ESNT, October 2017
Saclay, France

Coexistence of nuclear shapes: mean-field and beyond

Tamara Nikšić
University of Zagreb

Supported by: Croatian Science Foundation

Hrzz
Hrvatska zaklada za znanost

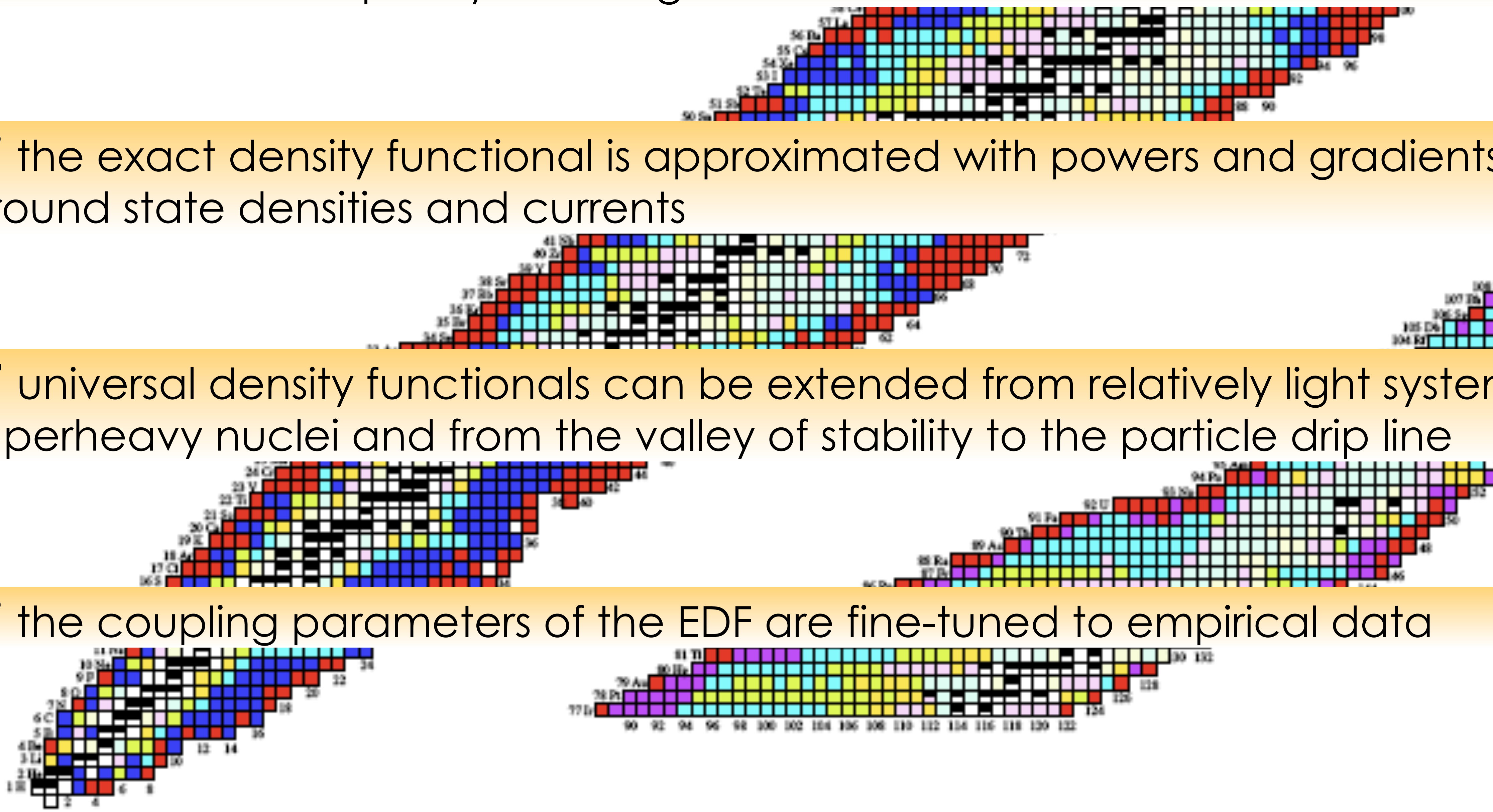
Theoretical framework: energy density functionals

✔ 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



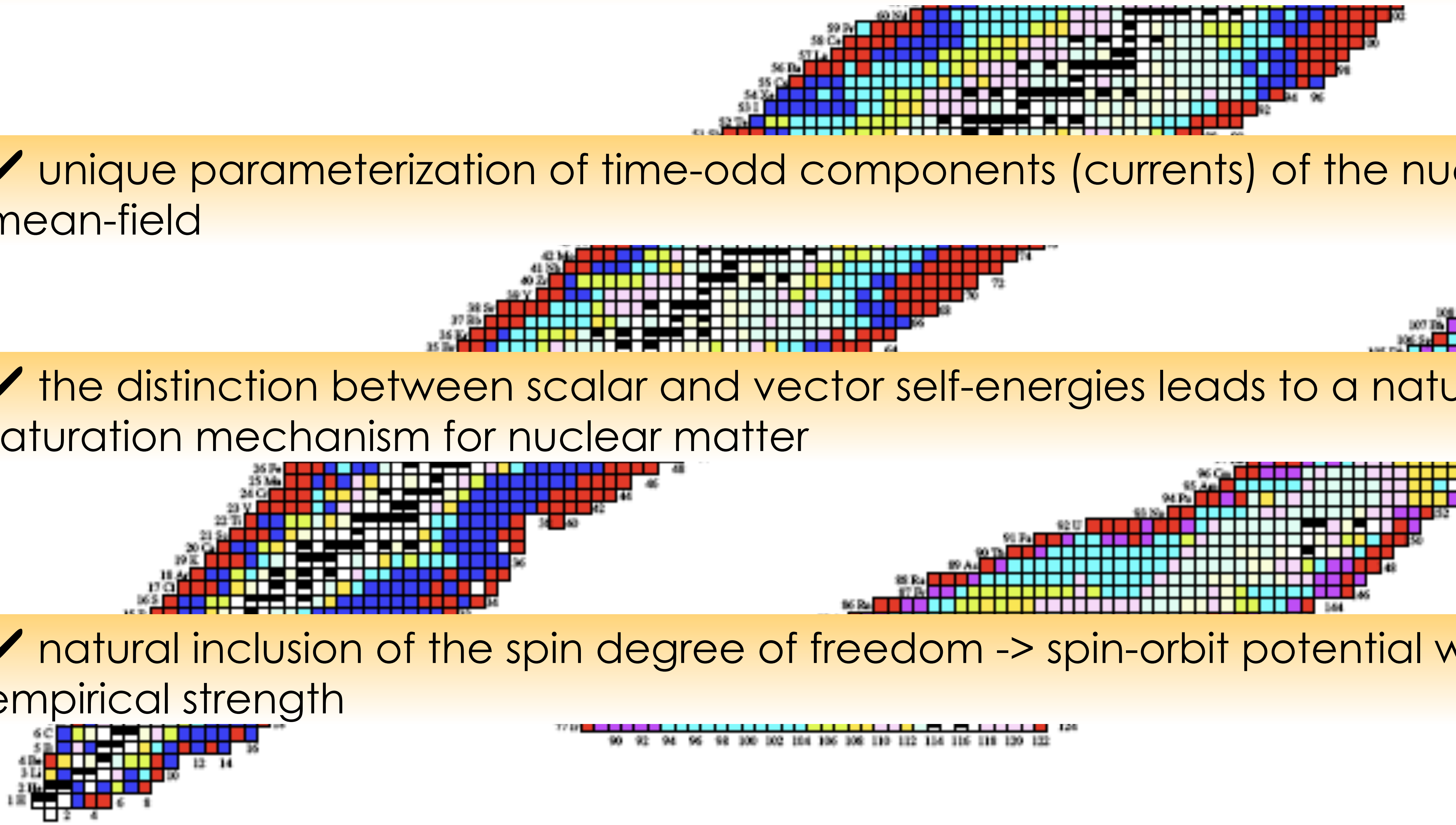
Covariant nuclear energy density functionals

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

✔ unique parameterization of time-odd components (currents) of the nuclear mean-field

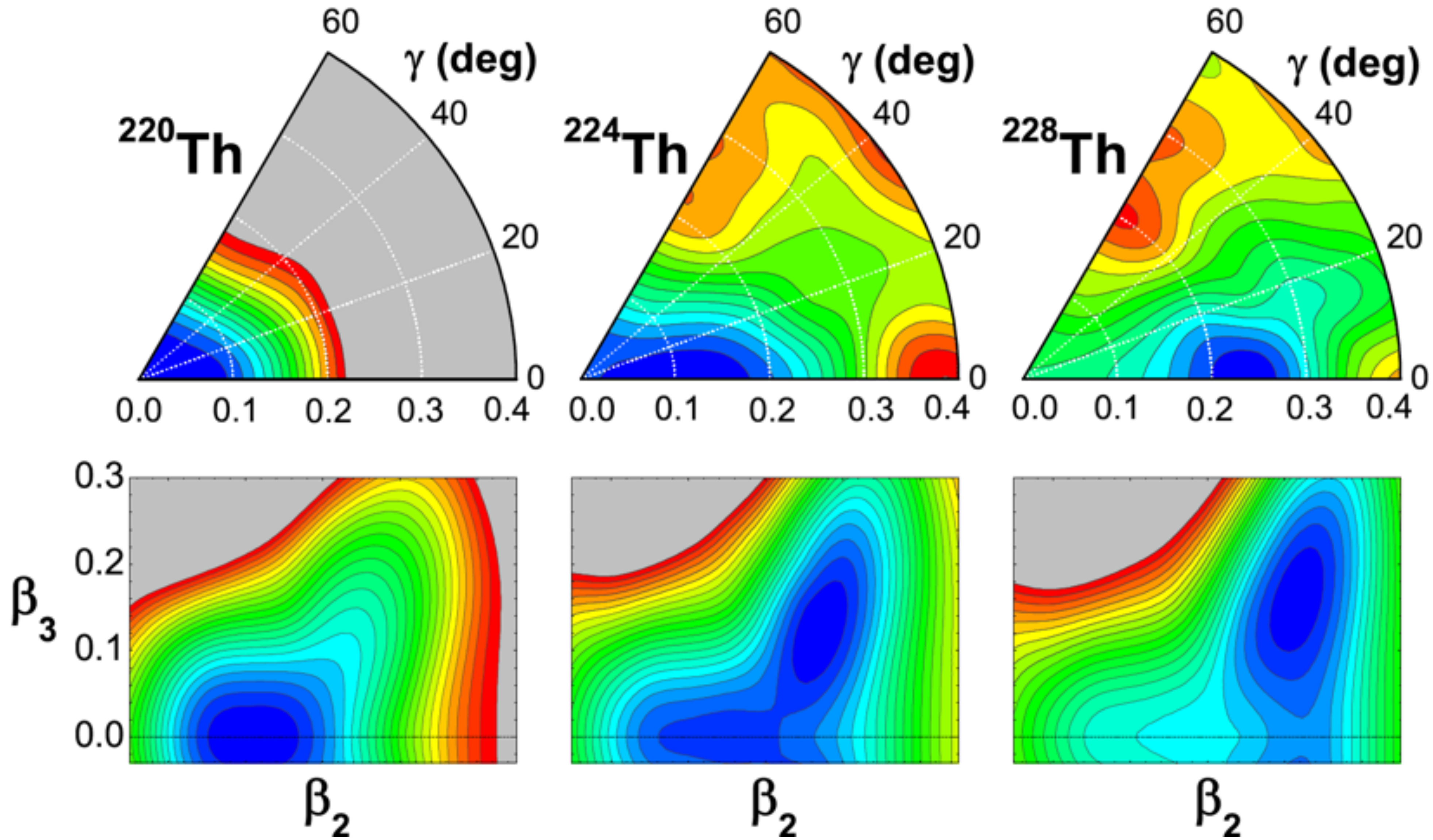
✔ the distinction between scalar and vector self-energies leads to a natural saturation mechanism for nuclear matter

✔ natural inclusion of the spin degree of freedom -> spin-orbit potential with empirical strength



Basic implementation: self-consistent mean-field method

- produces energy surfaces as functions of intrinsic deformation parameters

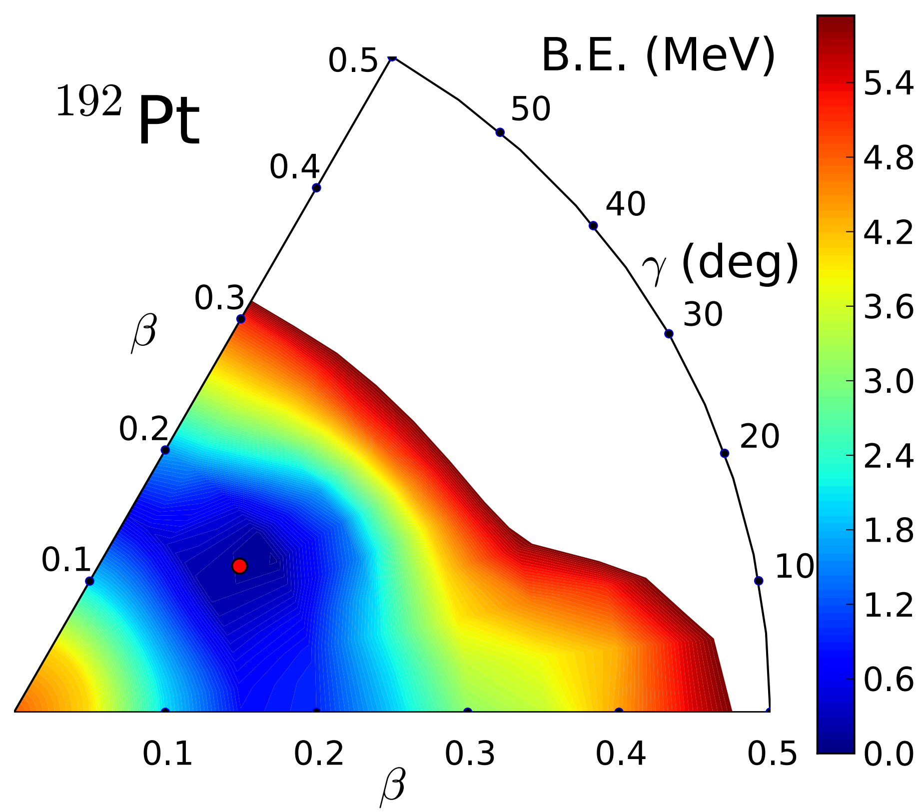


- includes static correlations: deformations and pairing
- does not include collective correlations originating from symmetry restoration and quantum fluctuations around mean-field minima

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



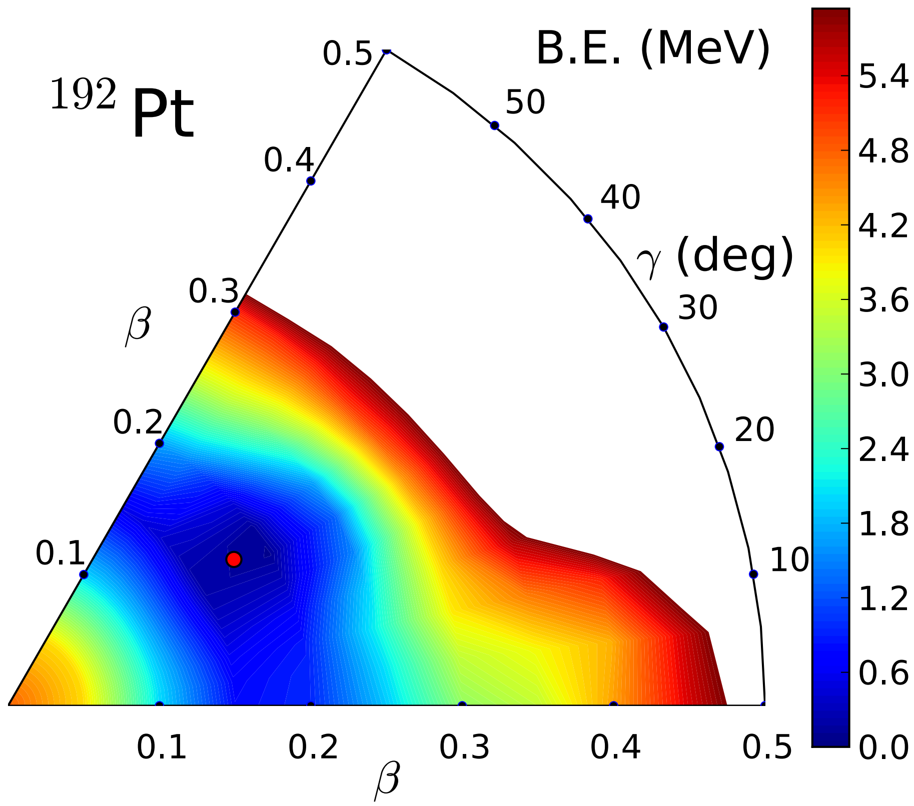
$$H_{\rm coll} = \mathcal{T}_{\rm vib}(\beta,\gamma) + \mathcal{T}_{\rm rot}(\beta,\gamma,\Omega) + \mathcal{V}_{\rm coll}(\beta,\gamma)$$

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

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

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.

