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Beauty and the Quantum

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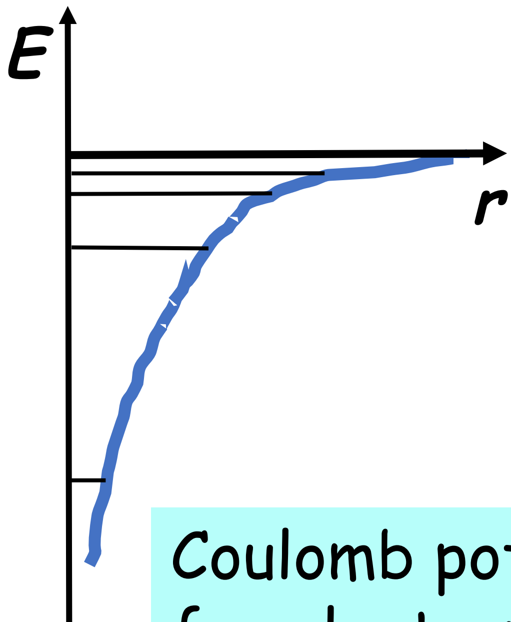
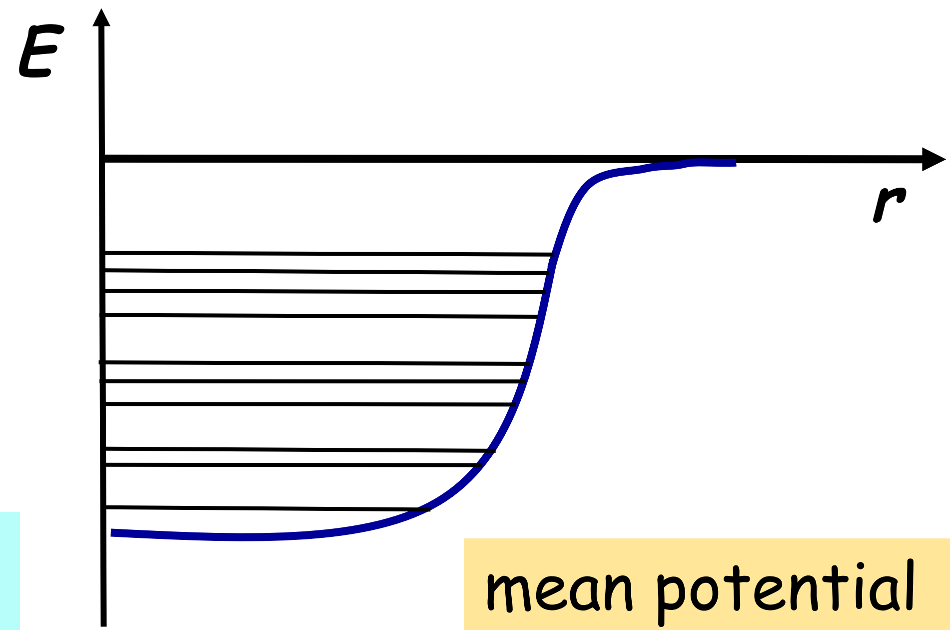
Single-particle states - starting point -

electrons in atom



Coulomb potential
for electrons
by the nucleus

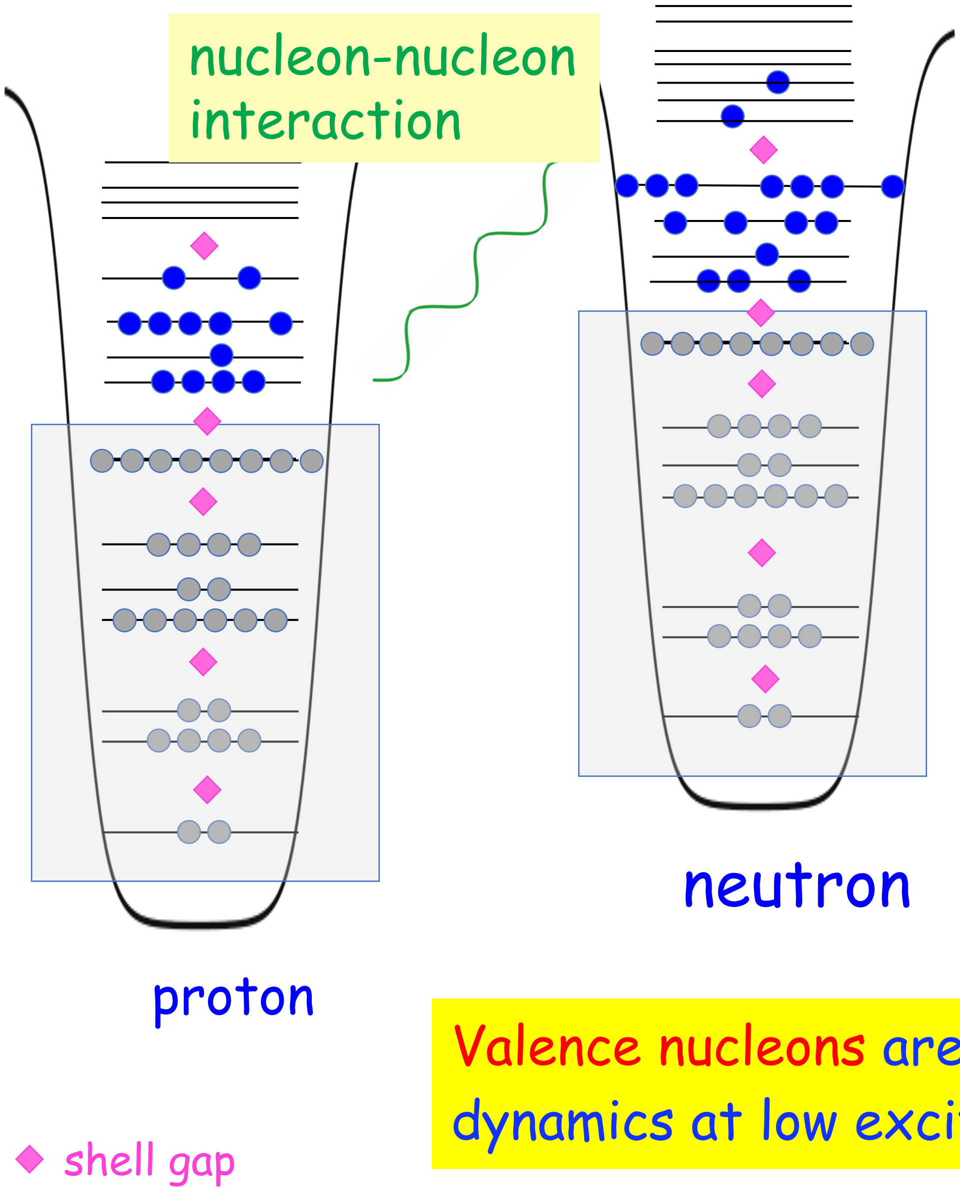
nucleons (protons and neutrons)
in atomic nucleus



