QPT vs shape coexistence in N≈90 rare-earth nuclei

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EUROPSKI STRUKTURNI I INVESTICIJSKI FONDOVI
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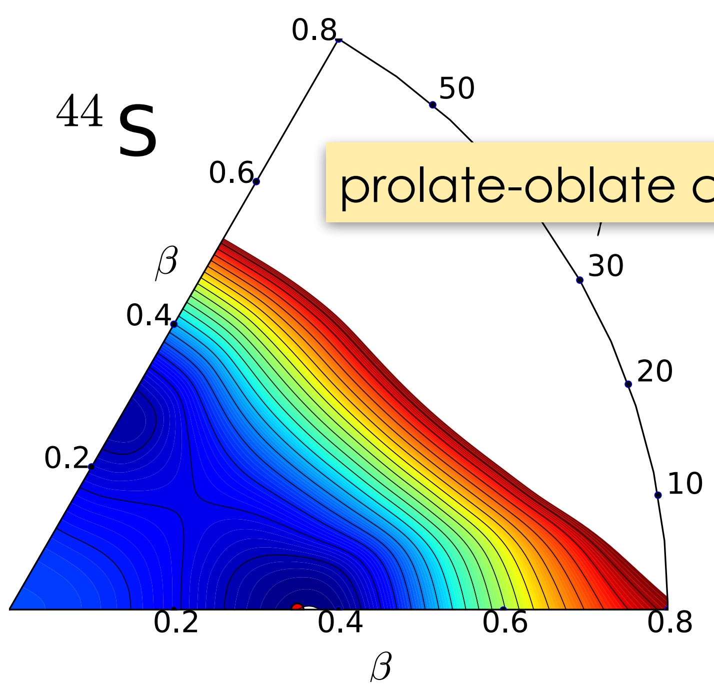
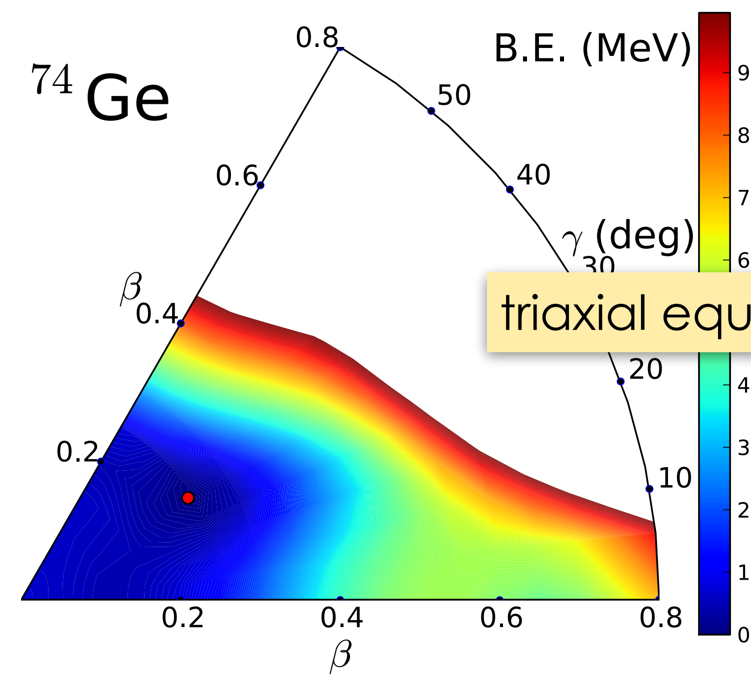
The self-consistent mean field method → produces semi-classical energy surfaces as functions of intrinsic deformation parameters.

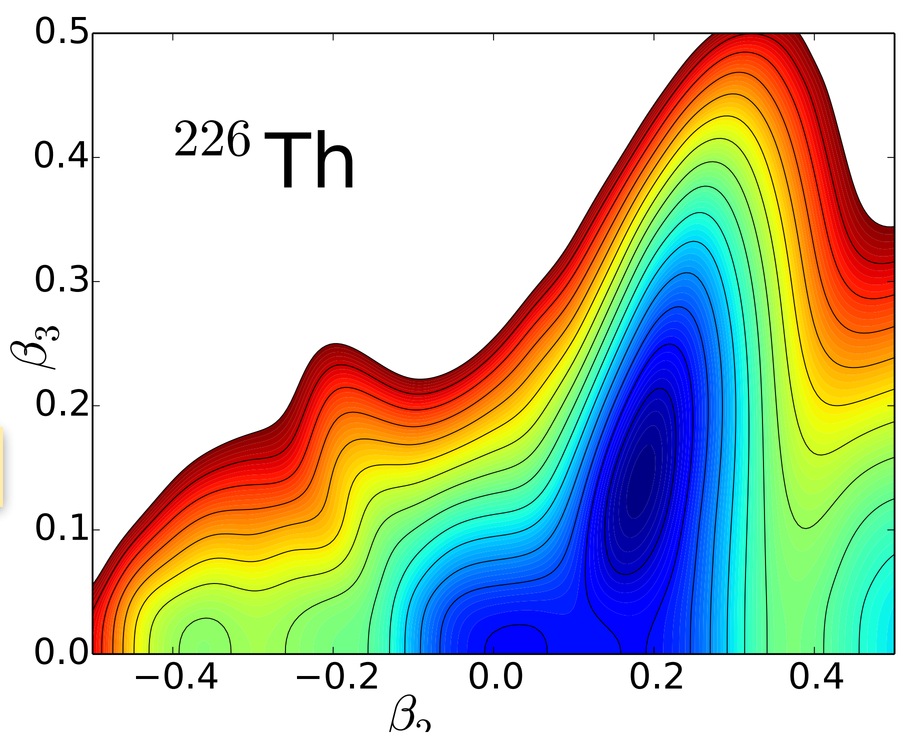


prolate-oblate coexistence



triaxial equilibrium shape

octupole deformation



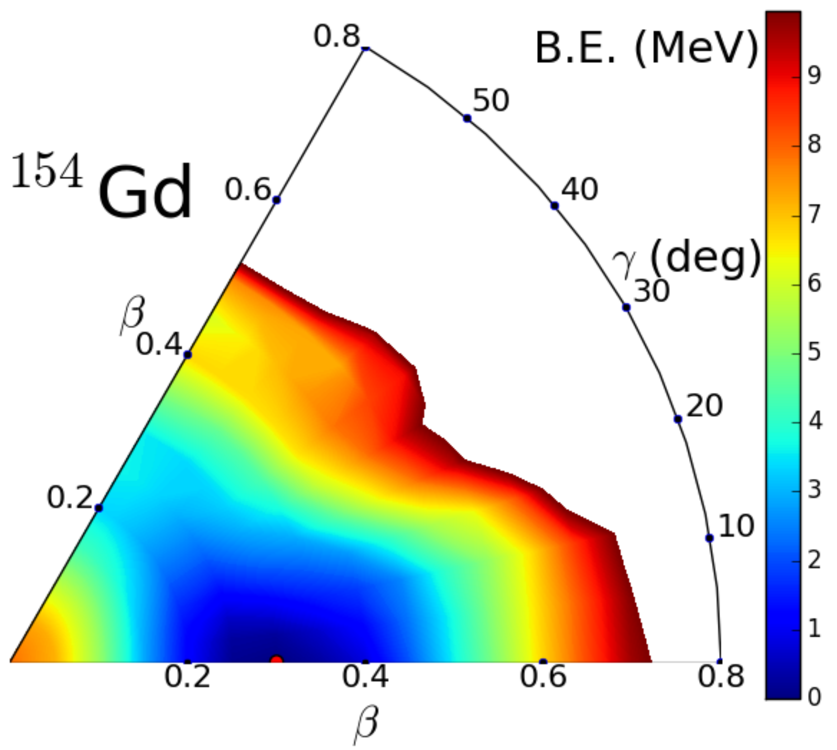
→ include static correlations: deformations & pairing

→ do not include dynamic (collective) correlations that arise from symmetry restoration and quantum fluctuations around mean-field minima

Collective Hamiltonian

Prog. Part. Nucl. Phys. **66**, 519 (2011).

Phys. Rev. C **79**, 034303 (2009).



