Hellenic Institute of Nuclear Physics

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Shape evolution in Hg isotopes within the covariant density functional theory

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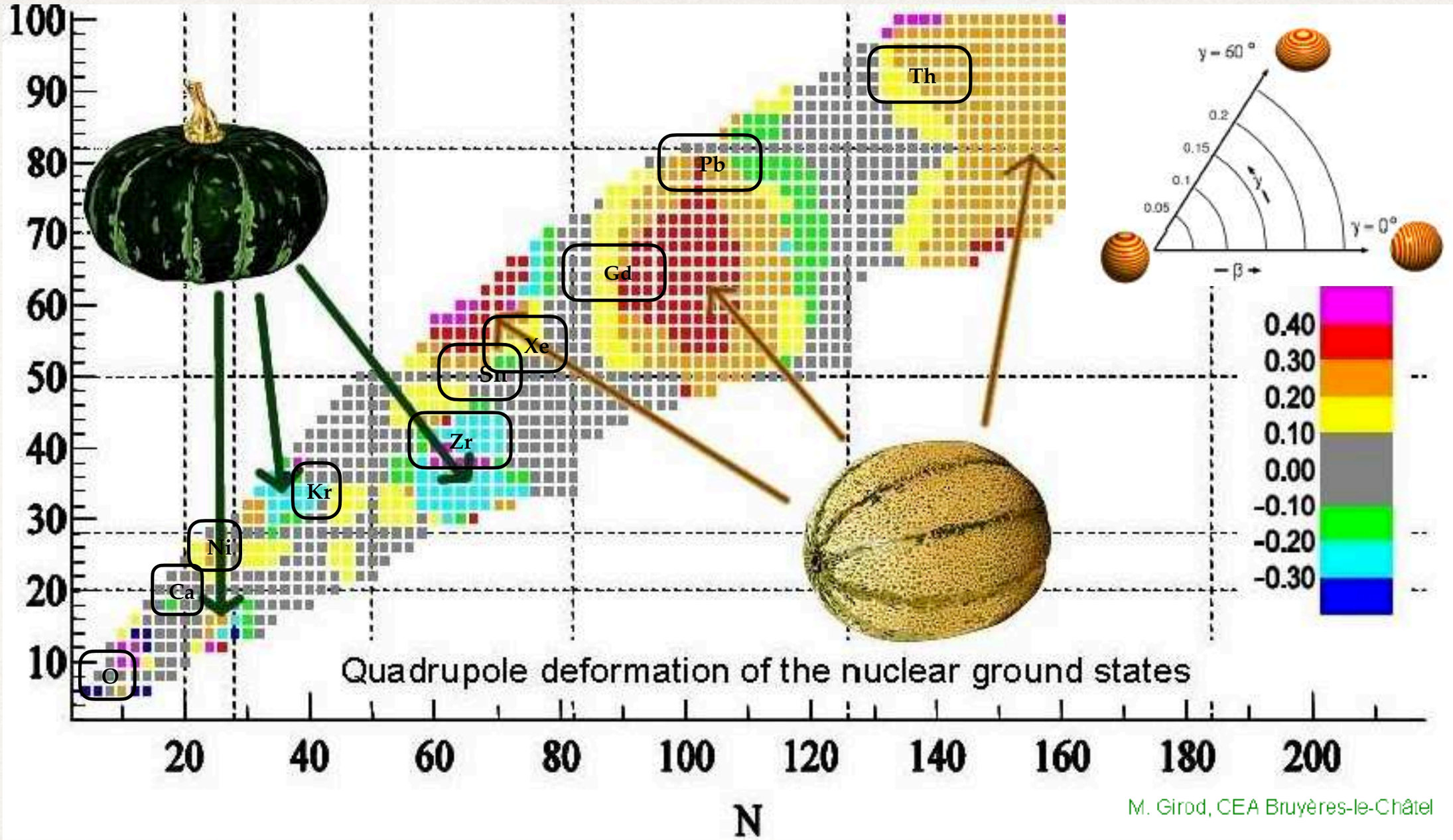
Nuclear shapes



Shell closures, or magic numbers, are marked by dotted lines.

Large prolate deformations (β>0) are found above the Z=50, N<82, and 90<N<110.

Small area of oblate shapes (β<0) for 28<Z<50 and N~40 or 60<N<70 shapes and for 60<Z<70 and N≈78