mean potential
for nucleons
by the nucleons

➡ magic numbers, shell structure, *etc.*

shell structure and nucleon-nucleon interaction

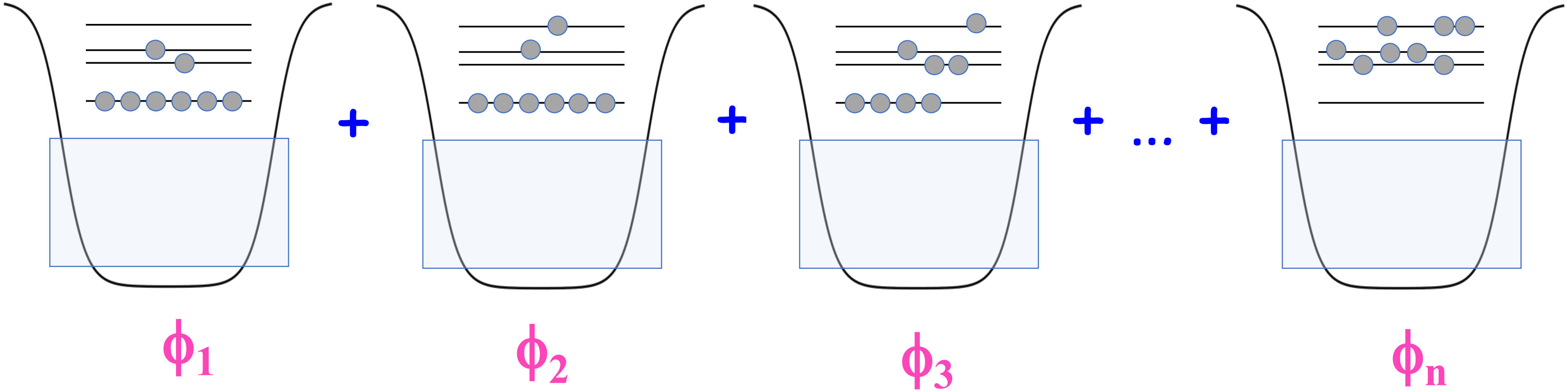


Protons and neutrons are orbiting in the mean potential like a "vase"
→ single-particle states

Lower orbits form the inert core (or closed shell)
(*shaded parts in the figure*)

Upper orbits are only partially occupied
(valence orbits and nucleons).

Valence nucleons are the major source of nuclear dynamics at low excitation energy.



The superposition of various configurations is fixed as an Eigenvalue problem

$$\mathbf{H}\,\Psi = \mathbf{E}\,\Psi$$

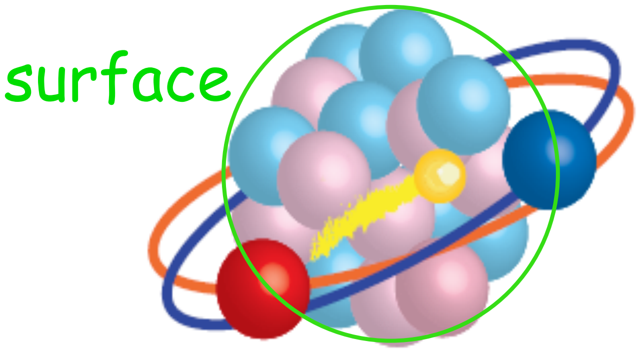
$$\Psi = c_1\,\phi_1 + c_2\,\phi_2 + c_3\,\phi_3 + \ldots..$$

c_i **probability amplitudes**

Solved by Monte Carlo Shell Model (like CI calc.) on supercomputers, for instance, *K* computer in Kobe.

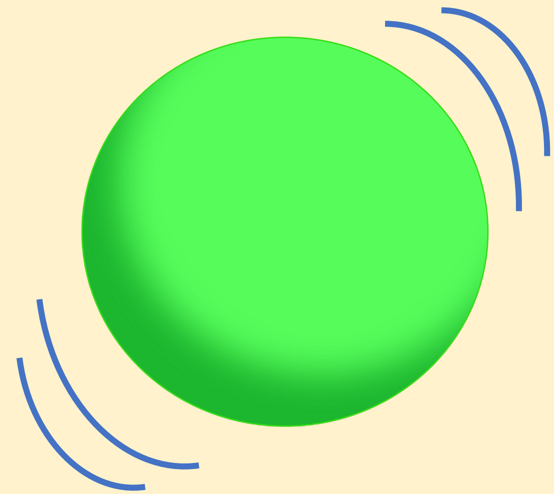
What properties appear from such correlations ?

