Nuclear structure and dynamics 2019 (NSD2019)
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Nuclear structure studies based on energy density functionals

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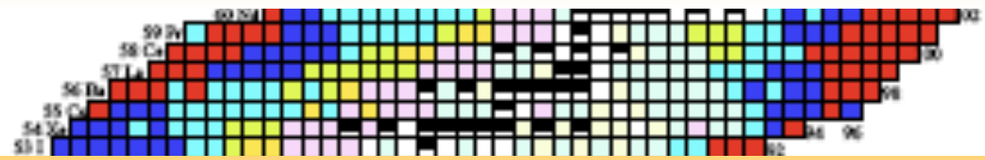
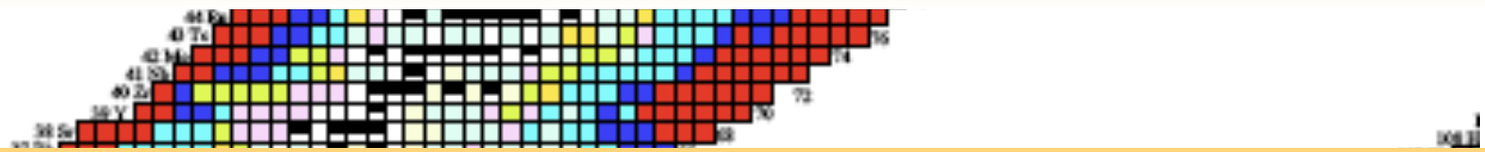
Universal theory framework: Energy Density Functionals

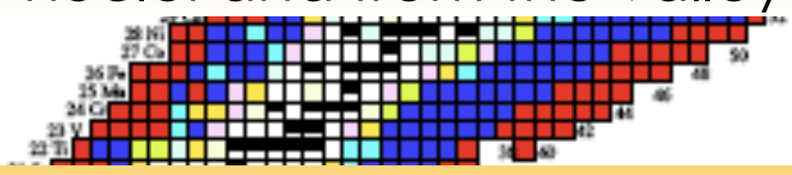
✔ the nuclear many-body problem is effectively mapped onto a one-body problem without explicitly involving internucleon interactions

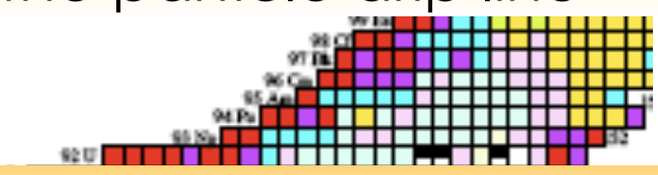


✔ the exact density functional is approximated with powers and gradients of ground state densities and currents

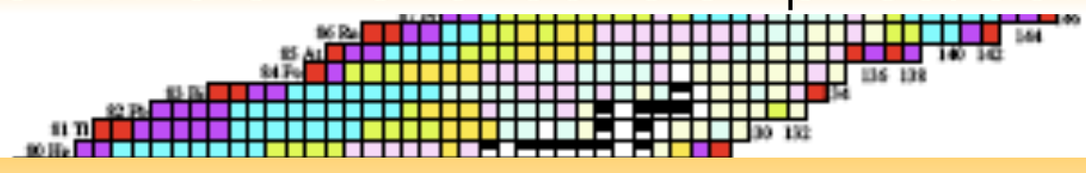


✔ universal density functionals can be extended from relatively light systems to superheavy nuclei and from the valley of stability to the particle drip line





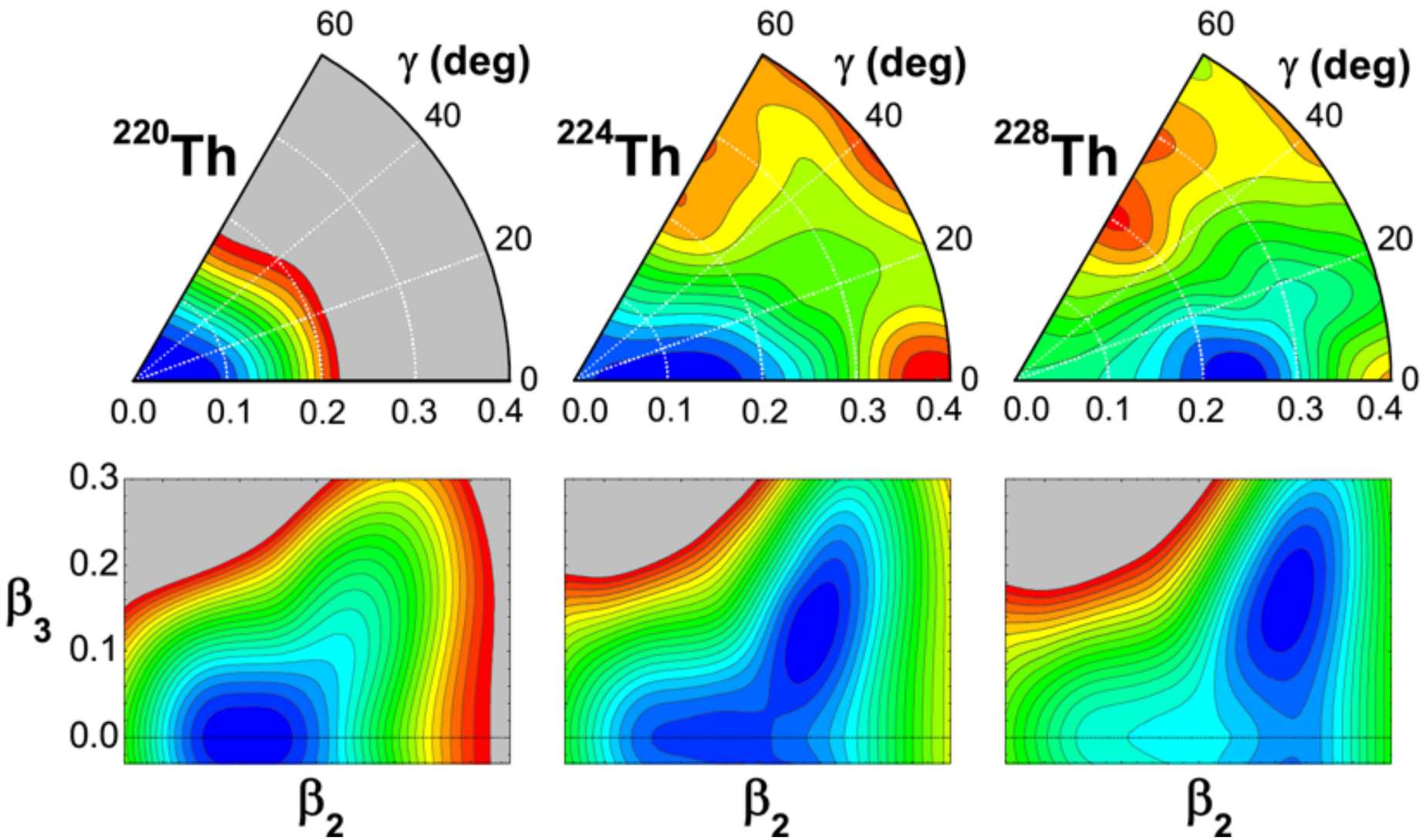
✔ the coupling parameters of the EDF are fine-tuned to empirical data