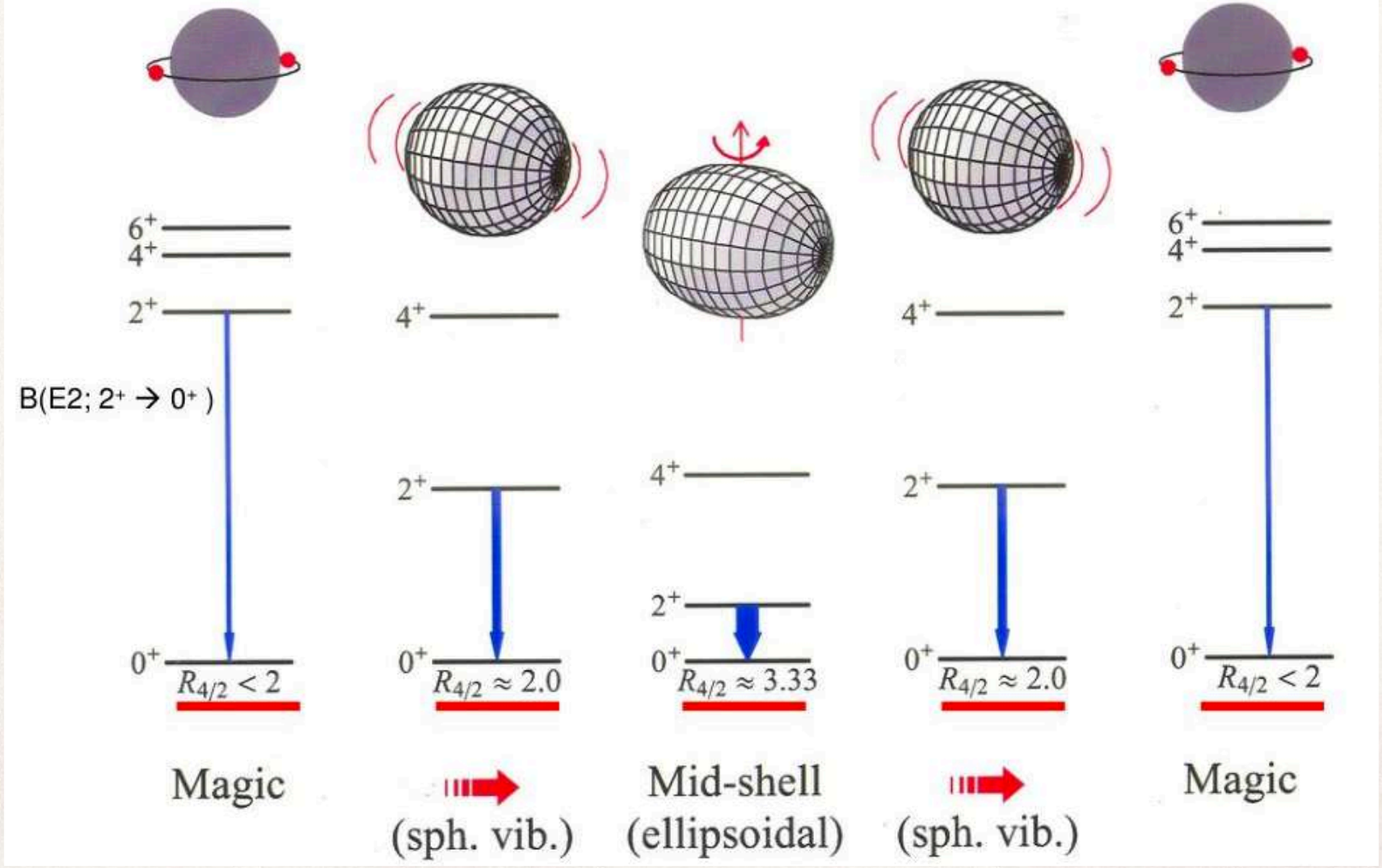
Phase transitions and phase coexistence in even-even nuclei, such us:

- **Sn (Z,N)~ (50, 66) and Pb (82, 104): the major shell gaps at 50 and 82 dictate the structures.**
- **Zr (Z,N) ~ (40, 60): subshell gaps are the cause of shape coexistence.**
- **Kr (Z,N)~ (36, 40), Xe (Z,N) ~ (54, 70), Gd (Z,N) ~(64, 90)**

Evolution of nuclear shapes

Shape transitions of the ground states can occur with the variation of nucleon numbers.
Identified from abrupt changes in the properties of the ground state that result in the rapid change of several observables:

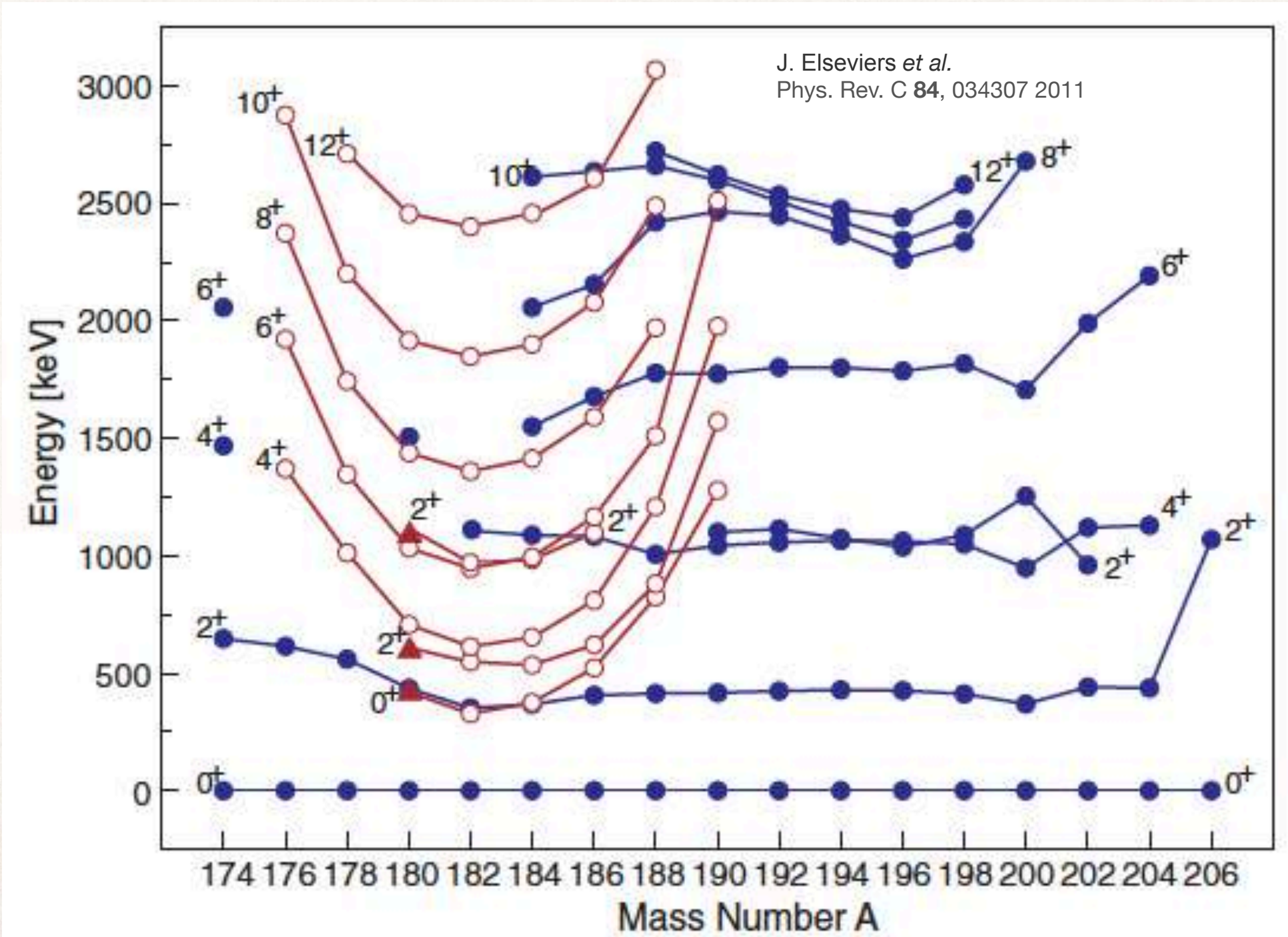
- **two-neutron separation energies,**
- large differences in the energies of the **first excited states** (i.e. the 2^+_1 state suddenly drops from 1223 keV in $^{98}_{40}$Zr to 270 keV in $^{100}_{40}$Zr),
- $\mathbf{R_{4/2}}$ =E(4+)/E(2+),
- **B(E2:4+ → 2+)** values,
- variation of the measured **mean square radii** (such as in Hg, Au or Pt isotopes).



