Int. Symp. on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2020)

Beppu
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Self-organization of quantum systems and nuclear collectivity

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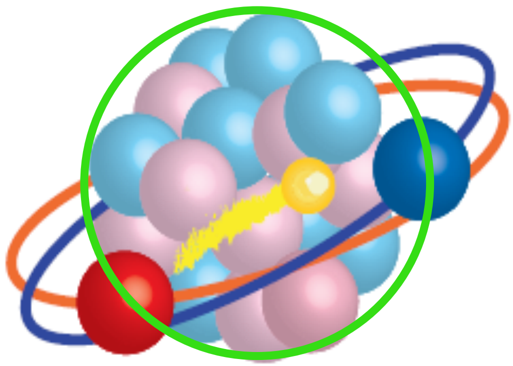
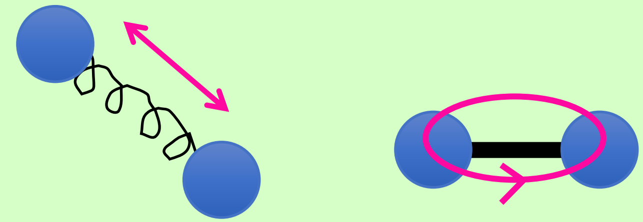
This work has been supported by MEXT and JICFuS as a priority issue (Elucidation of the fundamental laws and evolution of the universe) to be tackled by using Post 'K' Computer.

Nuclear surface

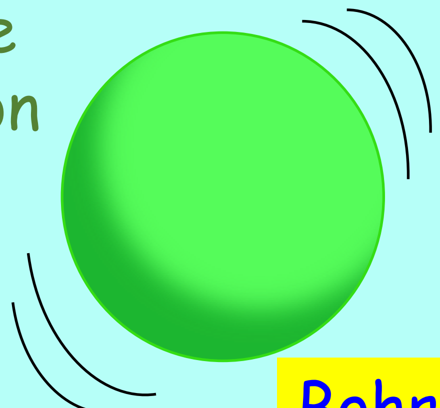


vibration or rotation of molecules

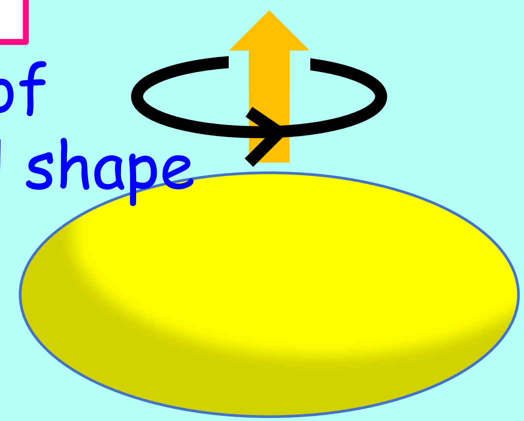


Nuclear Collectivity

Surface vibration



Rotation of ellipsoidal shape



Bohr-Mottelson-Rainwater showed that the nucleus can be an ellipsoid.