... nuclear excitations determined by quadrupole vibrational and rotational degrees of freedom:

$$H_{\rm coll} = \mathcal{T}_{\rm vib}(\beta,\gamma) + \mathcal{T}_{\rm rot}(\beta,\gamma,\Omega) + \mathcal{V}_{\rm coll}(\beta,\gamma)$$

$$\mathcal{T}_{\rm vib} = \frac{1}{2}B_{\beta\beta}\dot{\beta}^2 + \beta B_{\beta\gamma}\dot{\beta}\dot{\gamma} + \frac{1}{2}\beta^2 B_{\gamma\gamma}\dot{\gamma}^2$$

$$\mathcal{T}_{\rm rot} = \frac{1}{2}\sum_{k=1}^{3}\mathcal{I}_k\omega_k^2$$

The dynamics is determined by: the self-consistent collective potential, the three mass parameters: $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$, and the three moments of inertia I_k, functions of the intrinsic deformations β and γ.

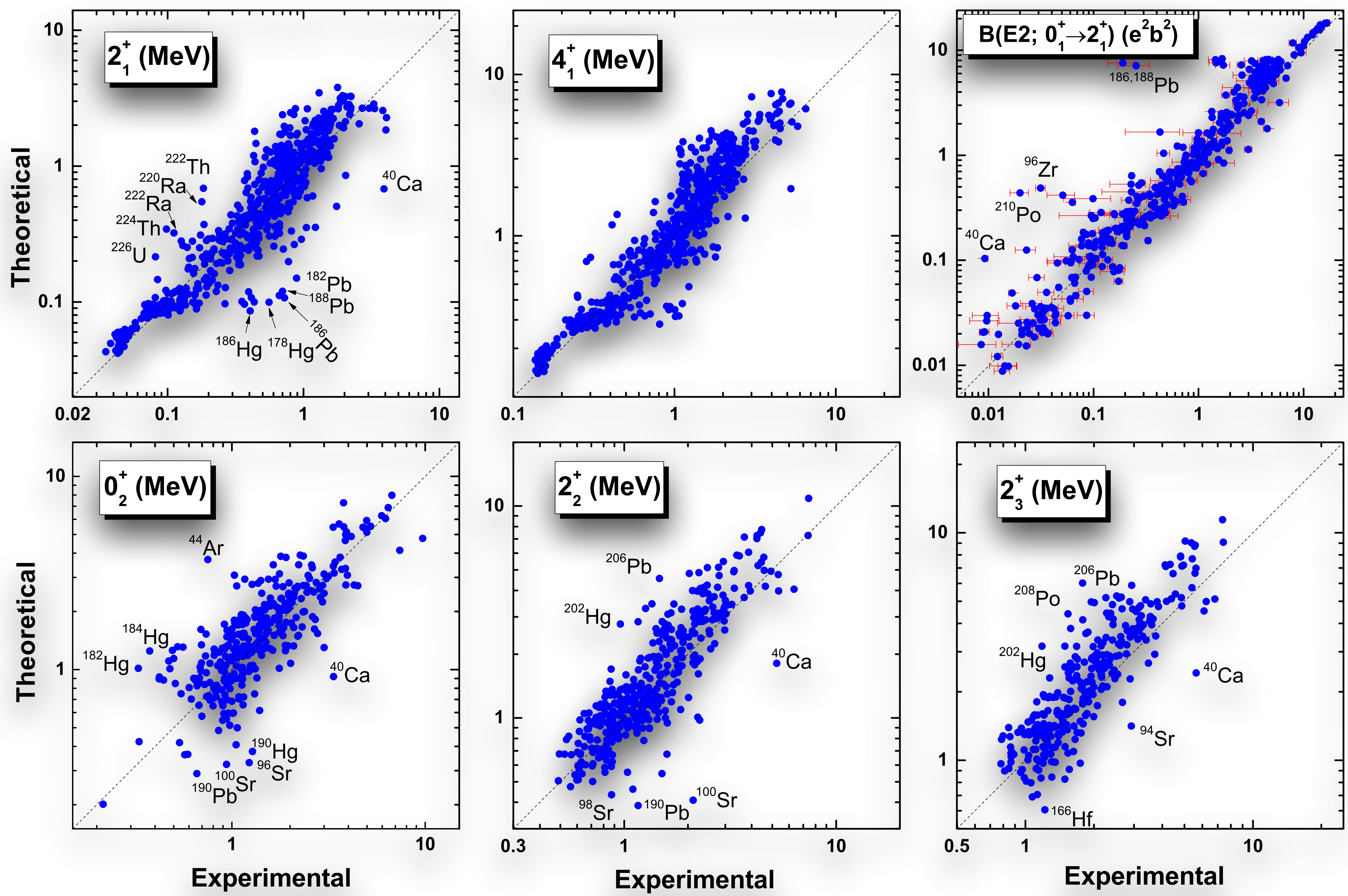
✔ an intuitive interpretation of mean-field results in terms of ***intrinsic shapes*** and ***single-particle states***

✔ the ***full model space*** of occupied states can be used; no distinction between core and valence nucleons, ***no need for effective charges!***

Global analysis of quadrupole shape invariants

Phys. Rev. C **95**, 054321 (2017).

621 even-even nuclei:



…the lowest-order quadrupole invariants:

$$q_2(0_i^+) = \langle 0_i^+ | Q^2 | 0_i^+ \rangle = \sum_j \langle 0_i^+ || Q || 2_j^+ \rangle \langle 2_j^+ || Q || 0_i^+ \rangle$$

$$q_3(0_i^+) = \sqrt{\frac{35}{2}} \langle 0_i^+ | Q^3 | 0_i^+ \rangle = \sqrt{\frac{7}{10}} \sum_{jk} \langle 0_i^+ || Q || 2_j^+ \rangle \langle 2_j^+ || Q || 2_k^+ \rangle \langle 2_k^+ || Q || 0_i^+ \rangle$$

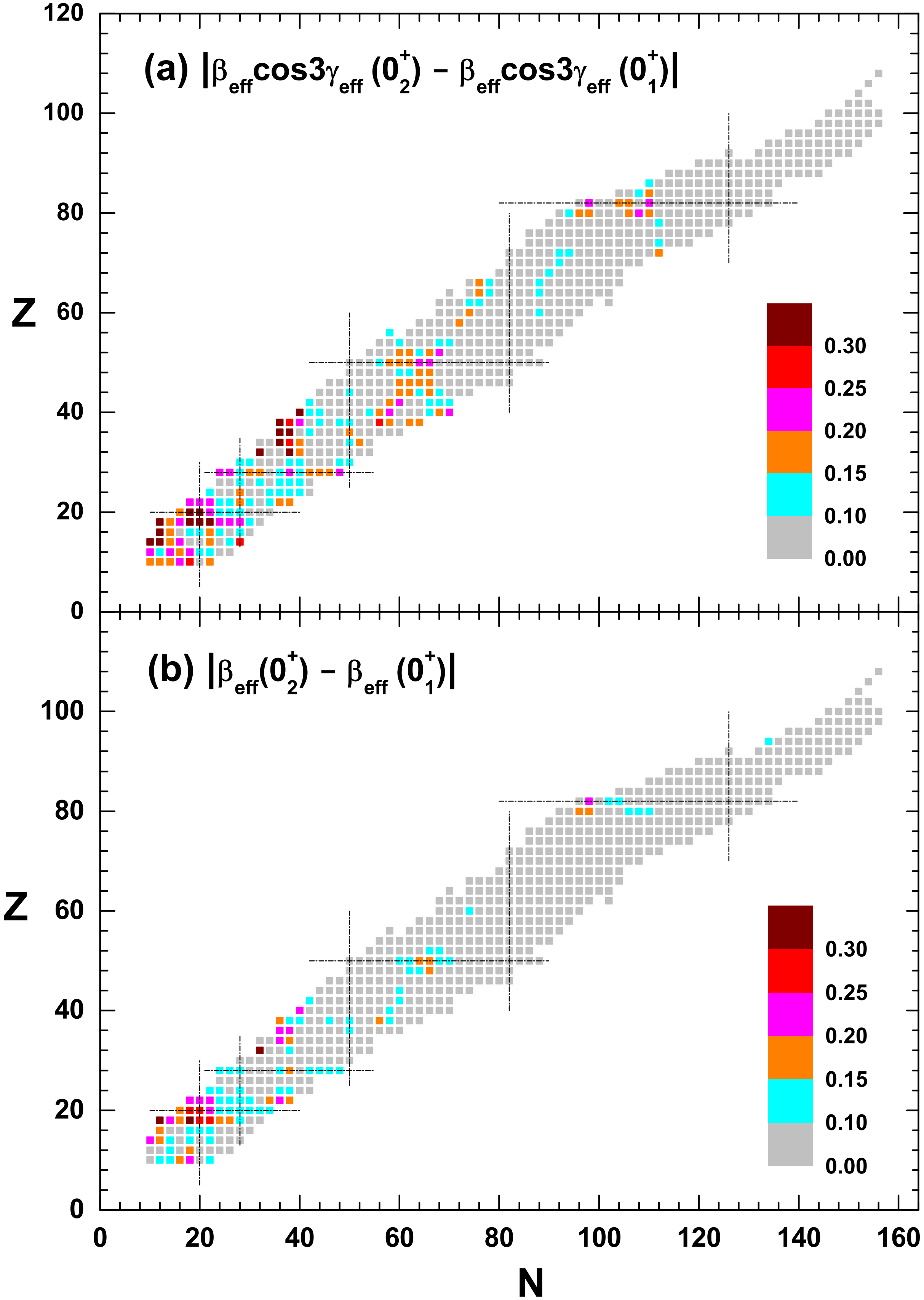
⇒ effective deformation parameters:

$$q_2(0_i^+) = \left(\frac{3ZeR^2}{4\pi} \right)^2 \langle \beta^2 \rangle \equiv \left(\frac{3ZeR^2}{4\pi} \right)^2 \beta_{\text{eff}}^2$$

$$\frac{q_3(0_i^+)}{q_2^{3/2}(0_i^+)} = \frac{\langle \beta^3 \cos 3\gamma \rangle}{\langle \beta^2 \rangle^{3/2}} \equiv \cos 3\gamma_{\text{eff}}$$

⇒ signatures of shape coexistence

Phys. Rev. C **95**, 054321 (2017).

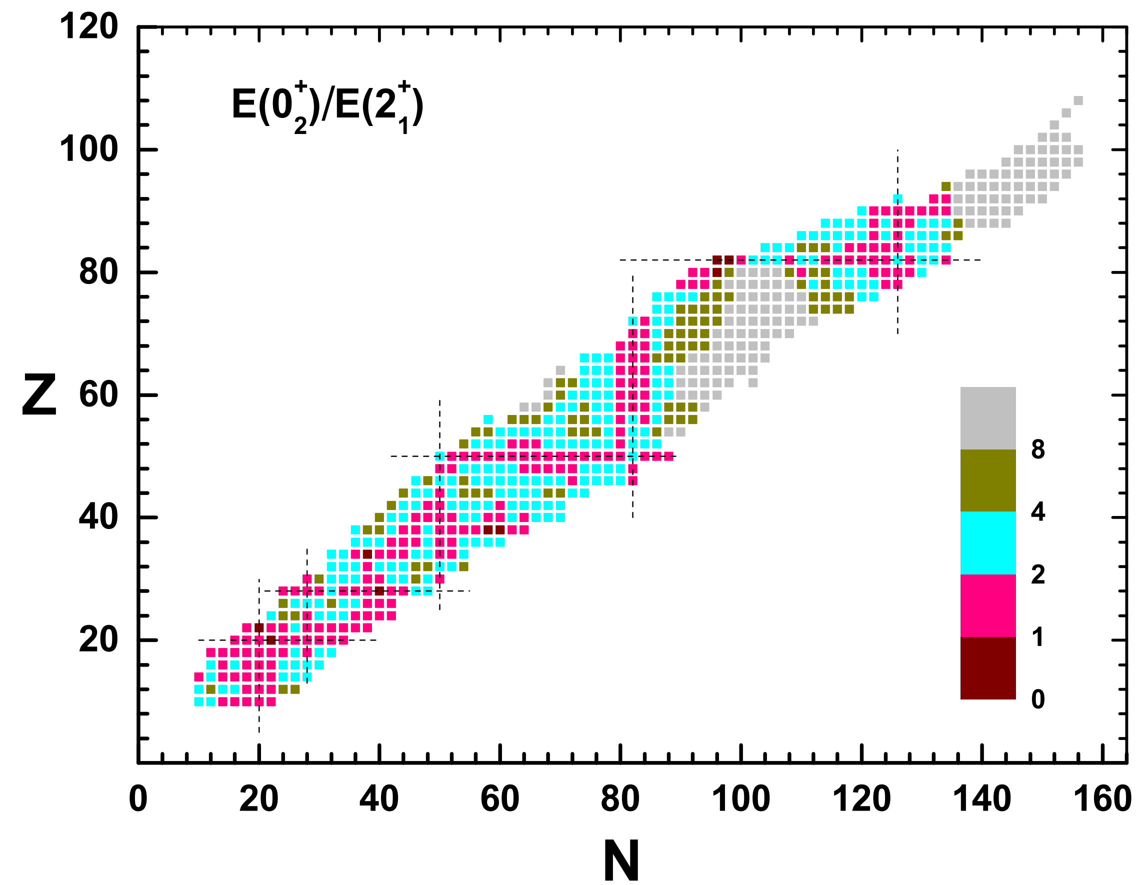


⇒ signatures of shape coexistence:

Large values of $|\beta_{eff}\cos3\gamma_{eff}\,(0^+_2) - \beta_{eff}\cos3\gamma_{eff}\,(0^+_1)|$

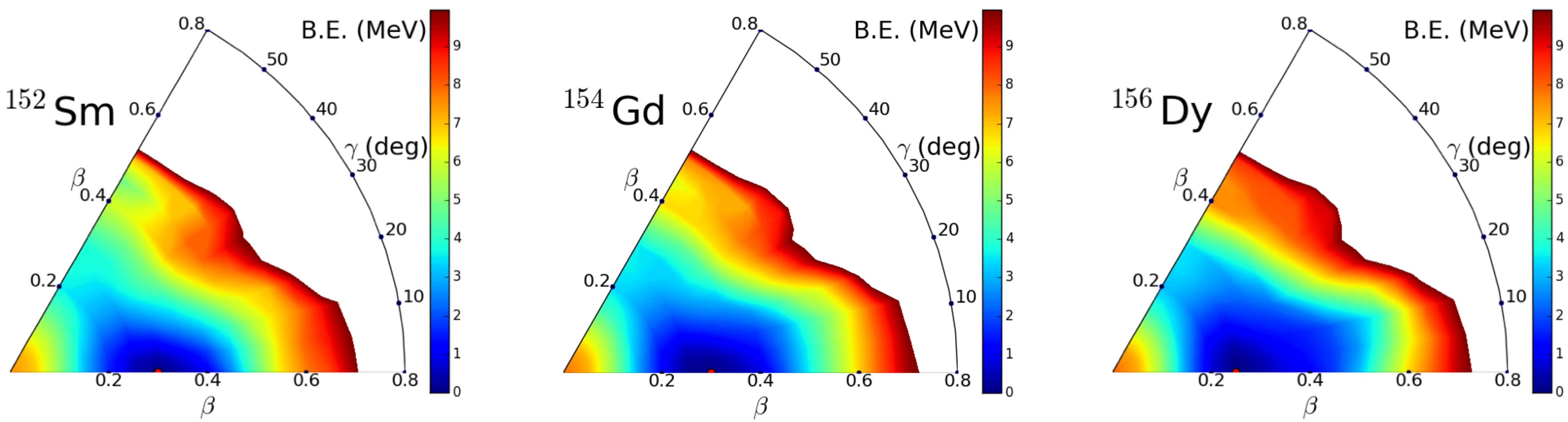
and $|\beta_{eff}(0^+_2) - \beta_{eff}\,(0^+_1)|$

First excited 0^+ state low in energy compared to the first 2^+.