Shape coexistence in Hg isotopes

Systematics of low-lying excited states in the even-mass Hg isotopes.

Shown to illustrate the clear 'parabolic' trend in the pattern of excitation energy of the shape coexisting structures.



Covariant density functionals

✔ the many-body problem is mapped onto a one body problem without explicitly involving inter-nucleon interactions!

✔ natural inclusion of the **spin degree of freedom** (spin-orbit potential with empirical strength)

✔ 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**

✔ A covariant formulation in terms of hadron degrees of freedom **incorporates the basic symmetries of QCD** (Lorentz invariance, parity conservation, isospin symmetry, spontaneously broken chiral symmetry).

Relativistic Hartree-Fock-Bogoliubov Theory

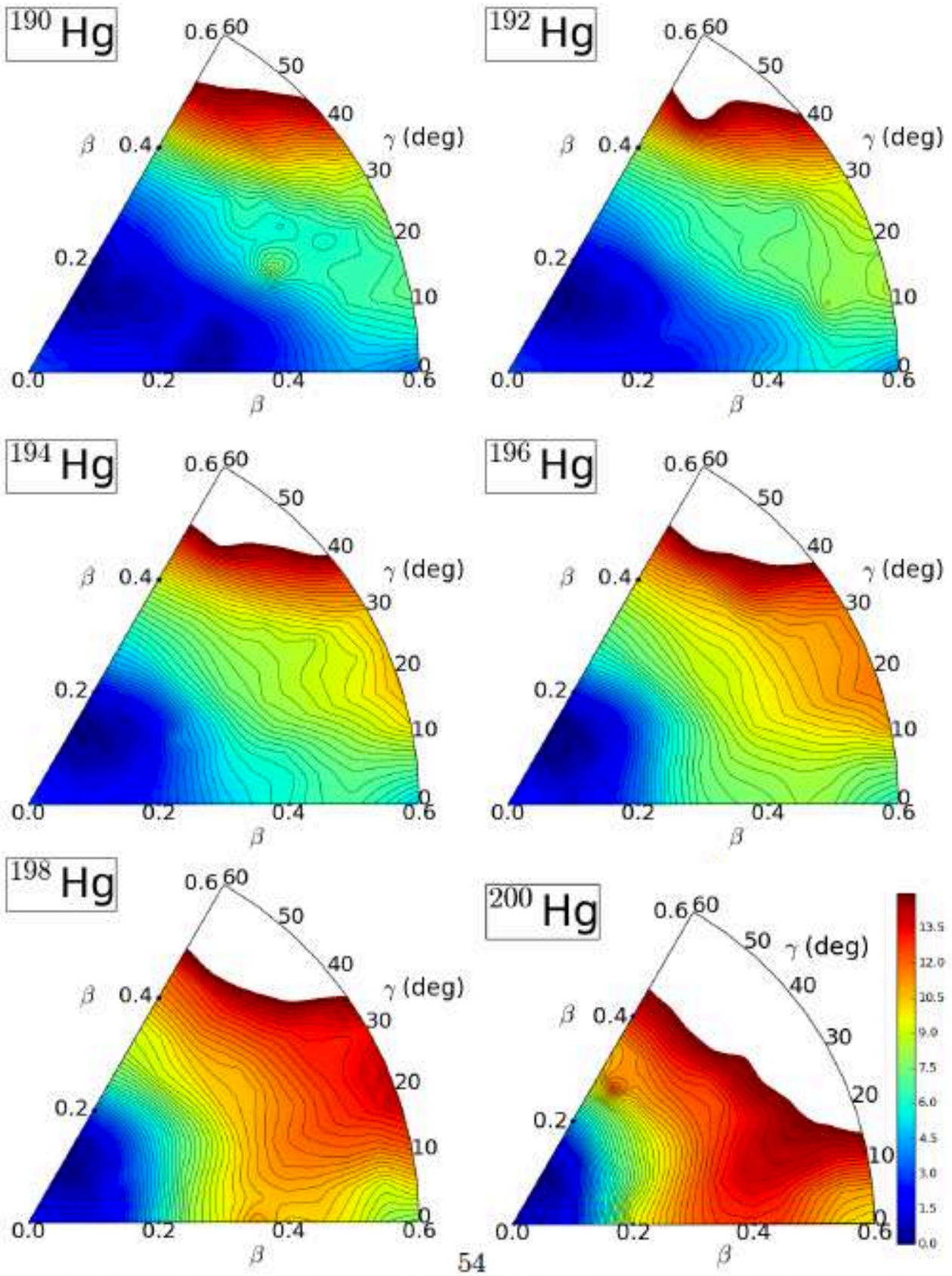
Analysis of **open-shell nuclei** (correlations in the self-consistent RMF).