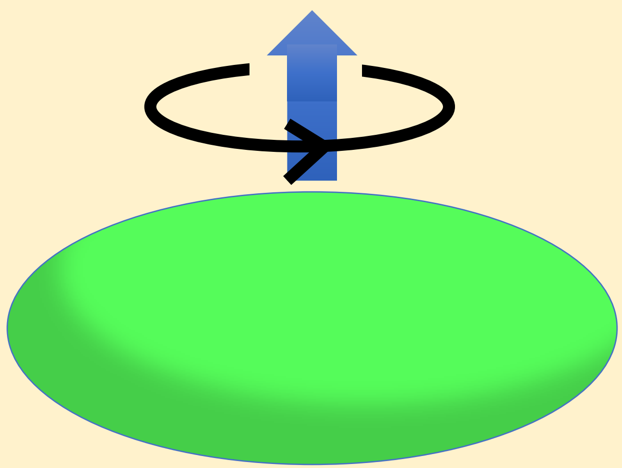
Assembly of
protons and neutrons



collective
motion

Vibration between
sphere and ellipsoid



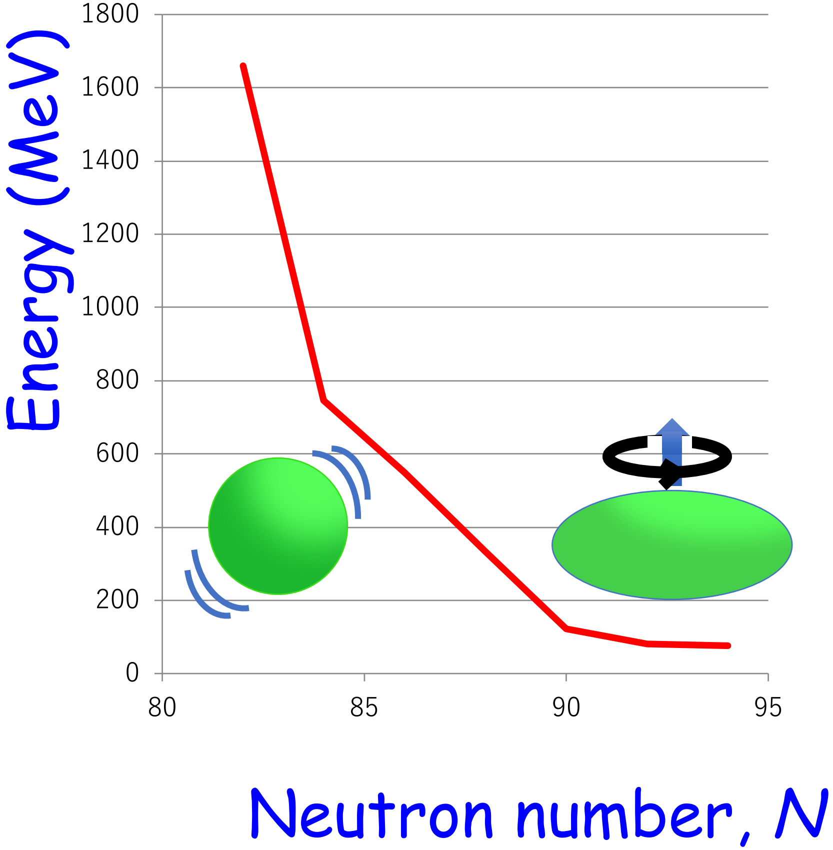


Rigid Ellipsoidal
Deformation
and its Rotation

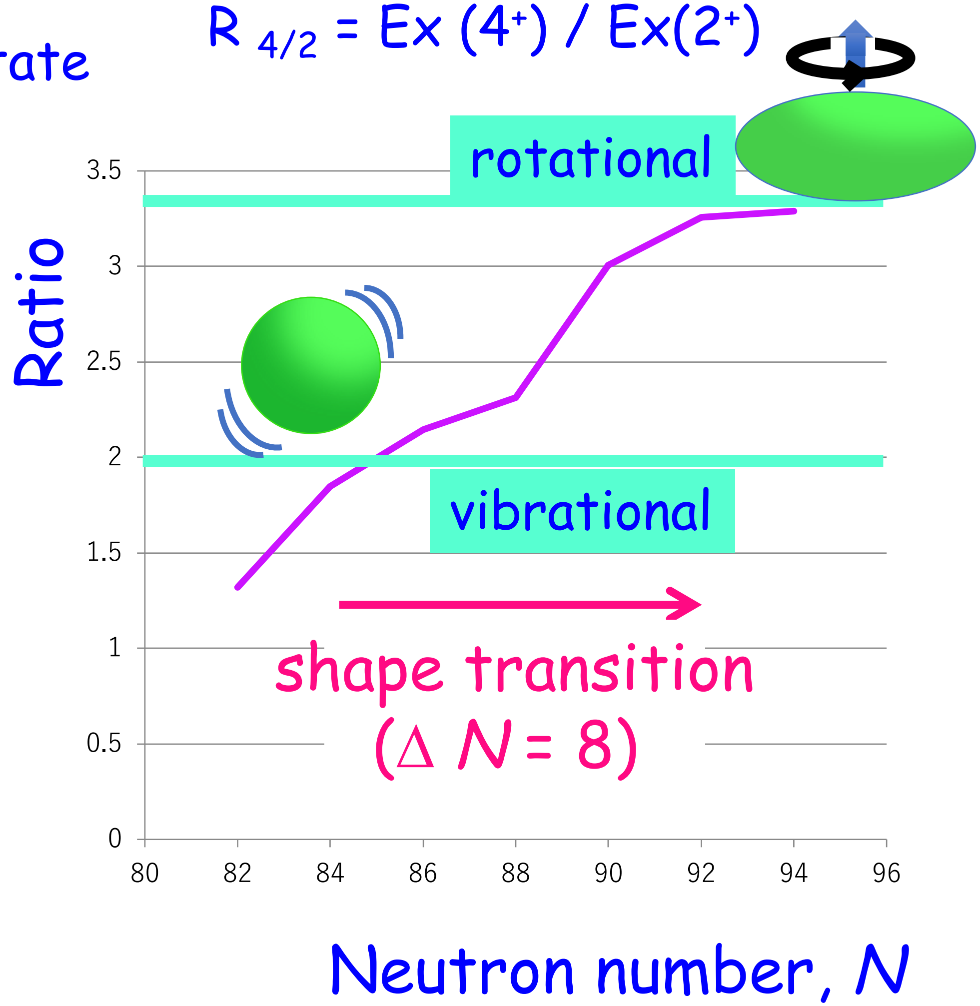
What properties appear ? : Shape change as a function of *N* (or *Z*)

2^+ and 4^+ level properties of Sm (Z=62) isotopes

Ex (2^+) :
excitation energy of first 2^+ state

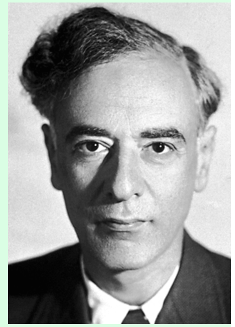


$R_{4/2}$ = Ex (4^+) / Ex(2^+)



Atomic nucleus is a quantum Fermi liquid :

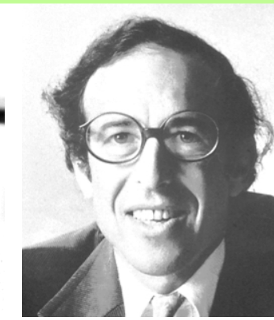
The nucleus is composed of almost free nucleons interacting weakly via residual forces in a (solid) (mean) potential like a solid vase.



Landau

The shape of atomic nucleus can be deformed dynamically (vibration) or statically (rotation) as collective modes (motions).

A. Bohr

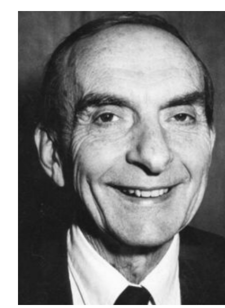


Mottelson

open question

T. Schaefer, Fermi Liquid theory: A brief survey in memory of Gerald E. Brown, NPA 2014)

G.E. Brown



One of Gerry's main scientific pursuits was to understand the nuclear few and many-body problem in terms of microscopic theories based on the measured two and three-nucleon forces. One of the challenges of this program is to understand how the observed single-particle aspects of finite nuclei, in particular shell structure and the presence of excited levels which carry the quantum numbers of single particle states, can be reconciled with the strong nucleon-nucleon force, and how single particle states can coexist with collective modes. A natural framework for addressing these questions is the Landau theory of Fermi liquids. Landau Fermi liquid theory

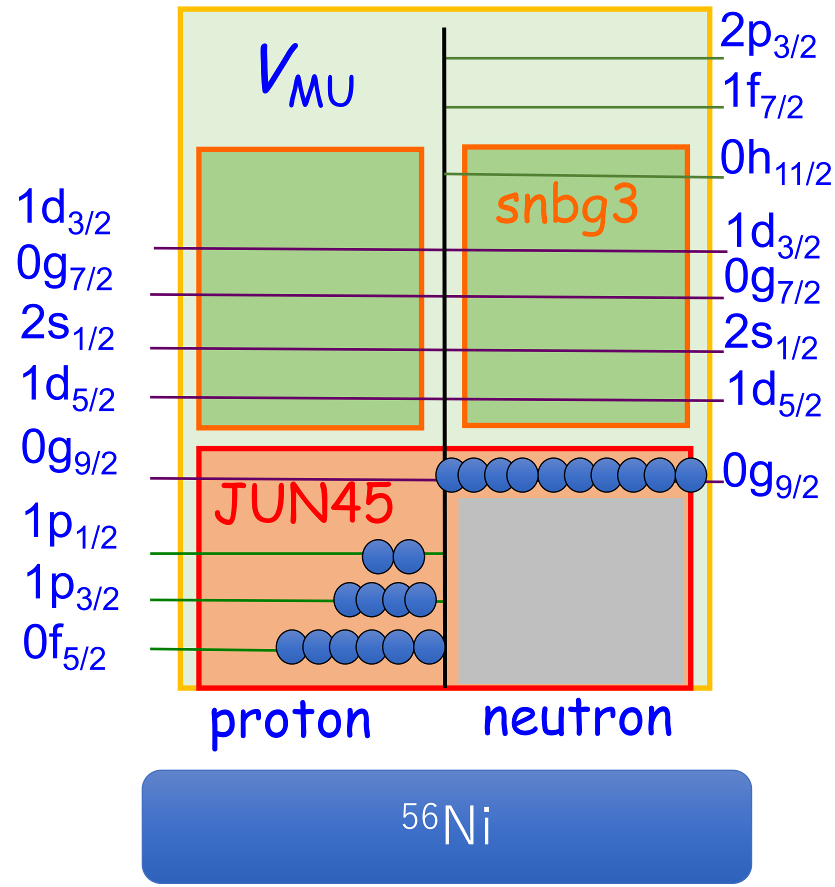
Quest for Quantum Phase Transition: Shapes of Zr isotopes by Monte Carlo Shell Model