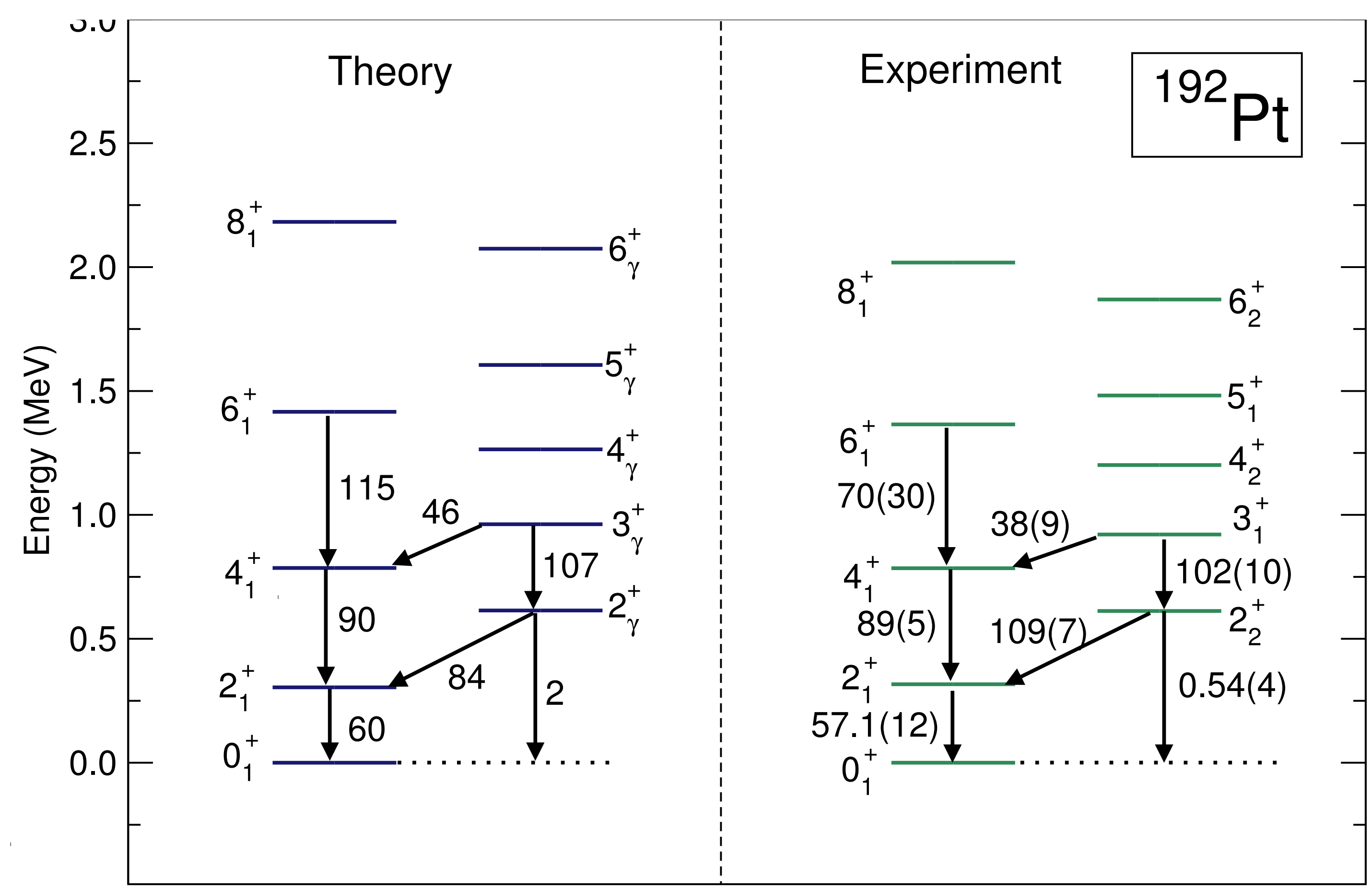
… collective eigenfunction: $\Psi_\alpha^{IM}(\beta,\gamma,\Omega) = \sum_{K\in\Delta I}\psi_{\alpha K}^{I}(\beta,\gamma)\Phi_{MK}^{I}(\Omega)$



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

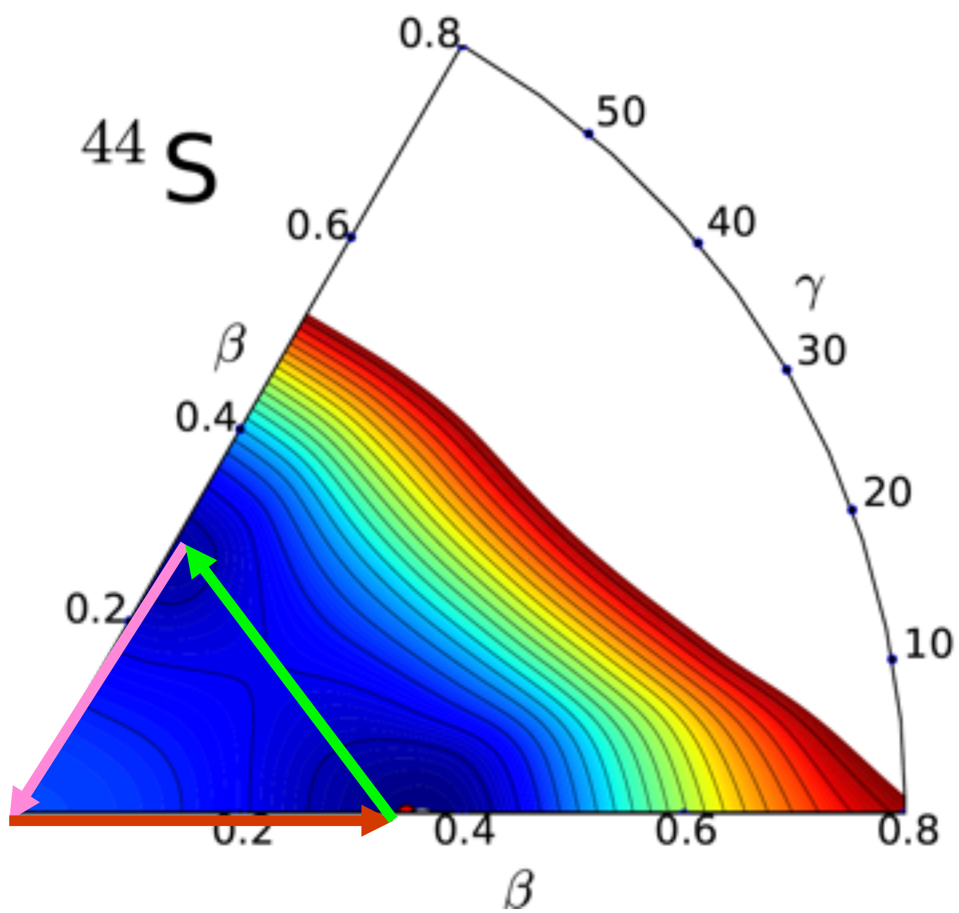
✔ the ***full model space*** of occupied states can be used; no distinction between core and valence nucleons, ***no need for effective charges!***

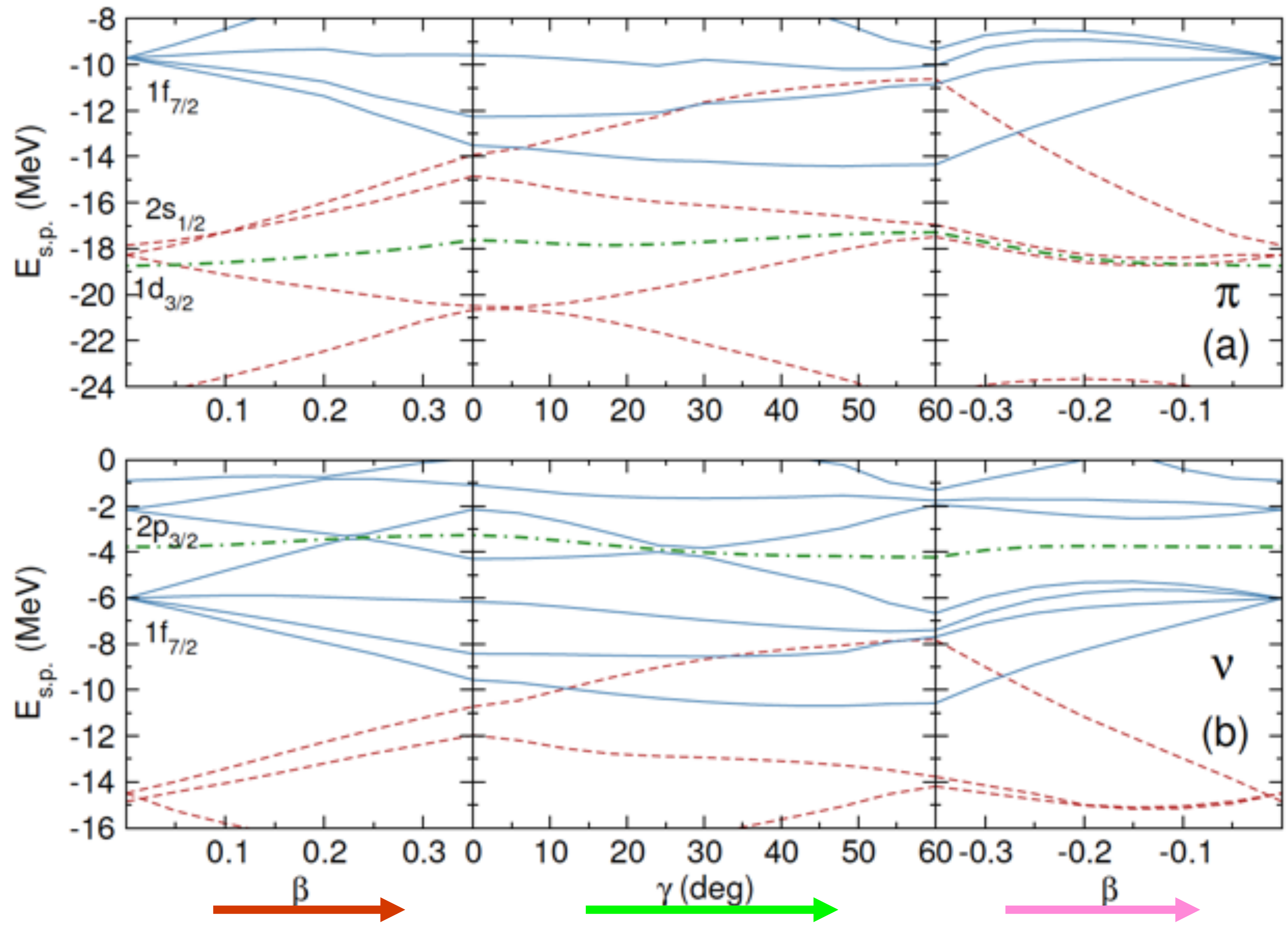
Prog. Part. Nucl. Phys. 66, 519 (2011).