Unified treatment of the nuclear MF (particle-hole (ph)) and pairing (particle-particle (pp)) correlations. Crucial for an accurate description of ground states and properties of excited states in weakly bound nuclei.

$$E[\hat{\rho}, \hat{\kappa}, \phi_m] = E_{RMF}[\hat{\rho}, \phi_m] + E_{pair}[\hat{\kappa}],$$

- It reduces the number of "unknowns" to just the density and the pairing tensor. Once these 2 objects are known (by solving the HFB equation), you can in principle calculate any observable.
- In the **particle hole channel** we use the **DD-PC1 parametrisation (adjusted to the experimental masses of a set of 64 axially deformed nuclei in the mass regions A ≈ 150–180 and A ≈ 230–250)**
- In the **particle-particle channel** a **separable pairing interaction** with its **strength fine-tuned to reproduce the odd-even mass differences in the mass region A ≈ 230–250**

Potential energy surfaces of Hg isotopes



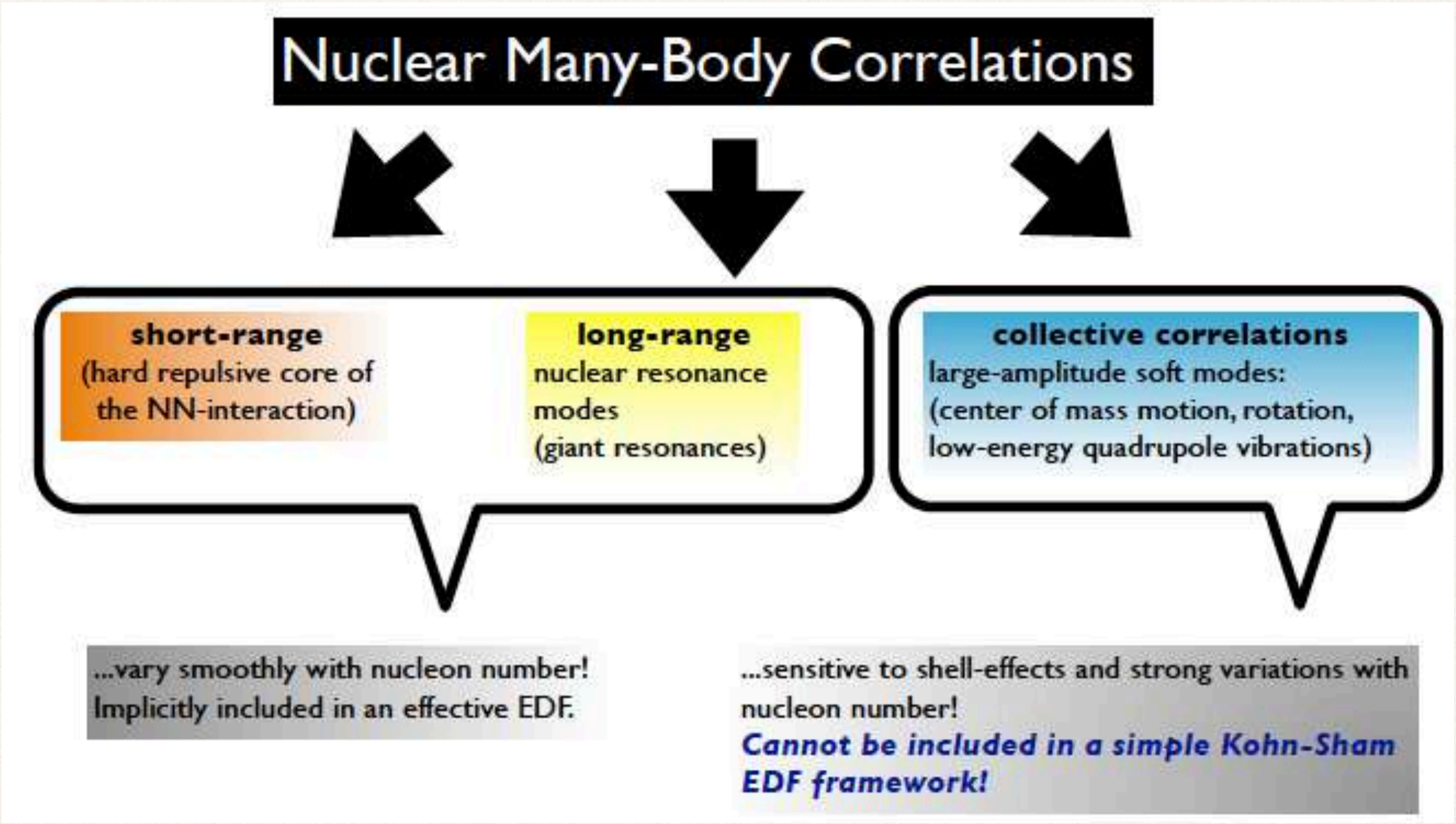
In **^{190}Hg** the energy surface is γ-soft with two minima within an energy difference of **500keV**, which indicates a case of **mixing between the two different shape configurations**. The more pronounced minimum is oblate deformed at $\beta \sim 0.15$ and the second one is prolate at $\beta \sim 0.25$.

In **^{192}Hg** the energy surface is still rather **soft in the γ-direction** with the equilibrium configuration on the oblate side at $0.1 < \beta < 0.2$.

The prolate minimum diminishes and **only the oblate one is seen in $^{194\text{-}198}$Hg.**

The **single oblate minimum becomes less deformed and approaches $\beta = 0$ in ^{200}Hg**, which implies a structural change from weakly oblate deformed to nearly spherical states.

