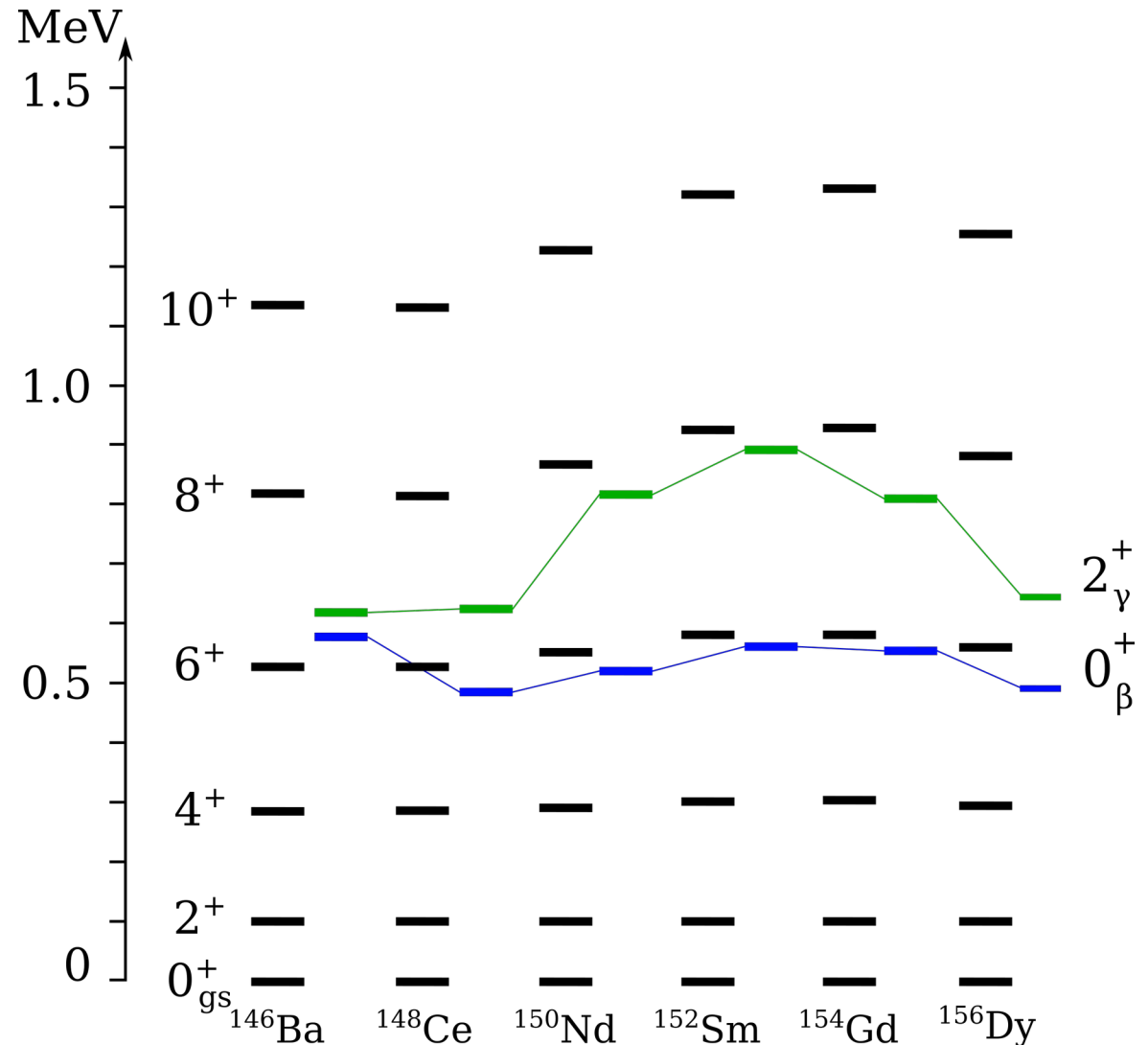
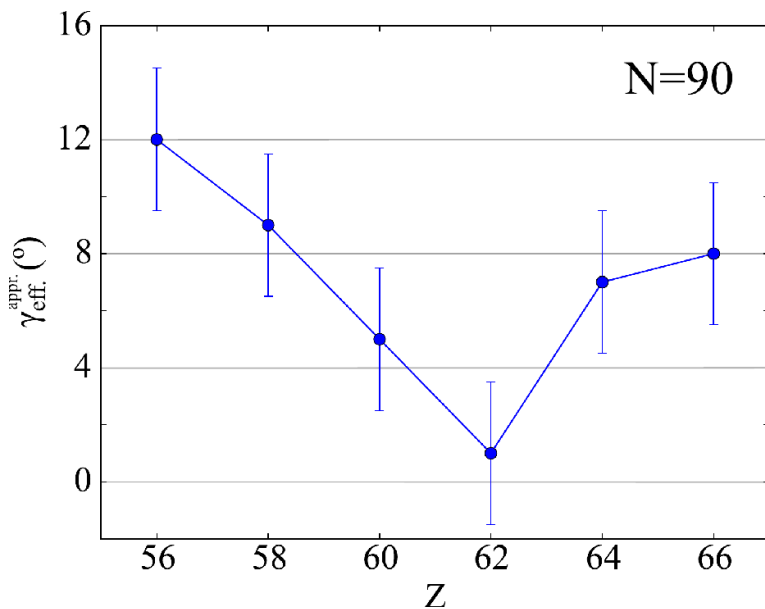
- The axial symmetry peaks around ^{152}Sm ($\gamma \approx 0^\circ$)
- It seems that in ^{148}Ce the axial asymmetry increases ($\gamma \neq 0^\circ$)



Slide from P. Koseoglou

N=90 isotones – axial asymmetry

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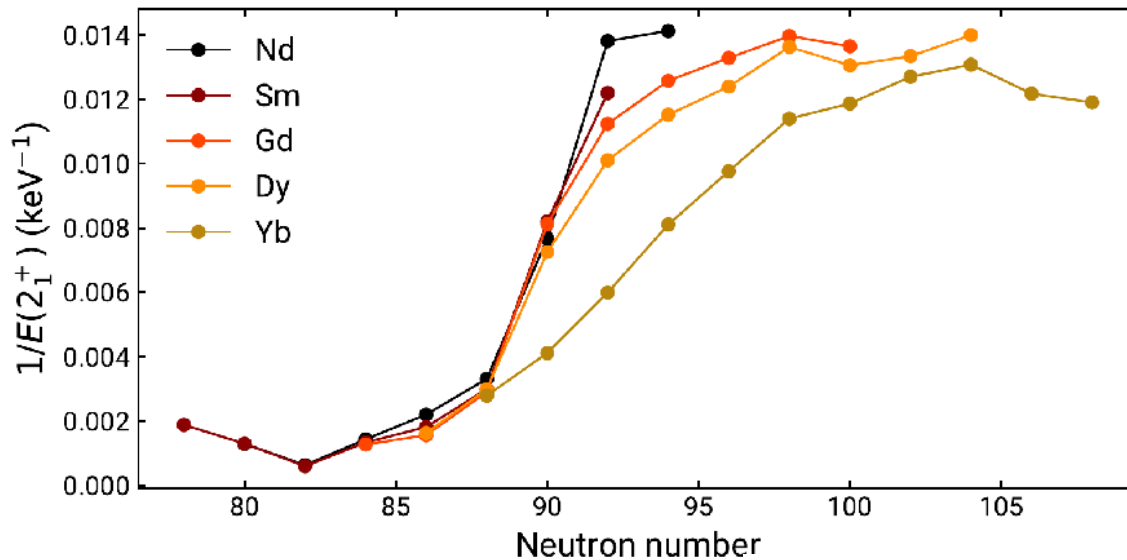


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From $N=90$ into the well(?) - deformed rare earth

Rare-Earth Basic Observables



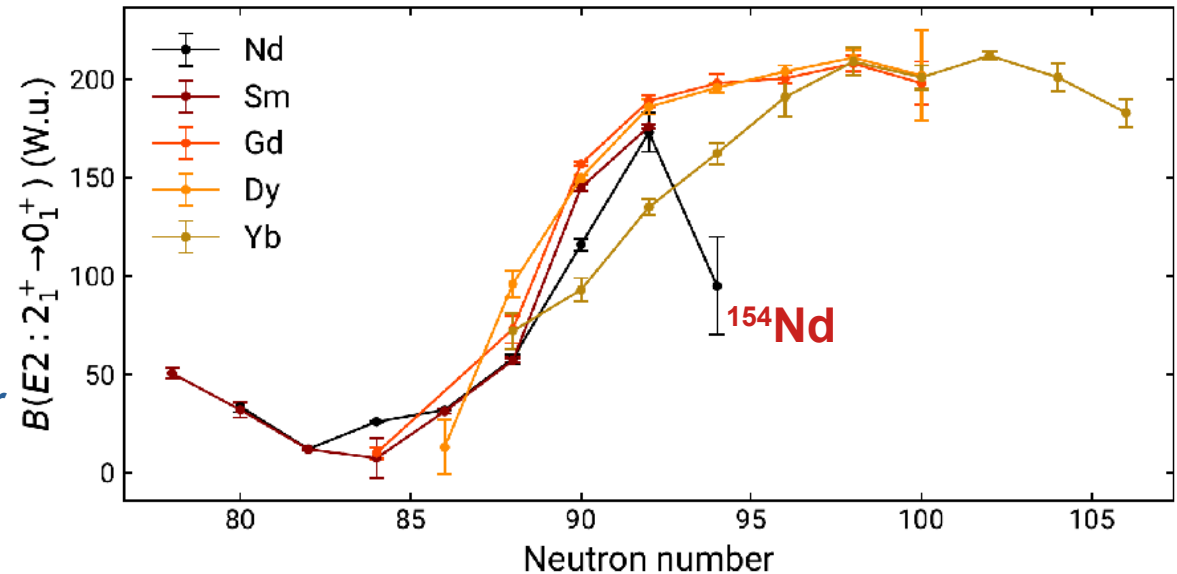
Isotopic chains

Inverse 2^+ energies:

- Fast rise at $N=90$ sph.-def. shape-phase transition
- Small variations thereafter