Coexisting shapes in N=28 isotones

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

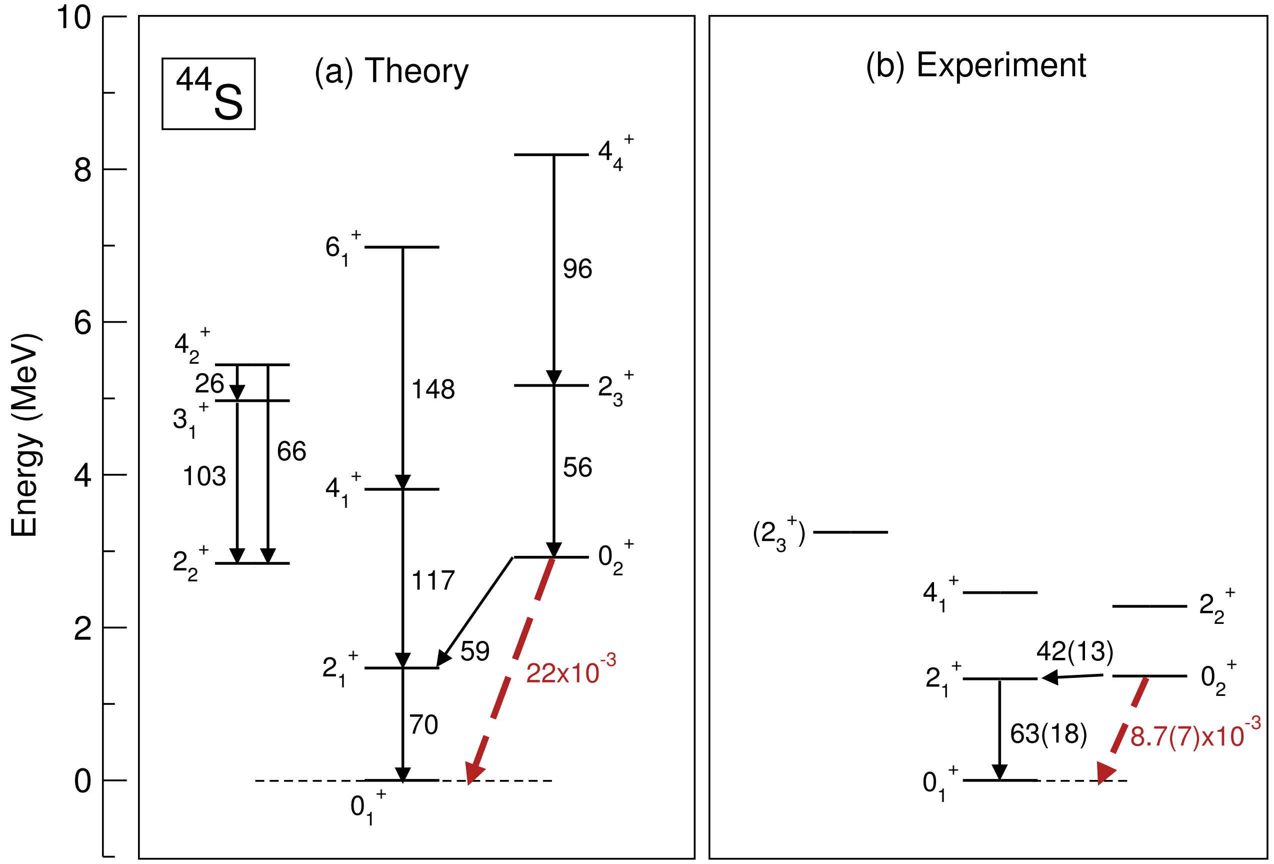


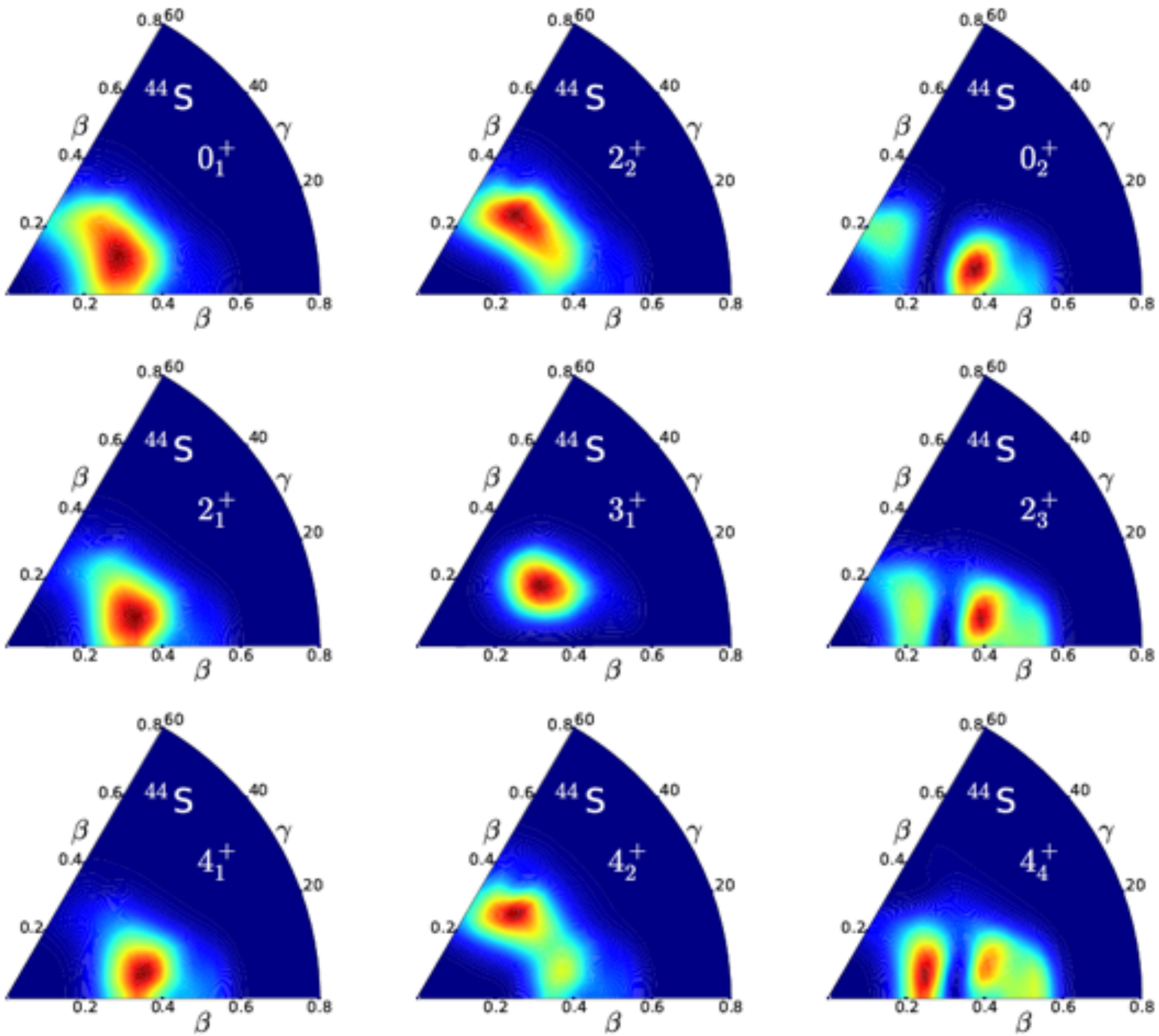


Coexisting shapes in N=28 isotones

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

Probability distributions in the β-γ plane

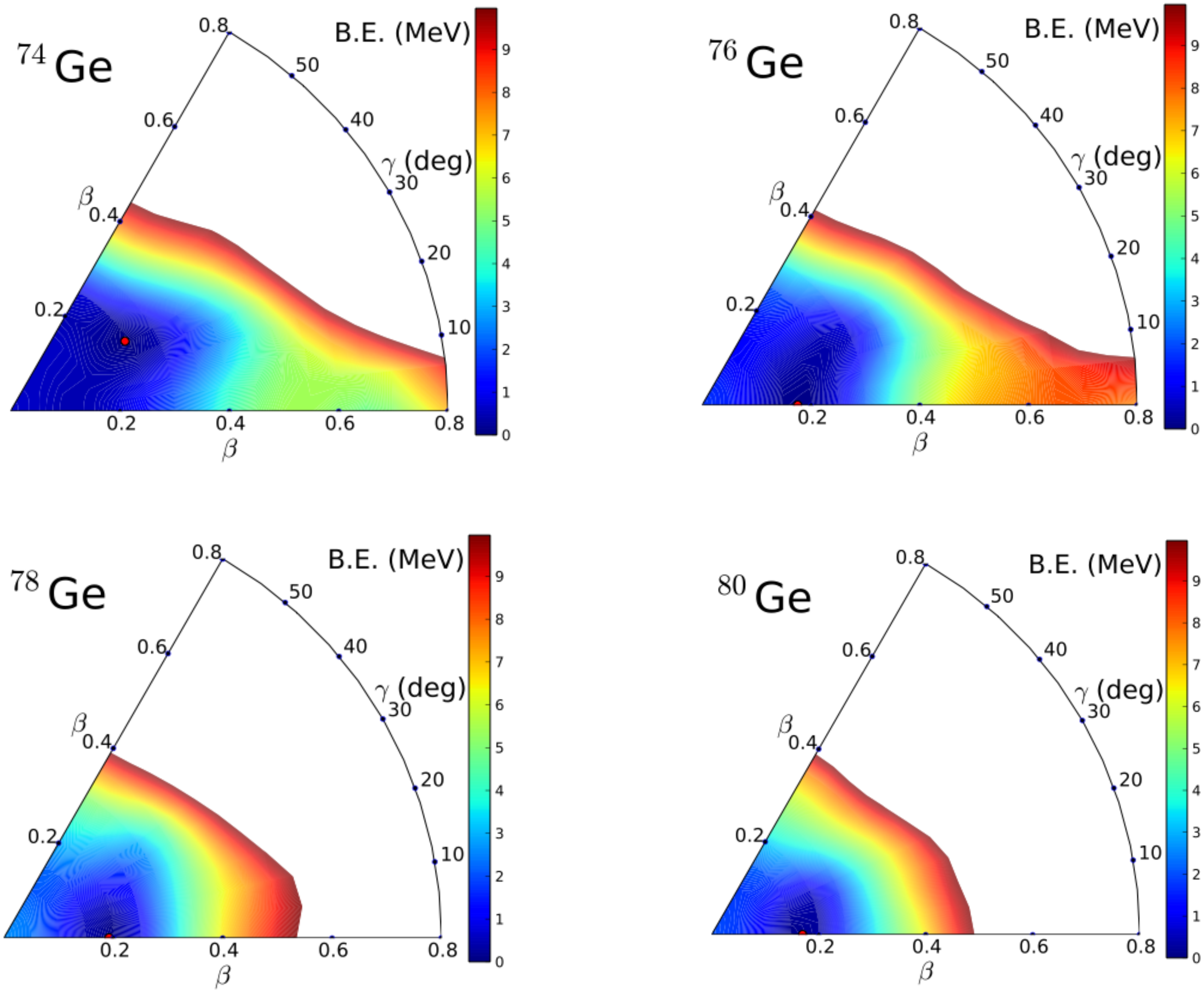


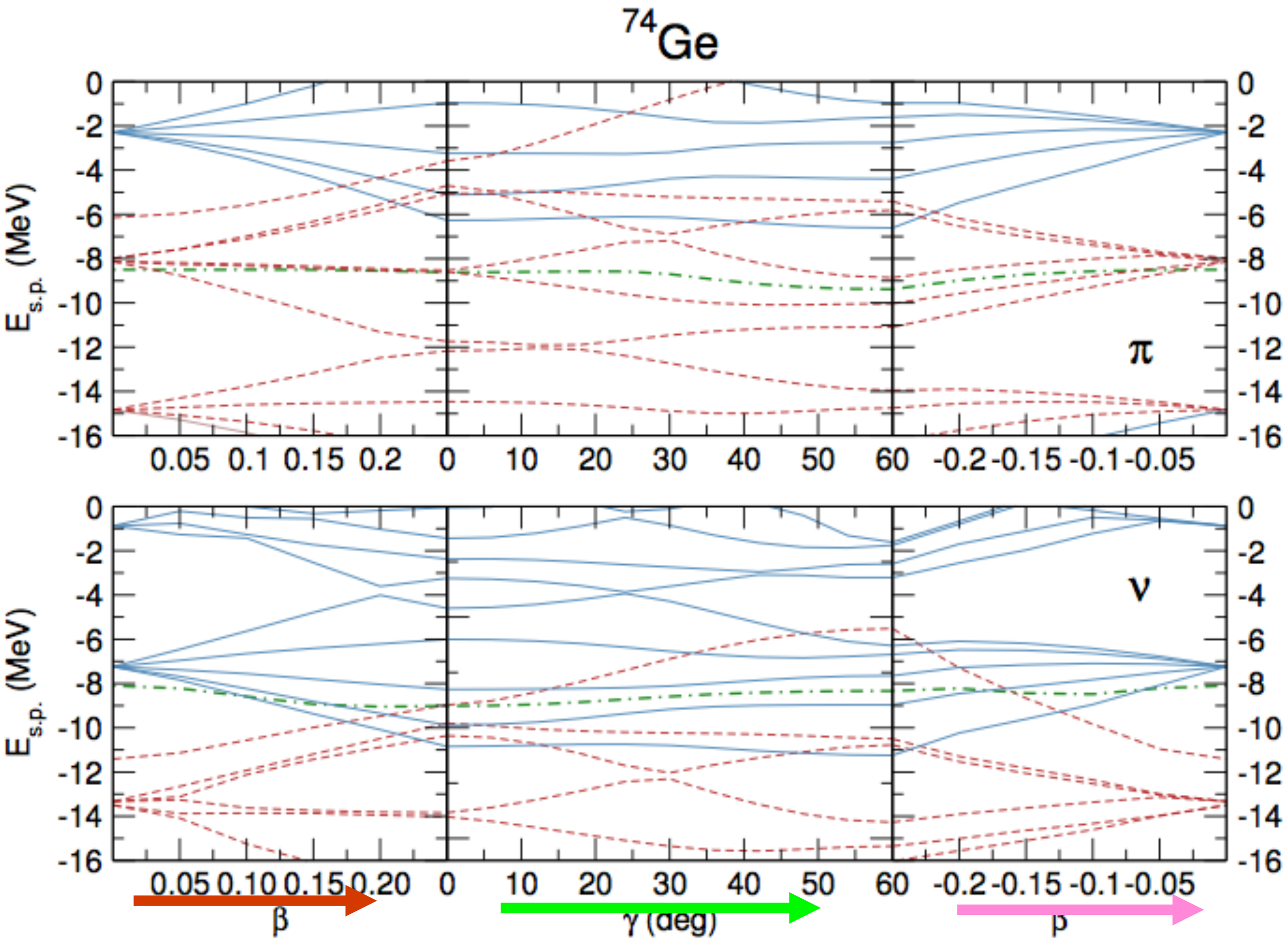


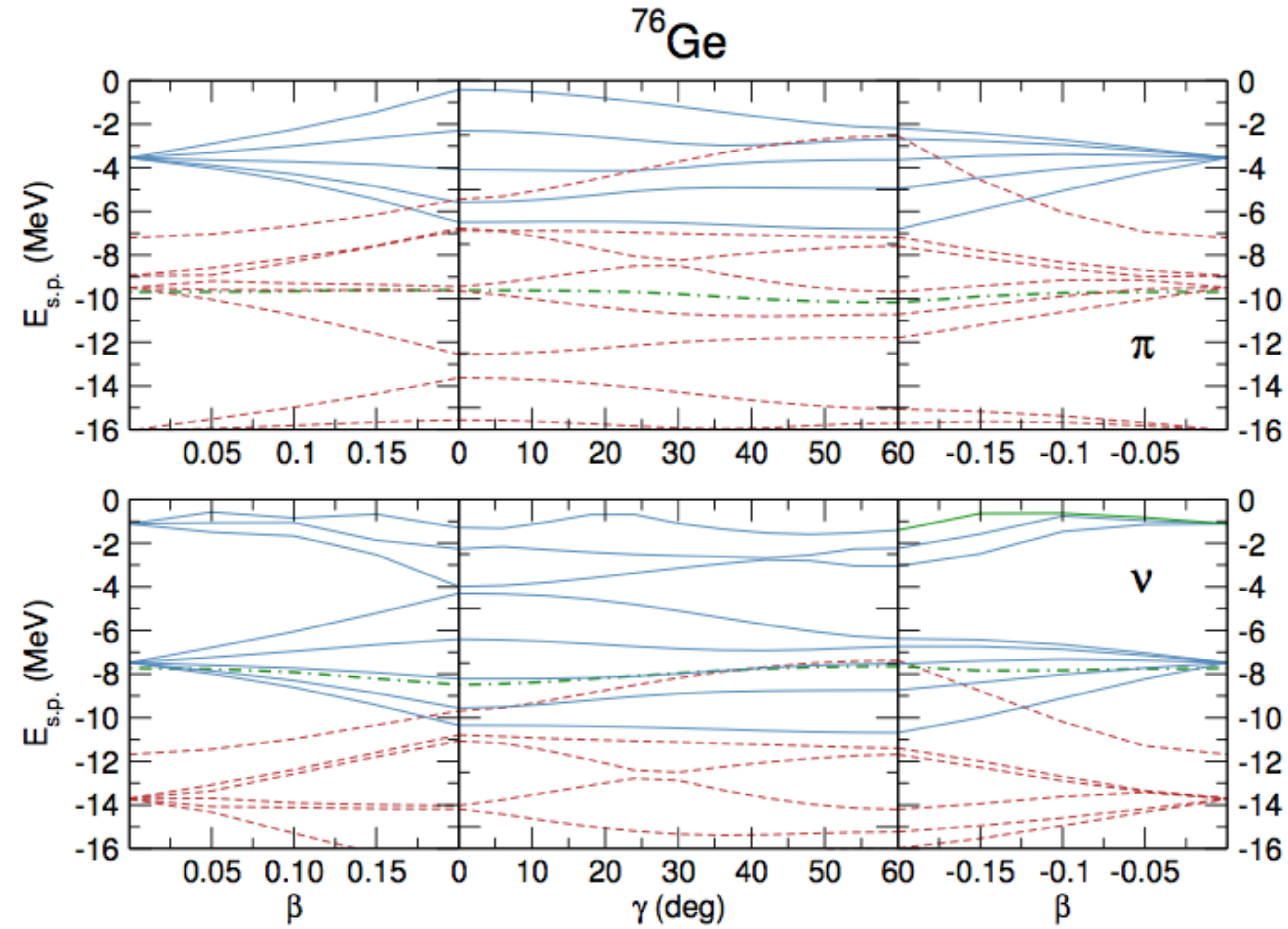
	$K=0$	$K=2$	Q_{spec}
2_1^+	89%	11%	−10.8
2_2^+	21%	79%	8.2
2_3^+	78%	22%	−7.3