Beyond mean field - 5DCH



Beyond mean field - 5DCH

To calculate transitions from nuclear states with good angular momenta we use the microscopic PES to build a collective Hamiltonian:

$$H_{\text{coll}} = T_{\text{vib}}(\beta, \gamma) + T_{\text{rot}}(\beta, \gamma, \Omega) + V_{\text{coll}}(\beta, \gamma),$$

with the vibrational kinetic energy: $T_{\text{vib}} = \frac{1}{2} B_{\beta\beta} \dot{\beta}^2 + \beta B_{\beta\gamma} \dot{\beta}\dot{\gamma} + \frac{1}{2} \beta^2 B_{\gamma\gamma} \dot{\gamma}^2,$

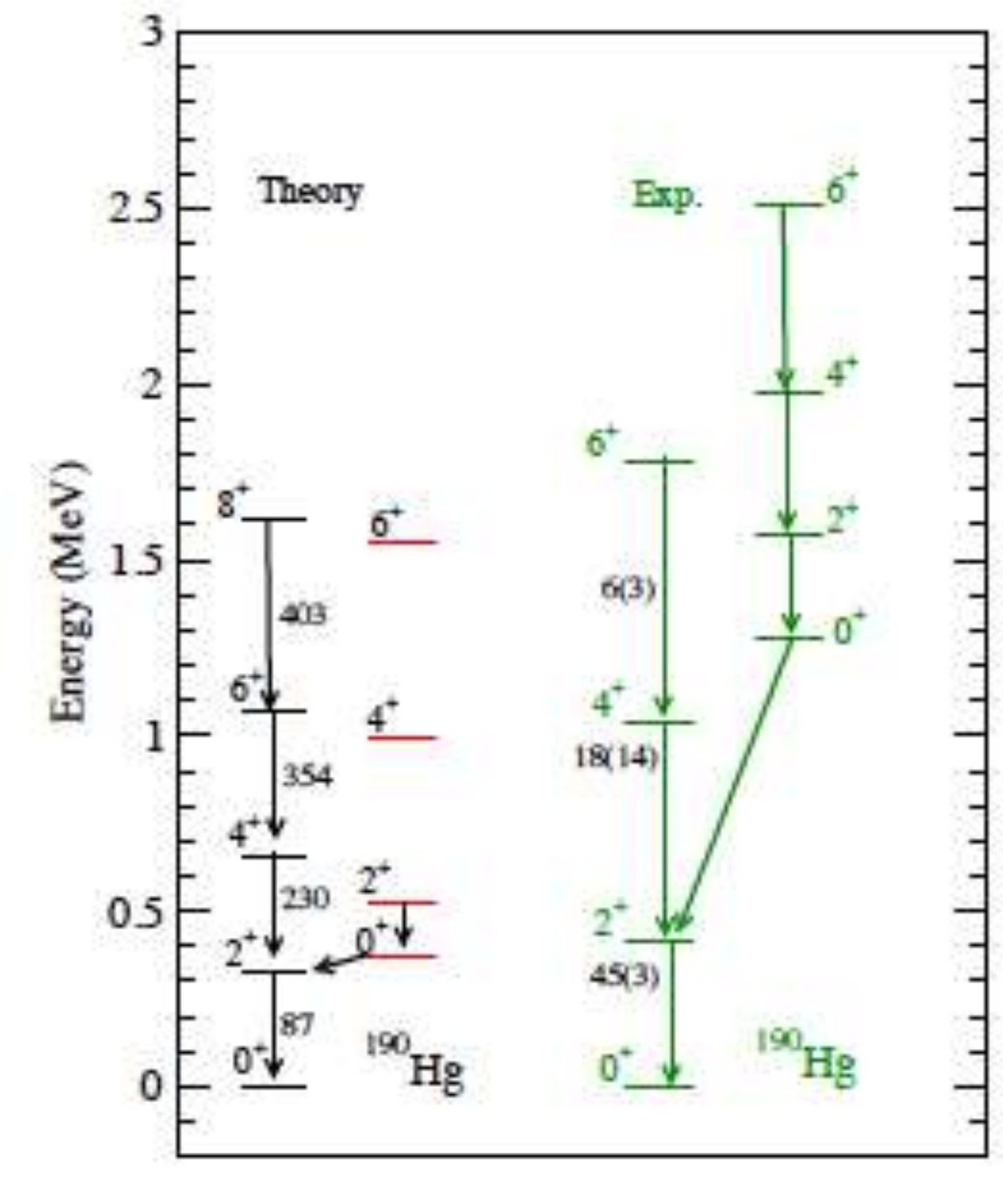
the rotational kinetic energy: $T_{\text{rot}} = \frac{1}{2} \sum_{k=1}^{3} \mathcal{I}_k \omega_k^2,$

and the collective potential energy terms: $V_{coll}(\beta,\gamma) = E_{tot}(\beta,\gamma) - \Delta V_{vib}(\beta,\gamma) - \Delta V_{rot}(\beta,\gamma)$

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**.

Moments of inertia are calculated by using the *Inglis-Belyaev formula*.
Mass parameters are calculated in the *cranking approximation*.
Mass parameters and moments of inertia are fully determined by the functional DD-PC1.