$B(E2)$ values:

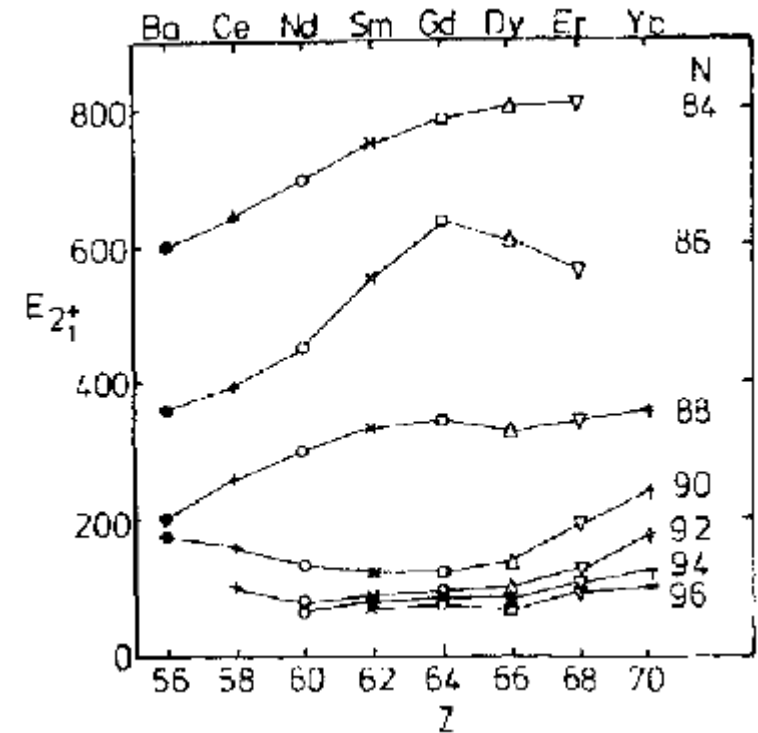
- Accordingly fast rise at $N=90$
- Small variations thereafter
- Something is seriously wrong with ^{154}Nd
(should be remeasured, in reach for GSI)



$E(2_1^+)$ Data from a Different Perspective

The most deformed rare-earth isotopes should have the

- largest moment of inertia (MOI)
- => lowest $E(2_1^+)$



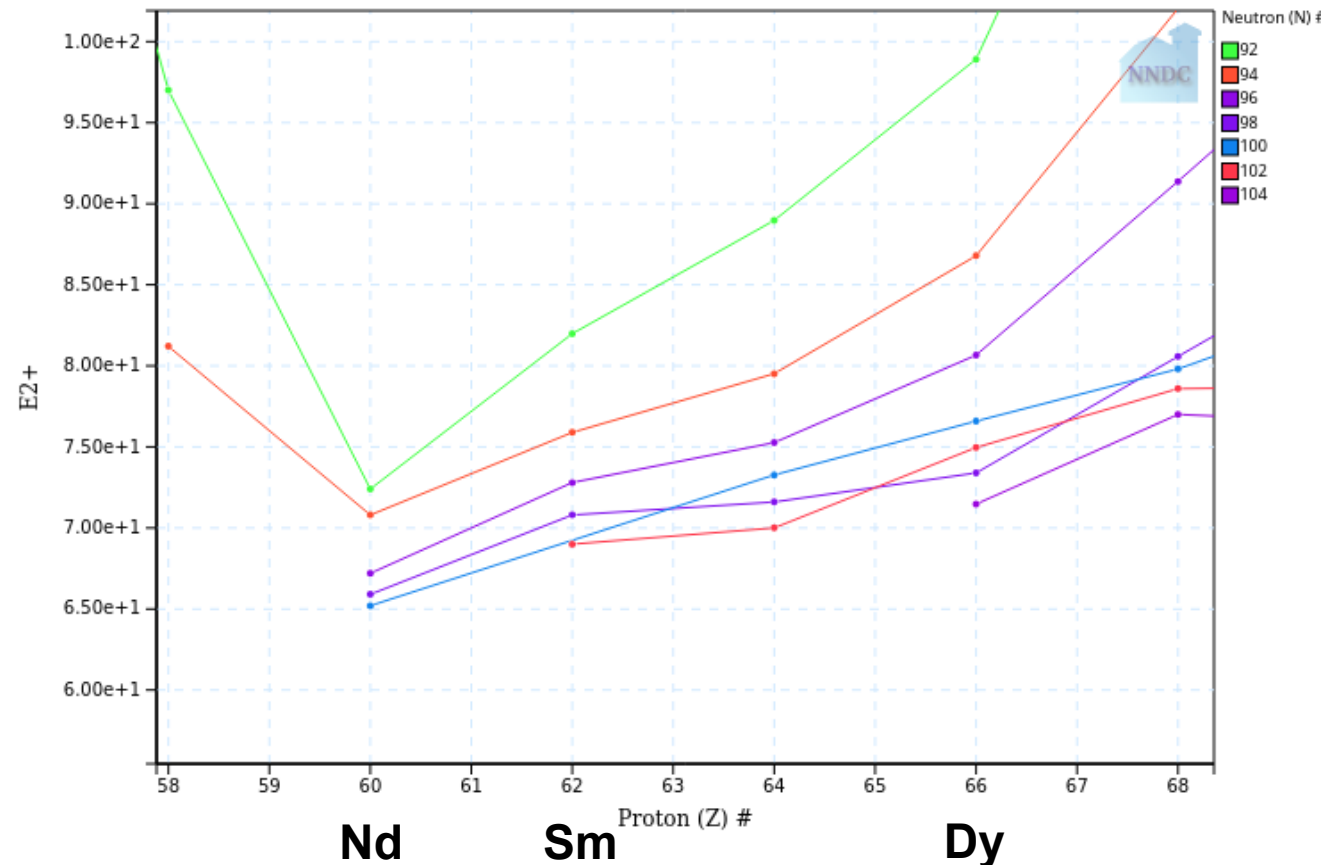
Rick Casten's text book

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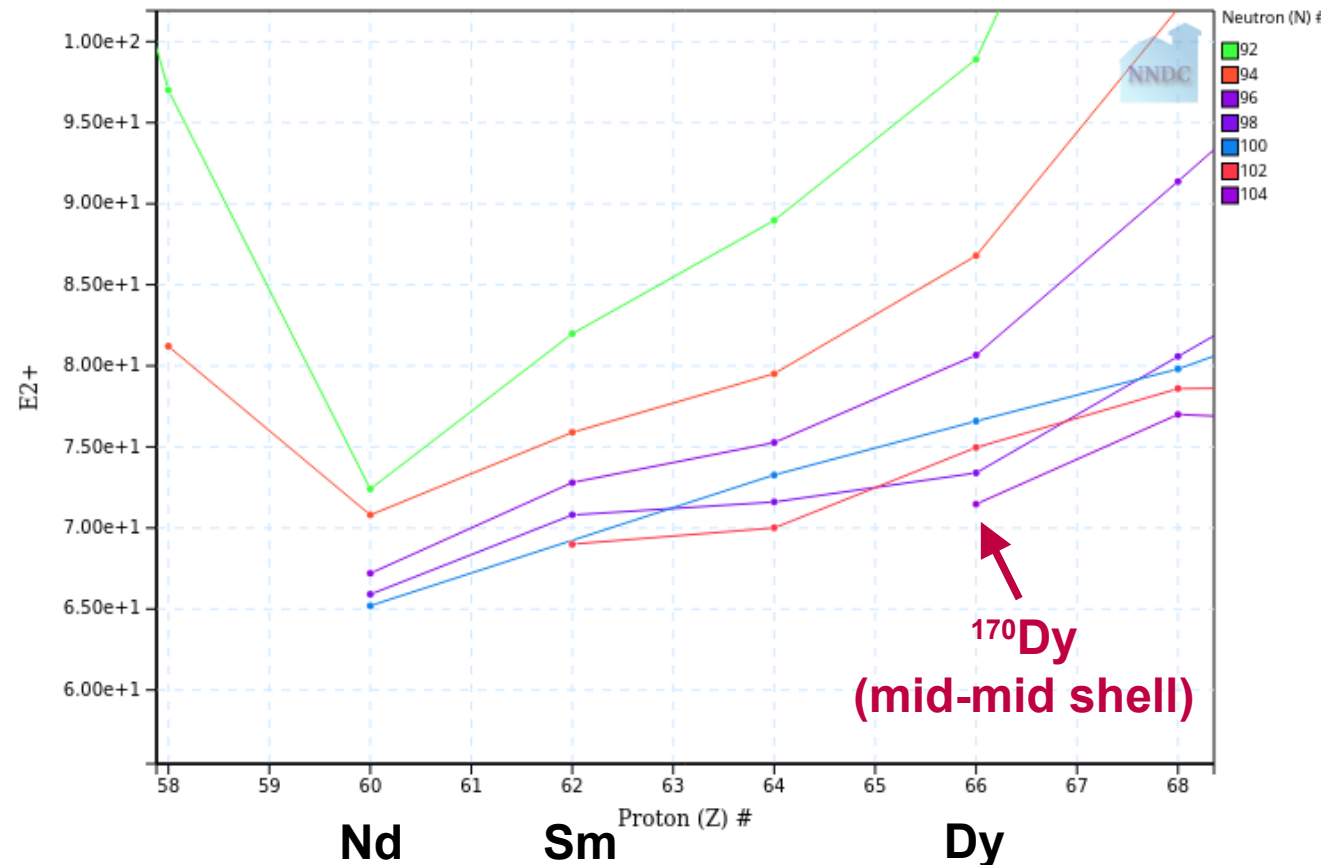