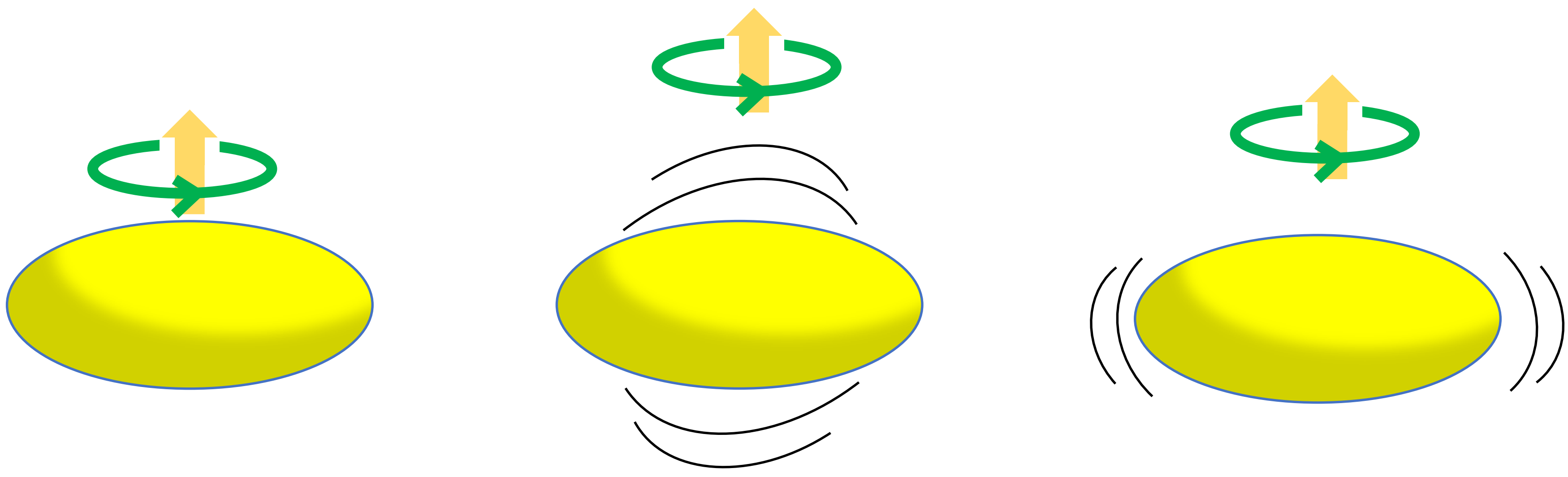
➔ characteristic patterns of excitation energies of many-body systems

Basic picture (*a la* Bohr & Mottelson)

Ground state : ellipsoid

Low-lying excited states : vibrations around the ellipsoid

Rotational motion is added on top of the vibrations.