Low-lying level scheme ^{190}Hg



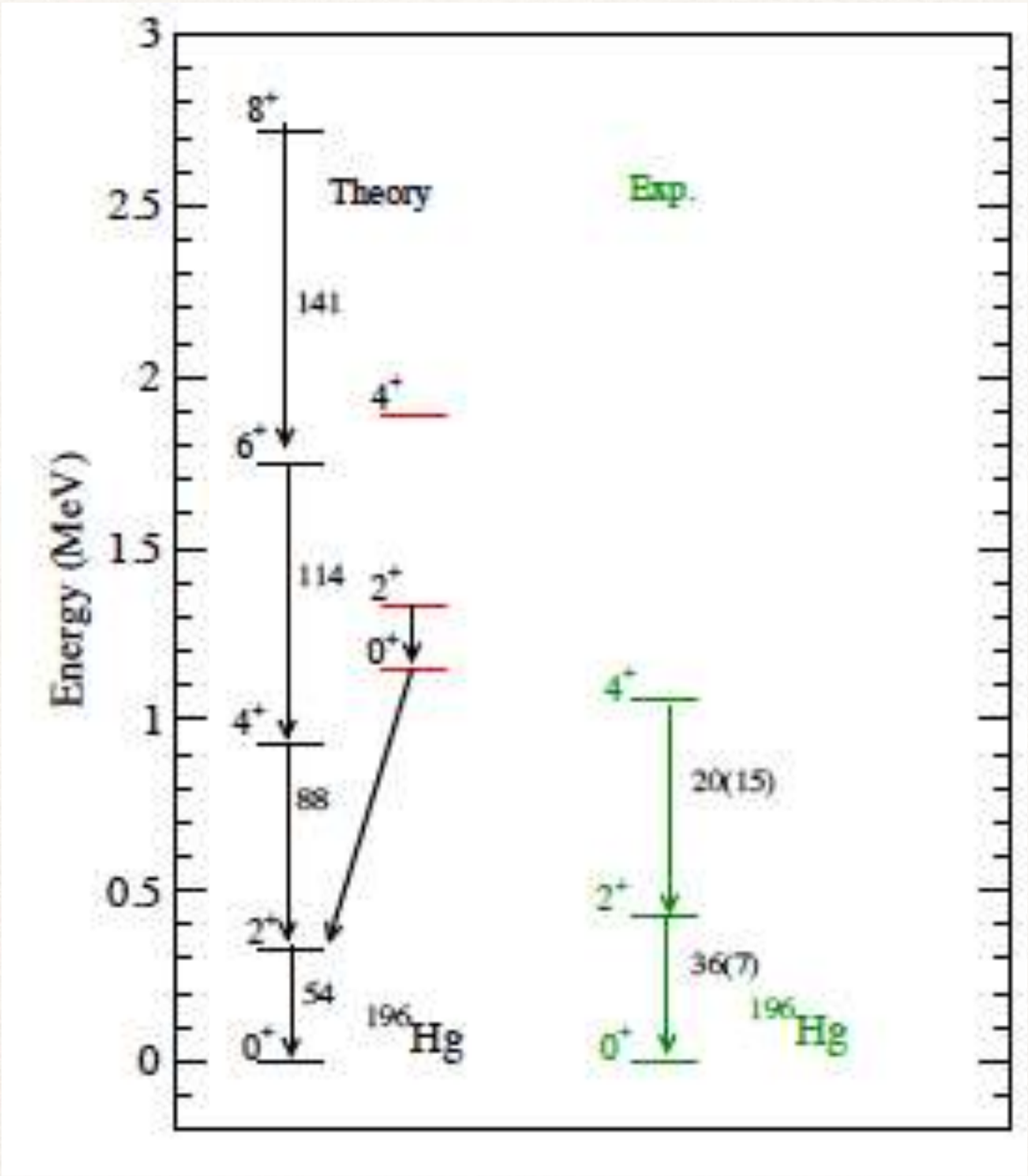
In **^{190}Hg** the comparison with data shows a rather reasonable agreement for states with $J^{\pi} < 4+$ in the g.s band.

2^{+}_{1} underestimated.

The calculated energies of the excited *0^{+}_{2} and 2^{+}_{2} states is between the 2^{+}_{1} and 4^{+}_{1} levels.*

Both indicate stronger mixing between the oblate ground state and the prolate configuration of the excited band in the theoretical calculations.

Low-lying level scheme ^{196}Hg

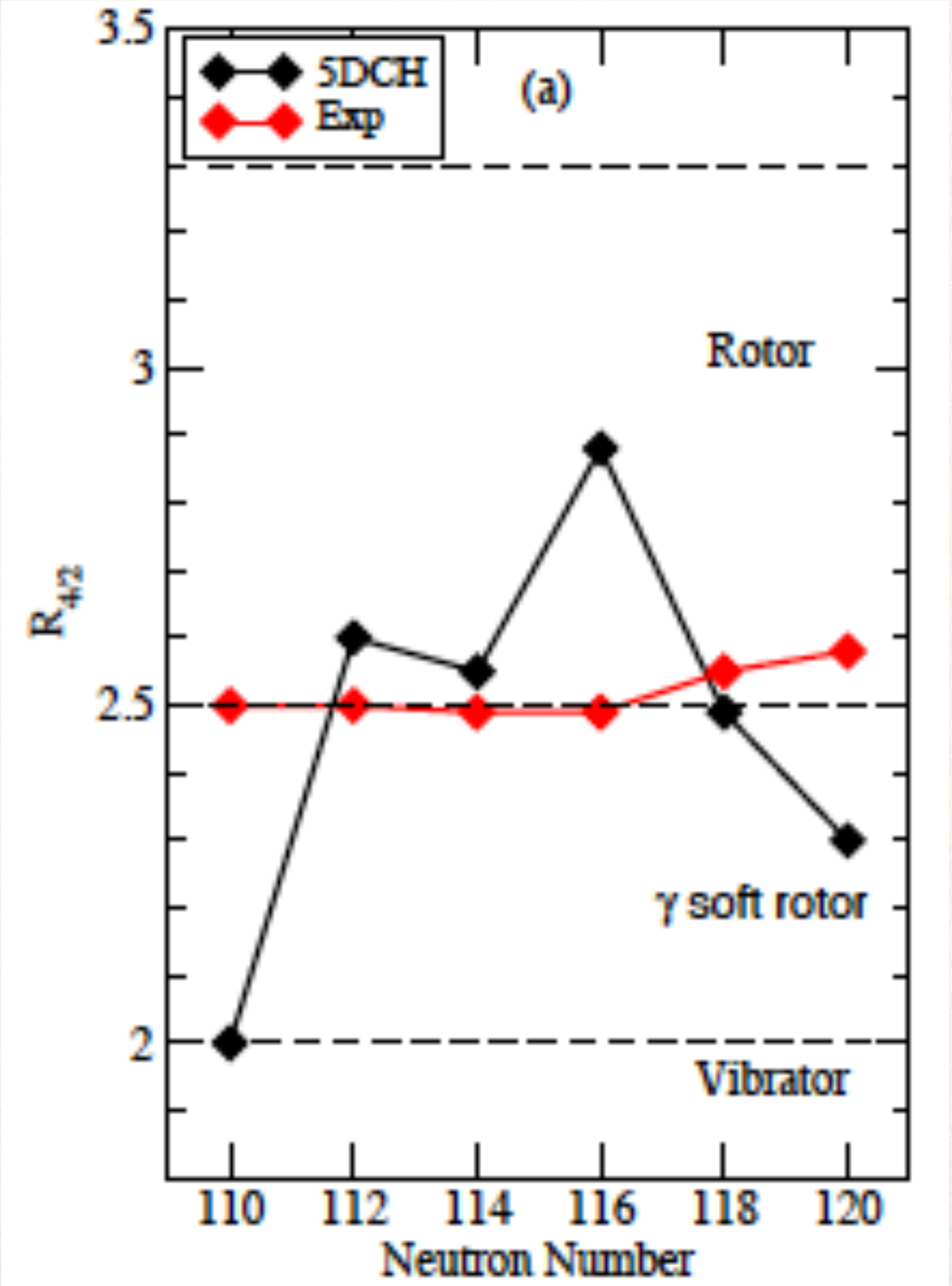


In **^{196}Hg** the model predicts a well-deformed oblate minimum at deformation $0.15 < \beta < 0.2$.