$E(2_1^+)$ Data from a Different Perspective



The most deformed rare-earth isotope should have the

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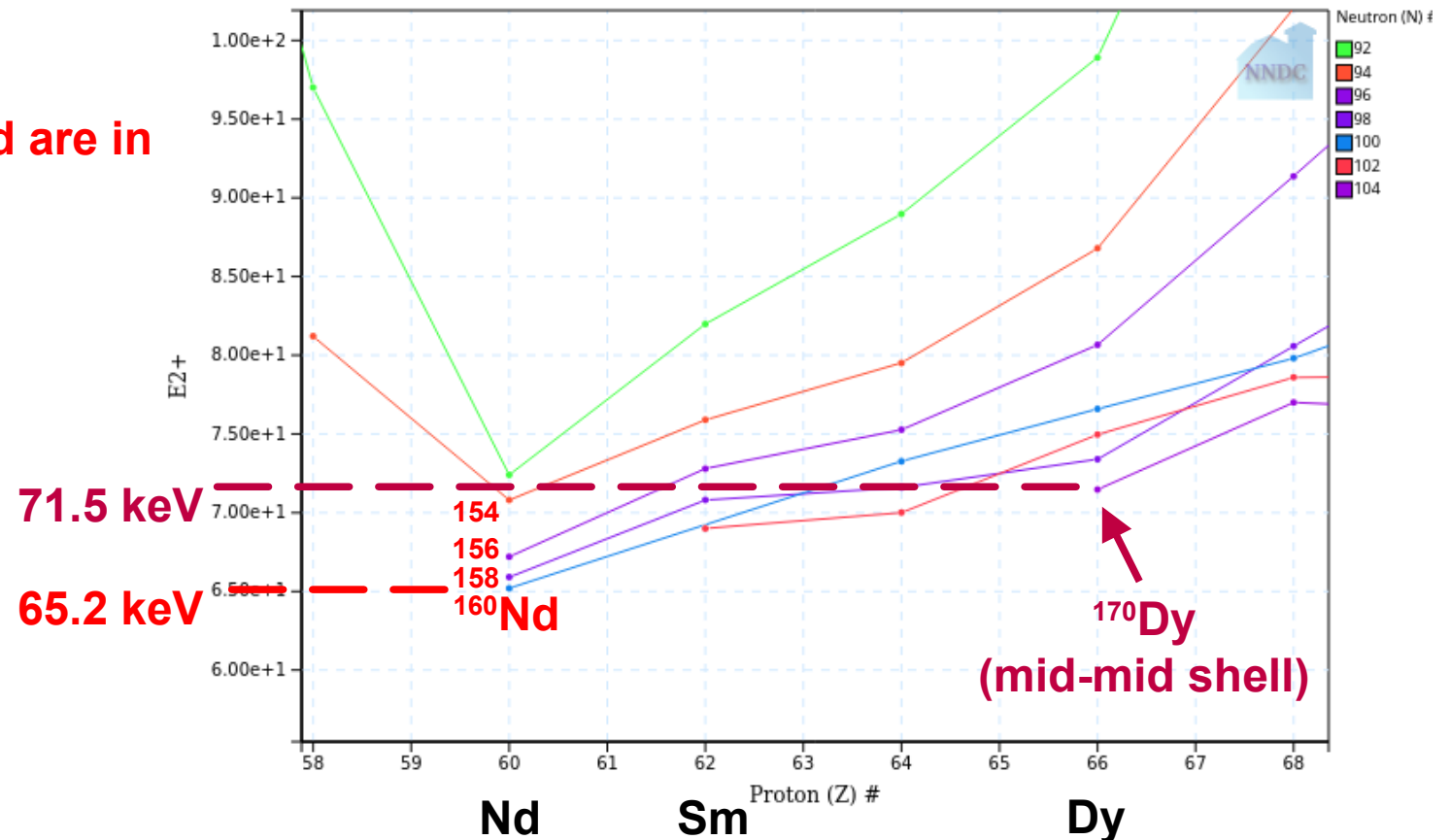


E(2₁⁺) Data from a Different Perspective



The most deformed rare-earth isotope should have the

- largest moment of inertia (MOI)
- => lowest E(2₁⁺)
- **The most deformed are in the Nd chain !**



Which are the most deformed ??



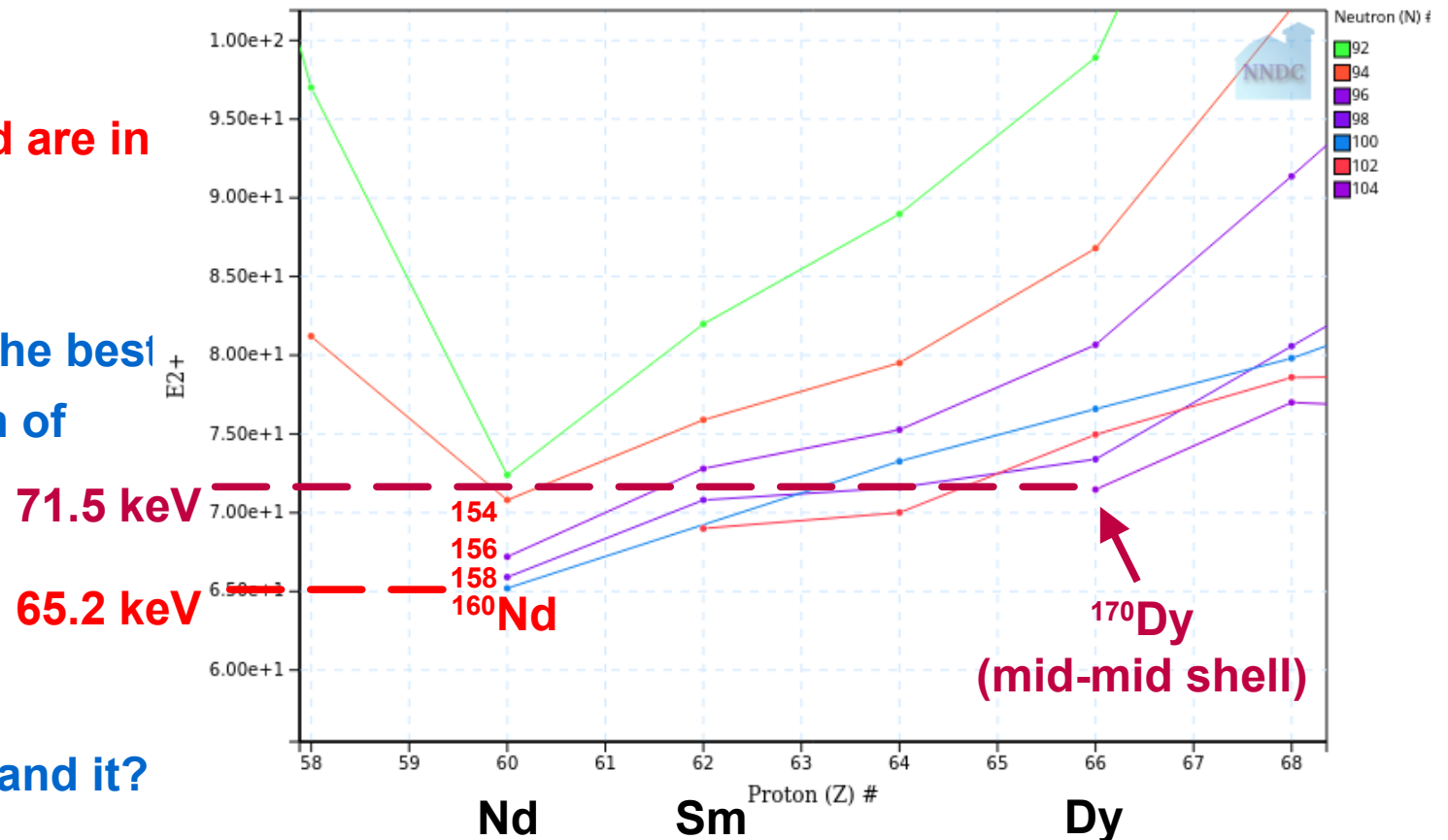
The most deformed rare-earth isotope should have the

- largest moment of inertia (MOI)
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• **The most deformed are in the Nd chain !**

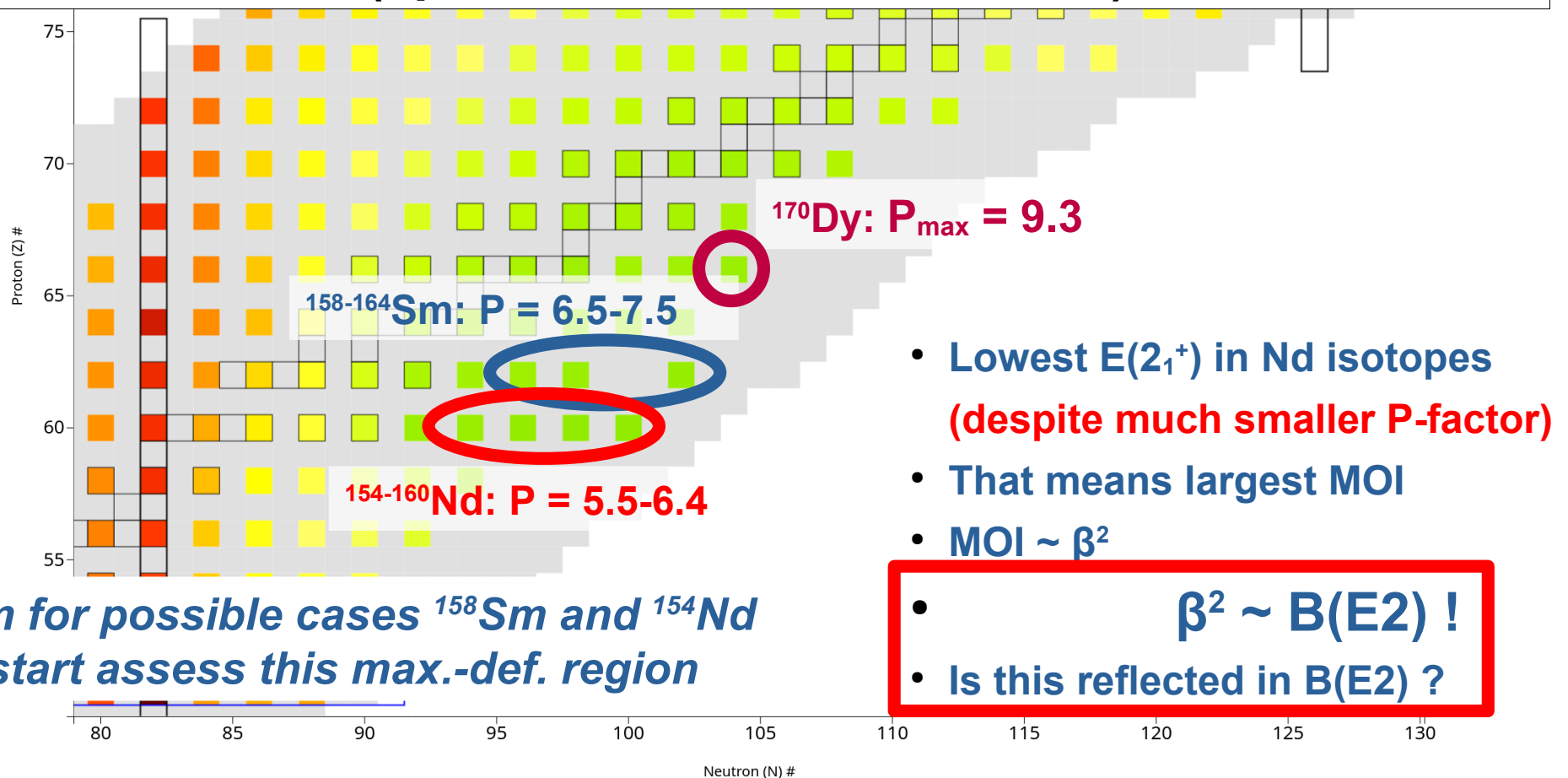
• This is rare earth, the best investigated region of deformation, the most pronounced nuclear property

• Yet, do we understand it?