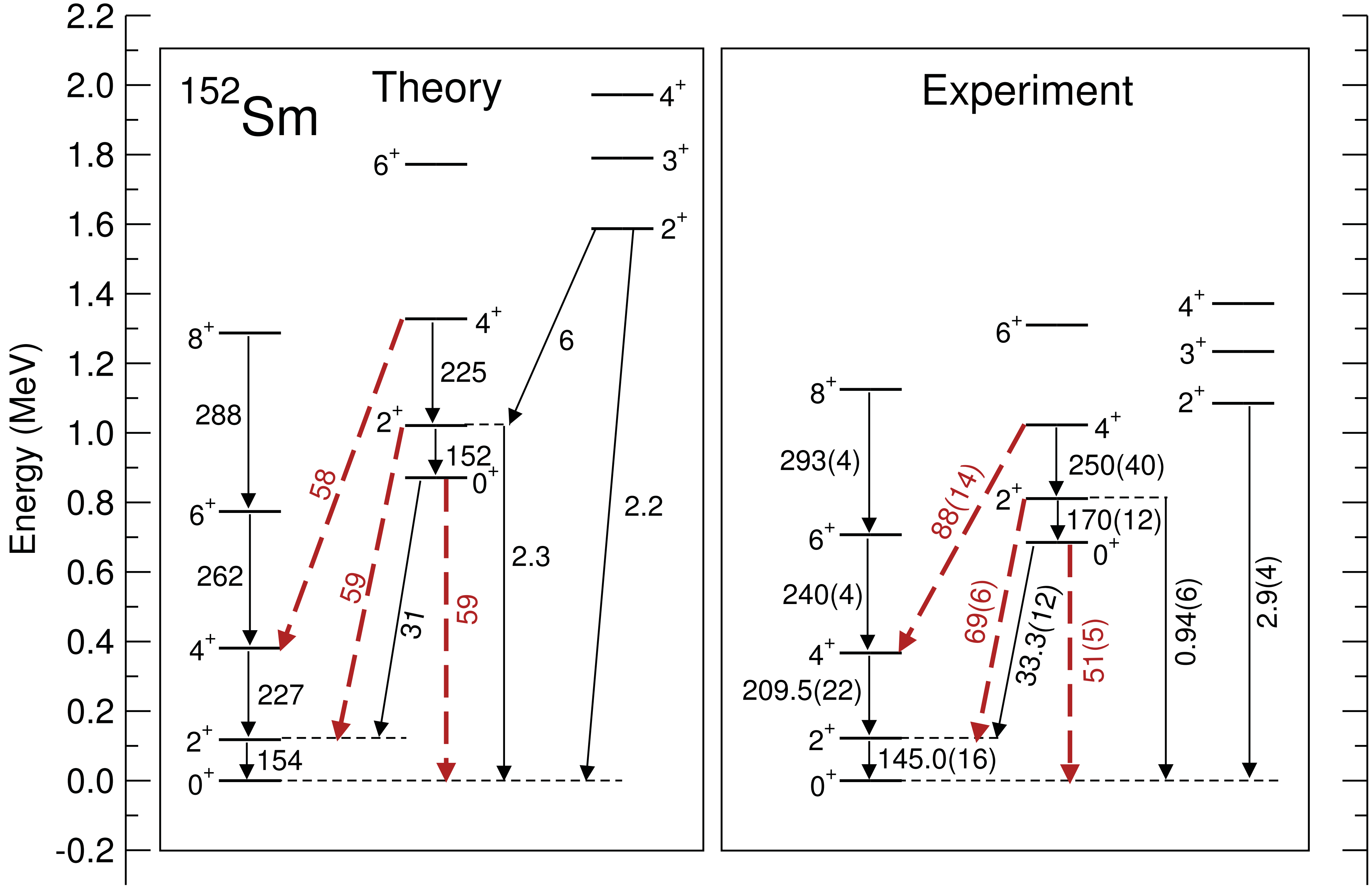


Lowest 0+ excitations in N ≈ 90 rare-earth nuclei

J. Phys. G: Nucl. Part. Phys. 43 (2016) 024005



… eigenspectra of the 5D quadrupole collective Hamiltonian:

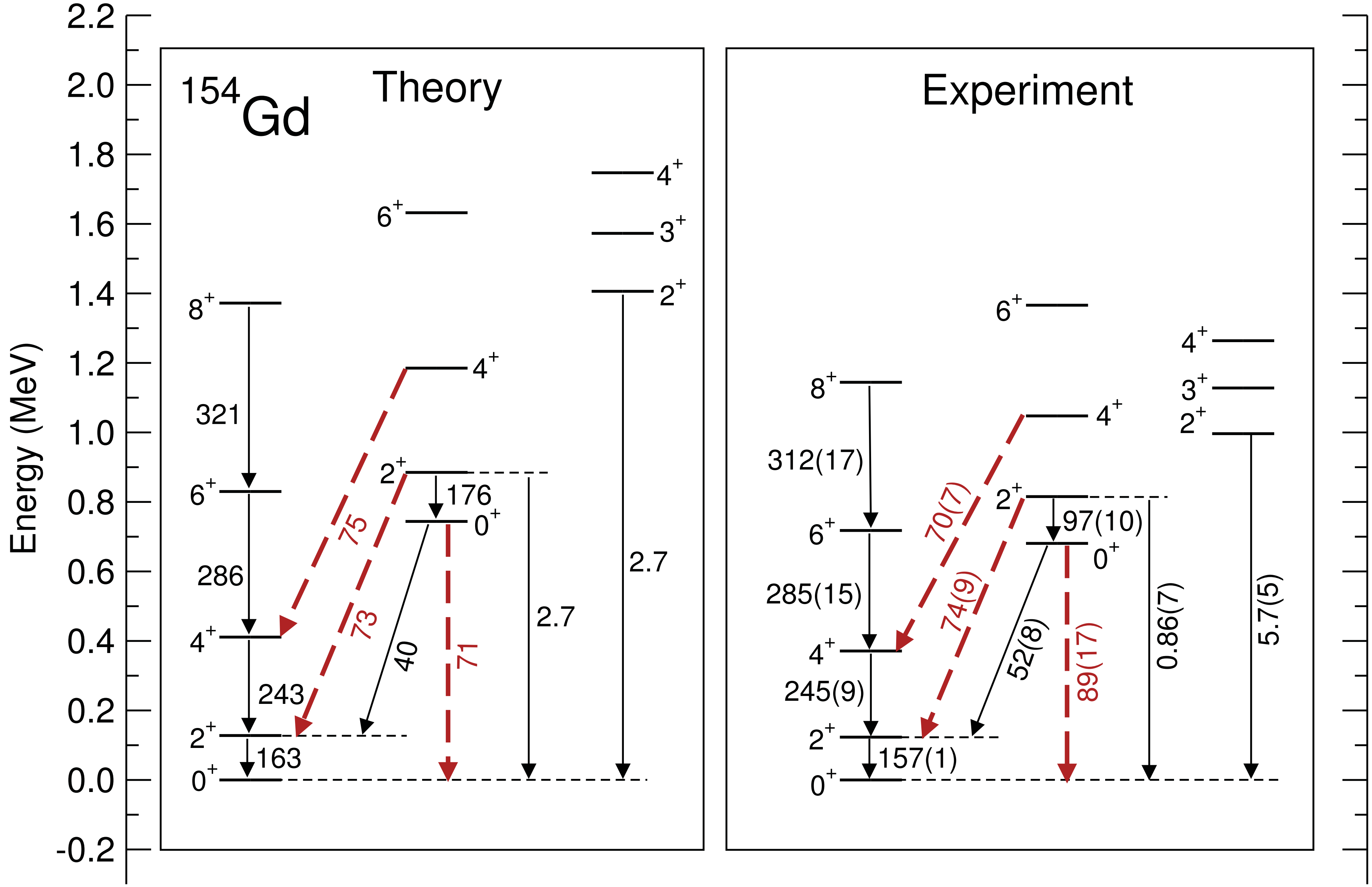


Criteria for the excited 0^+ state to be labelled as a β-vibration:

$$B(E2; 0_\beta^+ \to 2_1^+) \approx 12 - 33\ W.u.$$

$$B(E2; 2_\beta^+ \to 0_1^+) \approx 2.5 - 6\ W.u.$$

$$\rho^2(E0; 0_2^+ \to 0_1^+) \approx (85 - 230) \times 10^{-3}$$



Criteria for the excited 0⁺ state to be labelled as a β-vibration:

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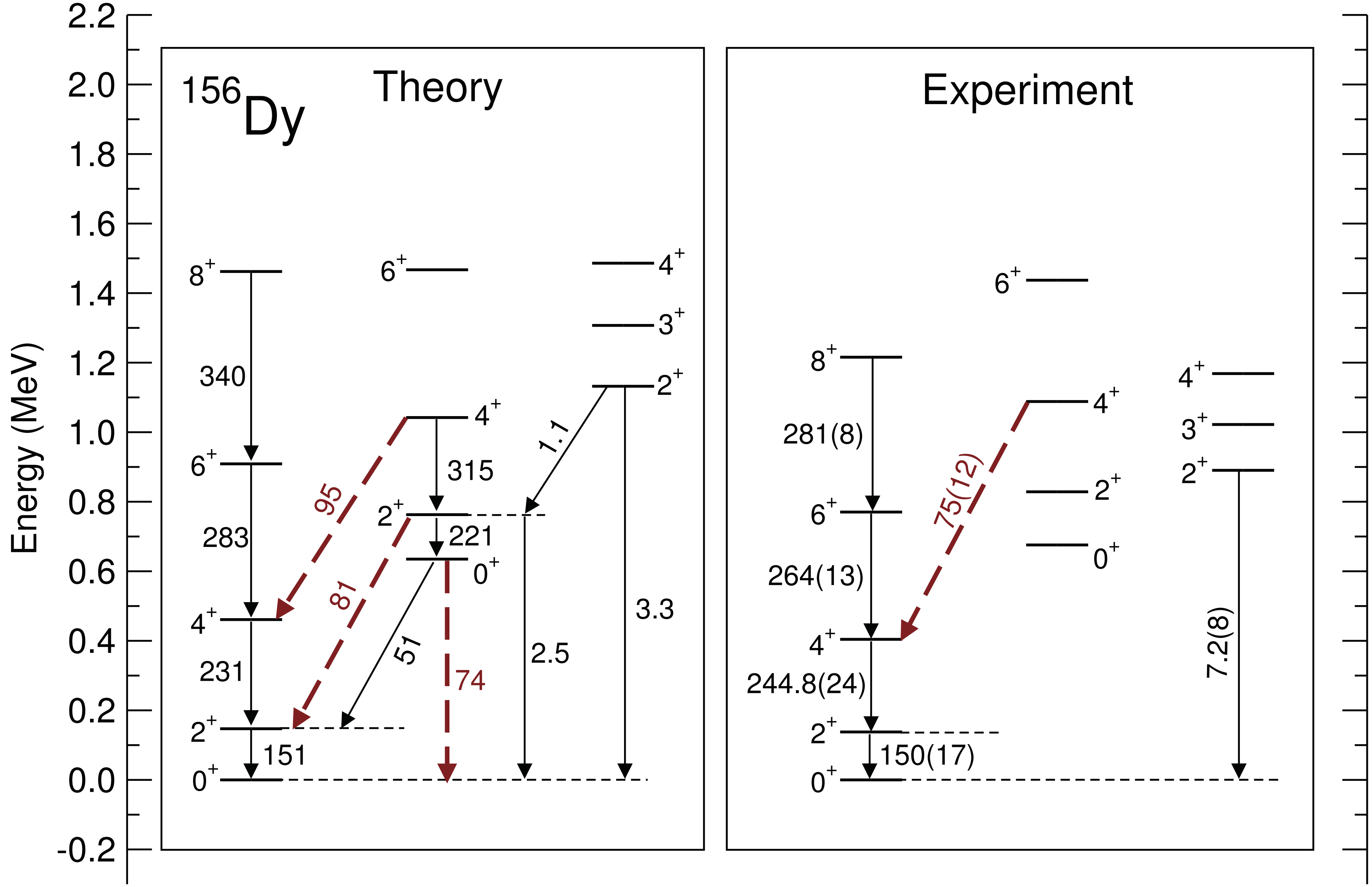

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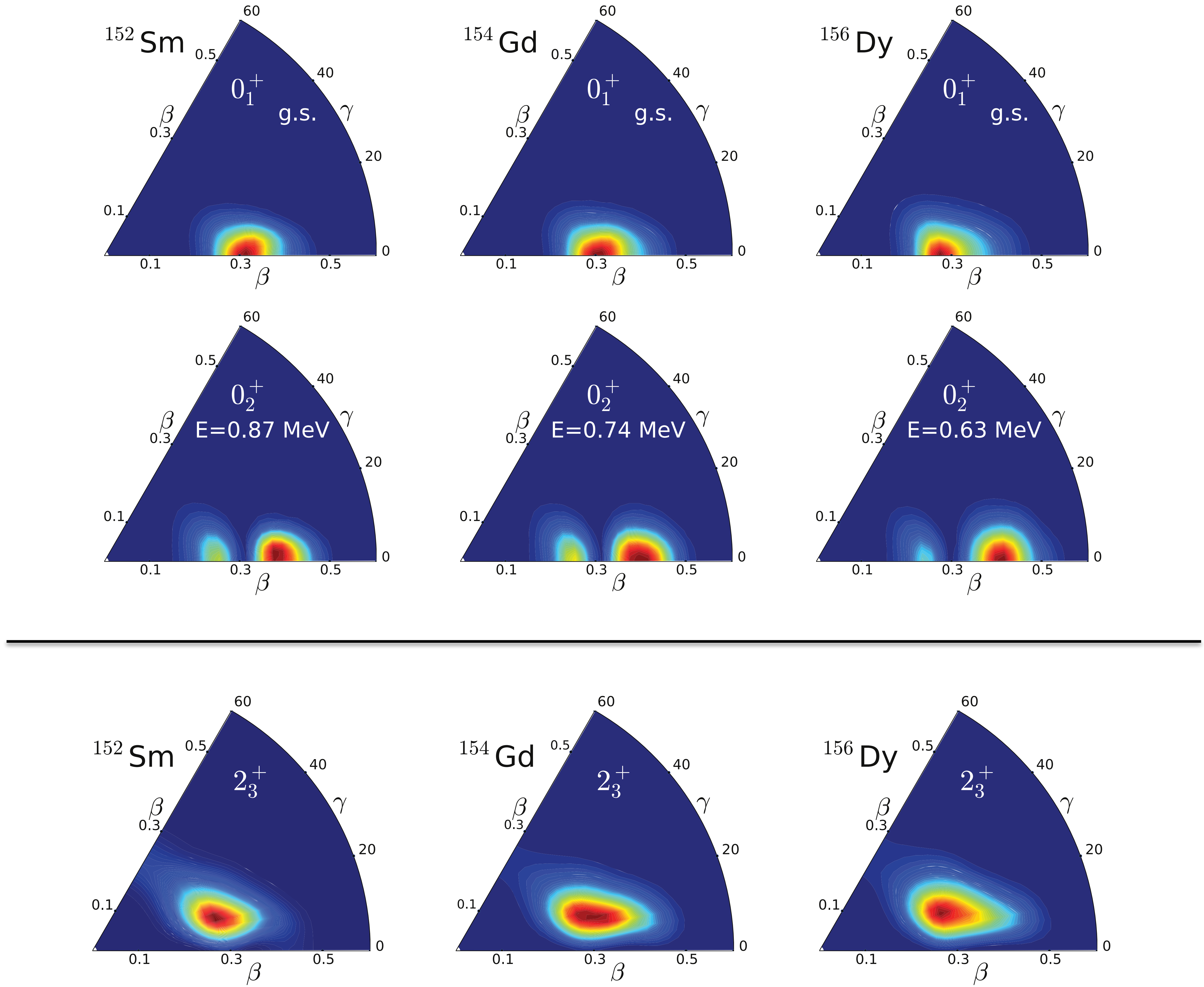
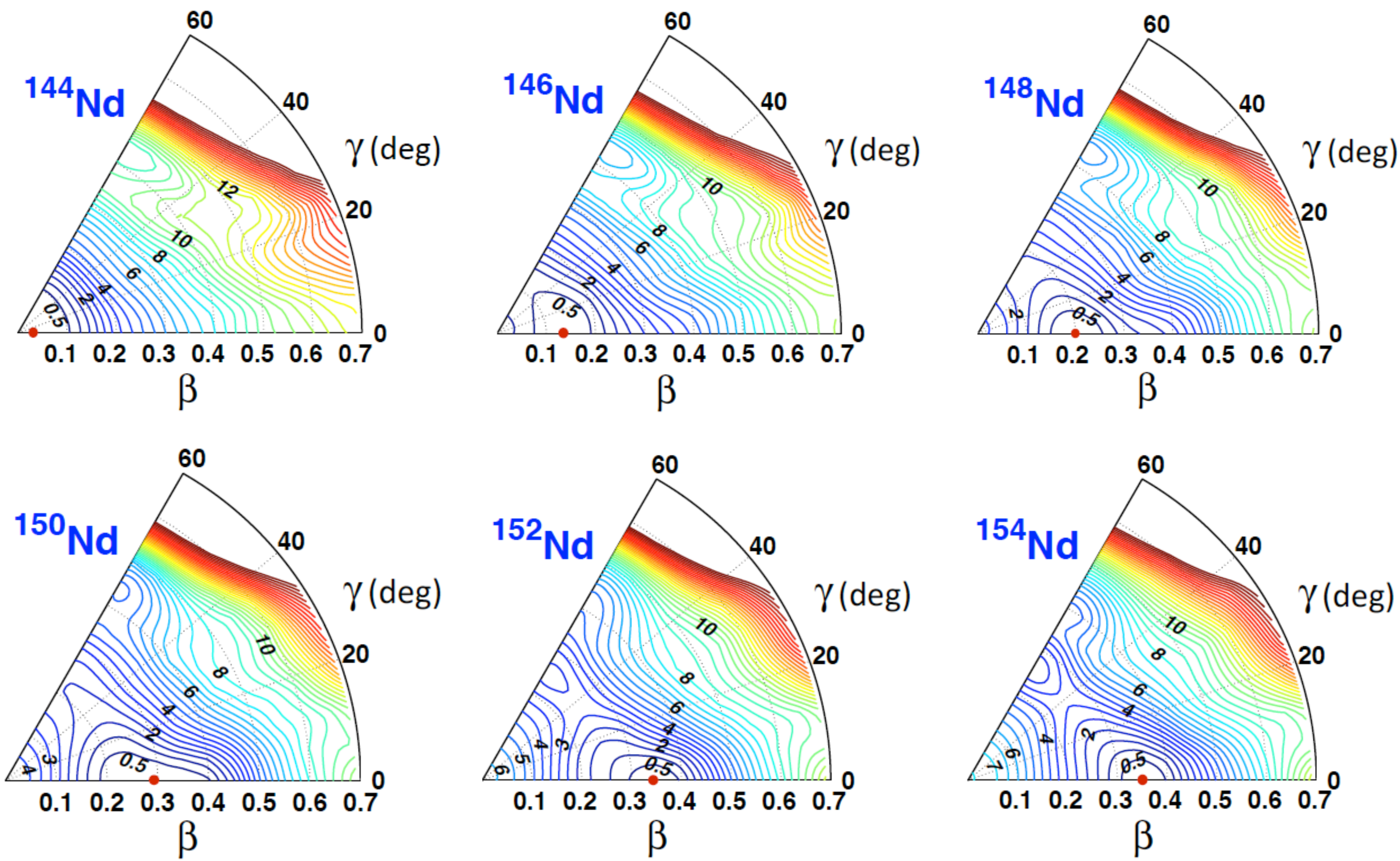
β-vibration or shape coexistence?