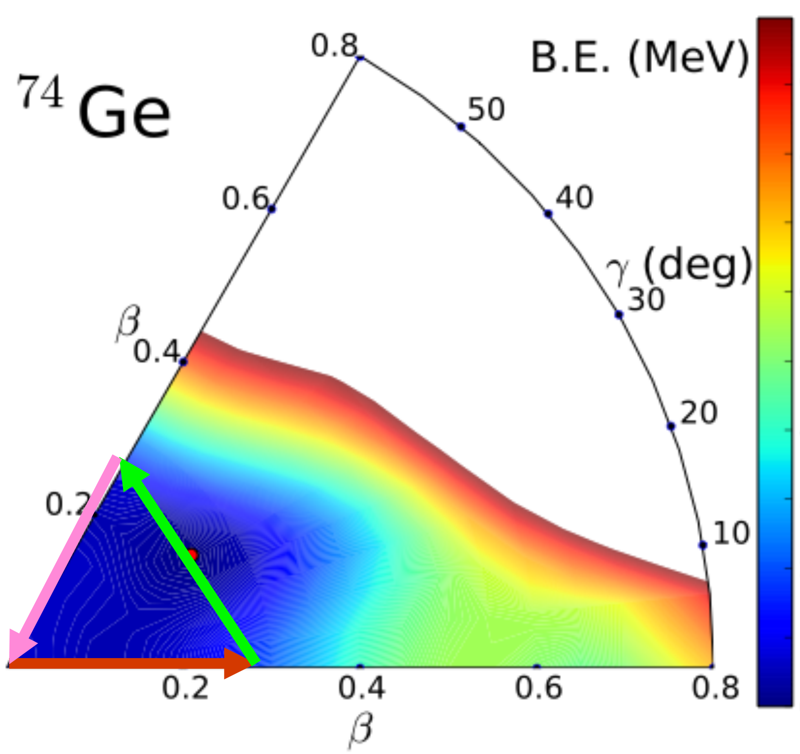
Shape evolution and triaxiality in germanium isotopes

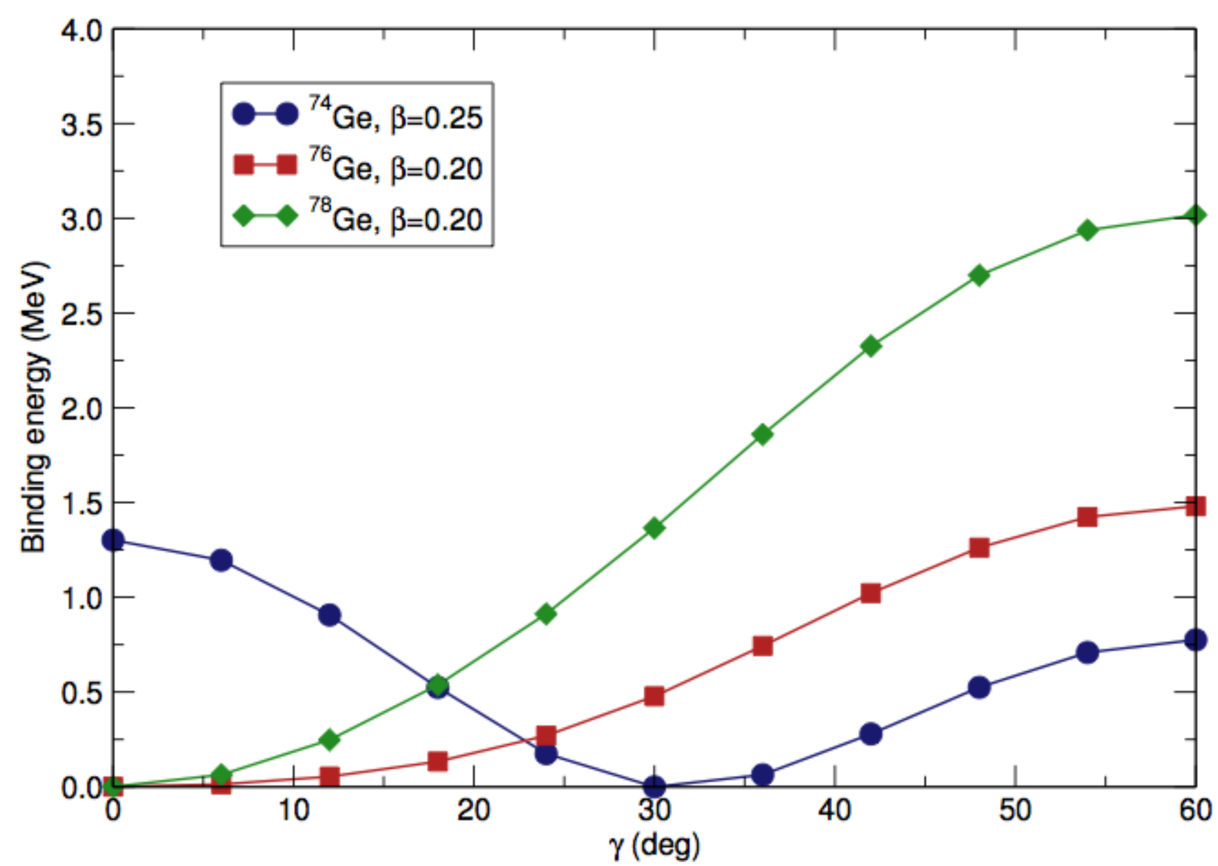
Phys. Rev. C 89, 044325 (2014).





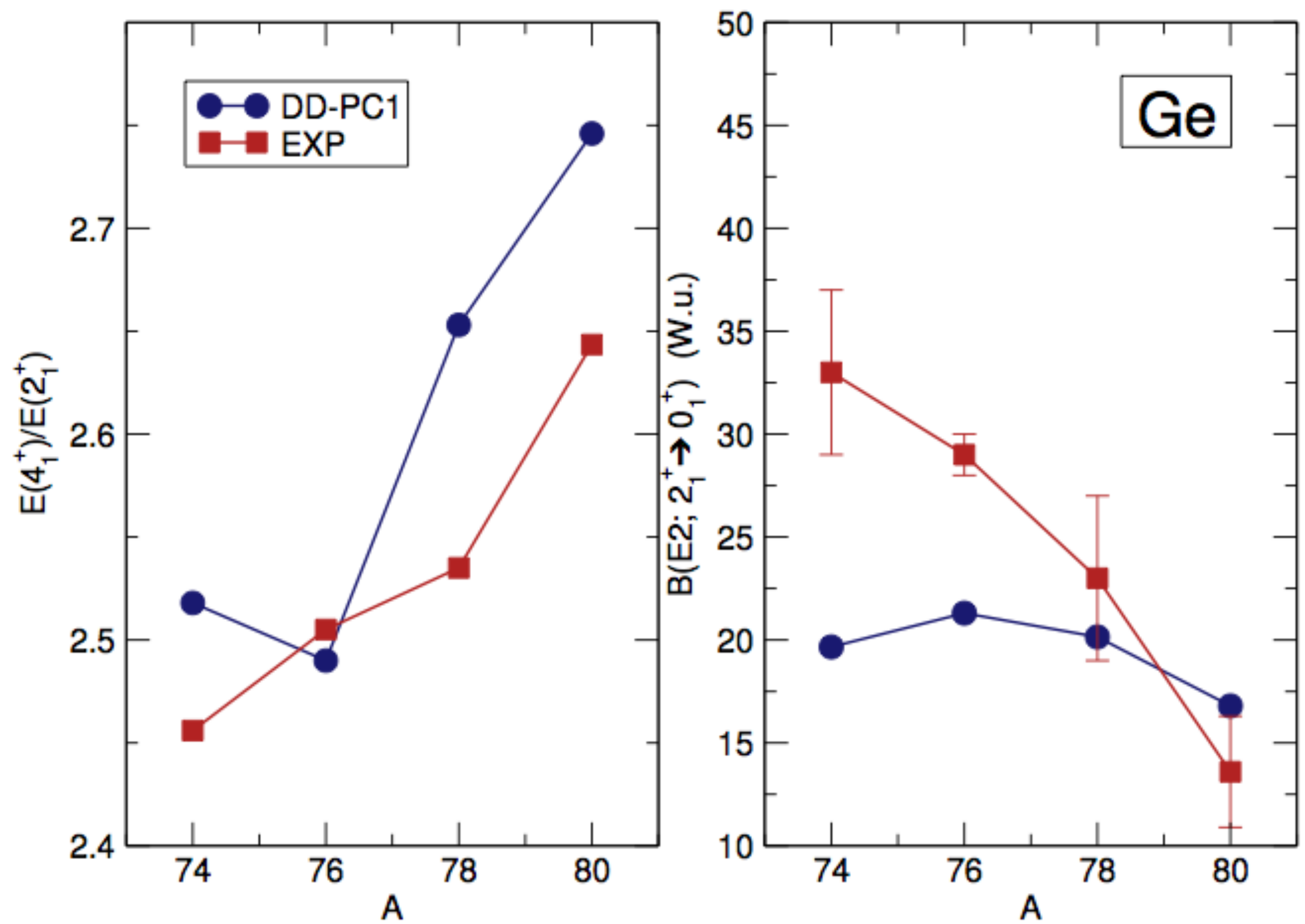


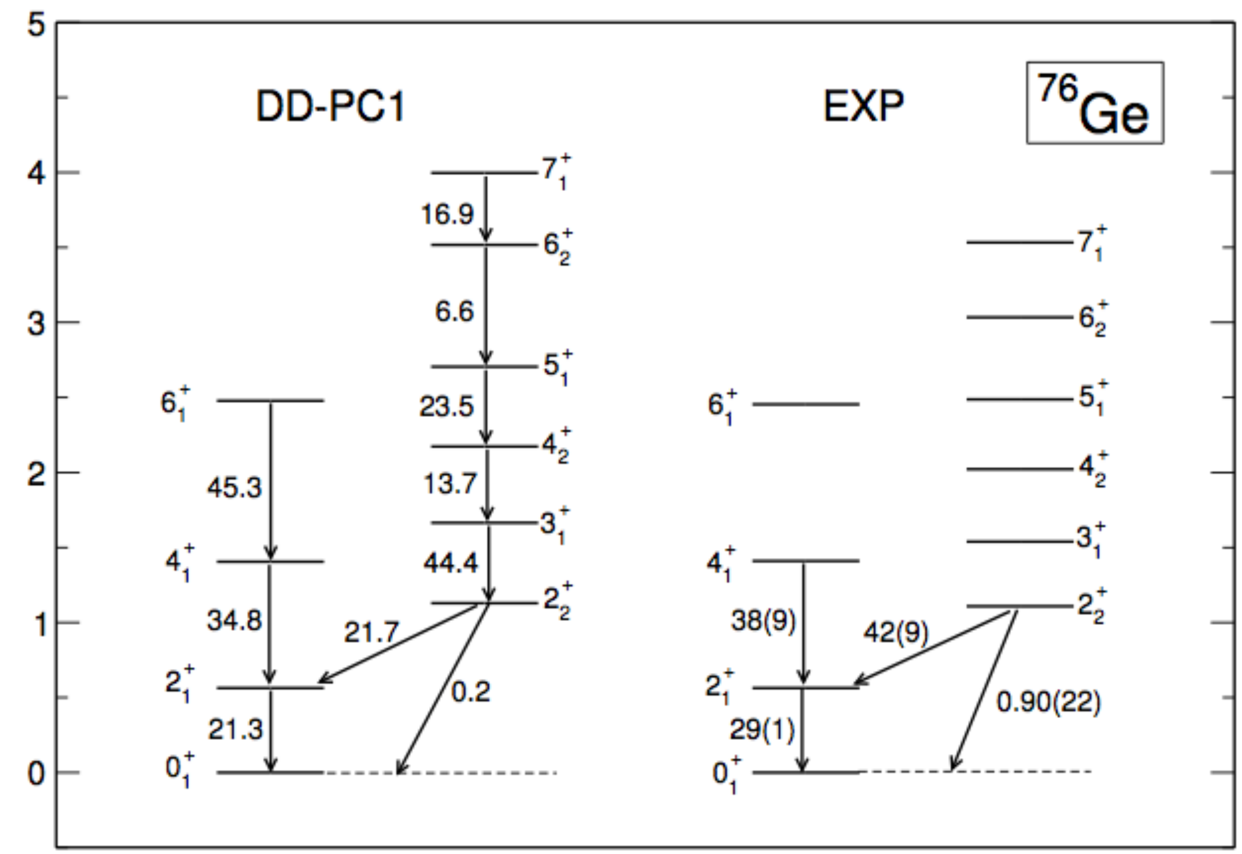




Phys. Rev. C 89, 044325 (2014).