Others should be much more collective / deformed

Measure of deformation/collectivity: P-factor = $N_{\pi} N_{\nu} / (N_{\pi} + N_{\nu})$
(sph. → def. Transition at $P \sim 5$)

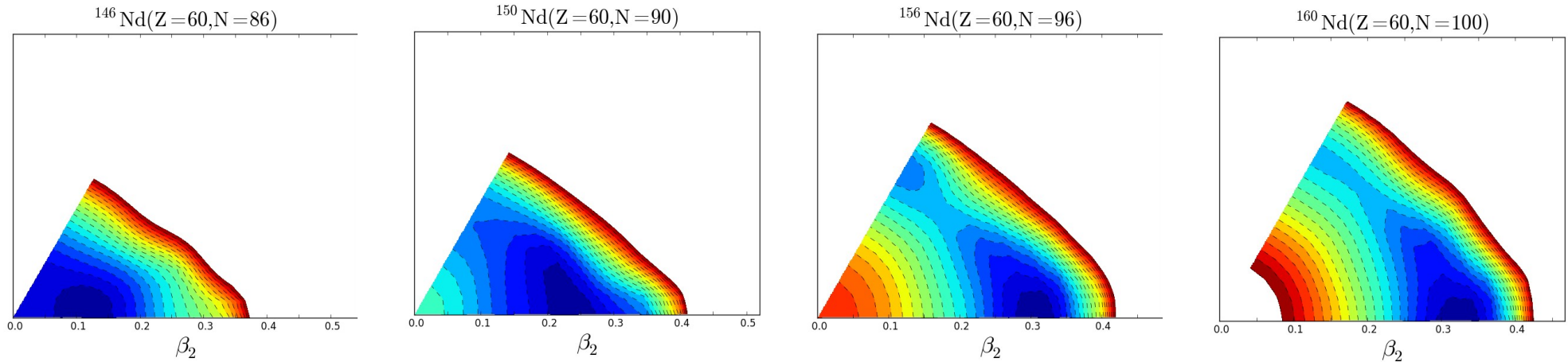


Aim for possible cases ^{158}Sm and ^{154}Nd to start assess this max.-def. region

Nd seem very (!) prolate

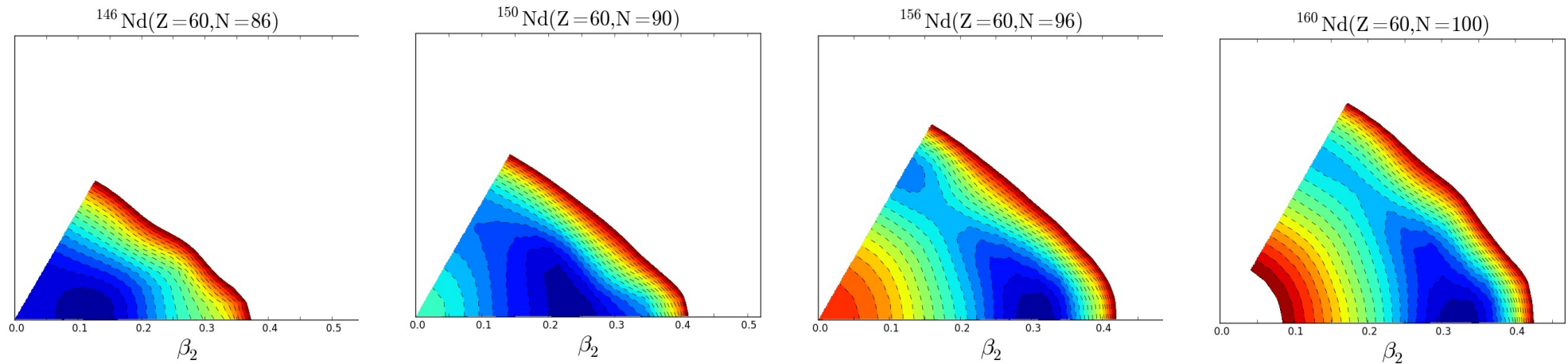


Nd potential energy surfaces *priv. Comm. T. Otsuka Y. Tsunoda*



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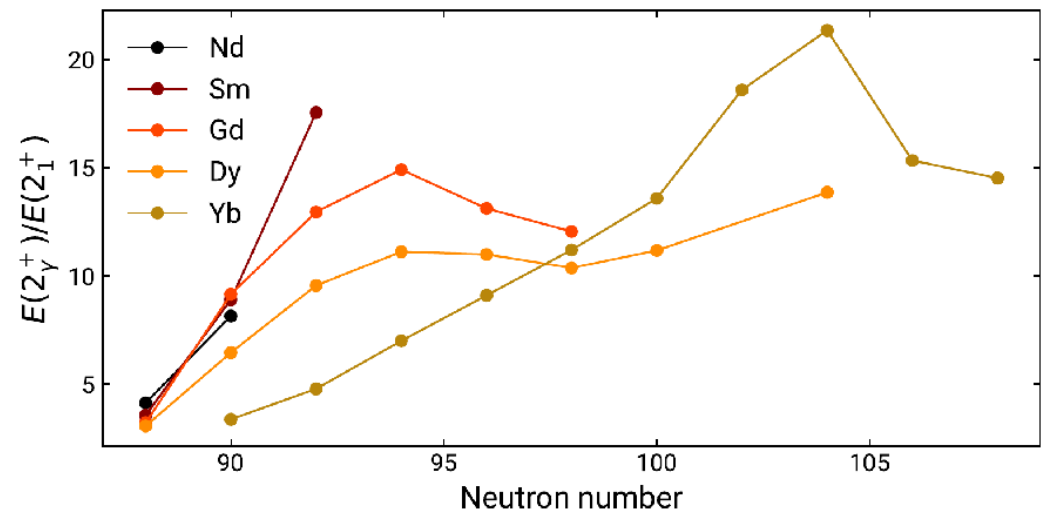
Nd potential energy surfaces *priv. Comm. T. Otsuka Y. Tsunoda*



Are the others (e.g. Dy) also just prolate? Or triax. degree of freedom?

Gamma bands in Gd/Dy tend to be low. Calculations produce “some” triaxiality for Dy – this may be the key. **But first we need to know the $B(E2)$ s !**

Proposal planned for ^{158}Nd @RIKEN



Thoughts ?



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Microscopic calculations for ^{148}Ce

- Axial Skyrme-Hartree-Fock-Bogoliubov (Skyrme-HFB) calculations (Skyrme interaction parametrization Svm1n): $\beta_2 = 0.248$
- Five-dimensional quadrupole collective Hamiltonian (5DQCH)

$$\hat{H}_{\text{coll}} = \hat{T}_{\text{vib}} + \hat{T}_{\text{rot}} + V_{\text{coll}}$$

- $\beta \sim 0.25$, the smallest in the N=90 region
- The extended potential minimum indicates significant γ -softness

Calculations by
Nikšić, Vretenar

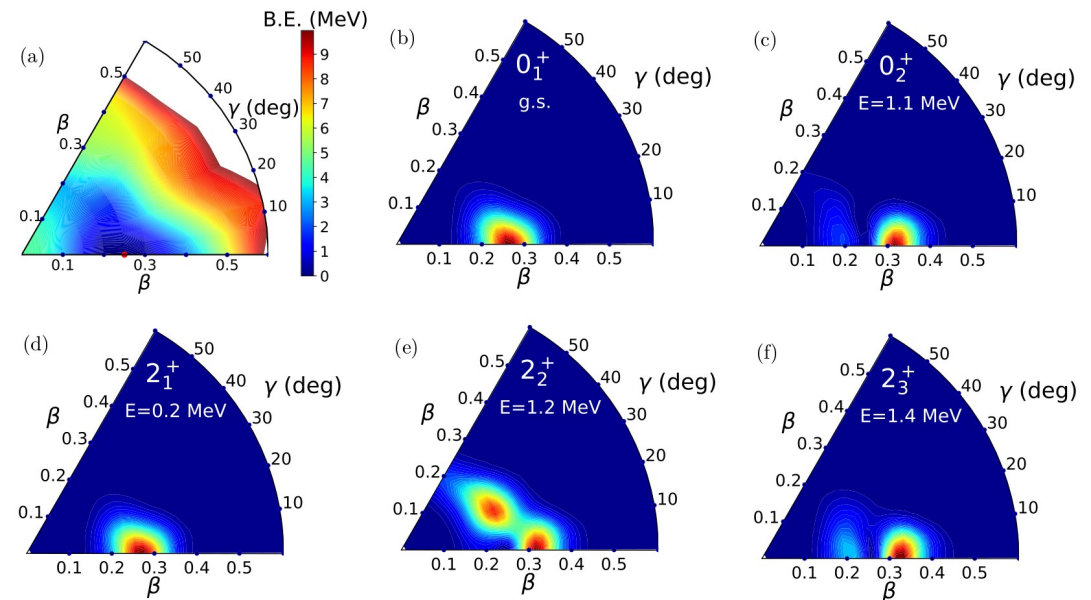


FIG. 9. (a) Self-consistent triaxial quadrupole constrained energy surfaces in the β - γ plane ($0 \leq \gamma \leq 60^\circ$). (b-f) Probability distributions in the β - γ plane for the wave function of the lowest collective 0^+ and 2^+ states of ^{148}Ce .