✔ covariant EDFs – built from densities and currents bilinear in the Dirac spinor field of the nucleon

Basic implementation: self-consistent mean-field method

- produces energy surfaces as functions of intrinsic deformation parameters

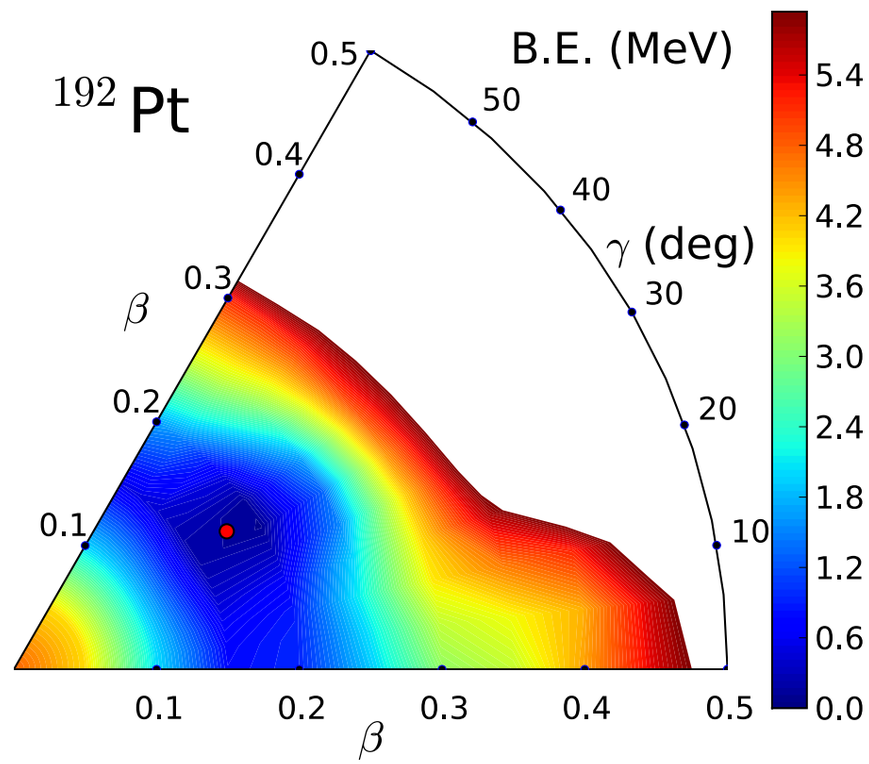


- includes static correlations: deformations and pairing
- does not include collective correlations originating from symmetry restoration and quantum fluctuations around mean-field minima

Beyond mean-field correlations: 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



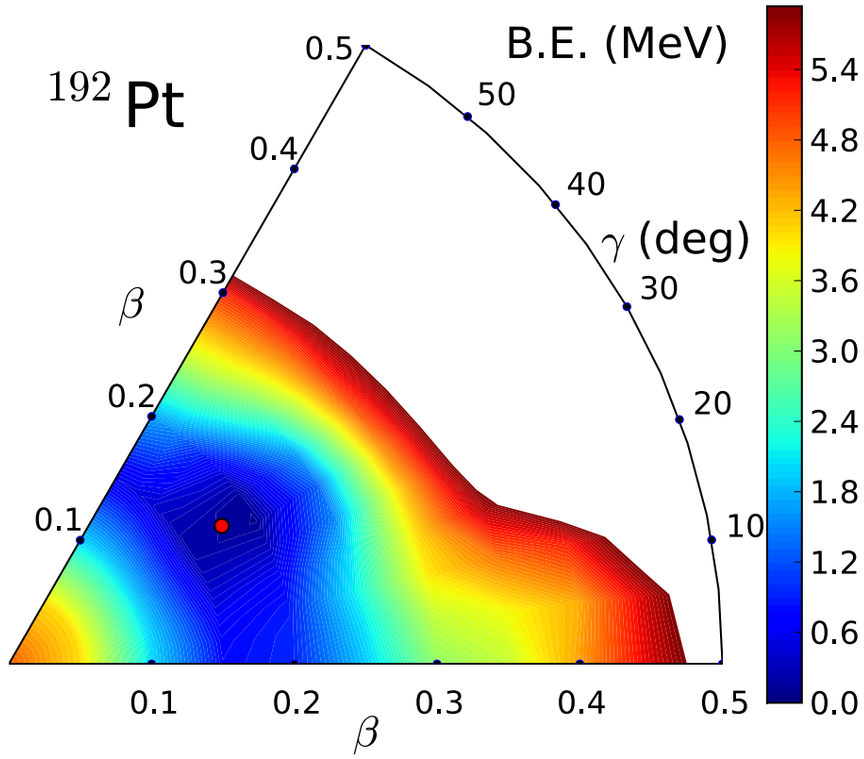
$$H_{\rm coll} = \mathcal{T}_{\rm vib}(\beta,\gamma) + \mathcal{T}_{\rm rot}(\beta,\gamma,\Omega) + \mathcal{V}_{\rm coll}(\beta,\gamma)$$