- Effective interaction:
  JUN45 + snbg3 + V_{MU}

  known effective interactions

  + minor fit for a part of T=1 TBME's

  Nucleons are excited fully within this model space (no truncation)



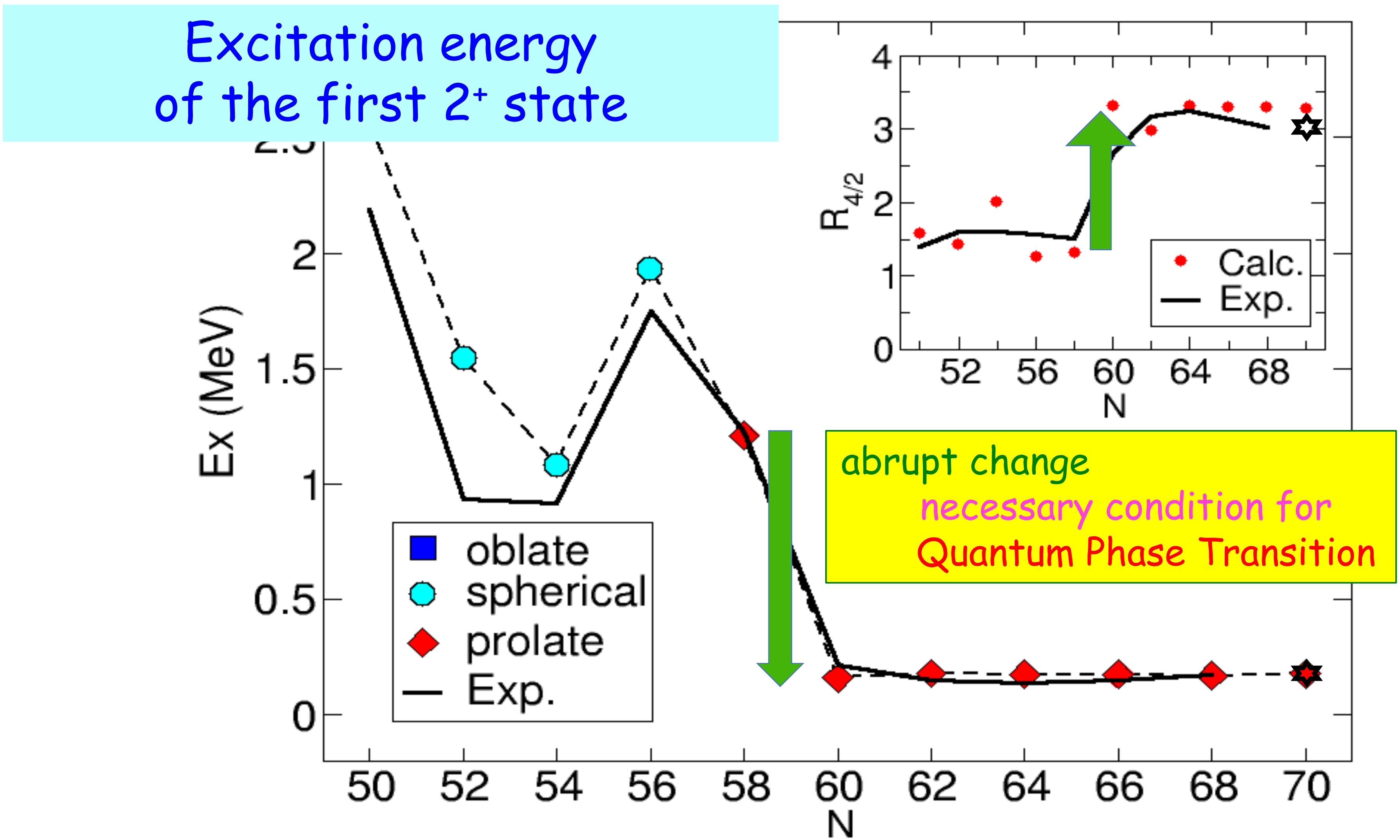
We performed Monte Carlo Shell Model (MCSM) calculations, where the largest case corresponds to the diagonalization of 3.7×10^{23} dimension matrix.

Togashi, Tsunoda, TO *et al.* PRL 117, 172502 (2016)

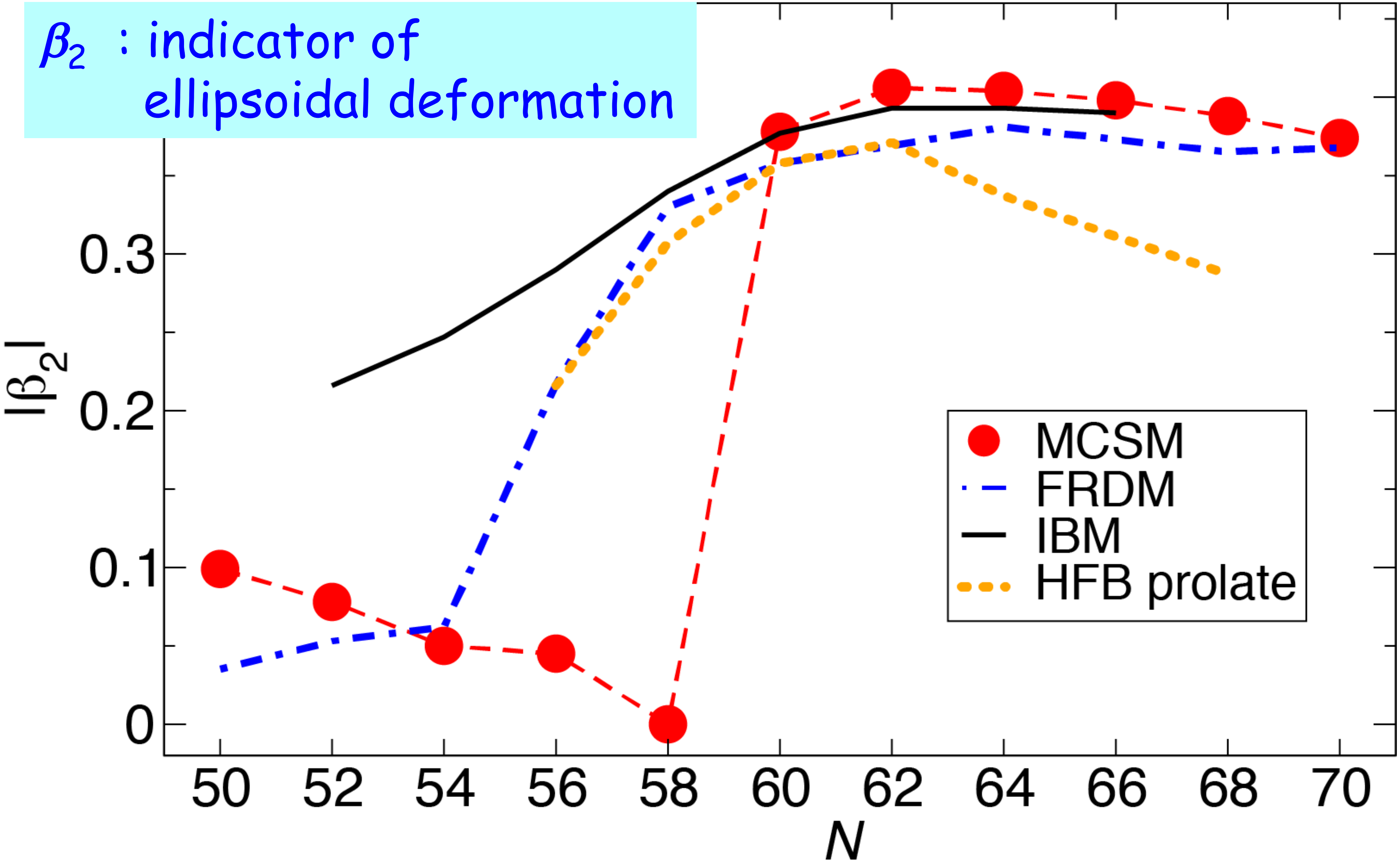
PRL 117, 172502 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