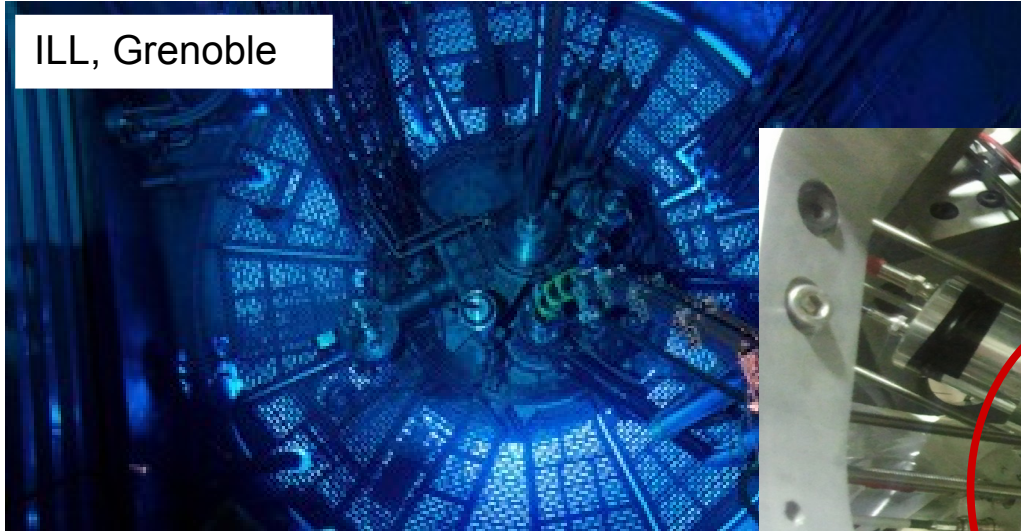
P. Koseoglou et al. Phys. Rev. C 101, 014303 (2020)

EXILL&FATIMA campaign



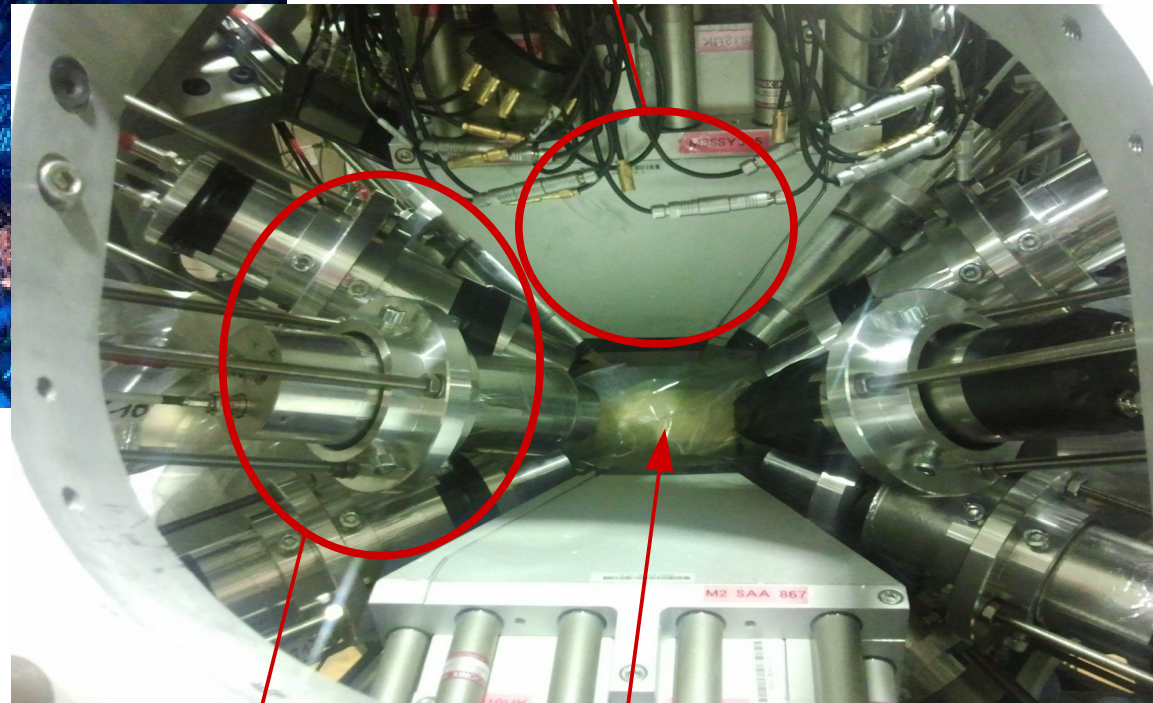
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ILL, Grenoble



Fission measurements in ILL
 $\Phi = 9 \times 10^7 \text{ neutr. cm}^{-2} \text{ s}^{-1}$

Ring of 8 BGO shielded EXOGAM clovers

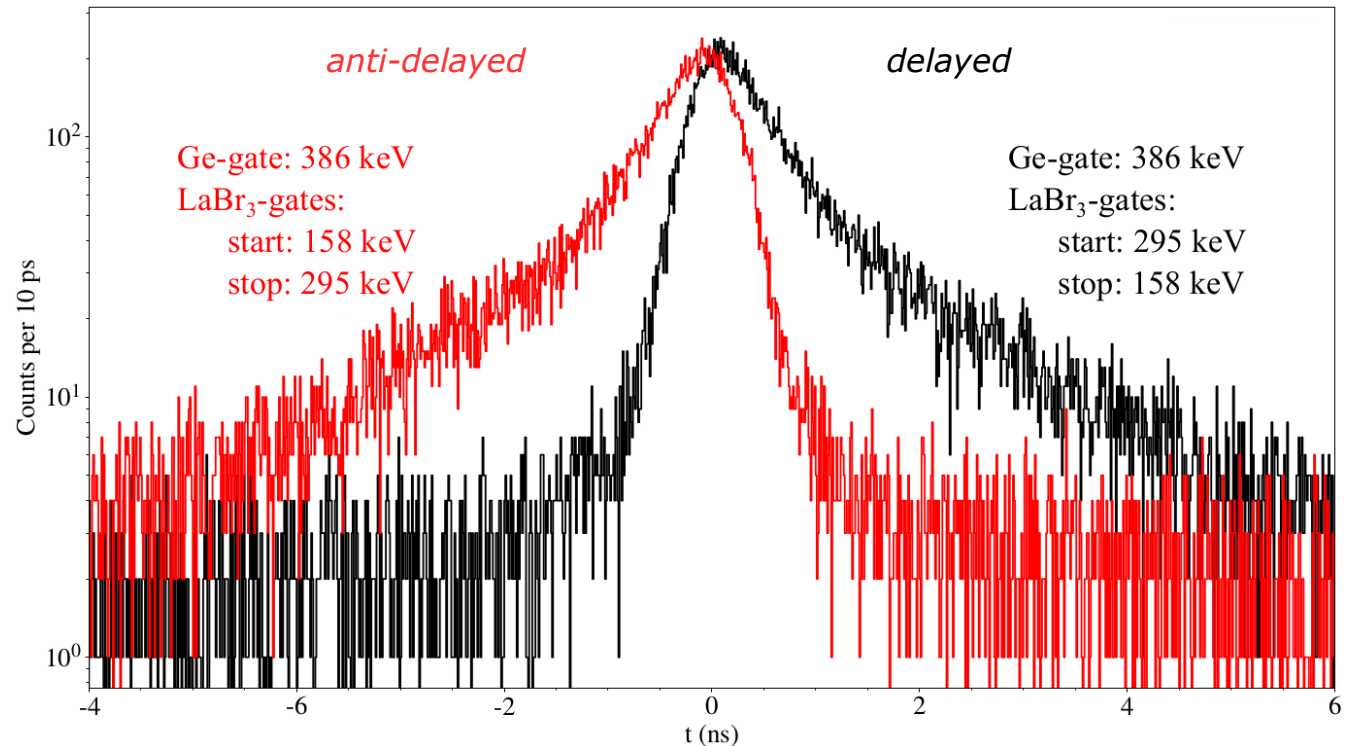
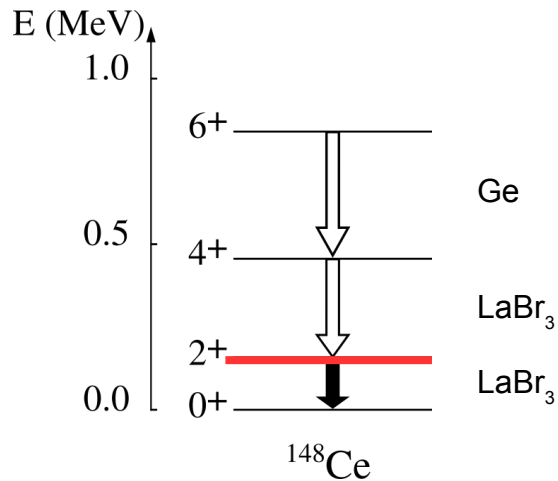


Target position [^{235}U / ^{241}Pu]

2 rings of 8 $\text{LaBr}_3(\text{Ce})$ each

official ILL web www.ill.eu/reactor-environment-safety/high-flux-reactor/
Jean-Marc Régis, 2nd EXILL meeting in Cologne (2013)