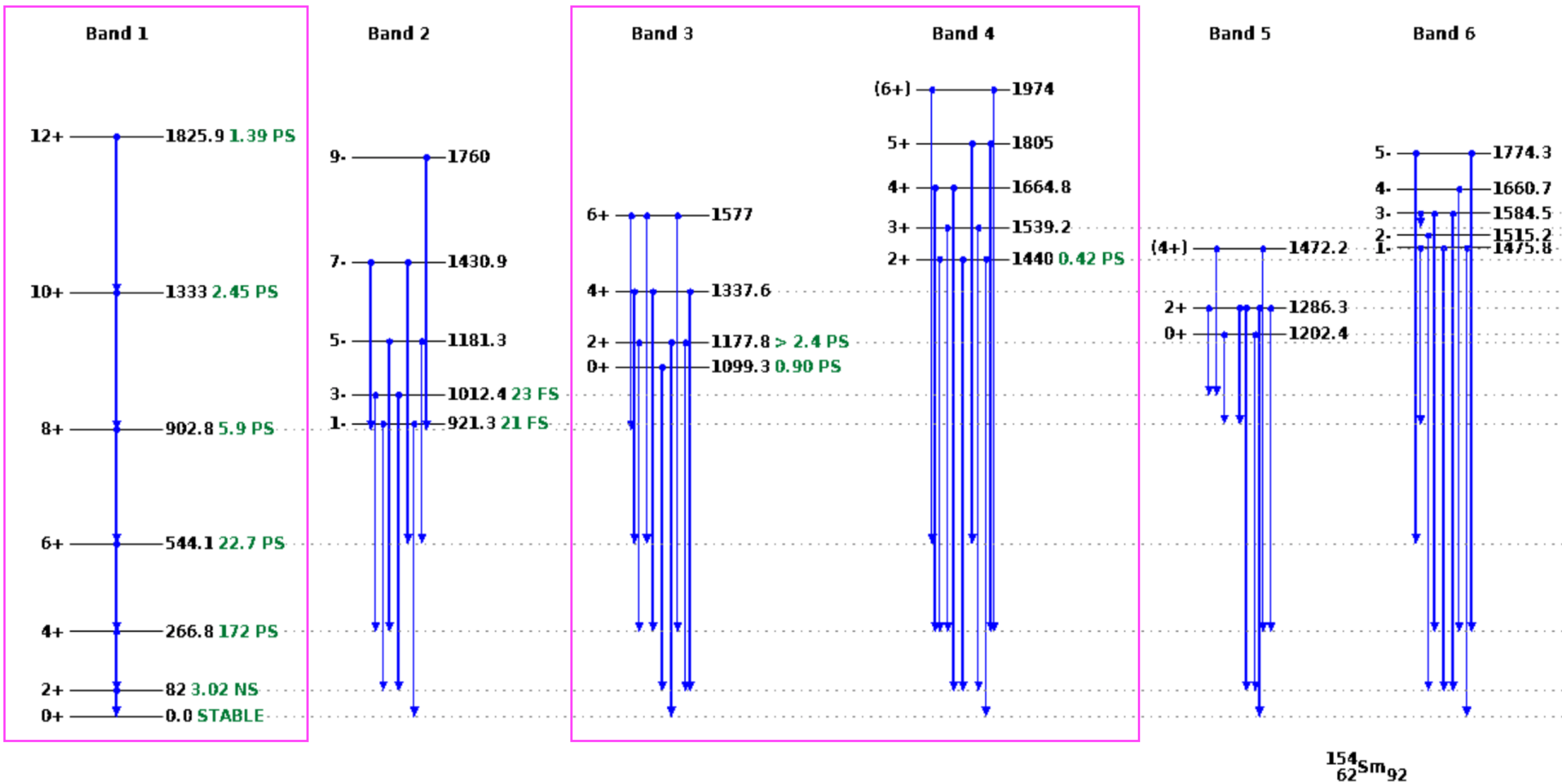


ground state — γ vibration — β vibration

ground band — γ band — β band

Examples of rotational bands : ^{154}Sm

experiments (nudat2)