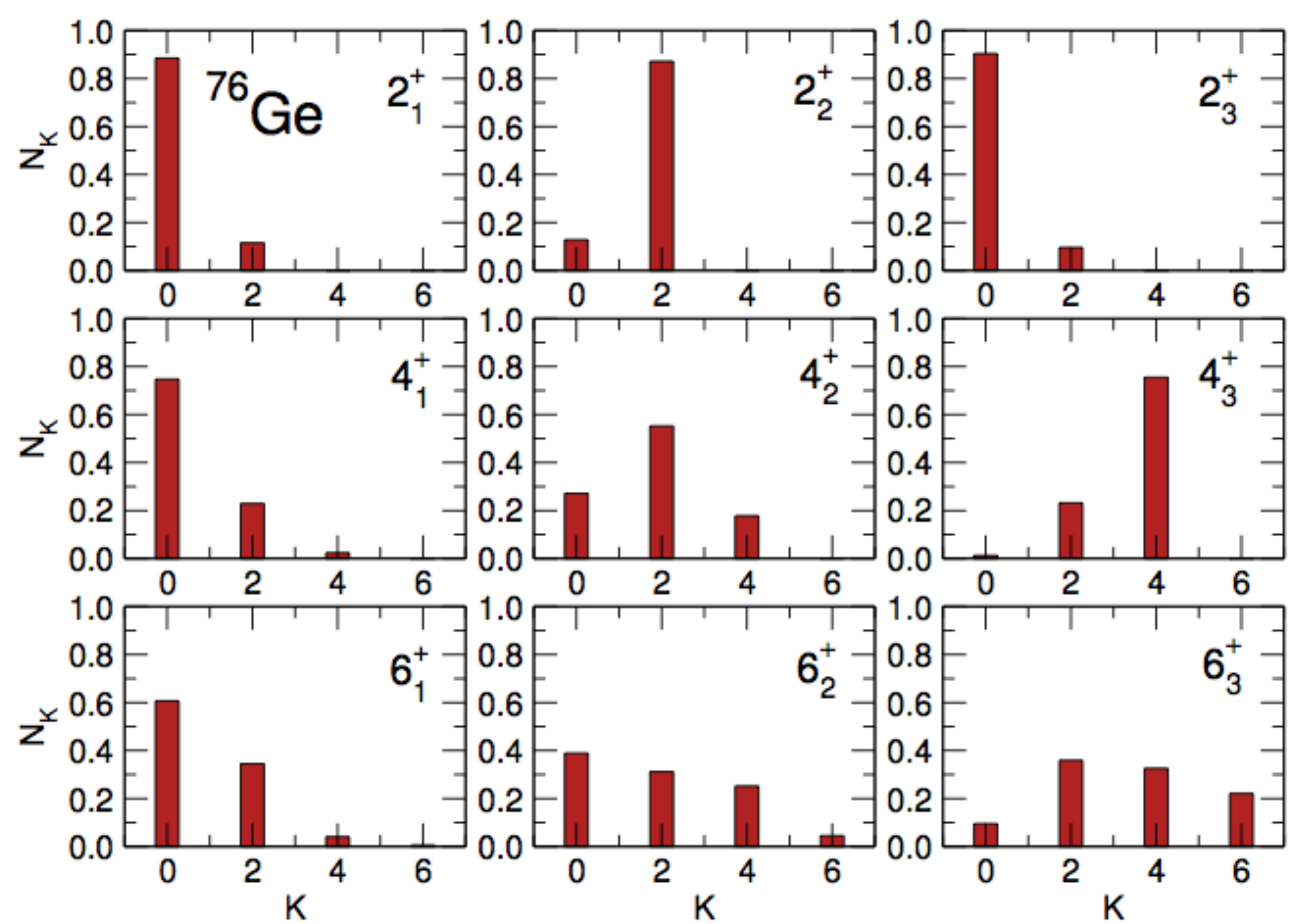
Quadrupole collective Hamiltonian based on the functional DD-PC1





Distribution of *K* components (projection of the angular momentum on the body-fixed symmetry axis) in the collective wave functions of the nucleus ^{76}Ge.

$$N_K = 6\int_0^{\pi/3}\int_0^{\infty} \left|\psi^J_{\alpha K}(\beta,\gamma)\right|^2 \beta^4 |\sin 3\gamma|\, d\beta\, d\gamma.$$



→ more K-mixing for states with higher angular momenta.

Phys. Rev. C 89, 044325 (2014).

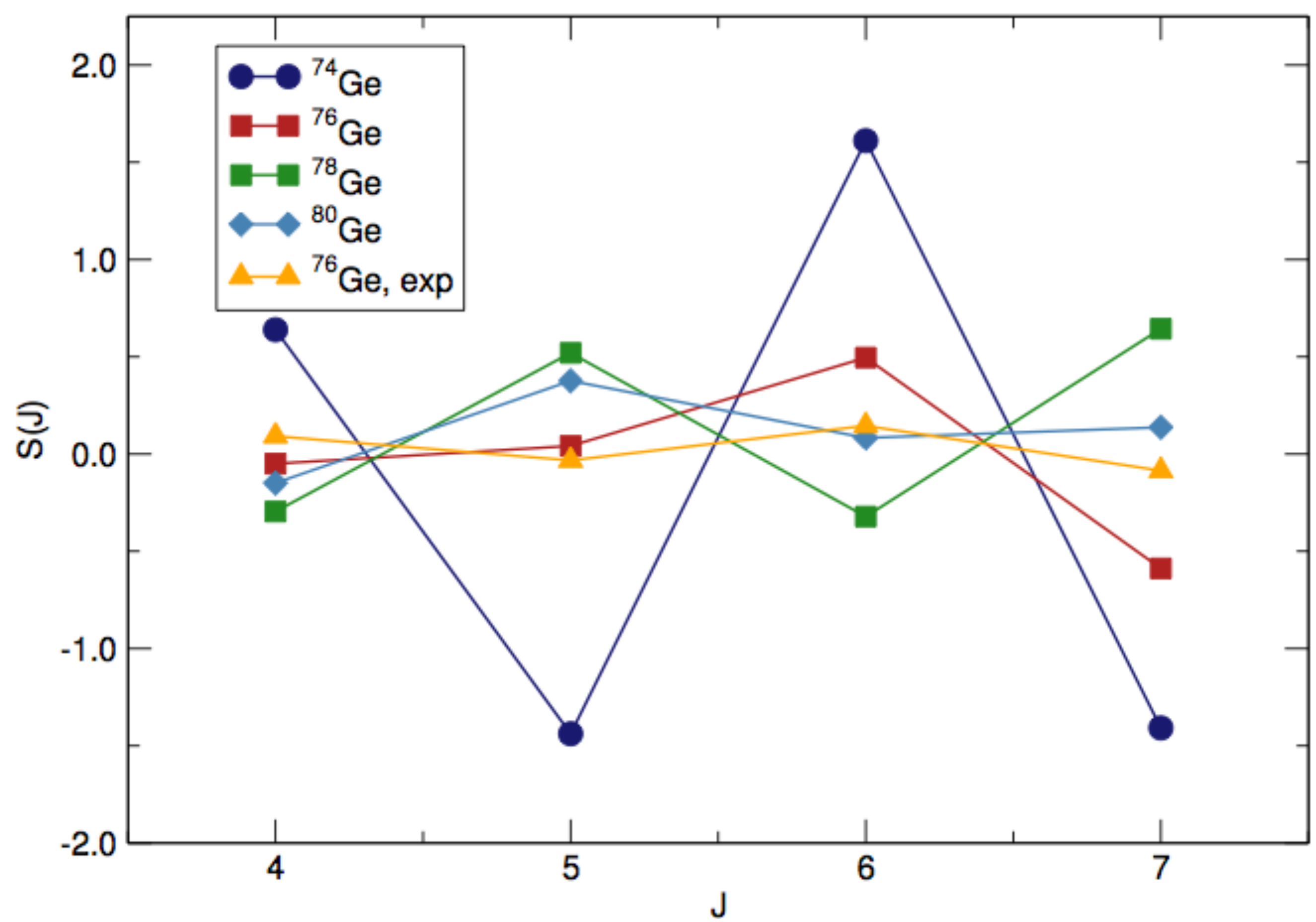
Phys. Rev. C 89, 044325 (2014).

The level of K-mixing is reflected in the staggering in energy between odd- and even-spin states in the γ band:

$$S(J) = \frac{E[J^+_\gamma] - 2E[(J-1)^+_\gamma] + E[(J-2)^+_\gamma]}{E[2^+_1]}$$

Deformed γ-soft potential ⇒ S(J) oscillates between negative values for even-spin states and positive values for odd-spin states.

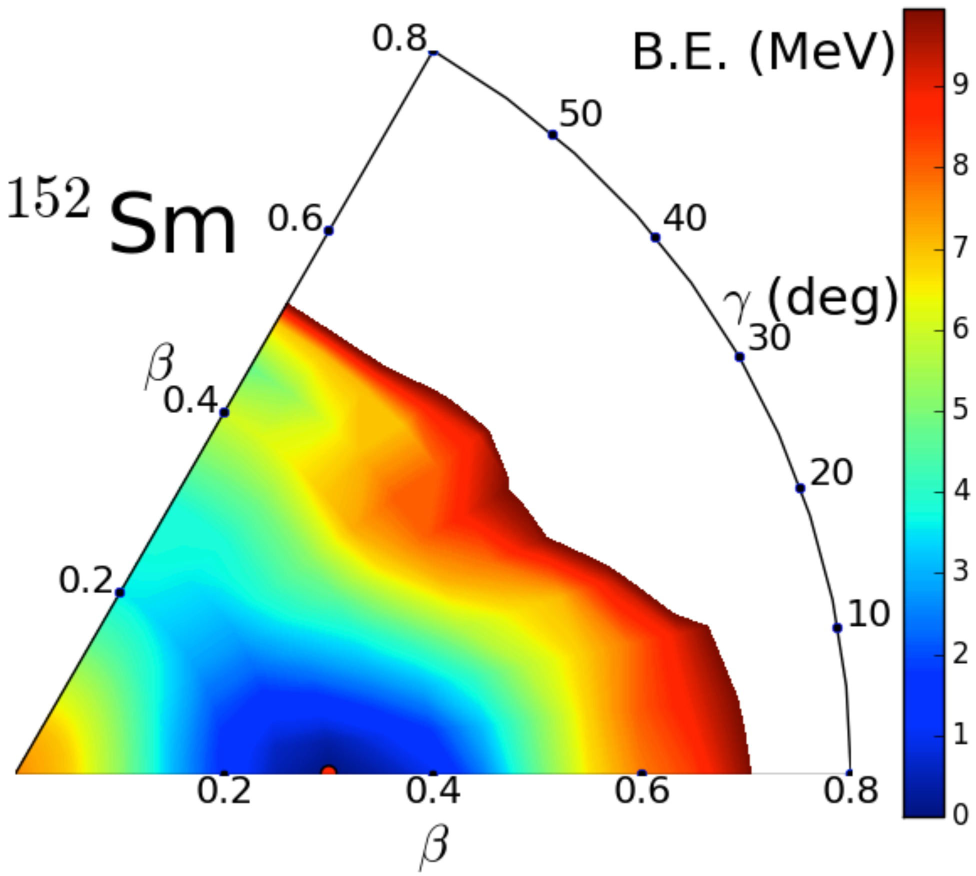
γ-rigid triaxial potential ⇒ S(J) oscillates between positive values for even-spin states and negative values for odd-spin states.

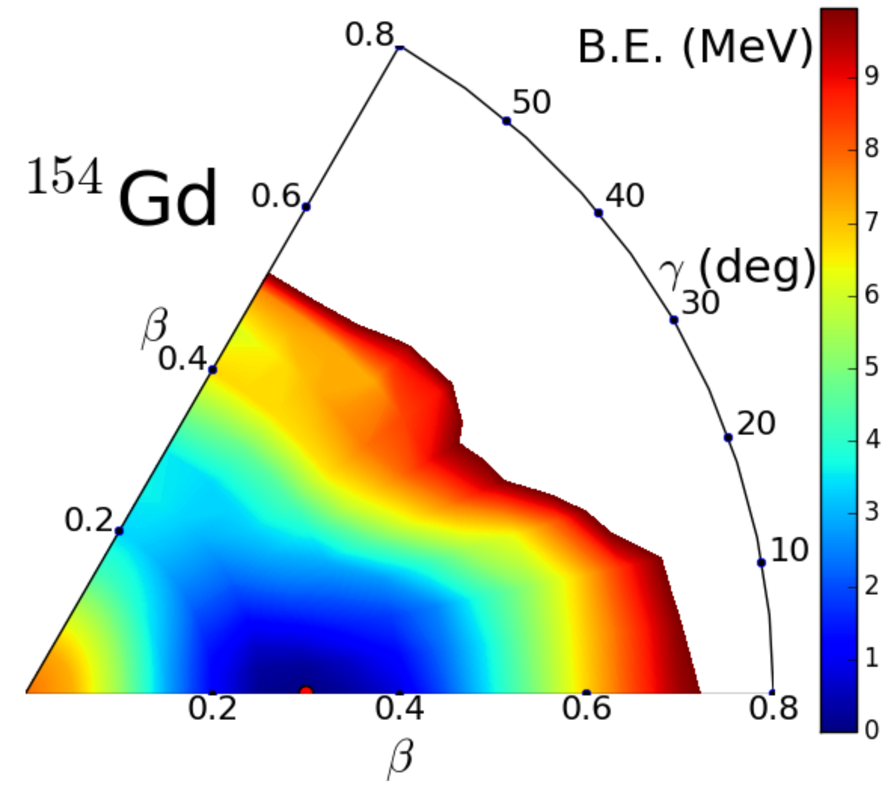


The mean-field potential of ^{76}Ge is γ soft. The inclusion of collective correlations (symmetry restoration and quantum fluctuations) drives the nucleus toward triaxiality, but they are not strong enough to stabilize a $\gamma \approx 30^\circ$ triaxial shape.