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

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

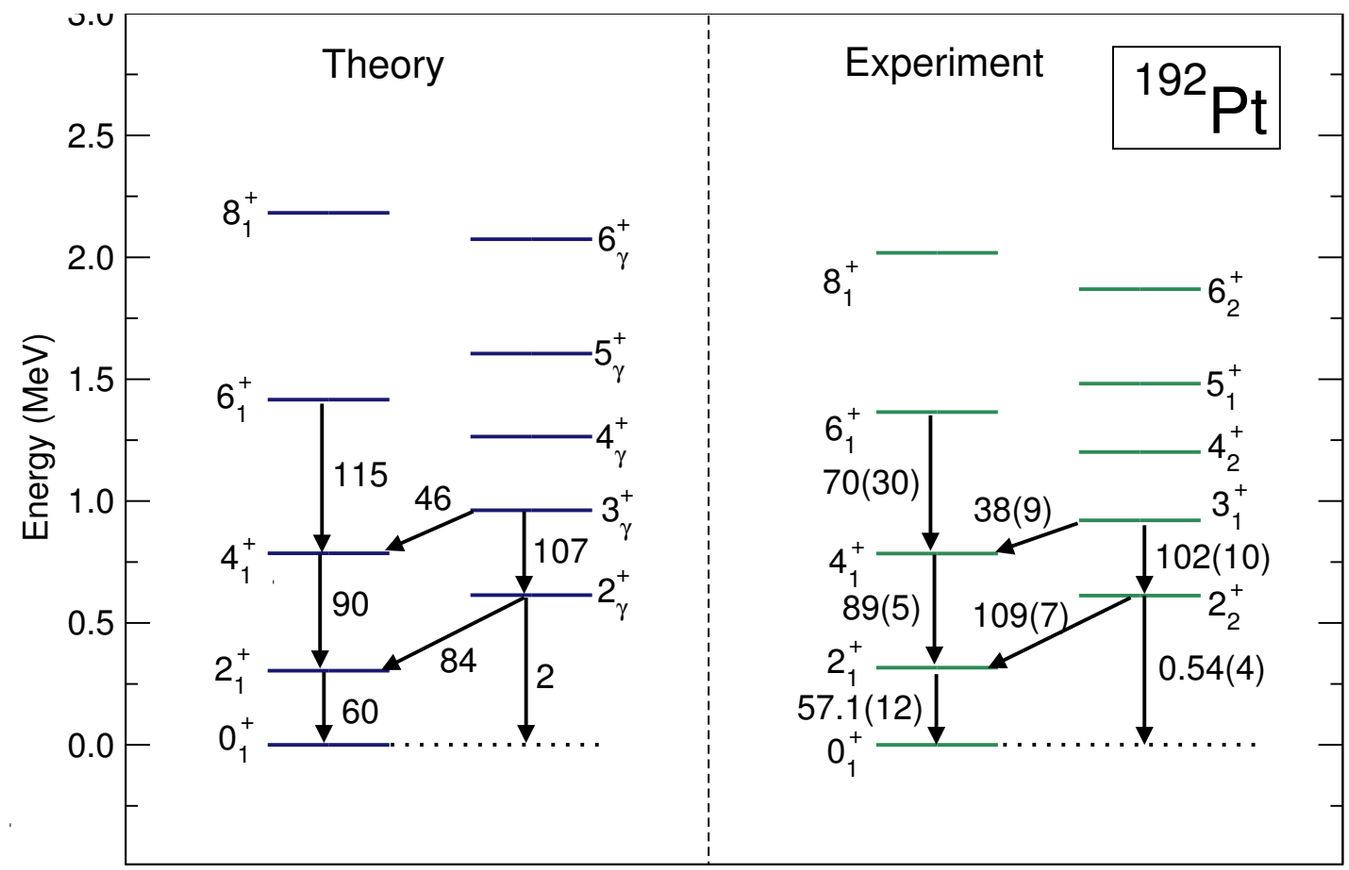
The entire dynamics of the collective Hamiltonian is governed by the seven functions of the intrinsic deformations β and γ: the collective potential, the three mass parameters: $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$, and the three moments of inertia I_k.

… collective eigenfunction: $\Psi_\alpha^{IM}(\beta,\gamma,\Omega) = \sum_{K\in\Delta I}\psi_{\alpha K}^{I}(\beta,\gamma)\Phi_{MK}^{I}(\Omega)$



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

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



✔ 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)

- Systematic analysis of characteristic signatures of coexisting shapes in different mass regions
- Calculation includes 621 even-even nuclei with Z,N>10 and for which 2_1^+ state has been determined in experiment

Following criteria for shape coexistence have been used:

- The difference between $\beta_{eff}\cos(3\gamma_{eff})$ for the two lowest 0^+ states is large
- The excitation energy of 0_2^+ is low in comparison to the excitation energy of the 2_1^+ state

Deformation parameters

- Calculated by using the quadrupole shape invariants

Global analysis of quadrupole shape invariants

Phys. Rev. C 95, 054321 (2017)

The lowest-order quadrupole invariants:

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

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

Deformation parameters:

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

$$R = r_0 A^{1/3}$$

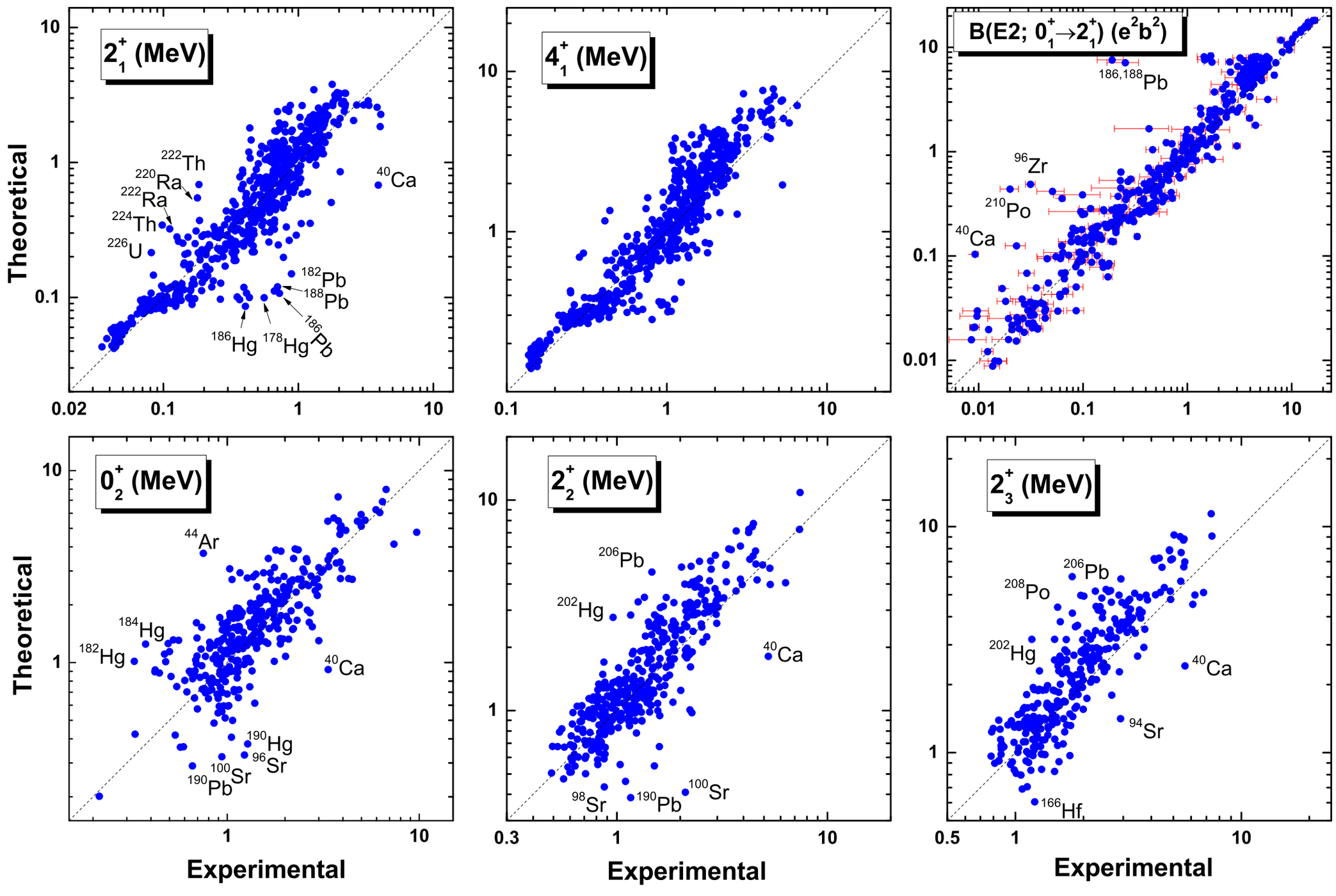
$$r_0 = 1.2 \text{ fm}$$

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

Global analysis of quadrupole shape invariants

Phys. Rev. C 95, 054321 (2017)

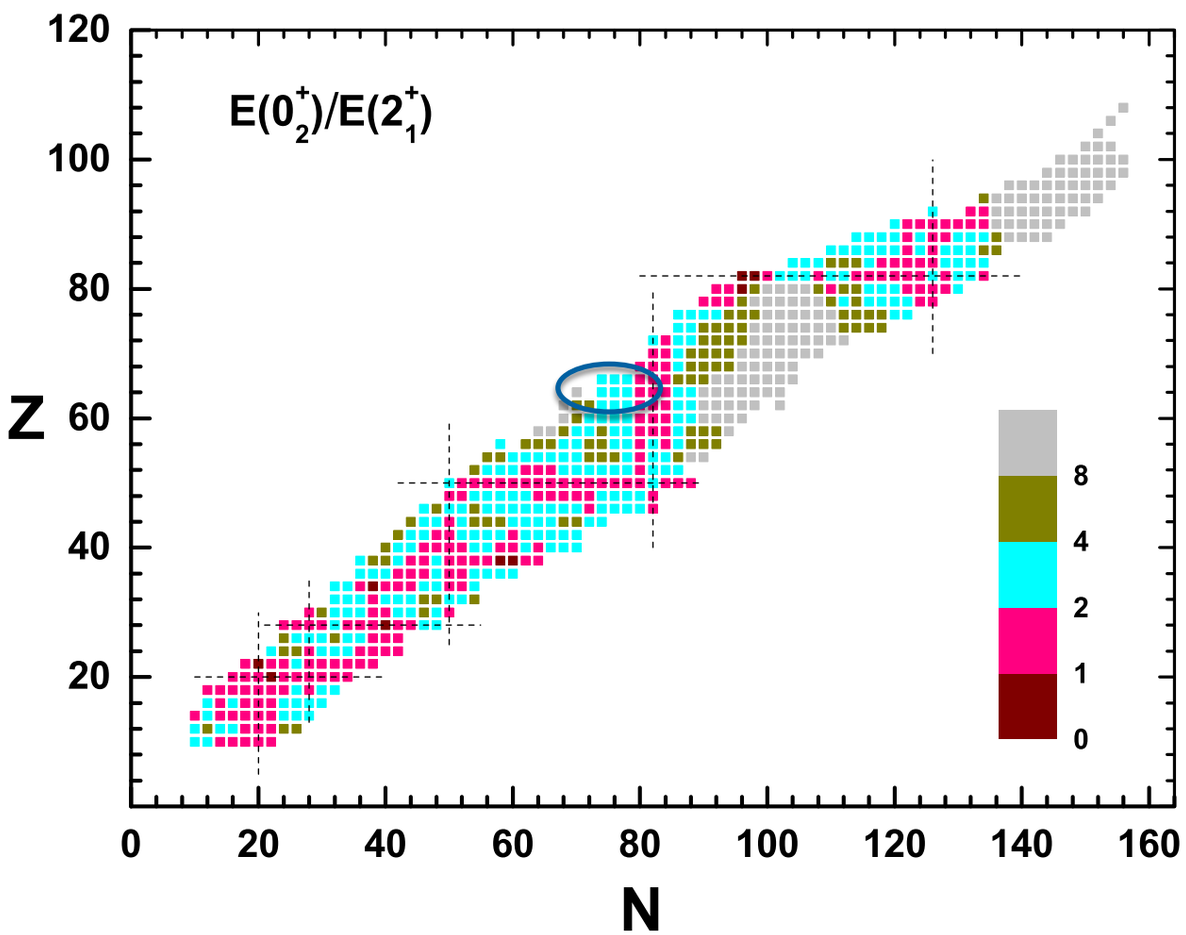
Test of the 5DCHM quality:

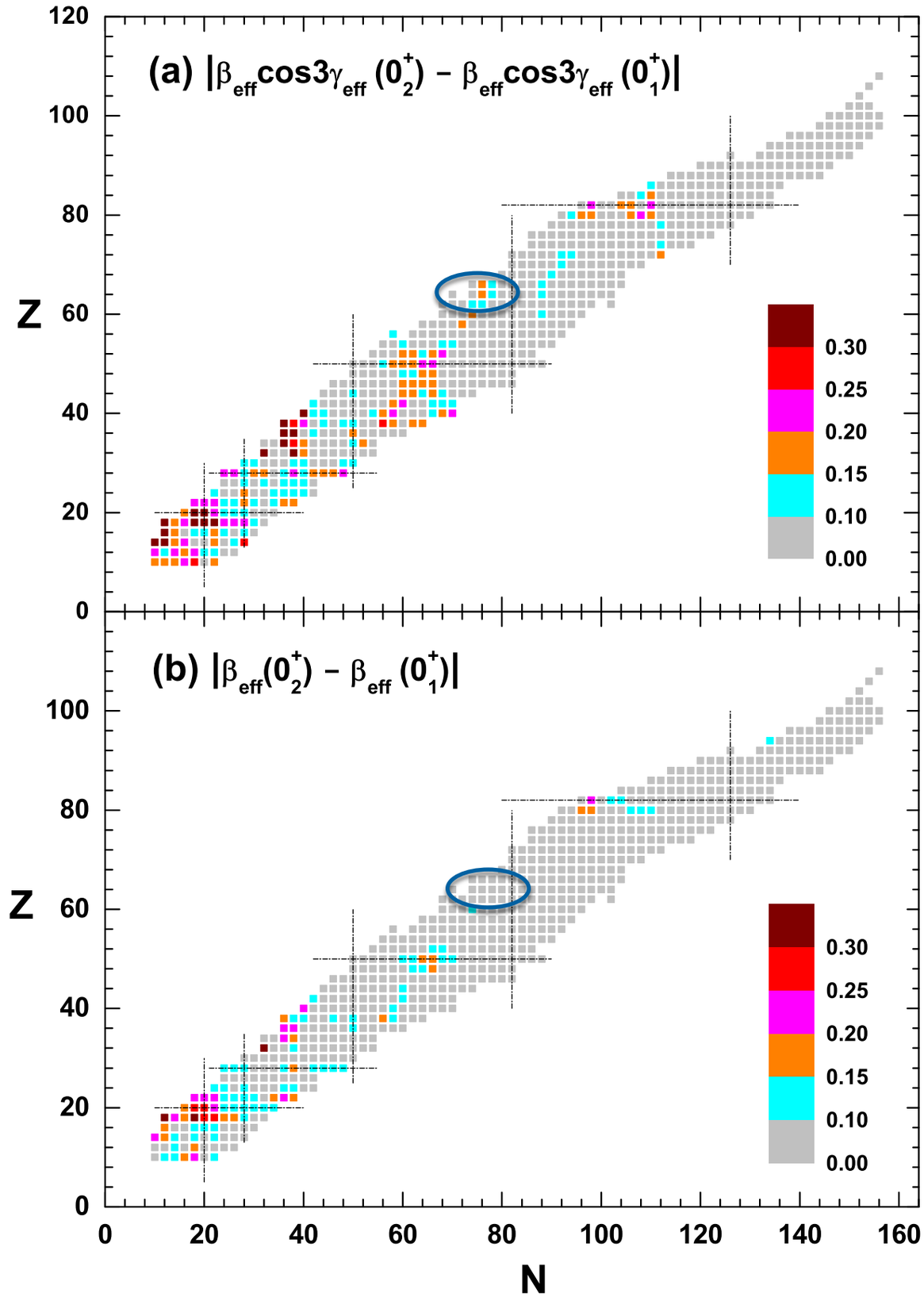


Global analysis of quadrupole shape invariants

Phys. Rev. C 95, 054321 (2017)

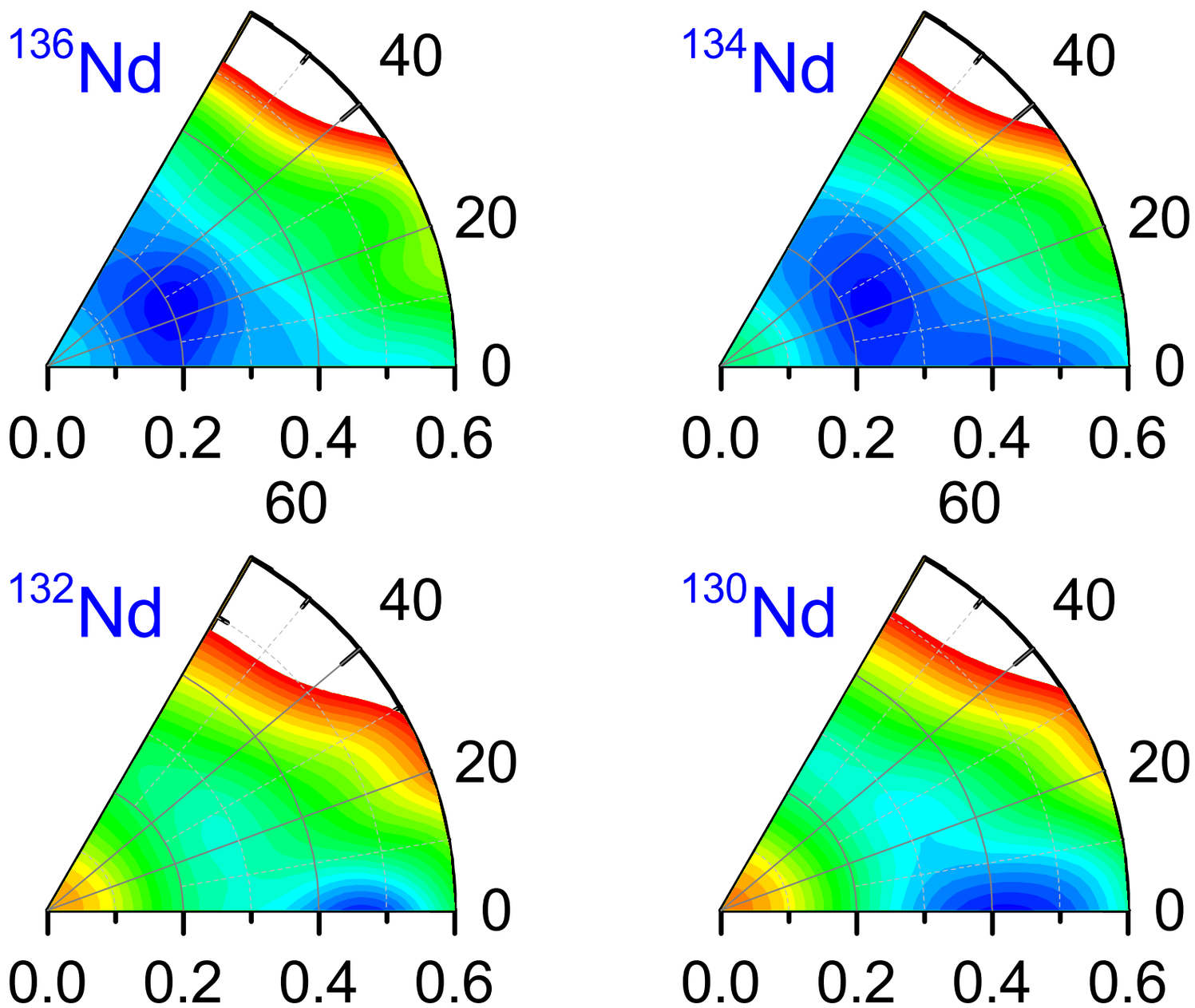
- Z≈64 and N≈76: medium deformed triaxial ground state coexisting with highly deformed prolate excited state





Coexisting shapes in neutron-deficient Nd and Sm isotopes

Phys. Rev. C 98, 054308 (2018)