Quantum Phase Transition in the Shape of Zr isotopes

Tomoaki Togashi,[1] Yusuke Tsunoda,[1] Takaharu Otsuka,[1,2,3,4] and Noritaka Shimizu[1]



β_2 : indicator of ellipsoidal deformation



FRDM: S. Moeller et al. At. Data Nucl. Data Tables 59, 185 (1995).

IBM: M. Boyukata et al. J. Phys. G 37, 105102 (2010).

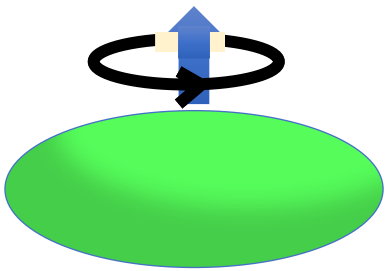
HFB: R. Rodriuez-Guzman et al. Phys. Lett. B 691, 202 (2010).

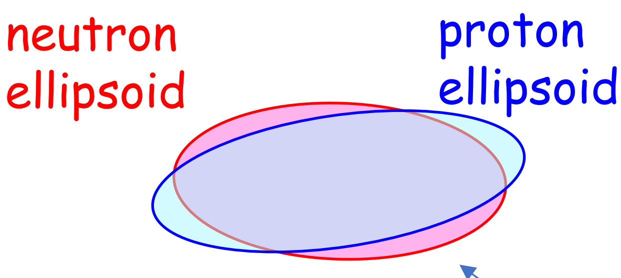
Beautiful regularities arise.

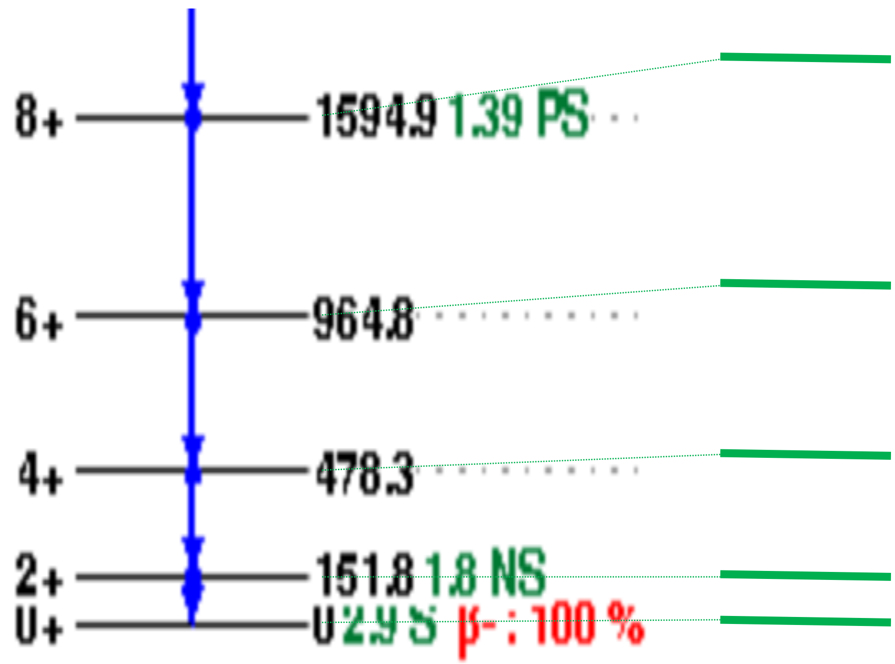
Example :
Rotational band in ^{102}Zr

exp.