$K^{\pi}=0^{+}$ ground band

$K^{\pi}=0^{-}$

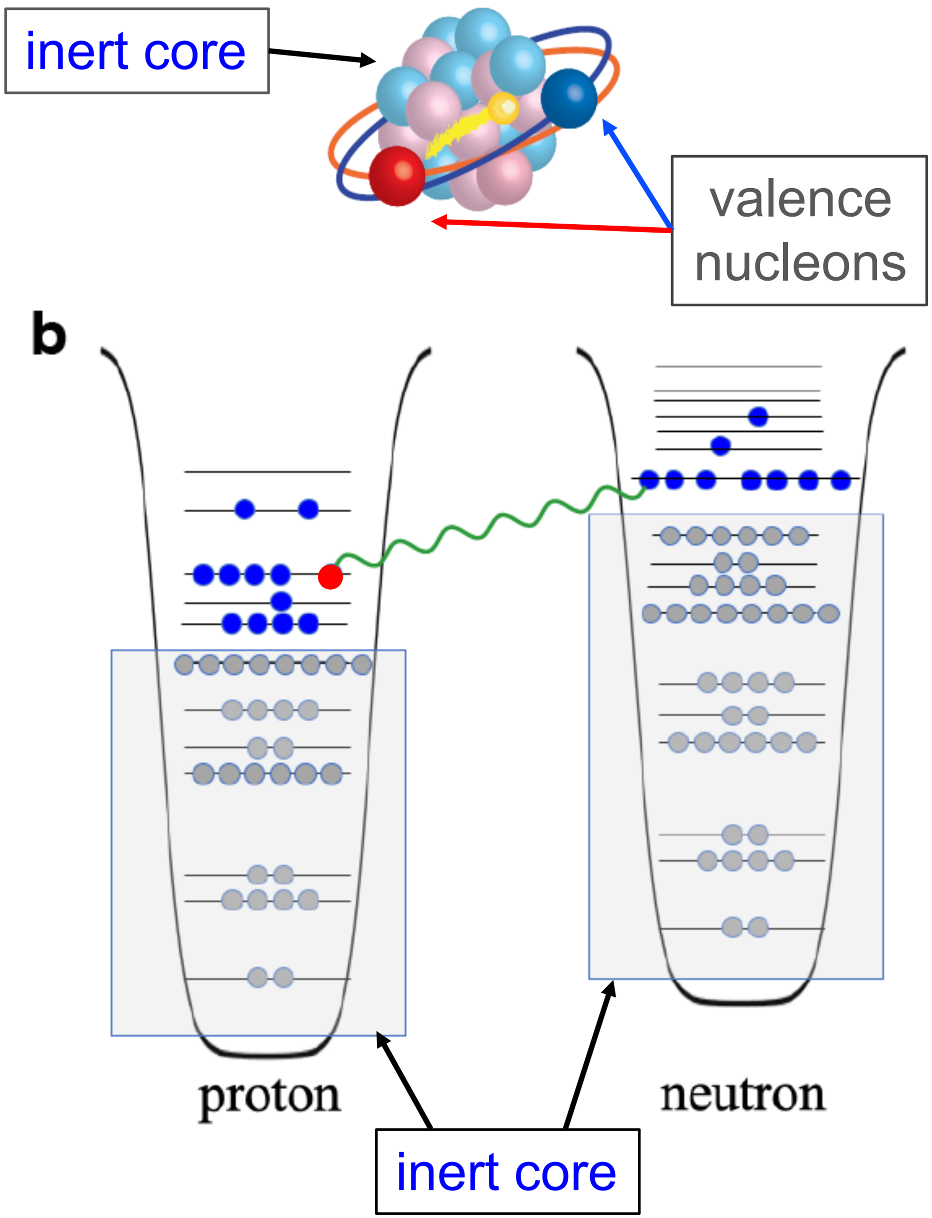
$K^{\pi}=0^{+}$ β-band

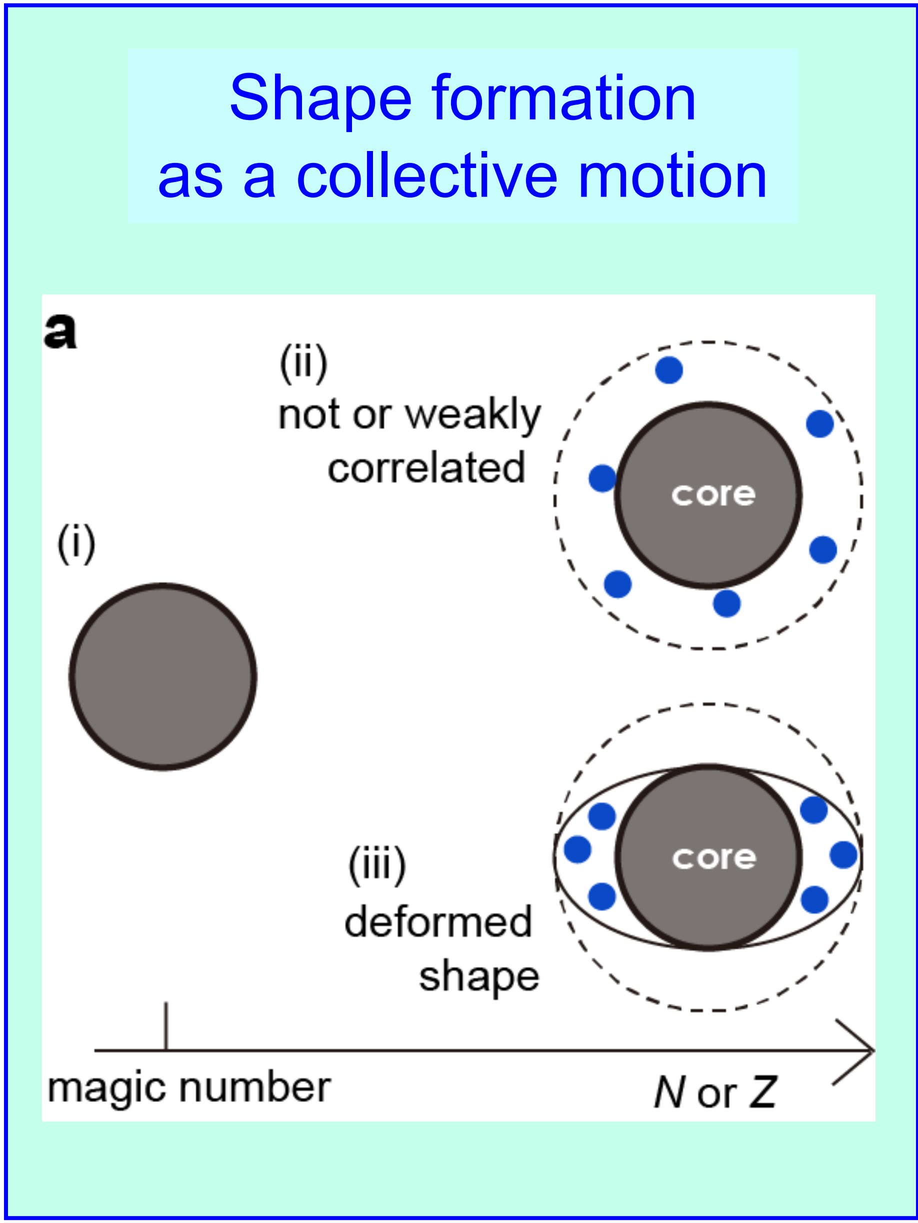
$K^{\pi}=2^{+}$ γ-band

$K^{\pi}=0^{+}$

$K^{\pi}=1^{-}$

Single-particle states and correlations in atomic nuclei

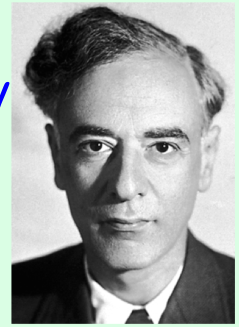




Single-particle states vs. collective modes : an old and still open question
Are they simply competing each other ?

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 described by the deformation of the "vase", a la Nilsson model.