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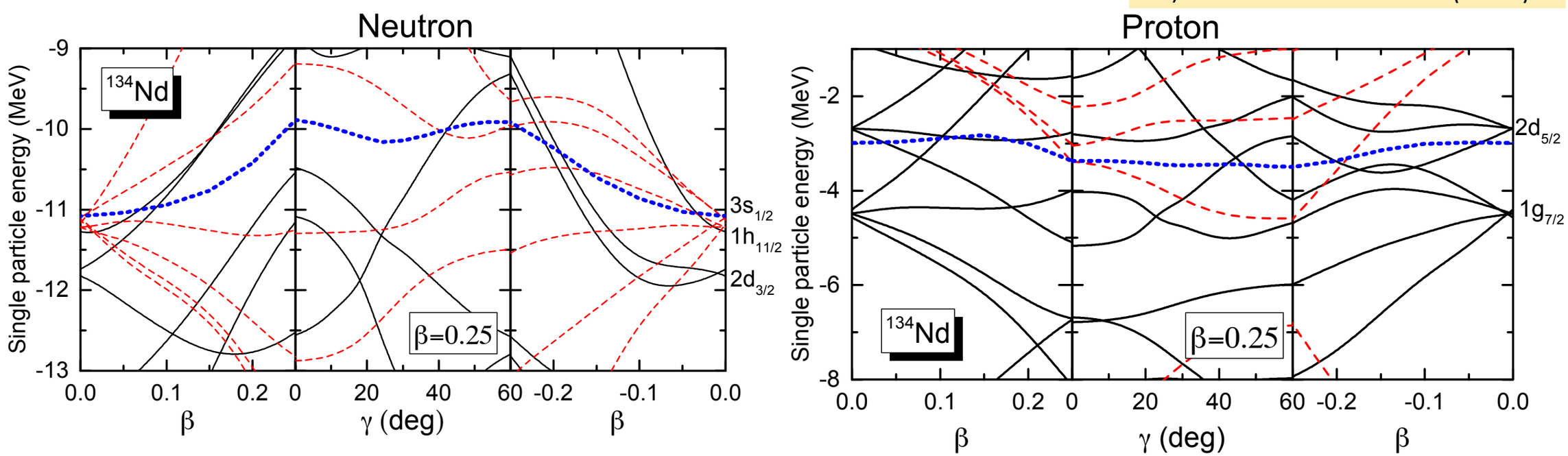