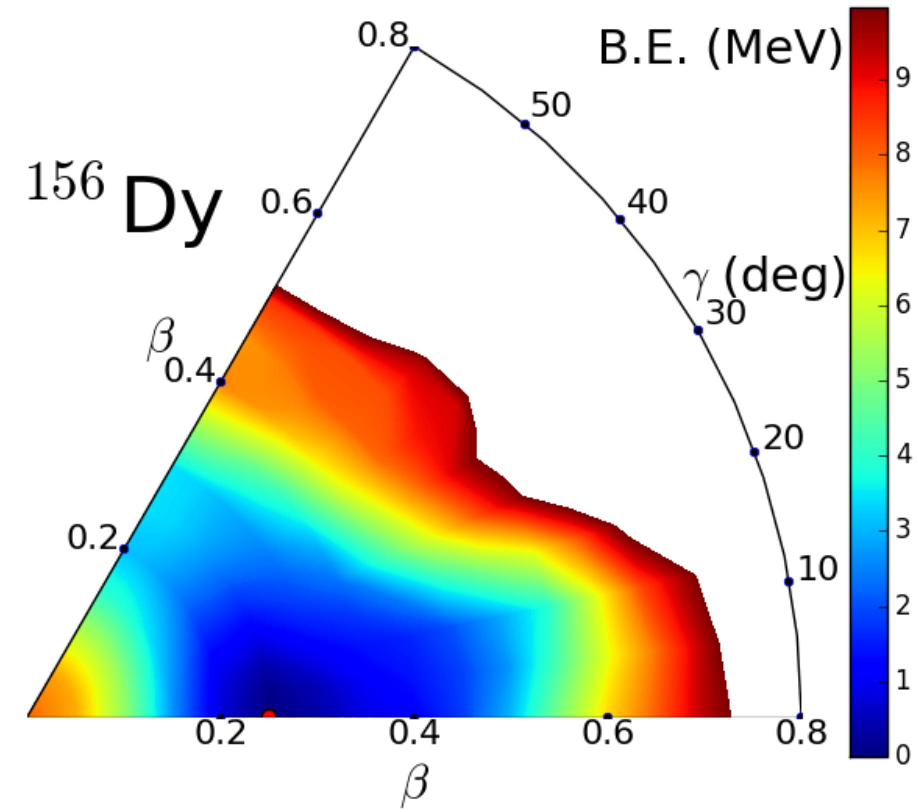
Lowest 0^+ excitations in N=90 rare-earth nuclei

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



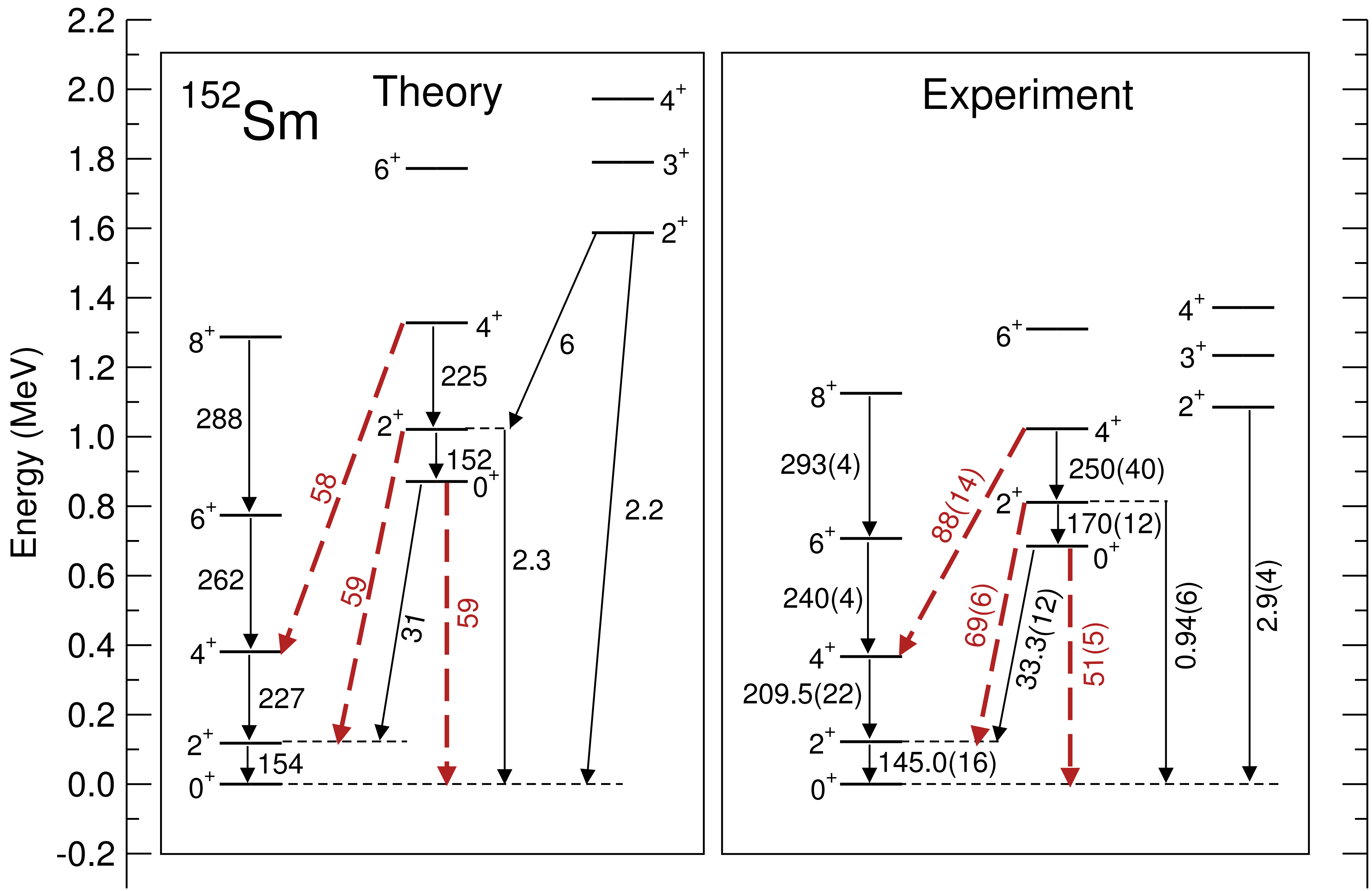


PES (β-γ plane) in N=90 rare-earth nuclei calculated with the DD-PC1 EDF.



Lowest 0^+ excitations in N=90 rare-earth nuclei

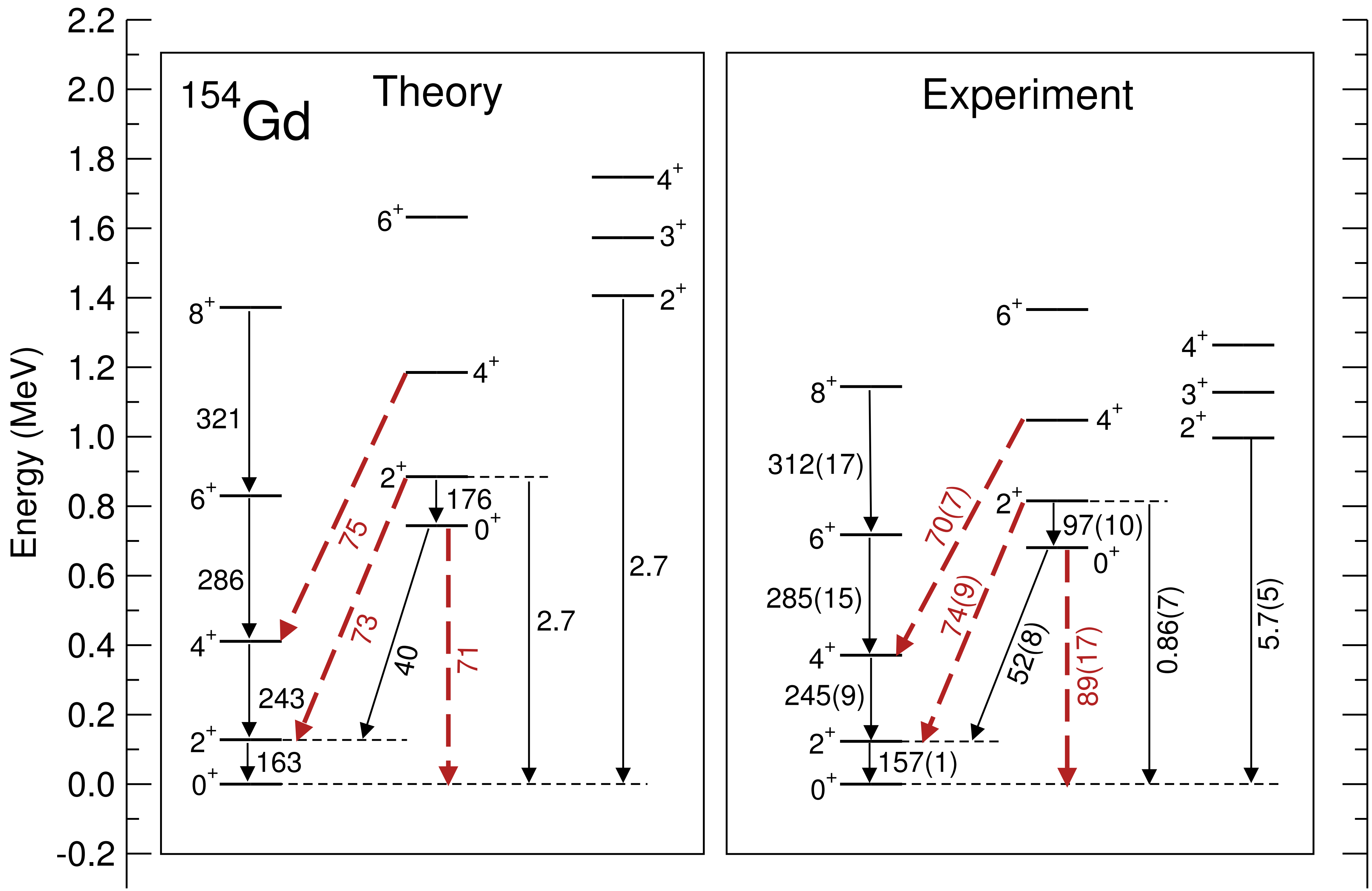
J. Phys. G: Nucl. Part. Phys. 43 (2016) 024005



Solid black lines: B(E2) values in Weisskopf units.
Dashed red lines: E0 transitions with the corresponding $\varrho^2(E0) \times 10^3$ values

Lowest 0^+ excitations in N=90 rare-earth nuclei

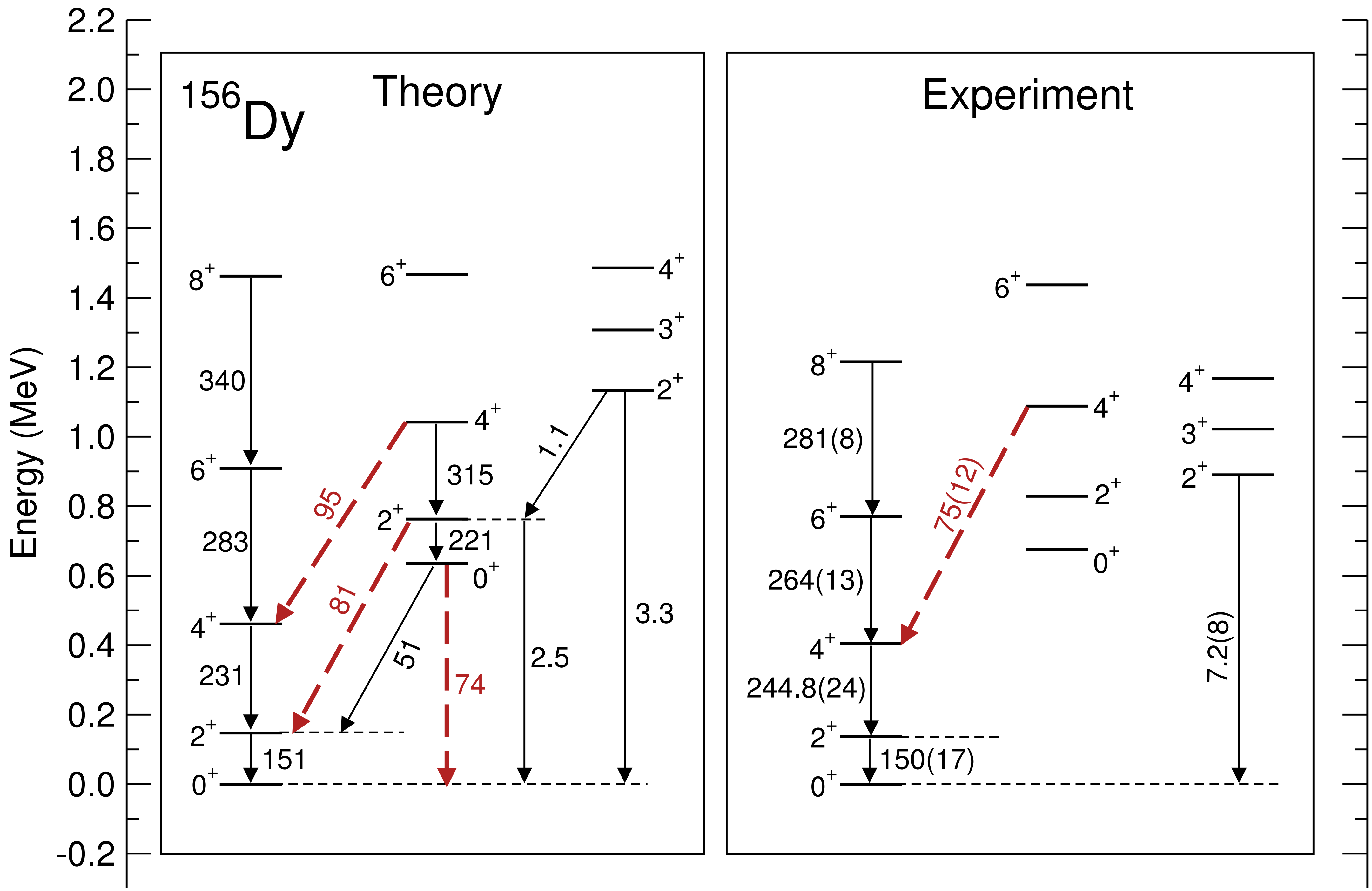
J. Phys. G: Nucl. Part. Phys. 43 (2016) 024005



Solid black lines: B(E2) values in Weisskopf units.
Dashed red lines: E0 transitions with the corresponding $\varrho^2(E0) \times 10^3$ values

Lowest 0^+ excitations in N=90 rare-earth nuclei

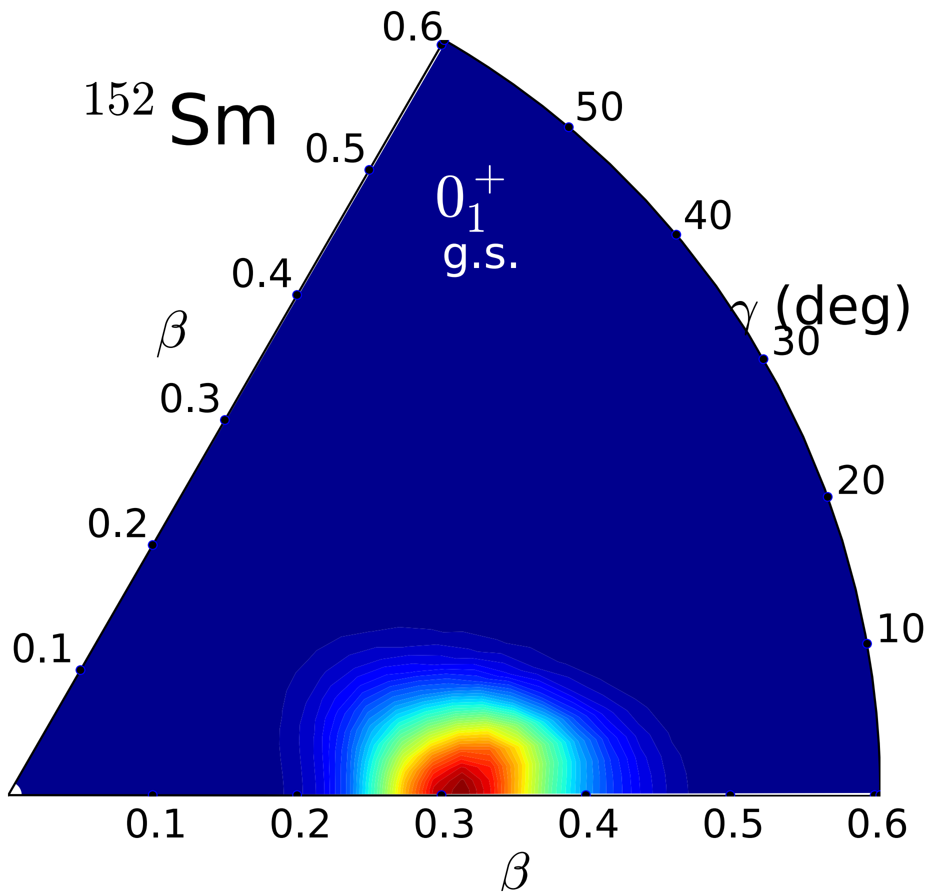
J. Phys. G: Nucl. Part. Phys. 43 (2016) 024005