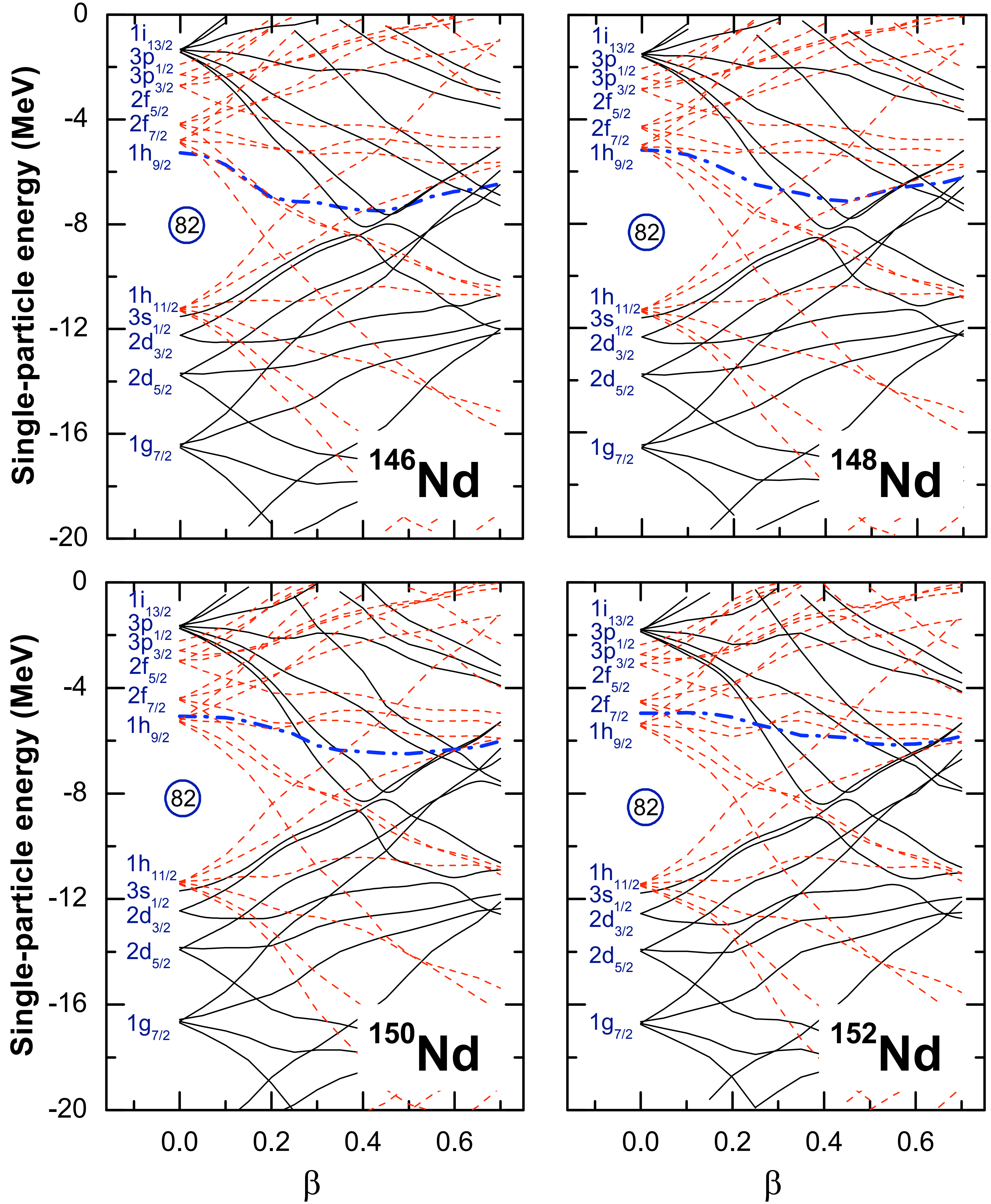


^{152}Sm
^{154}Gd
^{156}Dy
0_1^+
g.s.
0_2^+
E=0.87 MeV
E=0.74 MeV
E=0.63 MeV
2_3^+
β
γ
0.1
0.3
0.5
0
20
40
60

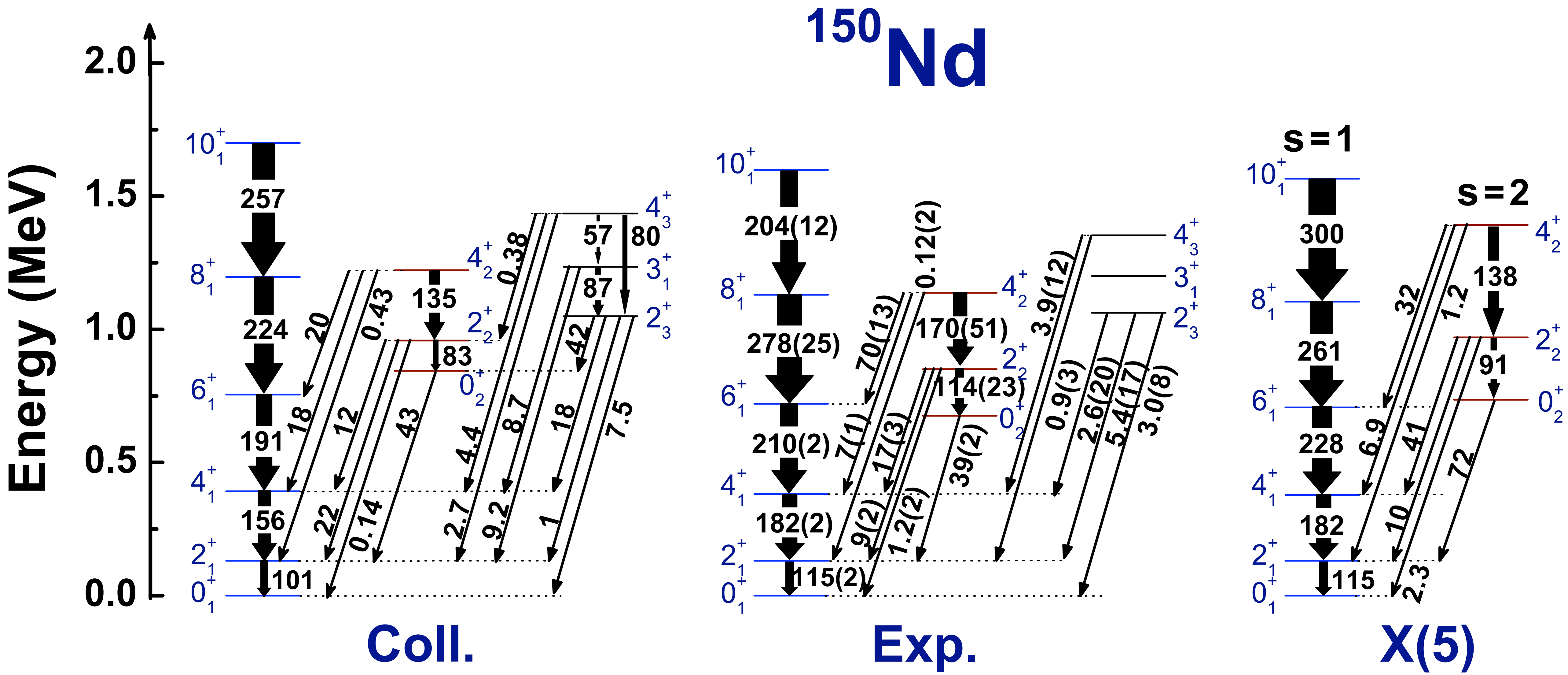
Transitions between spherical and axially deformed shapes in the chain of Nd-Sm-Gd isotopes.