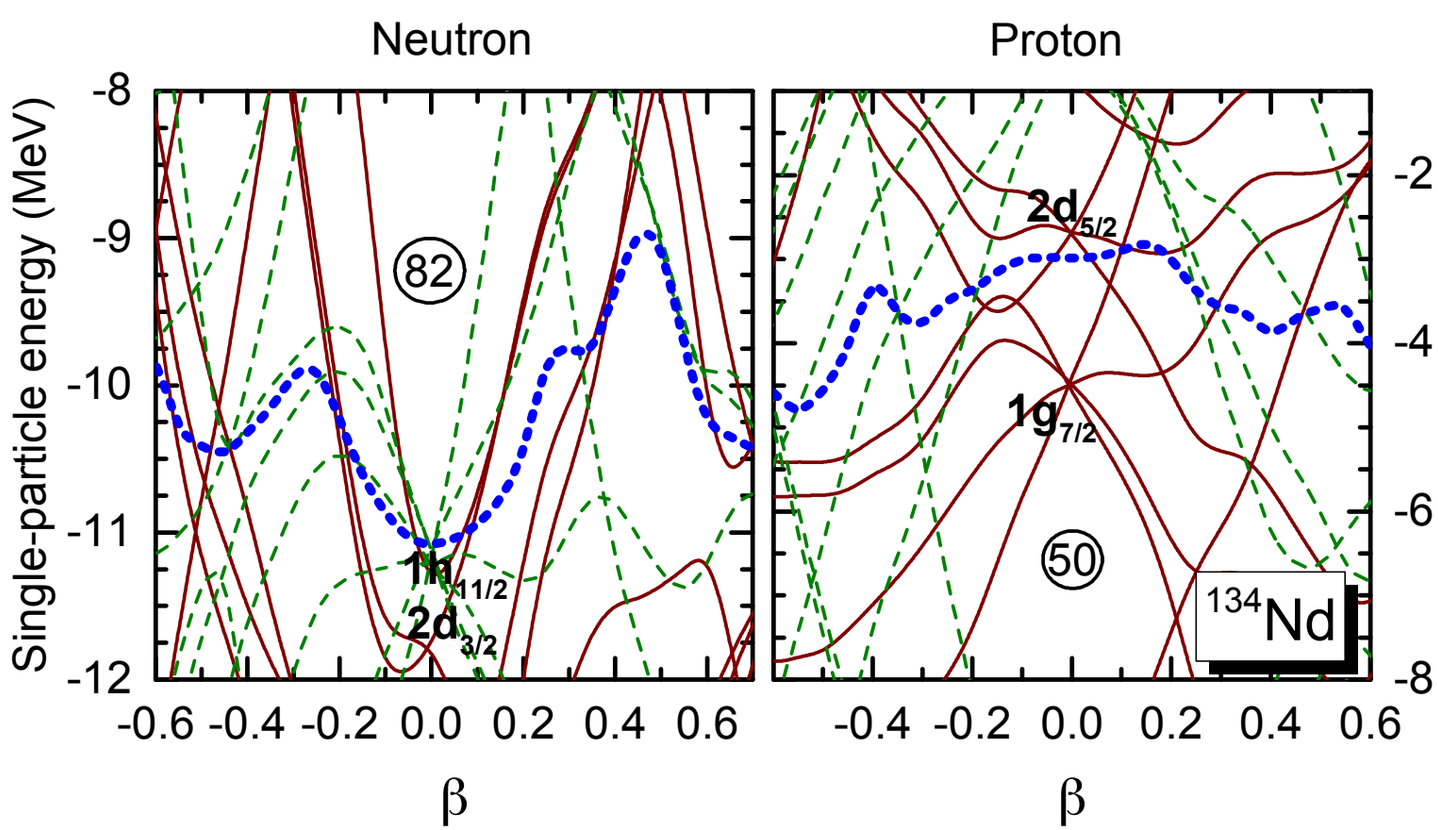

Coexisting shapes in neutron-deficient Nd and Sm isotopes

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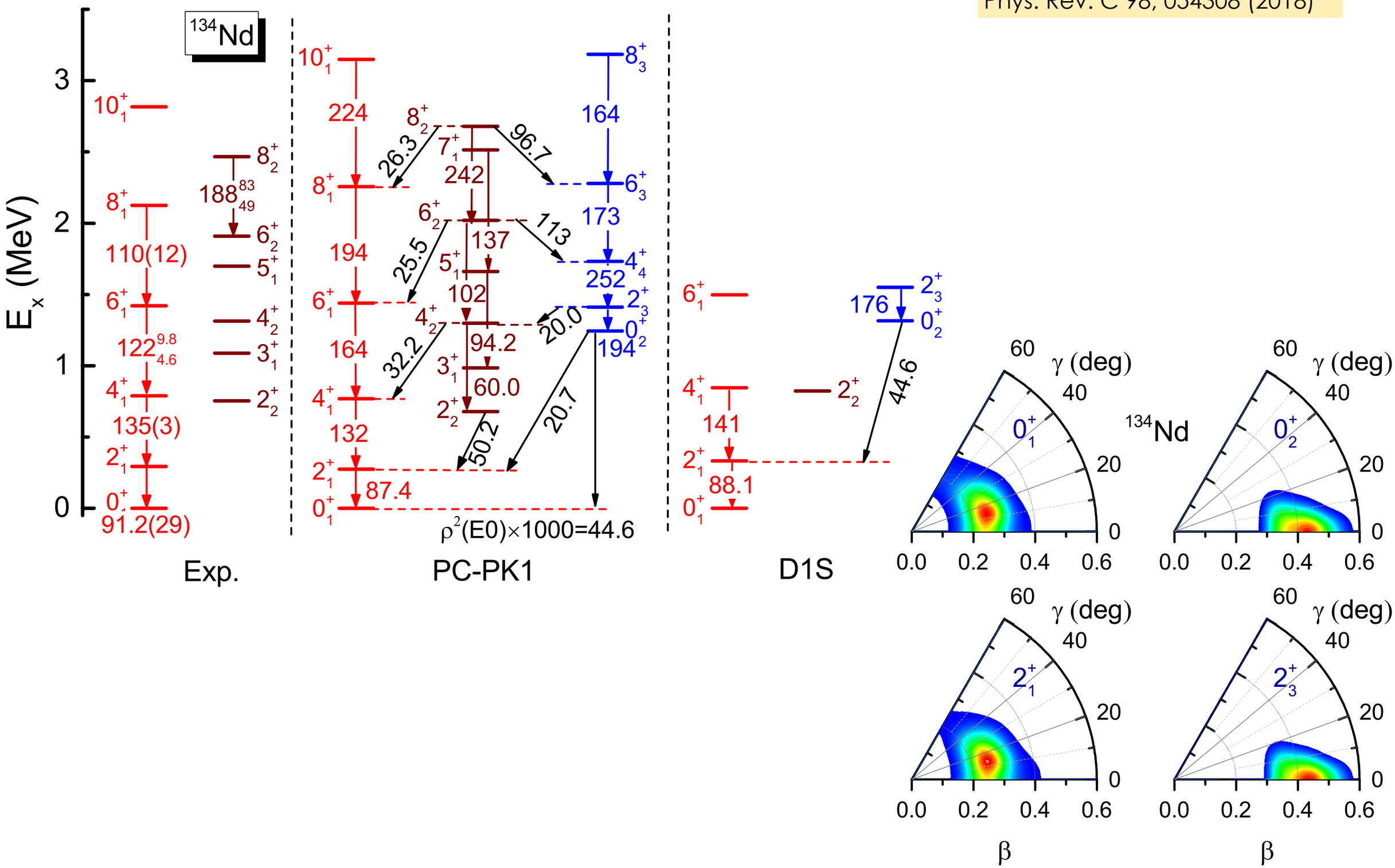


Linear response in deformed nuclei

Preliminary results

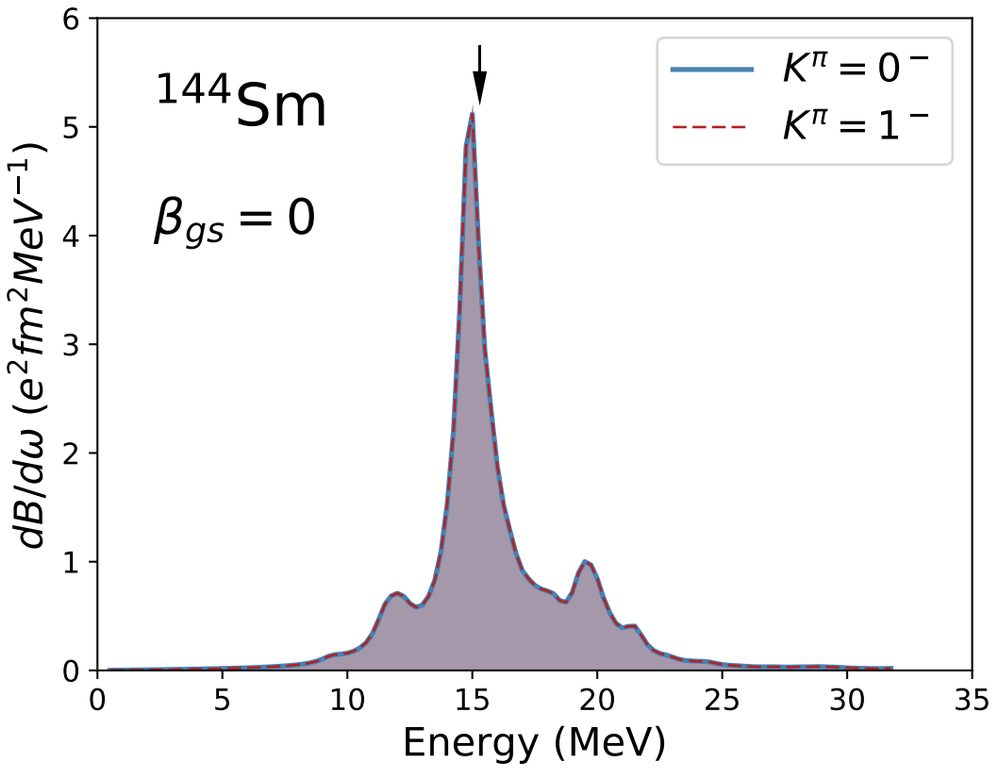
- Implementation of the finite amplitude method for axially symmetric nuclei
- Alternative to the matrix formulation of the QRPA
- Avoids calculating the matrix elements of the residual interaction and diagonalizing large QRPA matrices
- Requires only moderate modifications of the existing ground state solvers
- The only cutoff is the size of the oscillator basis
- Enables large-scale calculations of the response function

$$[E_\mu + E_\nu - \omega]X_{\mu\nu}(\omega) + \delta H^{20}_{\mu\nu}(\omega) = -F^{20}_{\mu\nu}$$