$^{148}\text{Ce } 2^+_{1}$ state life-time analysis



Slope method

- The life-time derives directly from the slope

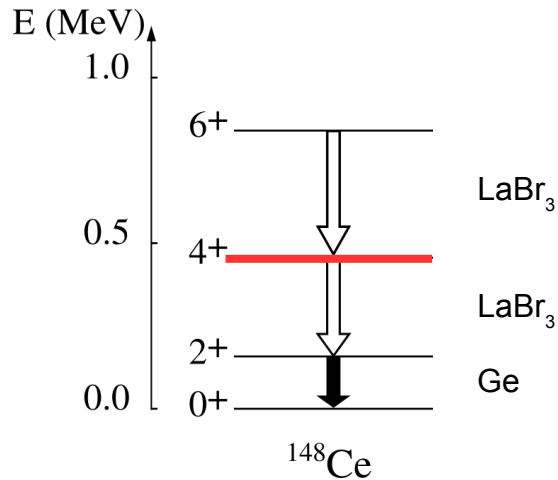
$$\tau_{2^+} = 1.482 (48) \text{ ns}$$

$$\tau_{2^+ \text{lit.}} = 1.457 (87) \text{ ns}$$

$$B(E2; 2^+_{1} \rightarrow 0^+_{1}) = 84 (3) \text{ W. u.}$$

P. Koseoglou et al. Phys. Rev. C 101, 014303 (2020)

^{148}Ce 4^+_1 state life-time analysis



General Centroid
Difference Method

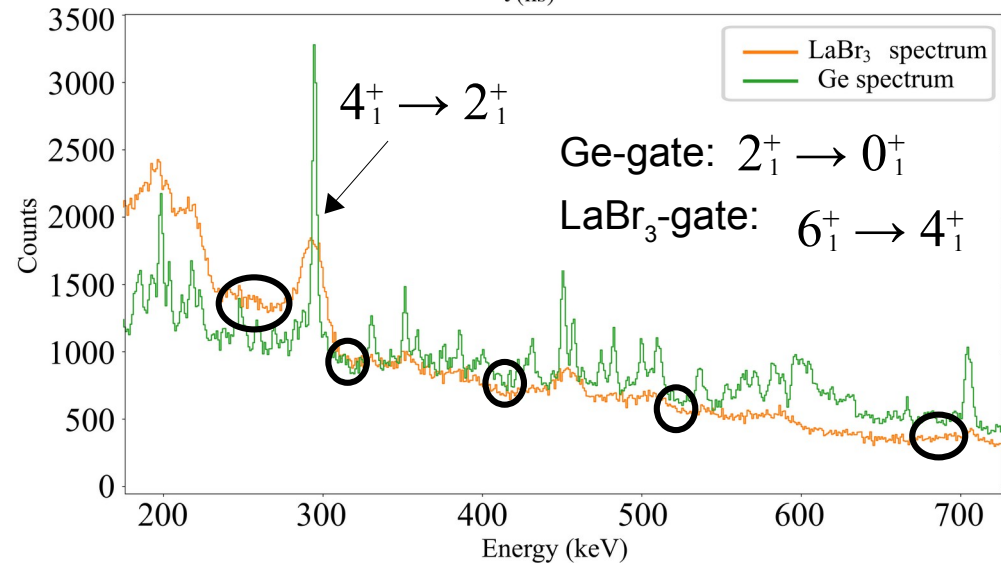
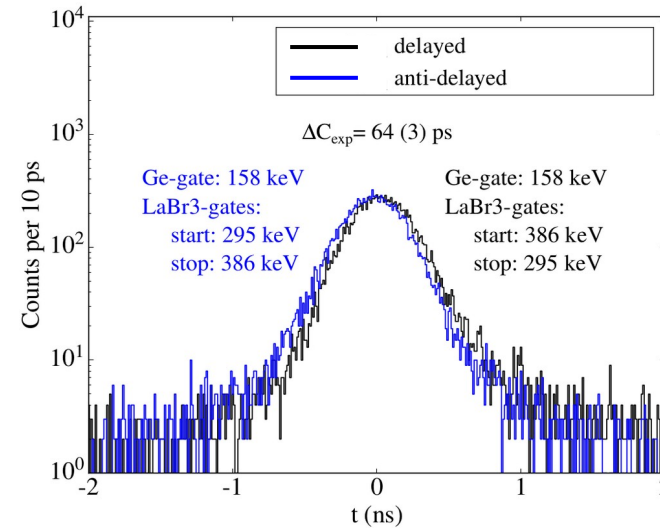
$$\Delta C = C_{stop} - C_{start} = PRD + 2\tau$$

J.-M. Regis, *et al.*, Nucl. Instr. Meth., A 622, 83-92 (2010)

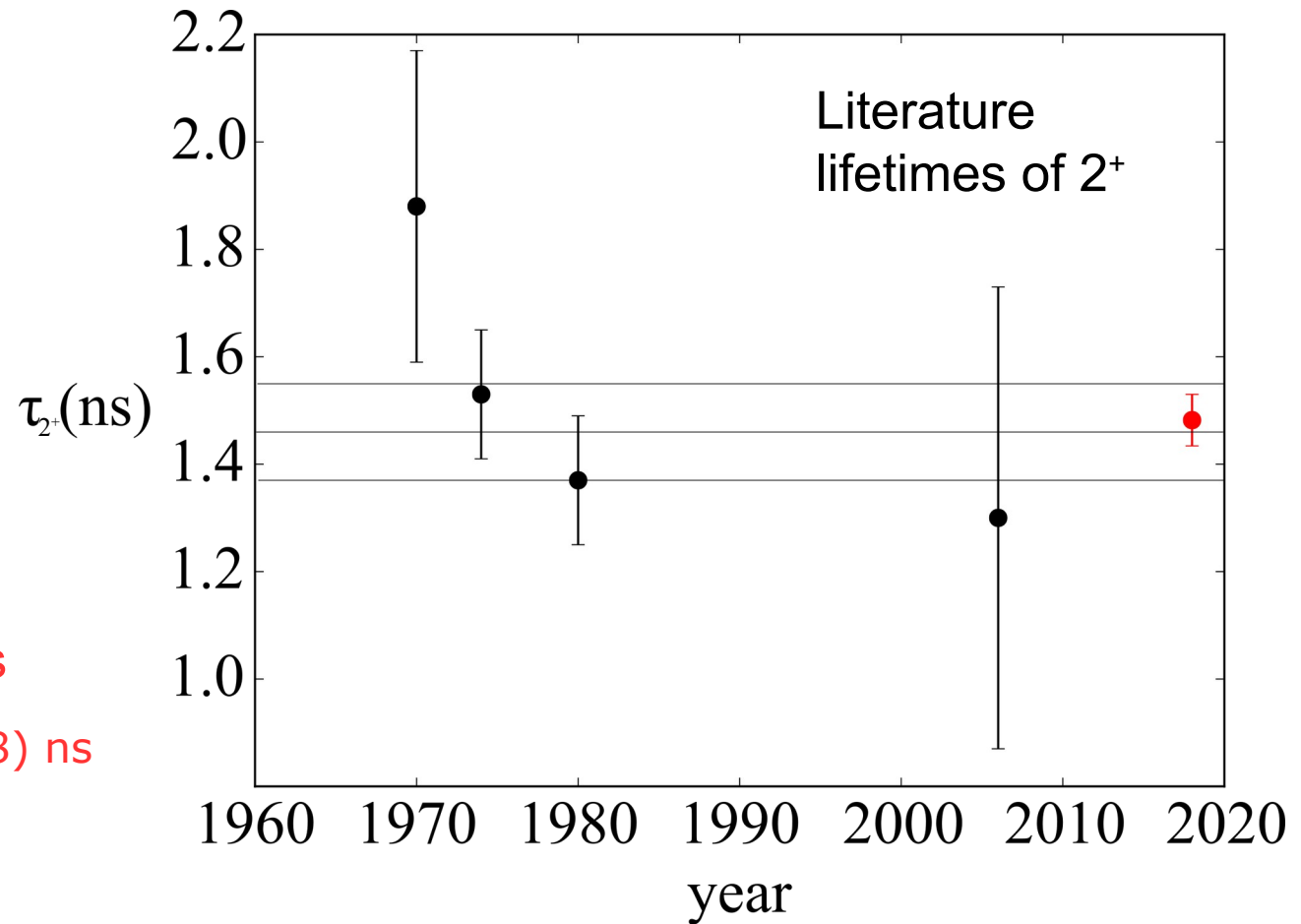
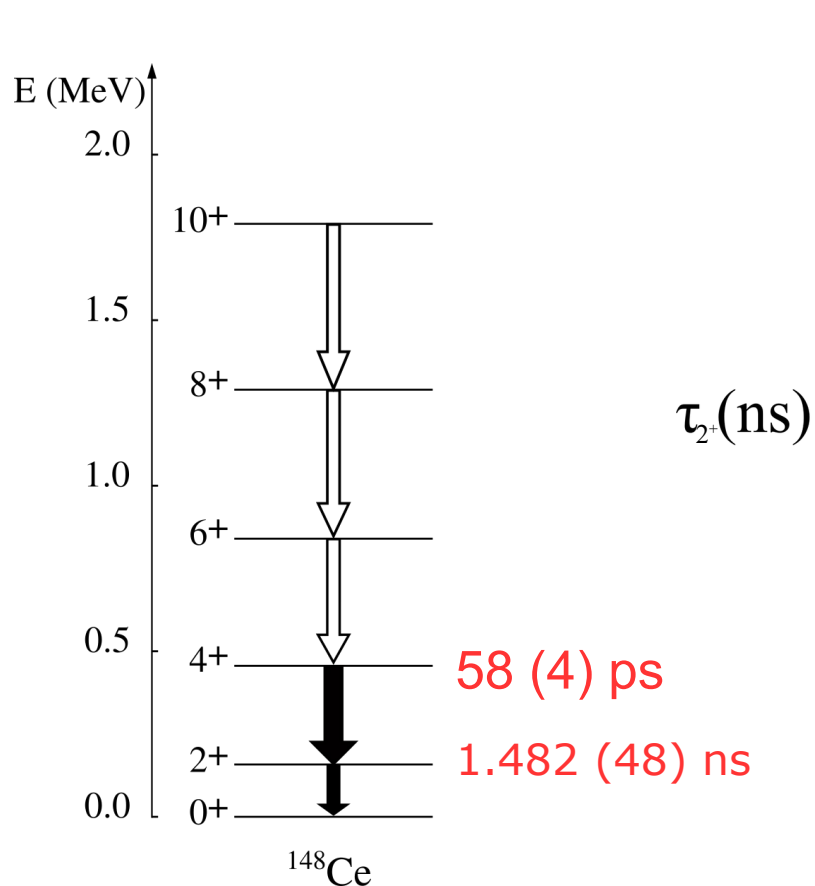
$$\tau_{4^+} = 58 (4) \text{ ps}$$