Neutron single-particle levels in Nd isotopes.

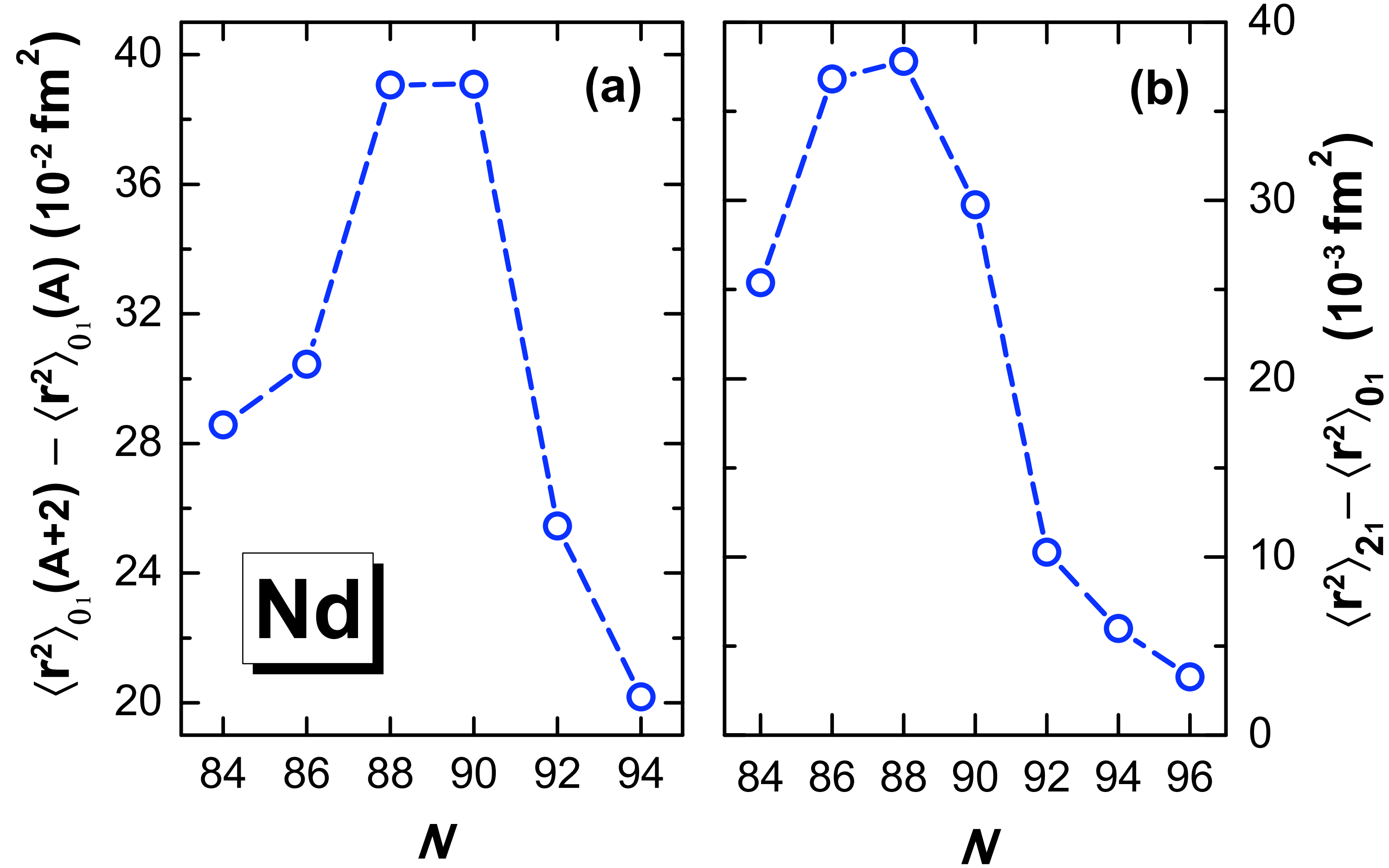


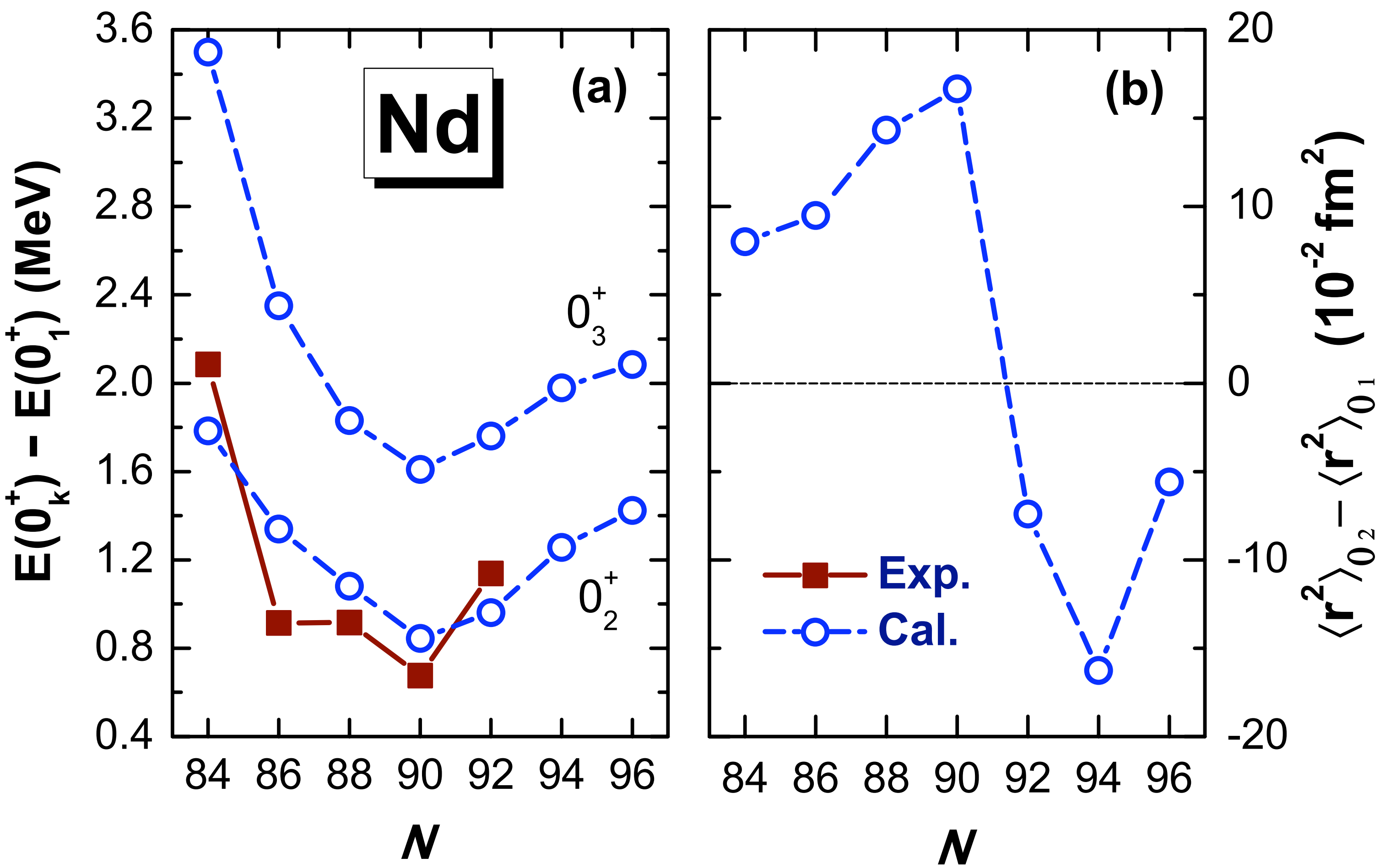
Experimental evidence for a first-order shape phase transition at N≈90