Comparison between the experimental and theoretical level structures reveals that, while a **vibrational-like level distribution is suggested experimentally** the **calculations exhibit a slightly more deformed rotational character**.

The predicted ground-state band is **more compressed for the** J^{π} **< 4+** state but **more stretched for** J^{π} **> 6+** levels than in the experiment.

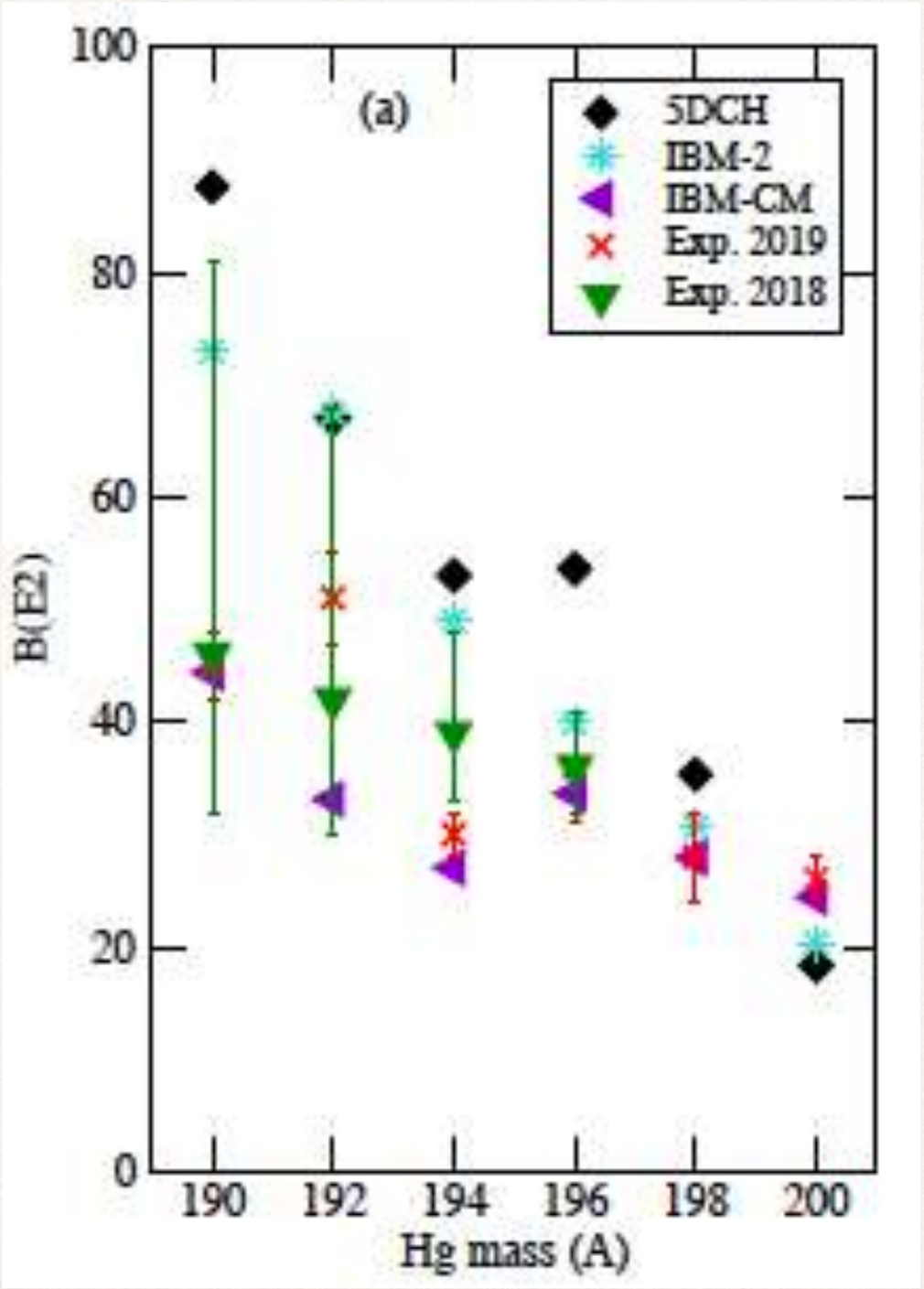
Evolution of the ratio $R_{4/2}$



In $^{192\text{-}198}$**Hg** **2.5< $R_{4/2}$ <3** disclosing the **γ-softness** of their potential energy surfaces and their rotational character.
In ^{190}**Hg** the ratio is **$R_{4/2}$ = 2** reaching the **spherical vibrator limit**.

The comparison with data reveals that the calculated values signify a more **vibrational structure for the isotope of ^{190}Hg** and a rather **more deformed rotational character for the ^{196}Hg** than the experimental values.
In ^{200}**Hg** the ratio is 2.3 indicating a **more γ-soft potential than the one given by data**.

B(E2) values



Calculated B(E2; 2^+_1->0^+_1) values with the 5DCH model.
Theoretical results with the IBM-2 and the IBM-CM models are presented for comparison.

The results **reproduce the general decreasing trend with neutron number**.

For all isotopes $^{190\text{-}198}$**Hg** an **increased collectivity in the 2^+_1 yrast states** is observed compared to data.