Quantized rigid rotor
$E_x(J) \propto J\,(J+1)$



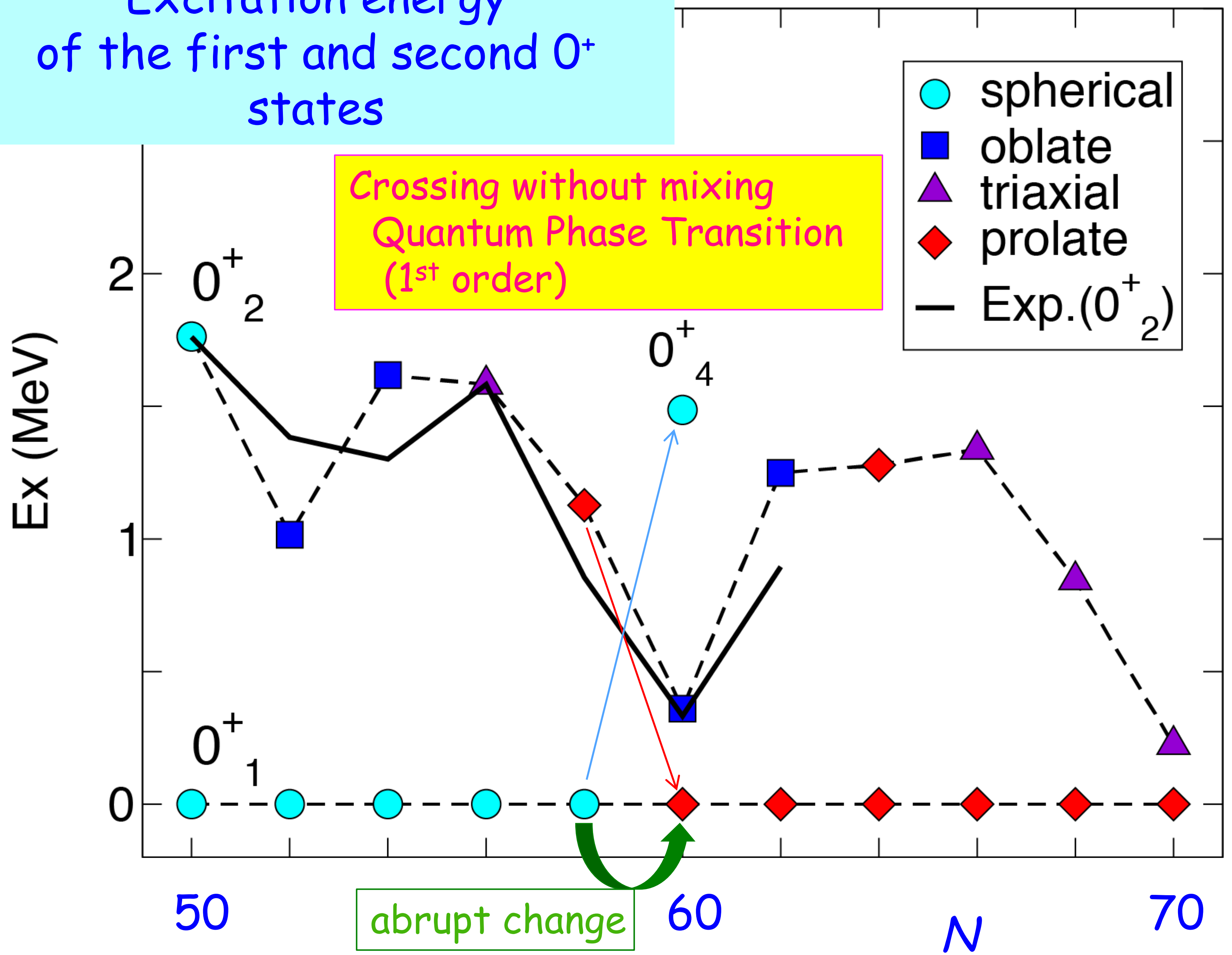


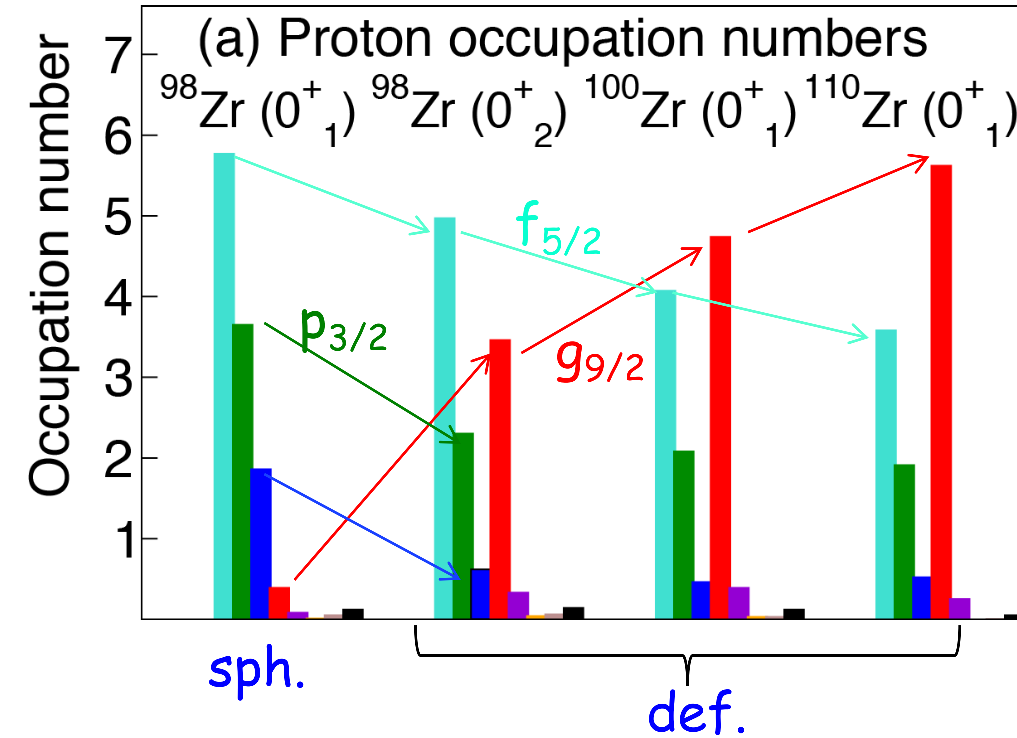


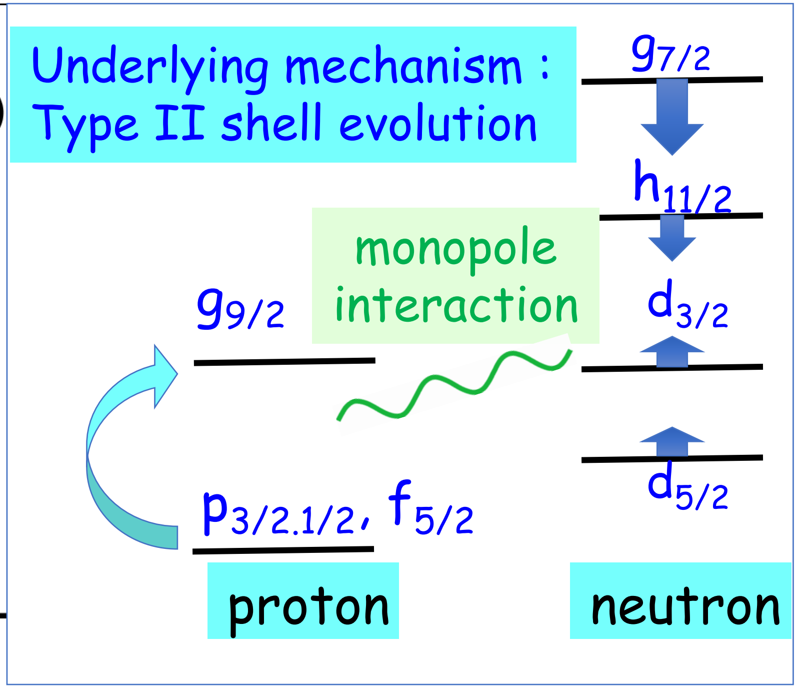
Origin : proton-neutron quadrupole-quadrupole interaction

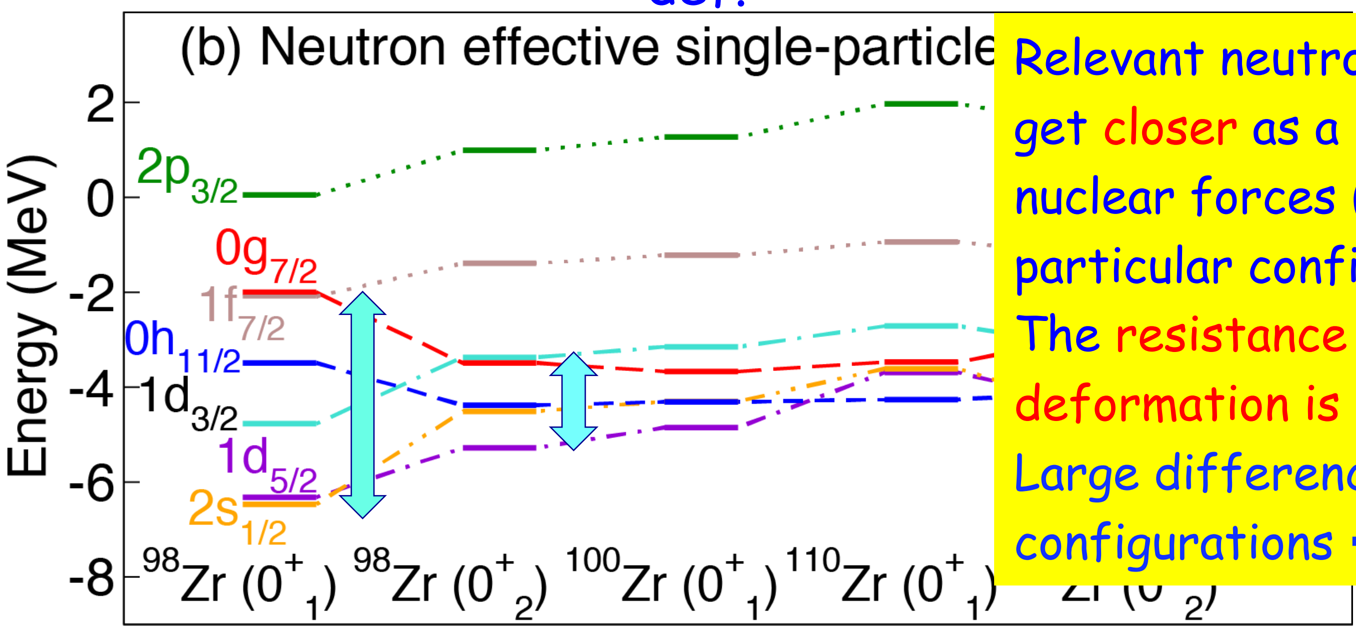
This is not the whole story !