$$B(E2; 4^+_1 \rightarrow 2^+_1) = 129 (9) \text{ W. u.}$$

P. Koseoglou *et al.* Phys. Rev. C 101, 014303 (2020)



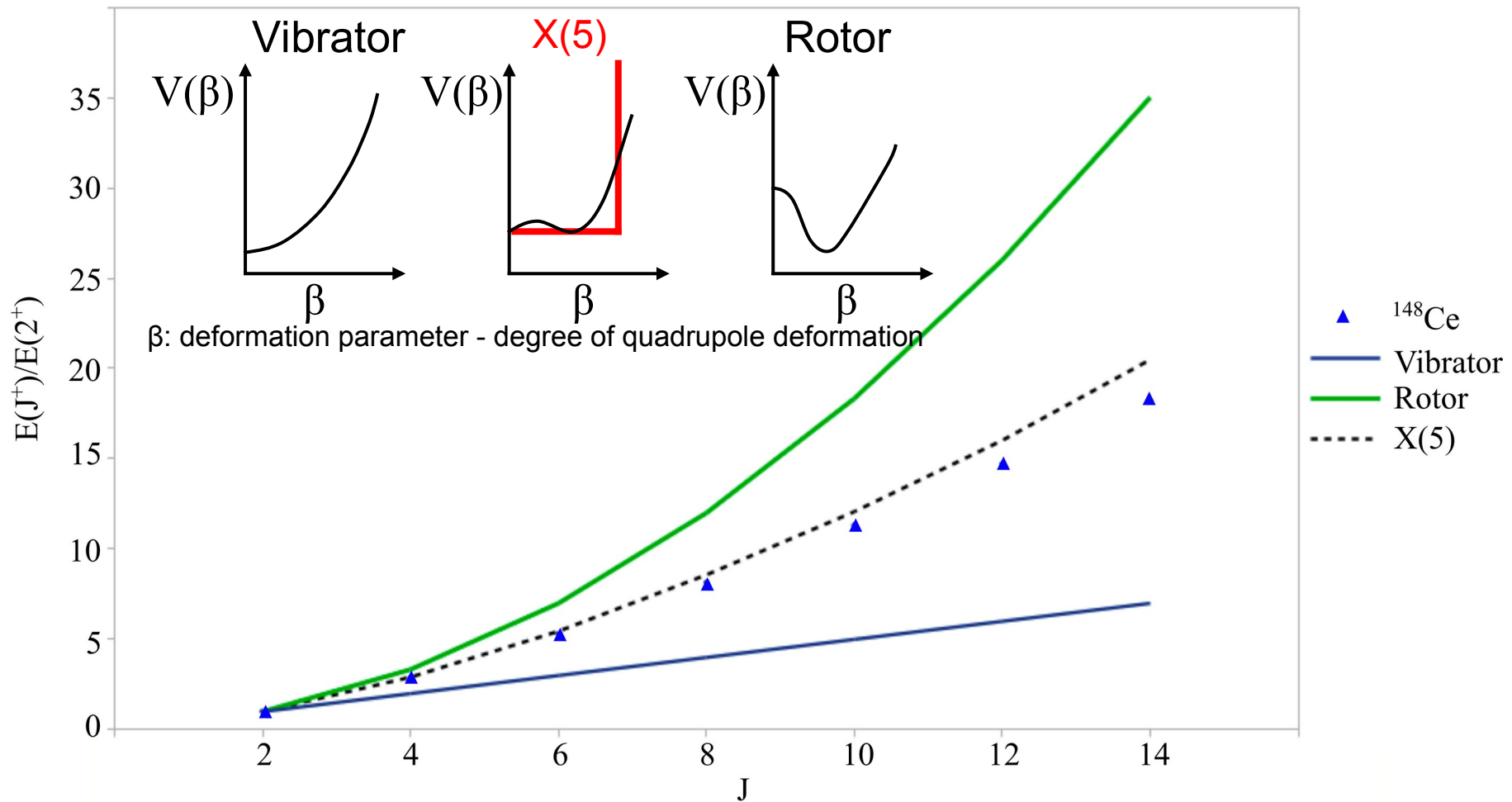
^{148}Ce $B_{4/2}$ ratio



P. Koseoglou et al. Phys. Rev. C 101, 014303 (2020)

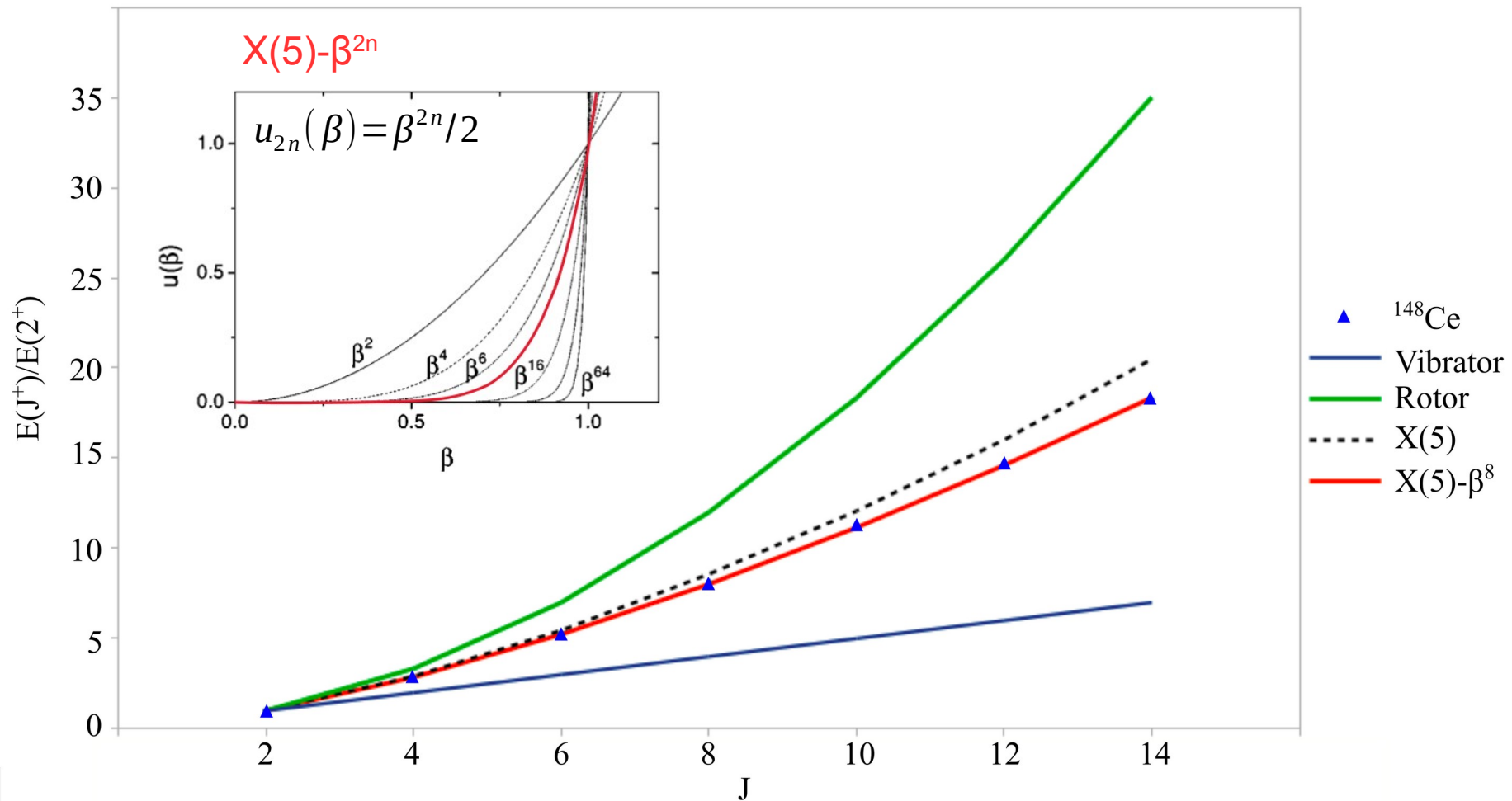
N. Nica, Nuclear Data Sheets 117 (2014), pp. 1–229