The largest discrepancy with the measured values is observed for the lighter isotope of ^{190}**Hg** for which the **5DCH model points out to shape coexistence**.

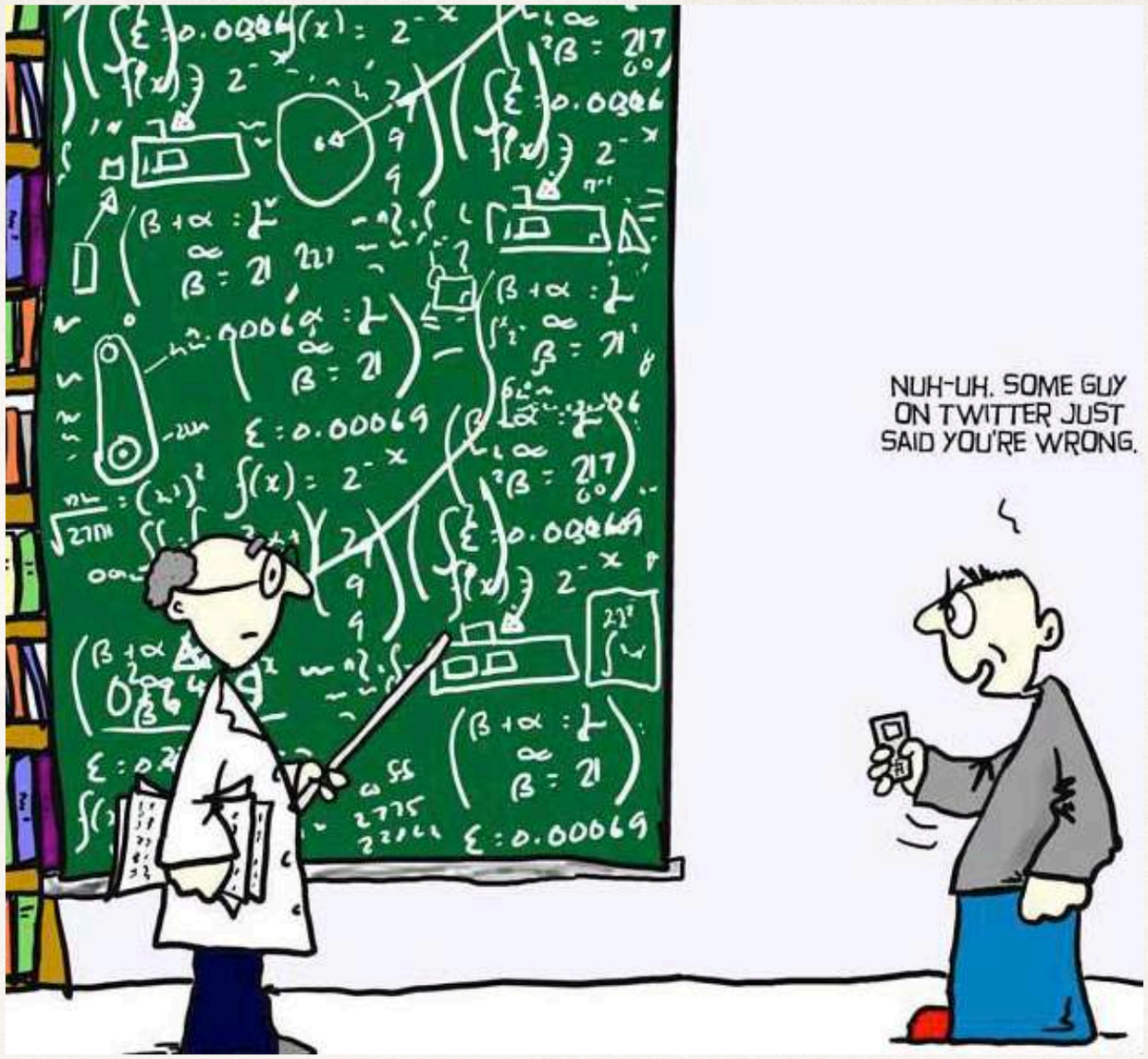
For the isotopes ^{192,194,198,200}Hg the accuracy of the calculations compared with the experimental values are of the same quality as those performed with the IBM-2 model.

Overview & conclusions

- Deformation constrained SCMF calculations have been performed with the relativistic Hartree-Bogoliubov method based on the universal energy density functional DD-PC1 and a separable pairing interaction.
  - The triaxial deformation energy surfaces obtained from the SCMF calculations for the even-even $^{190\text{-}200}$Hg isotopes predict a very interesting nuclear structure evolution: **coexistence of prolate and oblate deformed minima in ^{190}Hg**, **γ-soft oblate deformed potential in $^{192\text{-}198}$Hg**, and an **almost spherical deformation in ^{200}Hg**.
- A quadrupole collective Hamiltonian, with parameters determined by self-consistent constrained triaxial RHB calculations, has been used to calculate the low-energy spectra of Hg isotopes.
  - A **phase-transitional behavior** of the low-lying excitation spectra, that occurs between **^{190}Hg** and **^{192}Hg**, is predicted.
  - The energies of the low-lying ground state band in **^{190}Hg** are **underestimated** due to the **mixing between the dominant oblate deformed minimum and the prolate configuration**.
  - In **^{196}Hg with the model suggests a more rotational-like behavior**.
  - The results for the ratios $R_{4/2}$ validate the above assumptions.
  - The calculated B(E2) reduced transition probabilities for the 2^{+}_{1} yrast states of the **$^{190\text{-}196}$Hg** roughly reproduce the trend of the data. The resulted values lead to the assumption of **collective excitations in $^{190\text{-}198}$Hg**.

Theoretical and experimental efforts in the region of $^{190\text{-}200}$Hg predict shape transitions from nearly spherical configurations in ^{200}Hg to γ-softness in $^{192\text{-}198}$Hg and shape coexistence in ^{190}Hg. The results presented in this work verify these findings, demonstrating the potential of the semi-empirical REDFs including the explicit treatment of collective correlations using a microscopic collective Hamiltonian.

Thank you for your attention!



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