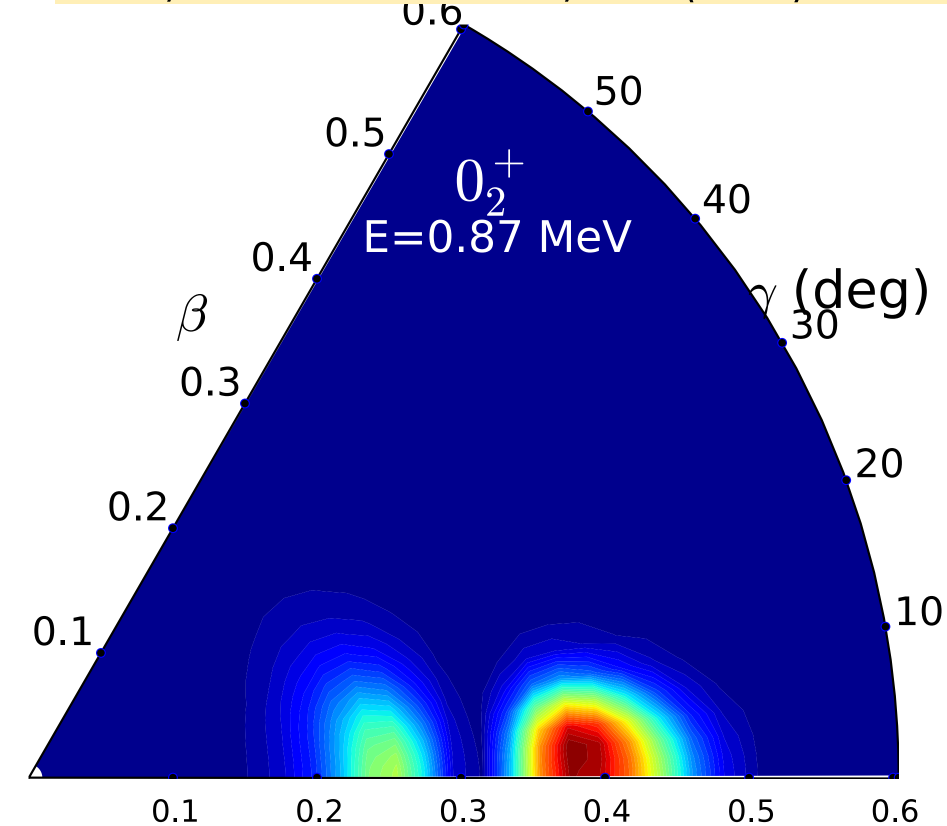


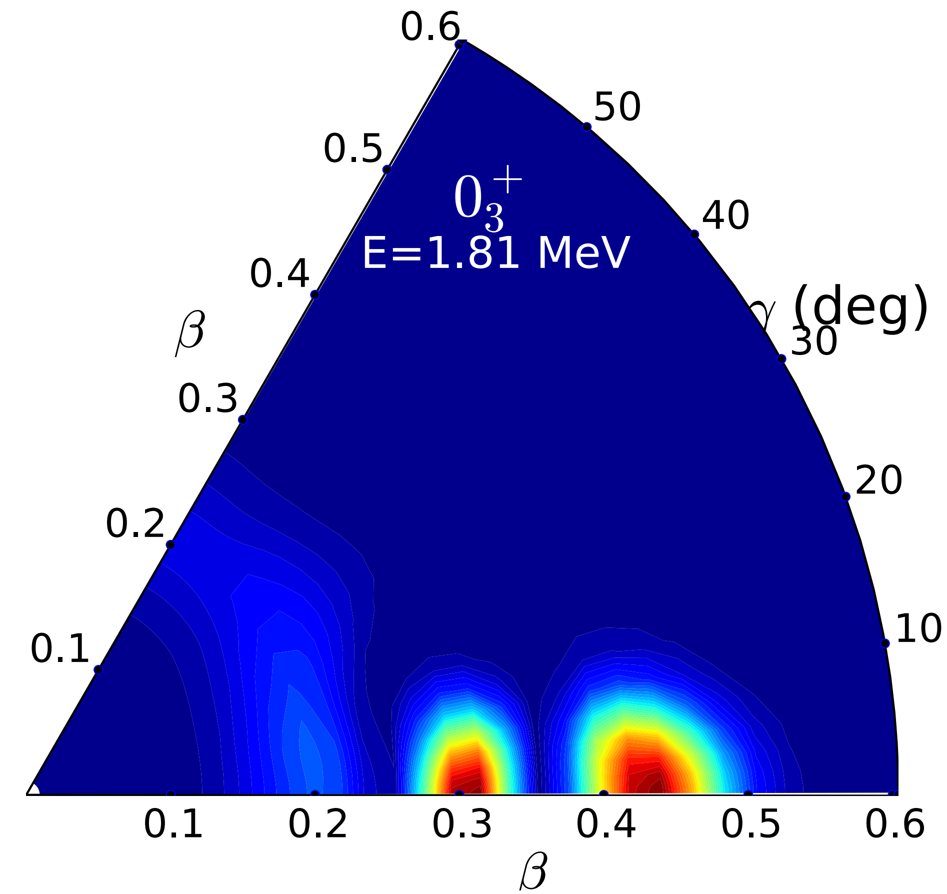
Solid black lines: B(E2) values in Weisskopf units.
Dashed red lines: E0 transitions with the corresponding $\varrho^2(E0) \times 10^3$ values

Lowest 0^+ excitations in N=90 rare-earth nuclei

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





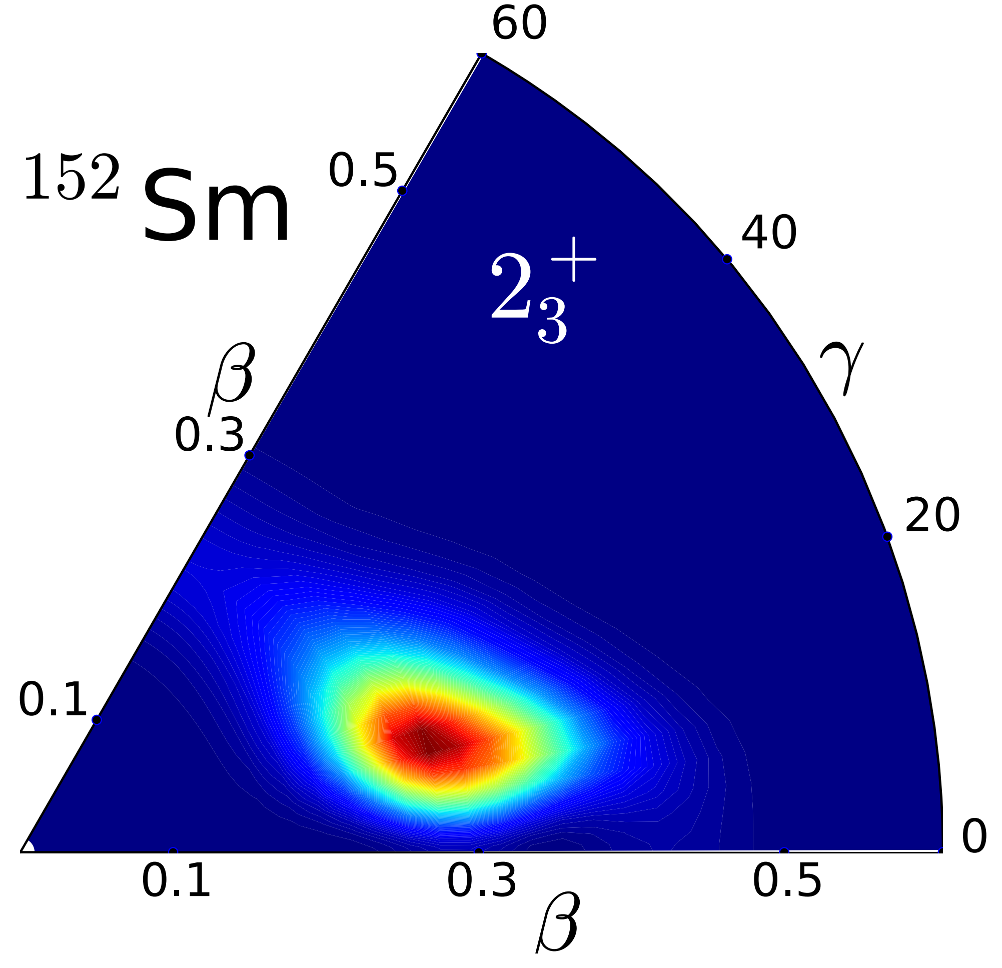


Probability distributions in the β-γ plane for the lowest collective 0^+ states of the ^{152}Sm isotope.

Lowest 0^+ excitations in N=90 rare-earth nuclei

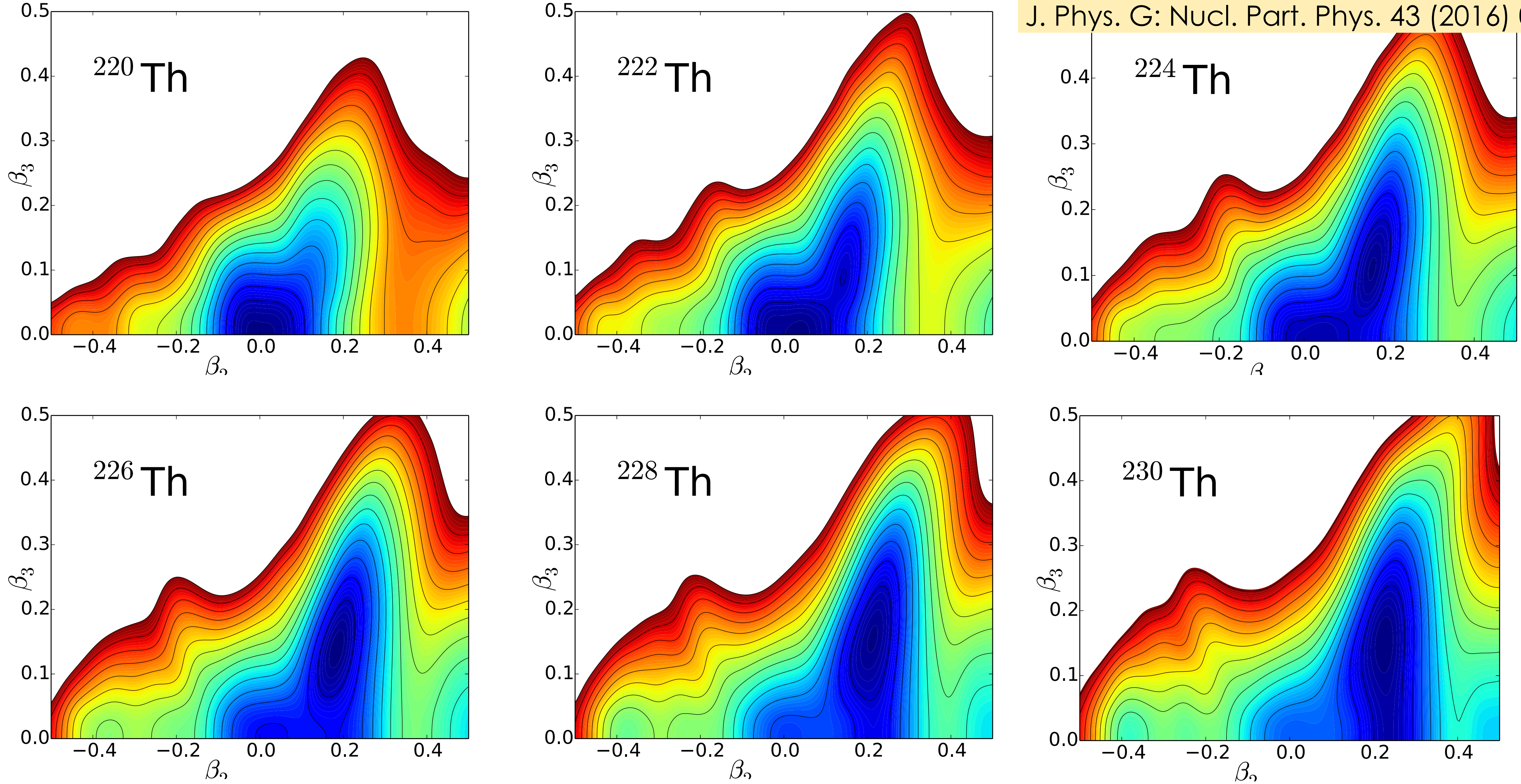
J. Phys. G: Nucl. Part. Phys. 43 (2016) 024005

Probability distributions in the β-γ plane for the band-head of the K=2 γ-band of the ^{152}Sm isotope.