Observables - Energy ratios



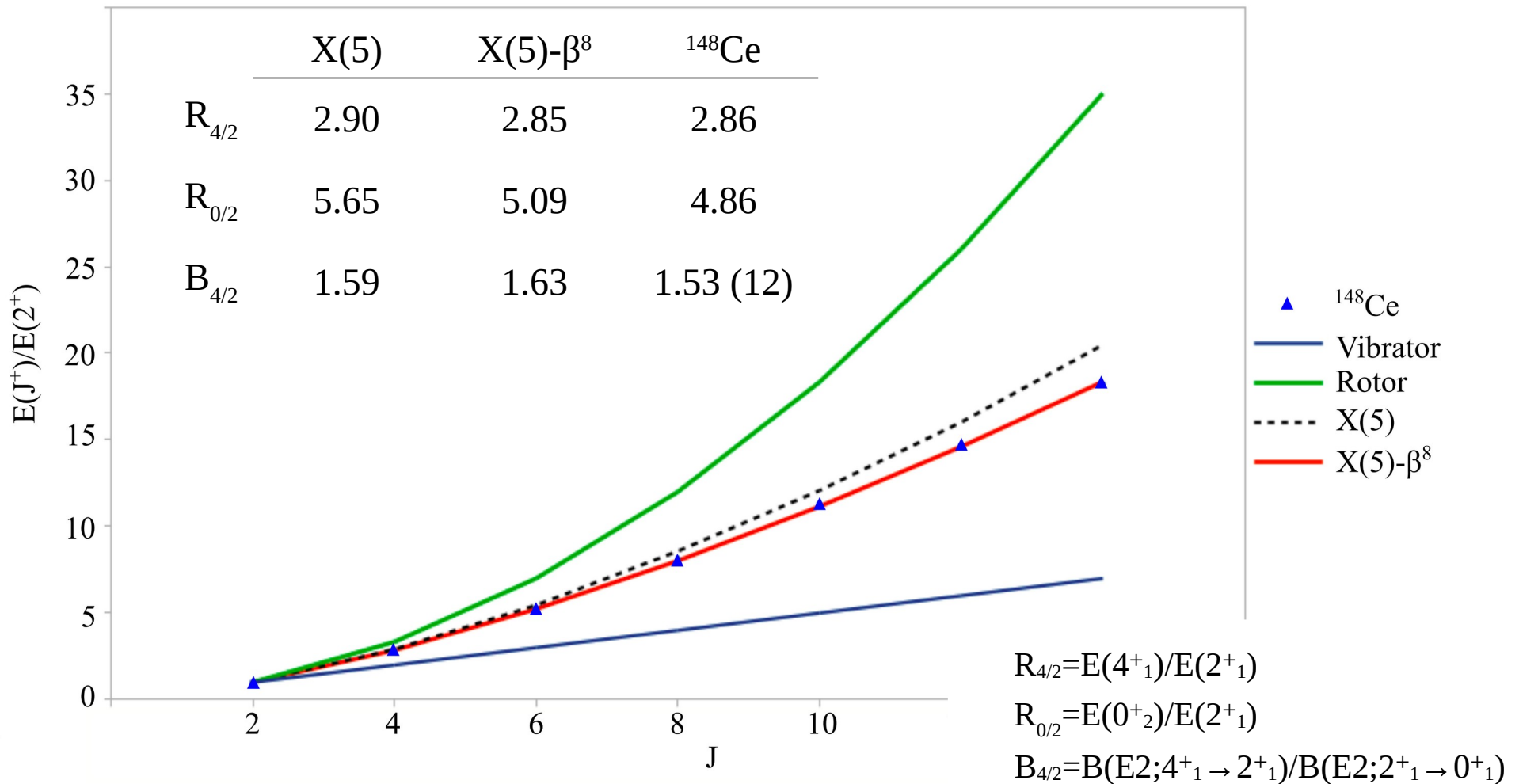
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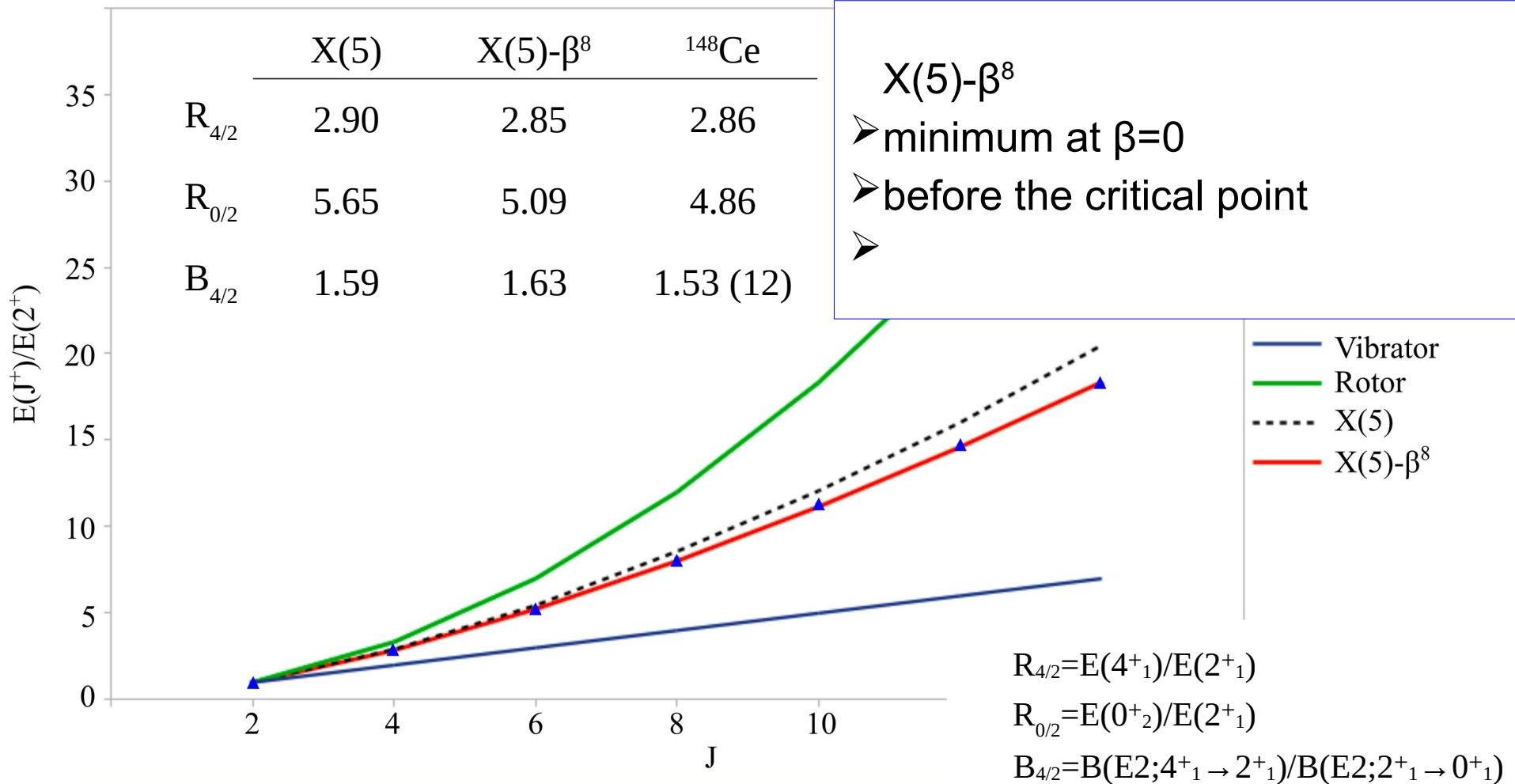
D. Bonatsos, et. al., Phys. Rev. C 69, 014302 (2004)

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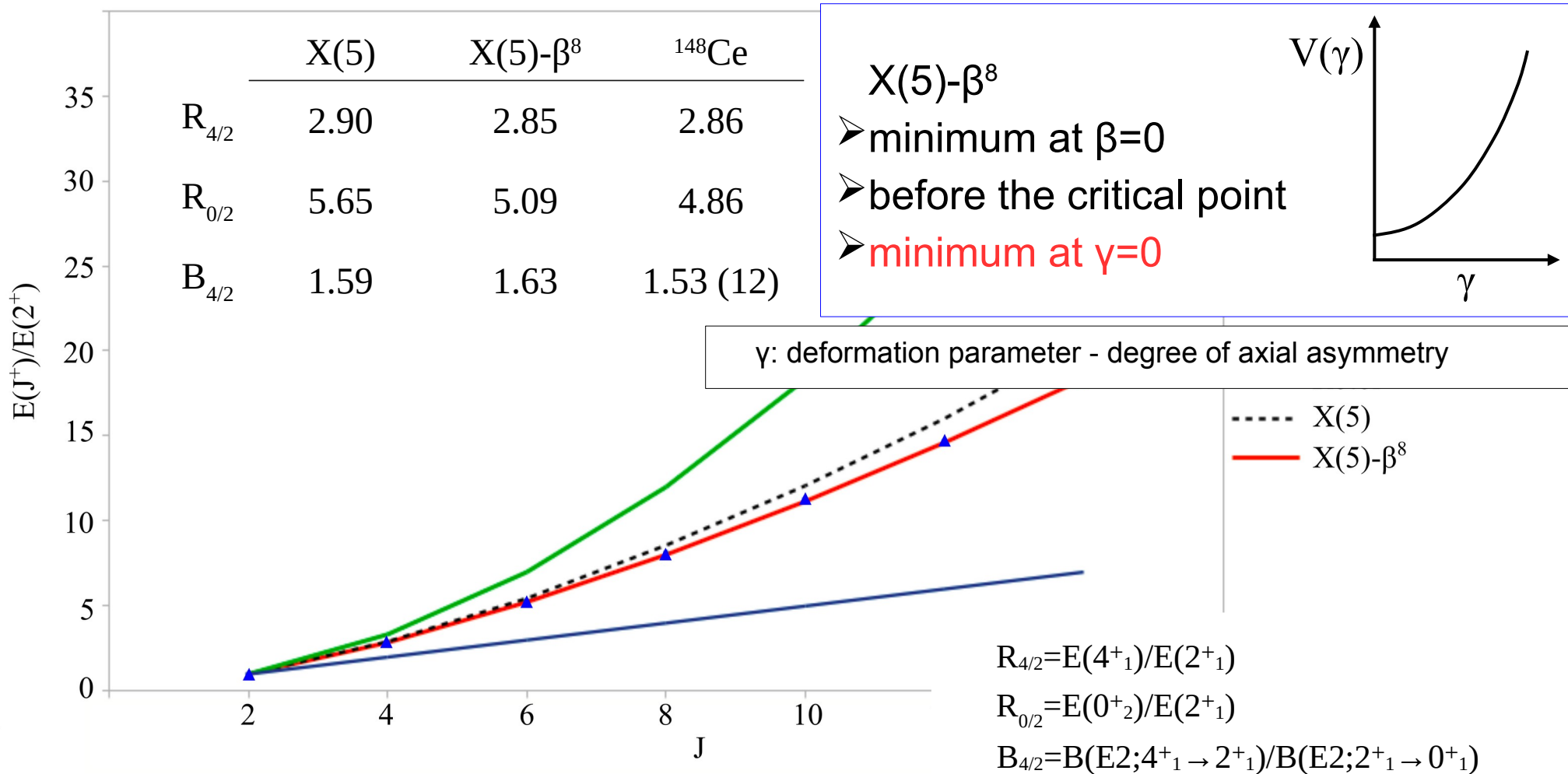
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