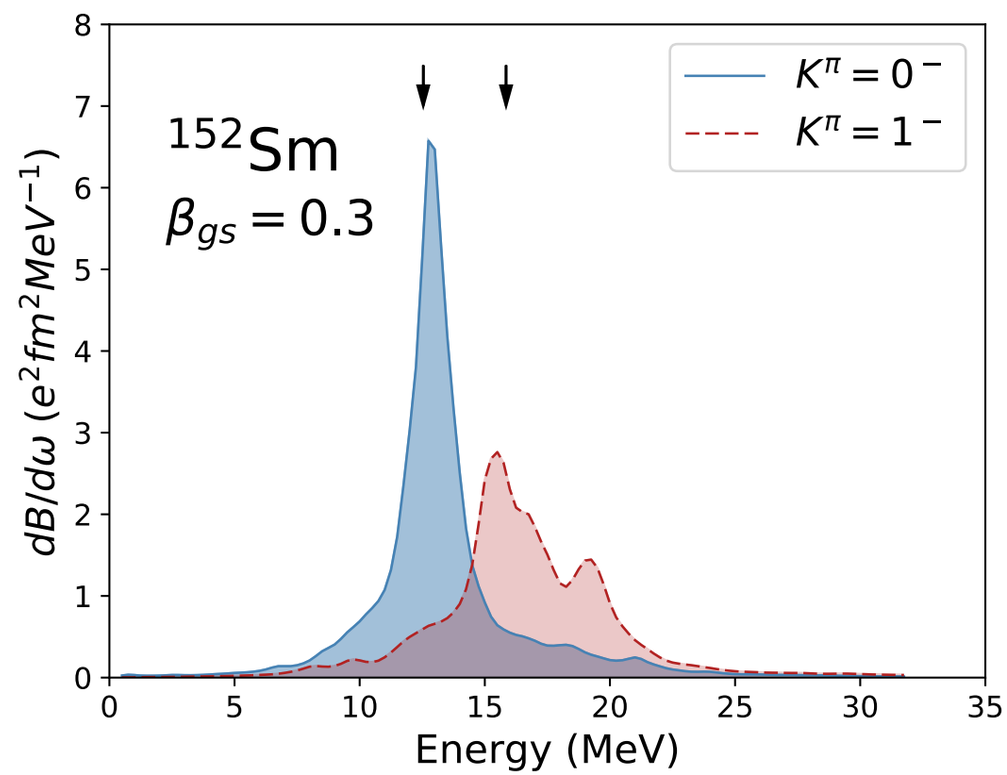
$$[E_\mu + E_\nu + \omega]Y_{\mu\nu}(\omega) + \delta H^{02}_{\mu\nu}(\omega) = -F^{02}_{\mu\nu}$$

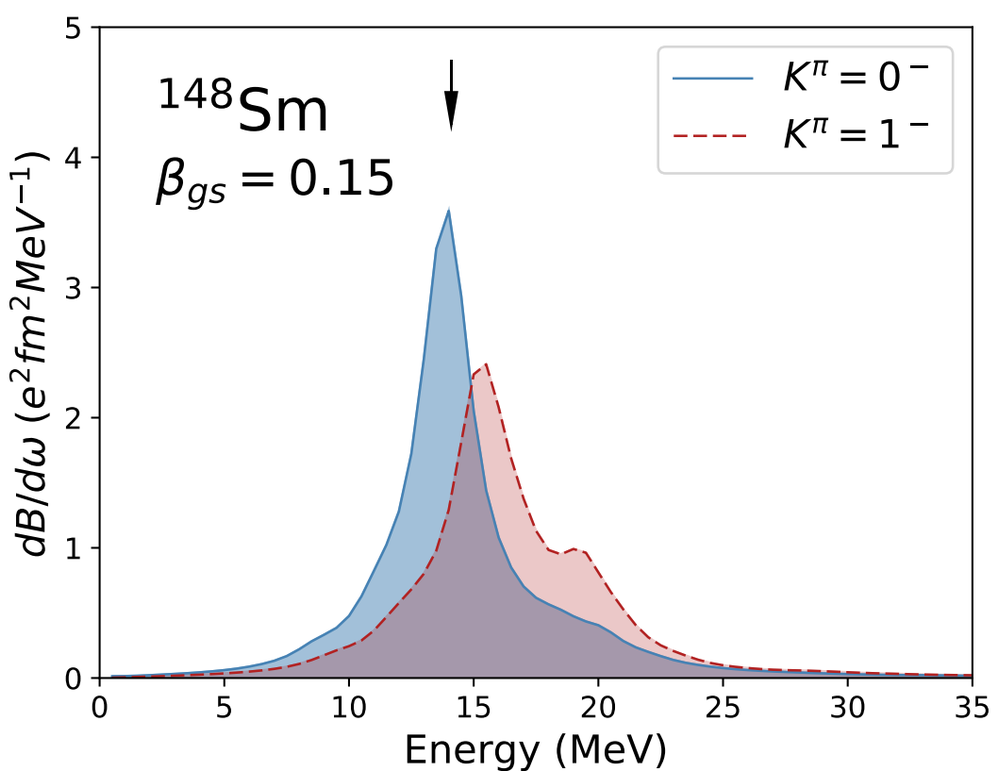
Linear response in deformed nuclei

Preliminary results



- Isovector dipole strength in ^{144}Sm, 148Sm and ^{152}Sm





Some other recent applications...

Work in progress

✔ level of accuracy (rms deviation of experimental masses) of covariant EDFs is still below the state-of-the-art non-relativistic HFB mass models: additional terms should be included in the EDF – e.g. improving the effective mass

J. Phys. G. 42, 034008 (2015)

✔ quantification of theoretical uncertainties within the EDF framework

Phys. Rev. C 95, 054304 (2017)
Phys. Rev. C 94, 024333 (2016)

✔ is it possible to systematically reduce the number of parameters defining the EDF? ➔manifold boundary approximation method

Phys. Rev. C 99, 014618 (2019)
Phys. Rev. C 96, 024319 (2017)
Phys. Rev. C 93, 044315 (2016)
Phys. Rev. C 89, 064315 (2015)

✔ Description of fission dynamics (fission barriers, paths and lifetimes; induced fission dynamics)

Summary

✔ NEDFs provide an economic, global and accurate microscopic approach to nuclear structure that can be extended from relatively light systems to superheavy nuclei, and from the valley of β-stability to the particle drip-lines.

✔ NEDF-based structure models that take into account collective correlations → microscopic description of low-energy observables: excitation spectra, transition rates, changes in masses, isotope and isomer shifts, related to shell evolution with nuclear deformation, angular momentum, and number of nucleons.

✔ NEDF-based models are applicable to large-scale calculations

Collaborators

✔ ***UniZg***: Dario Vretenar, Nils, Paar, Kosuke Nomura, Tomohiro Oishi, Antonio Bjelcic, Luka Gulin, Giacomo Accorto

✔ ***PKU, CAS, Southwest University***: Jie Meng, Shan-Gui Zhou, Zhipan Li, Jie Zhao

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For more information please visit:
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https://strukturnifondovi.hr/

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