Quadrupole and octupole shape transition in thorium

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



…quadrupole-octupole collective Hamiltonian:

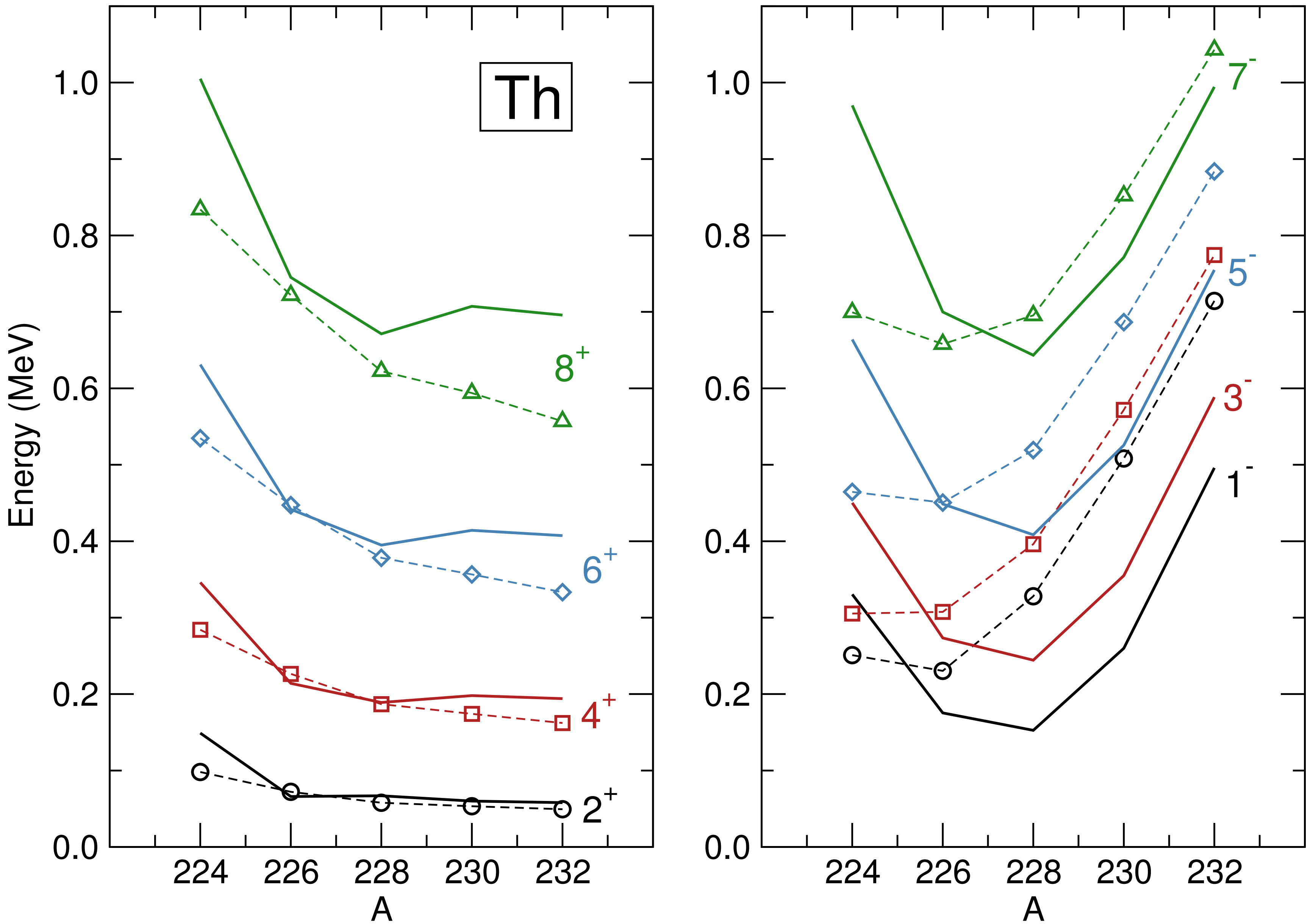
$$H_{coll} = -\frac{\hbar^2}{2\sqrt{w\mathcal{I}}}\left[\frac{\partial}{\partial\beta_2}\sqrt{\frac{\mathcal{I}}{w}}B_{33}\frac{\partial}{\partial\beta_2} - \frac{\partial}{\partial\beta_2}\sqrt{\frac{\mathcal{I}}{w}}B_{23}\frac{\partial}{\partial\beta_3} - \frac{\partial}{\partial\beta_3}\sqrt{\frac{\mathcal{I}}{w}}B_{23}\frac{\partial}{\partial\beta_2} + \frac{\partial}{\partial\beta_3}\sqrt{\frac{\mathcal{I}}{w}}B_{22}\frac{\partial}{\partial\beta_3}\right]$$

$$+\frac{\hat{J}^2}{2\mathcal{I}} + V(\beta_2, \beta_3)$$

Quadrupole and octupole shape transition in thorium

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

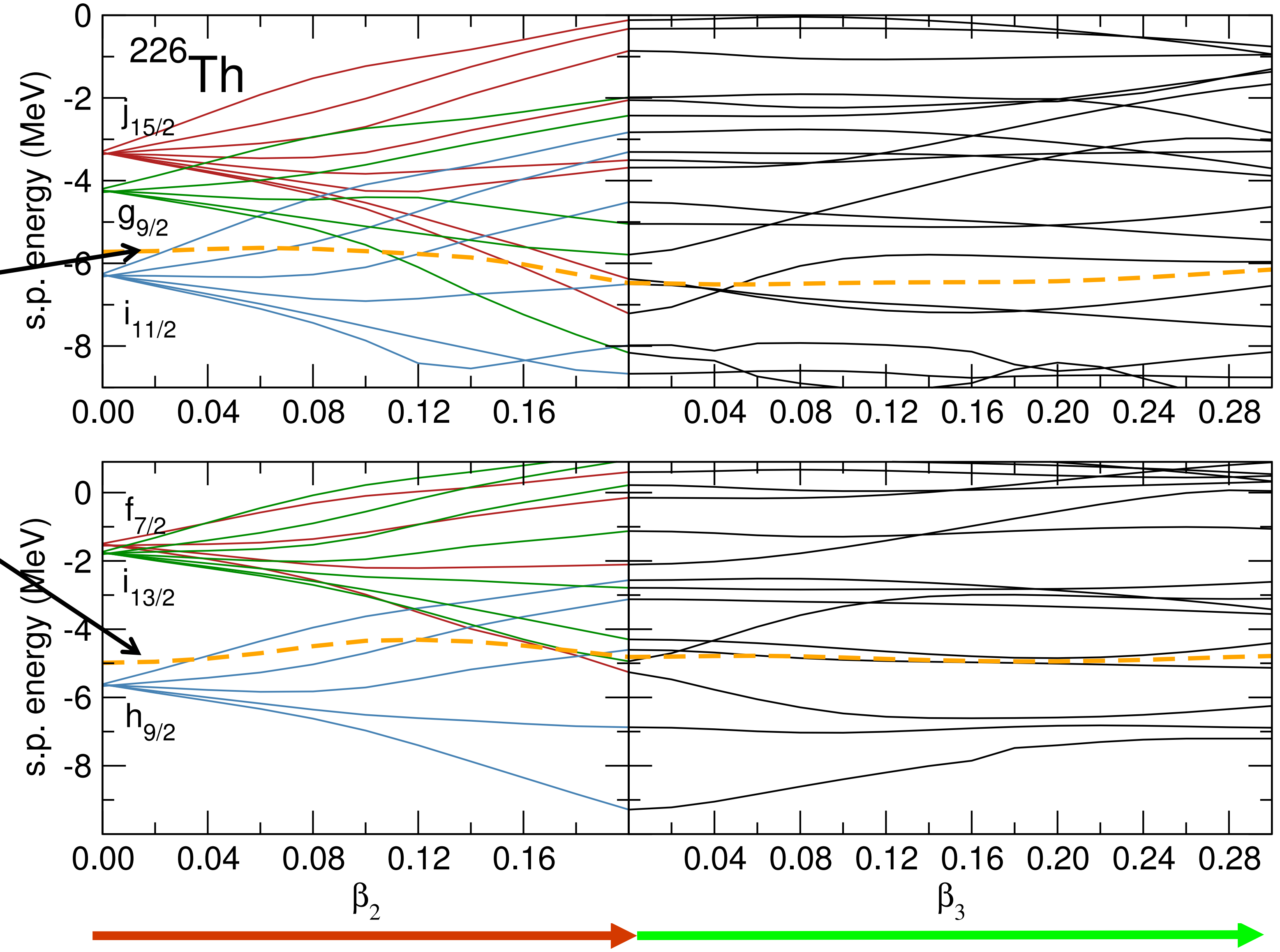
… systematics of energy spectra of the positive-parity ground- state band ($K^\pi = 0^+$) and the lowest negative-parity ($K^\pi = 0^-$) sequences in $^{224-232}$Th.

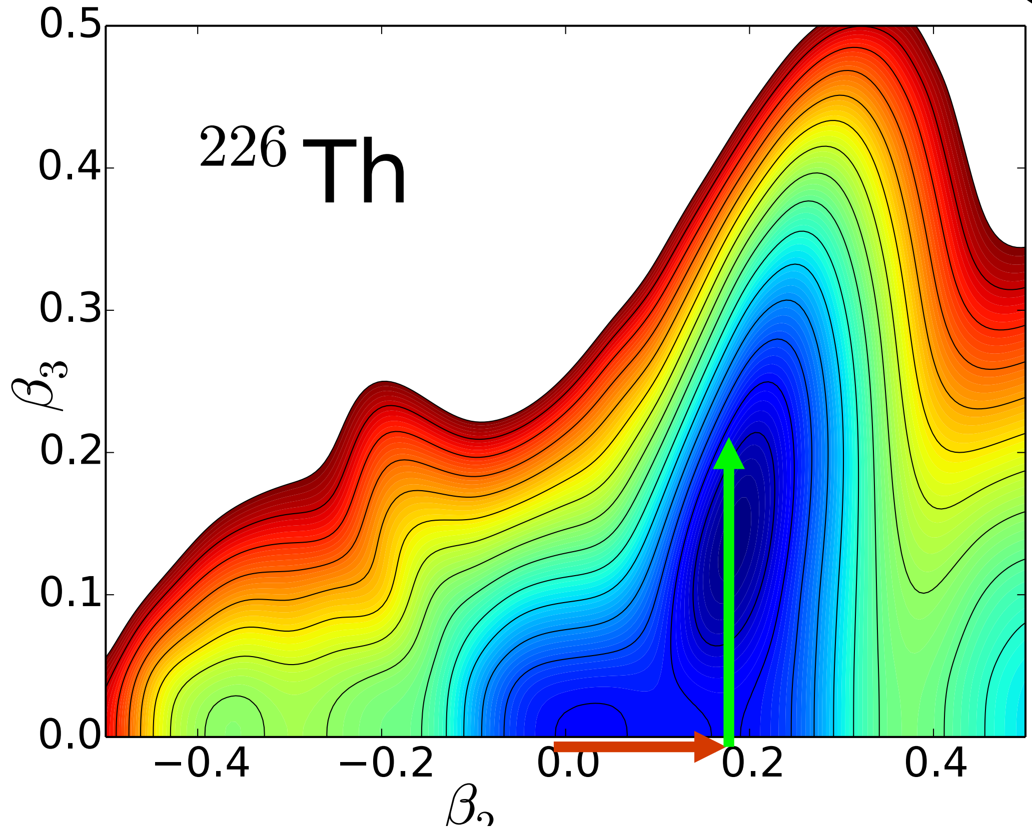


Quadrupole and octupole shape transition in thorium

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

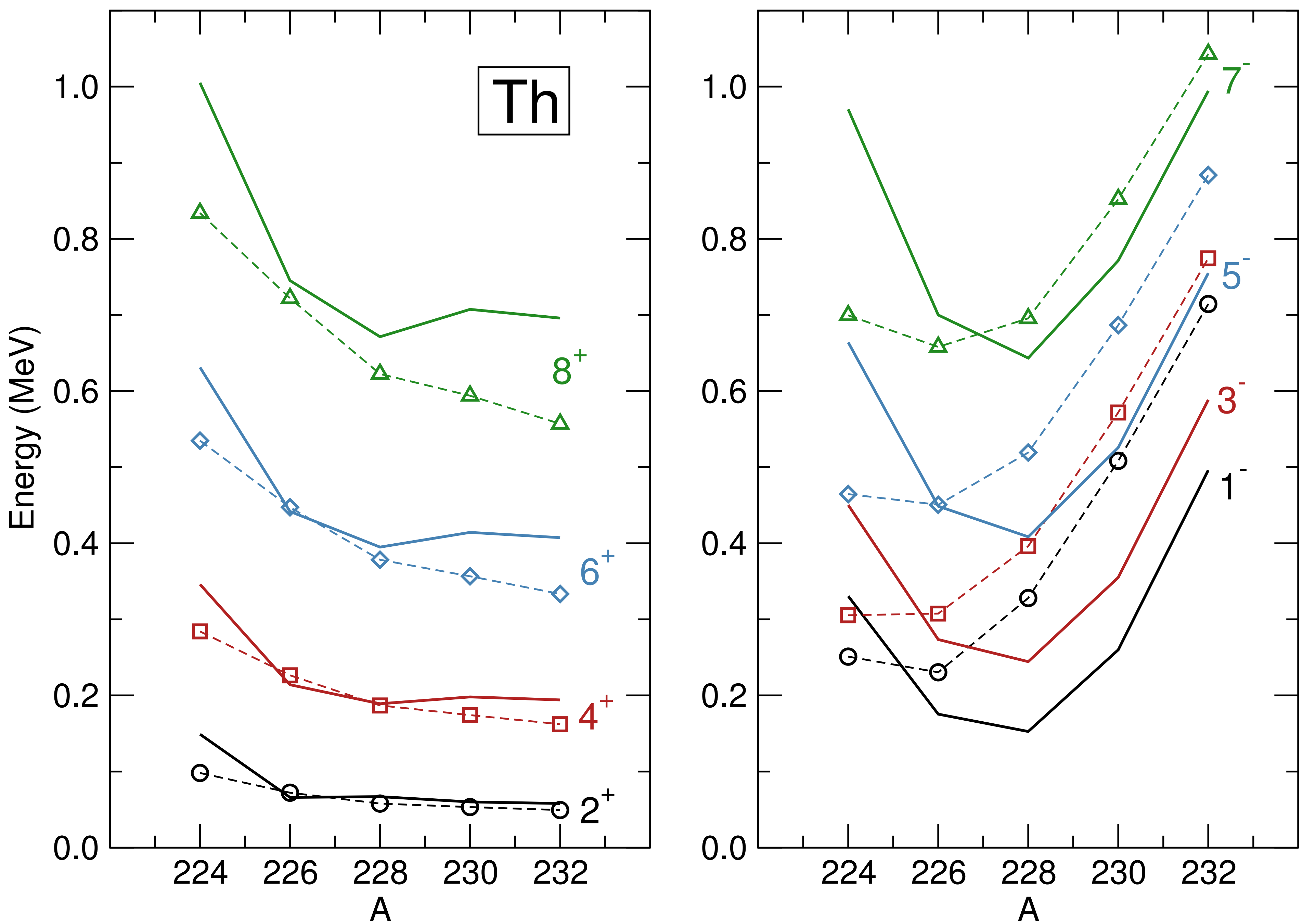
Fermi level





Quadrupole and octupole shape transition in thorium

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



Solid lines – theory

Dashed lines – exp.

Some other recent applications…

✔ level of accuracy (rms deviation of experimental masses) of covariant EDFs is still below the state-of-the-art non-relativistic HFB mass models: Should additional terms be included in the EDF? (price to pay: increased model complexity)

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

✔ Extrapolation to superheavy elements (energy gaps; sparation energies; Q_α-values; K-isomers…)

Nucl. Phys. A 944, 415 (2015)
Phys. Rev. C 91, 034324 (2015)
Phys. Rev. C 89, 024312 (2014)

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

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

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.

Collaborators

✔ ***UniZg***: Dario Vretenar, Kosuke Nomura (University of Tsukuba), Jie Zhao (China Academy of Engineering Physics, Chengdu), Vaia Prassa (Thessaloniki)

✔ ***PKU, CAS, Southwest University***: Jie Mong, Shan-Gui Zhou, Bing-Nan Lu, Zhipan Li, Jiangming Yao