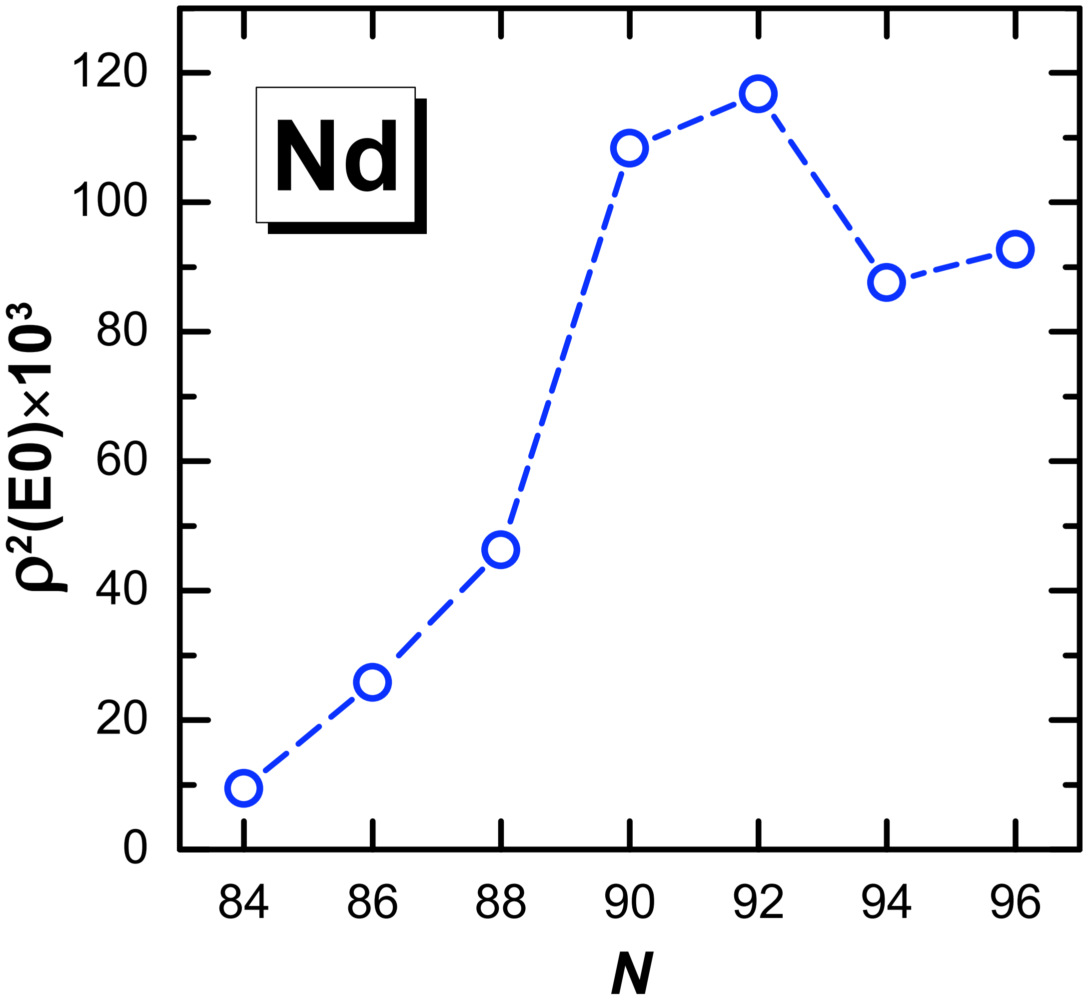
Nikšić, Vretenar, Lalazissis, Ring, Phys. Rev. Lett. **99**, 092502 (2007)
Li, Nikšić, Vretenar, Meng, Lalazissis, Ring, Phys. Rev. C **79**, 054301 (2009)

... using collective wave functions obtained by diagonalization of the five-dimensional Hamiltonian ...





... microscopic calculation of order parameters for a first-order nuclear QPT between spherical and axially deformed shapes.

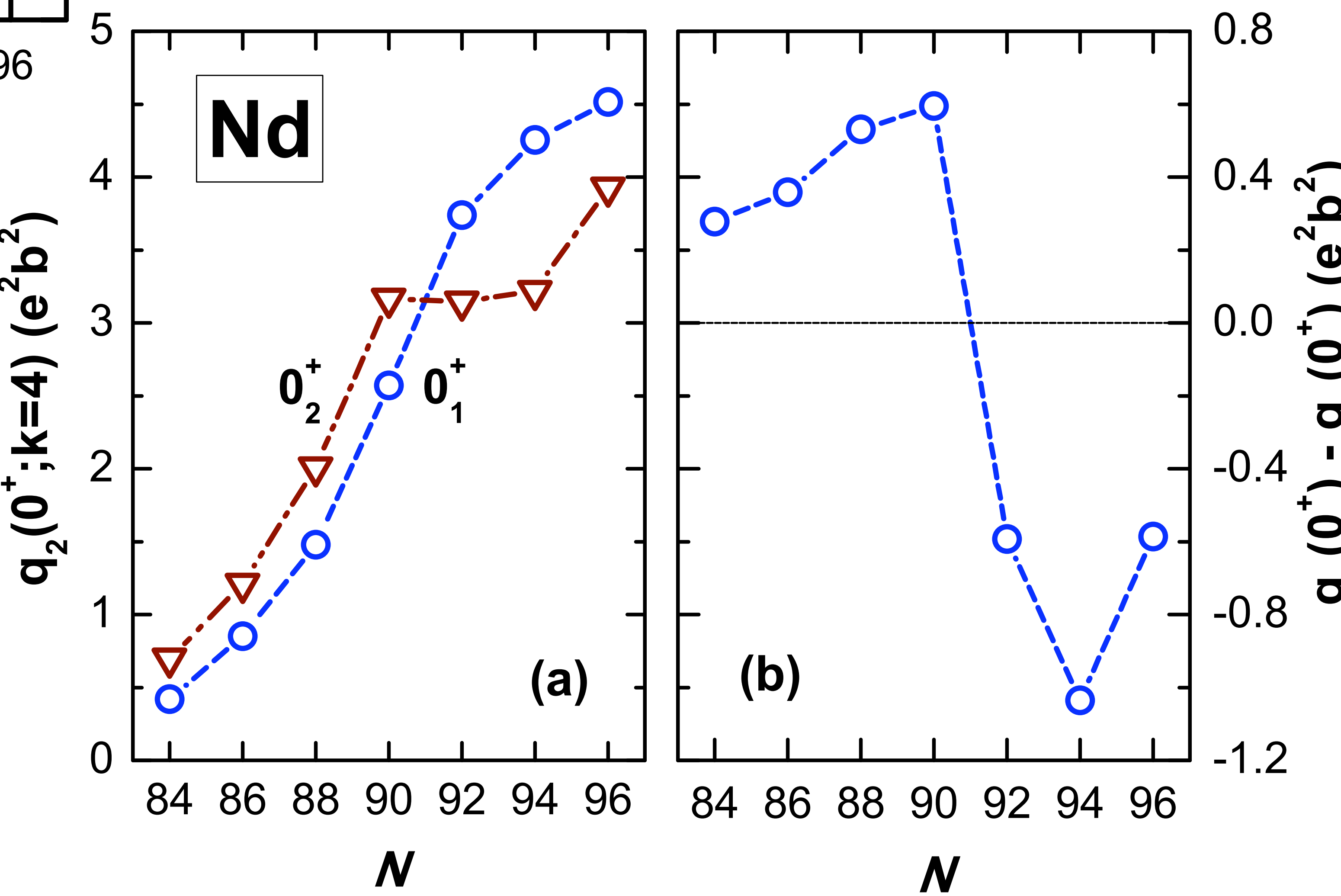


$$\hat{T}(E0) = \sum_k e_k r_k^2$$

$$\rho^2(E0; 0_2^+ \rightarrow 0_1^+) = \left| \frac{\left\langle 0_2^+ | \hat{T}(E0) | 0_1^+ \right\rangle}{eR^2} \right|^2$$

q shape invariants:

$$q_2(0_n^+; k) = \sum_{j=1}^{k} B(E2; 0_n^+ \rightarrow 2_j^+)$$



✘ identification of ***order parameters***? Accuracy of the EDF-based collective models used to calculate excitation spectra and transition rates?

✘ How much are the discontinuities at a phase transitional point smoothed out in finite nuclei?

✘ discrete integer values for the control parameter - ***nucleon number*** ➔ how precisely can a QPT point be assigned to a particular nucleus?