Excitation energy of the first and second 0^+ states









Relevant neutron single-particle levels get closer as a combined effect of nuclear forces (tensor and central) and particular configurations.

The resistance power against deformation is then reduced.

Large difference in ESPEs and configurations ➔ crossing w/o mixing

This is one of the cases of

Quantum Self Organization

$$\text{deformation} = \frac{\text{quadrupole force}}{\text{resistance power}}$$

resistance power ← pairing force

↖ single-particle energies

Atomic nuclei can "organize" their single-particle energies by taking particular configurations of protons and neutrons optimized for each eigenstate, thanks to orbit-dependences of monopole components of nuclear forces (*e.g.*, tensor force).

→ an enhancement of Jahn-Teller effect.

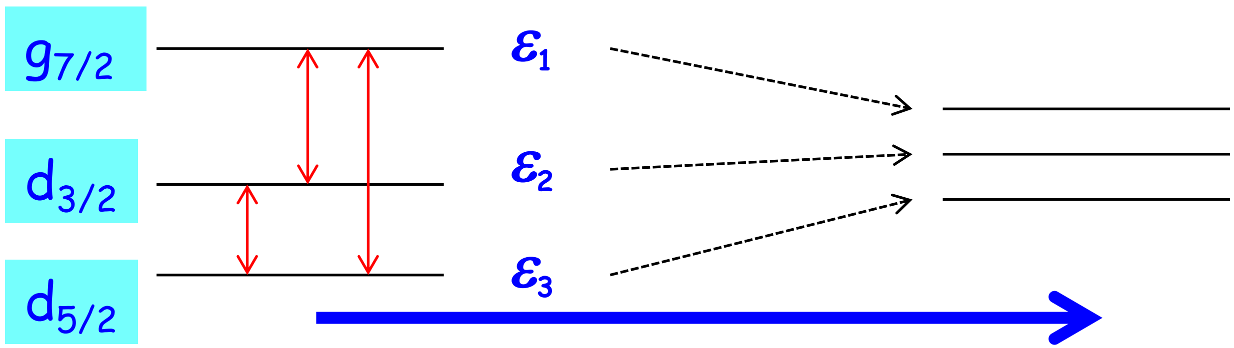
Reminder : Jahn–Teller effect for nuclear deformation

(Self-consistent) quadrupole deformed field $\propto Y_{2,0}(\theta,\phi)$
mixes the orbits below

$$\Psi(J_z=1/2) = c_1\,|g_{7/2}; j_z=1/2\rangle + c_2\,|d_{3/2}; j_z=1/2\rangle + c_3\,|d_{5/2}; j_z=1/2\rangle$$

stronger mixing = larger quadrupole deformation

Mixing depends not only on the strength of the $Y_{2,0}(\theta,\phi)$ field,
but also the spherical single-particle energies ε_1, ε_2, ε_3, etc.

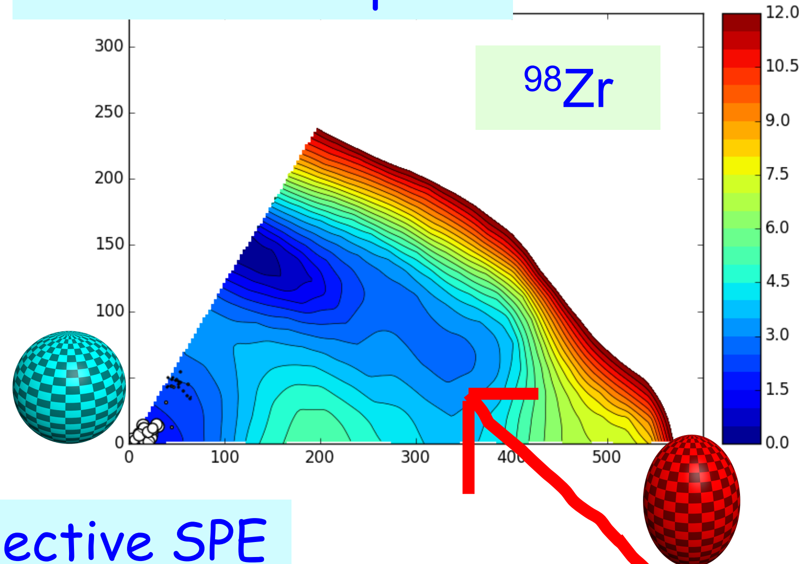


closer to degeneracy, large deformation

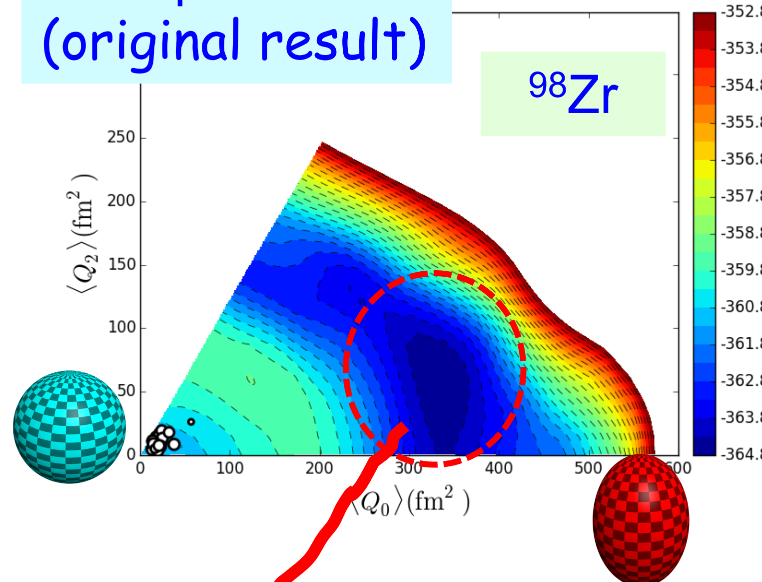
Note: single-particle states are enemies against collective modes
if their splitting is too large

Anatomy of this effect : Freezing this monopole effect

Frozen monopole

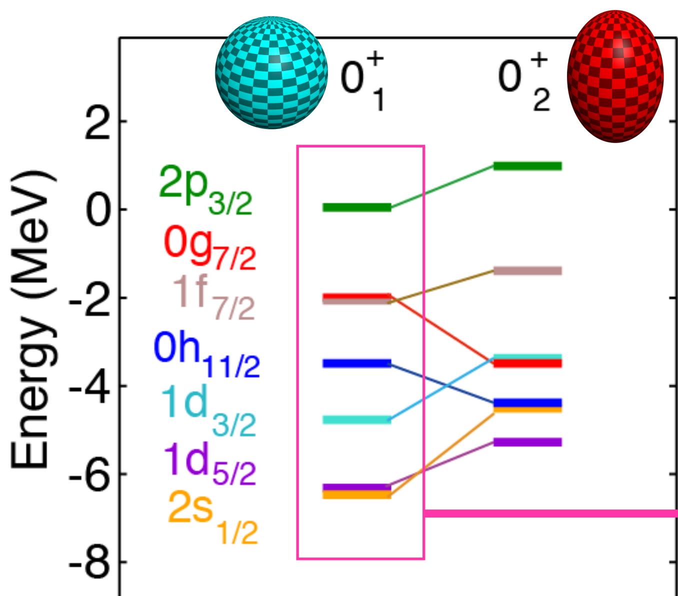


monopole active
(original result)



energy minimum for ellipsoid is gone

Effective SPE



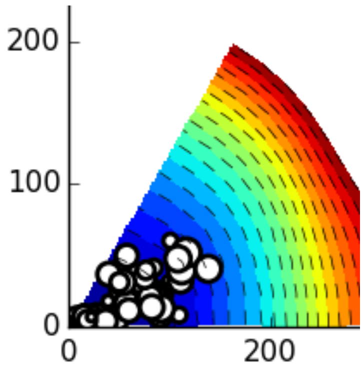
Use them as constant single-particle energies *independent of configurations, putting monopole int. aside*
➔ Frozen monopole treatment

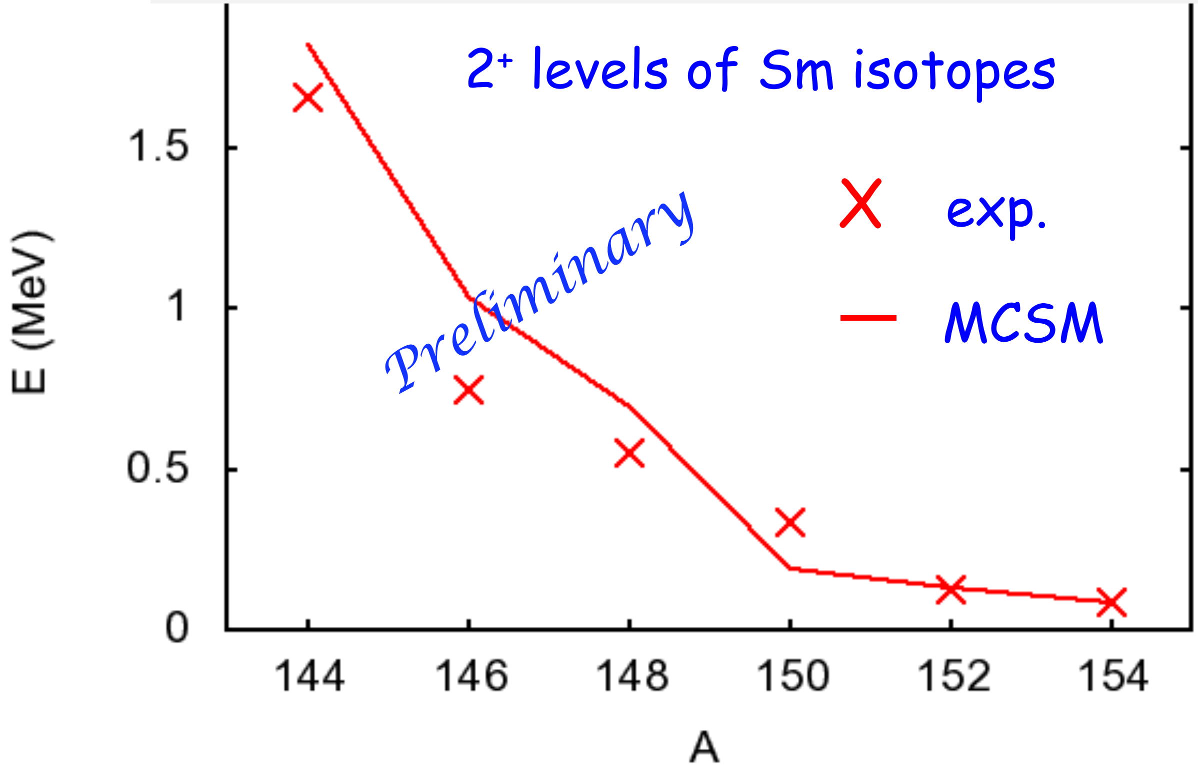
Sm isotopes

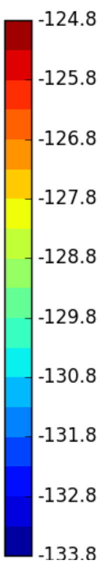
proton 8 orbits
neutron 10 orbits

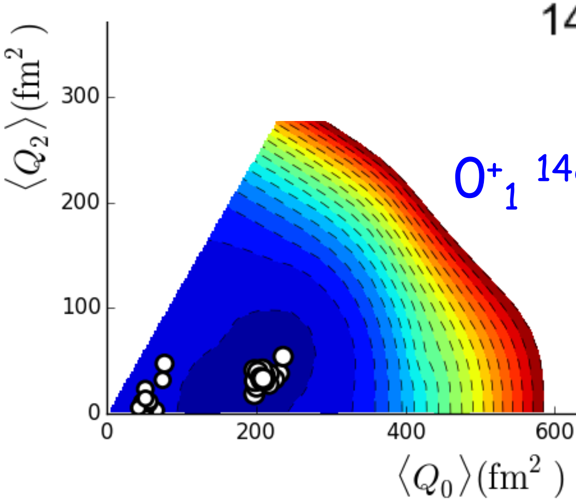
Interaction VMU (gaussian central + π+ρ tensor)

0^+_1 ^{144}Sm



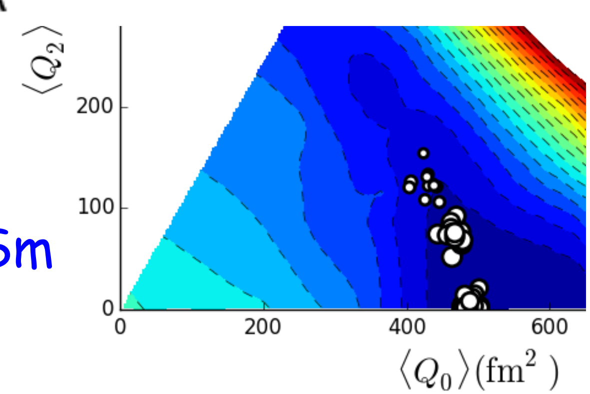


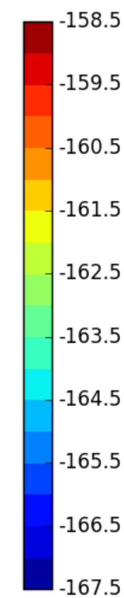




0^+_1 ^{148}Sm

0^+_1 ^{154}Sm





$$\text{deformation} = \frac{\text{quadrupole force}}{\text{resistance power}}$$

resistance power ← pairing force

↖ single-particle energies

Analogy to electric current,

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

Remarks

Naïve Fermi liquid picture (a la Landau) is revised, as *atomic nuclei are not necessarily like simple solid vases containing almost free nucleons*.

Nuclear forces are rich enough to optimize single-particle energies for each eigenstate (especially in the cases of collective-mode states), as referred to as quantum self-organization.

The quantum self-organization produces sizable effects with
(i) two quantum fluids (protons and neutrons),
(ii) two major forces : *e.g.*, quadrupole interaction to drive collective mode
monopole interaction to control resistance

Quantum phase transition, shape coexistence, various deformation, fission, … are releted to the quantum self-organization.

Thus, non-specific forces work coherently so that the beauty of the collective modes is achieved or enhanced : single-particle states are not always enemies but friends of collective modes.

Time-dependent version for reactions is of great interest (e.g., fission).
A more intriguing topic is a possible relation to biological evolution.