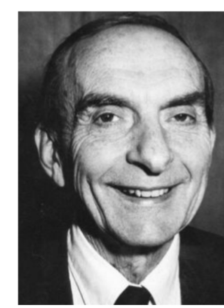

A. Bohr


Mottelson


Nilsson

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

calc. by Y. Tsunoda

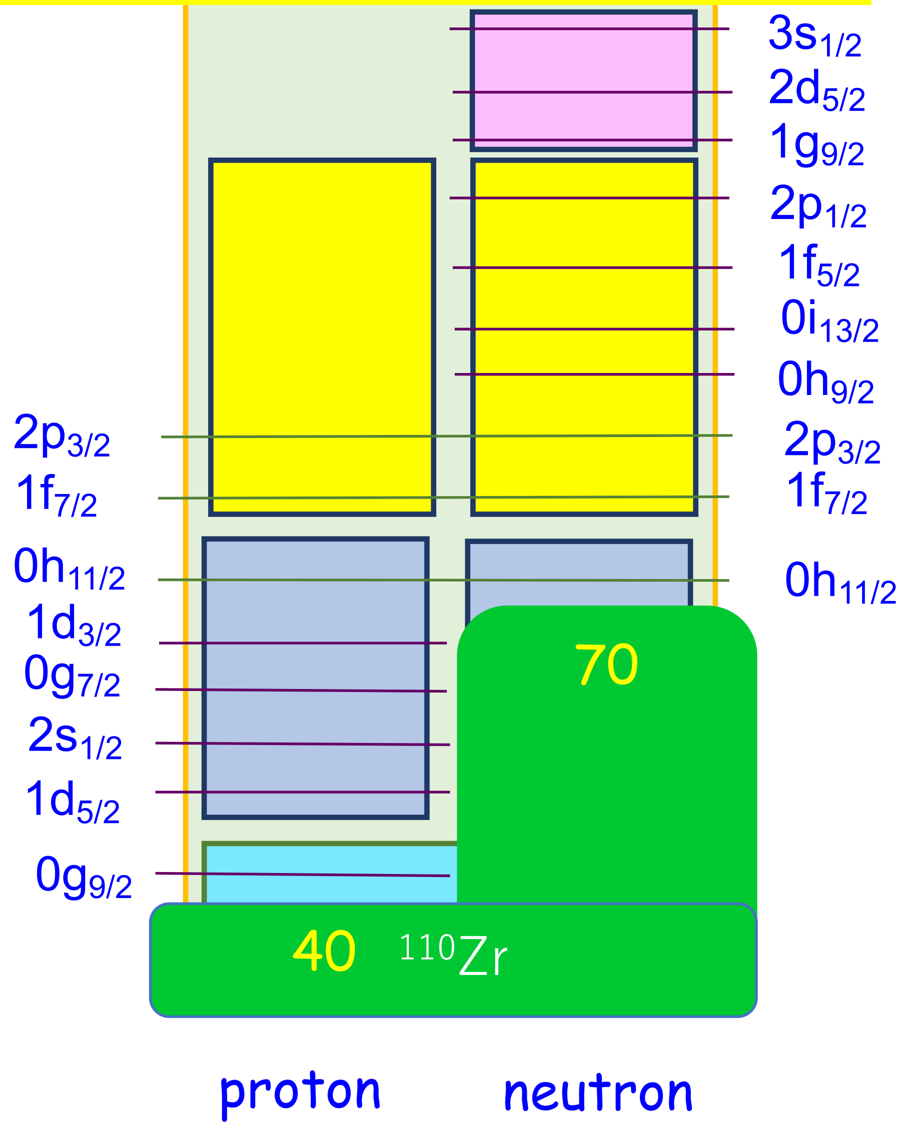
Sm isotopes by Monte Carlo Shell Model (MCSM)

- Effective interaction:
  G-matrix* + V_{MU}

  * Brown, PRL 85, 5300 (2000)

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 3.9×10^{31} dimension matrix.



PHYSICAL REVIEW LETTERS **123**, 222502 (2019)

Editors' Suggestion

Underlying Structure of Collective Bands and Self-Organization in Quantum Systems

T. Otsuka,[1,2,3,*] Y. Tsunoda,[4] T. Abe,[4] N. Shimizu,[4] and P. Van Duppen[3]

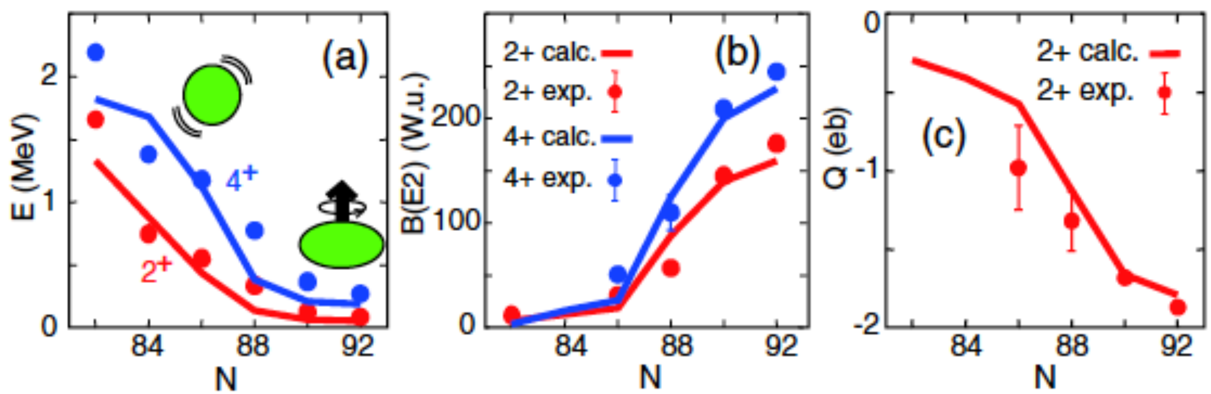
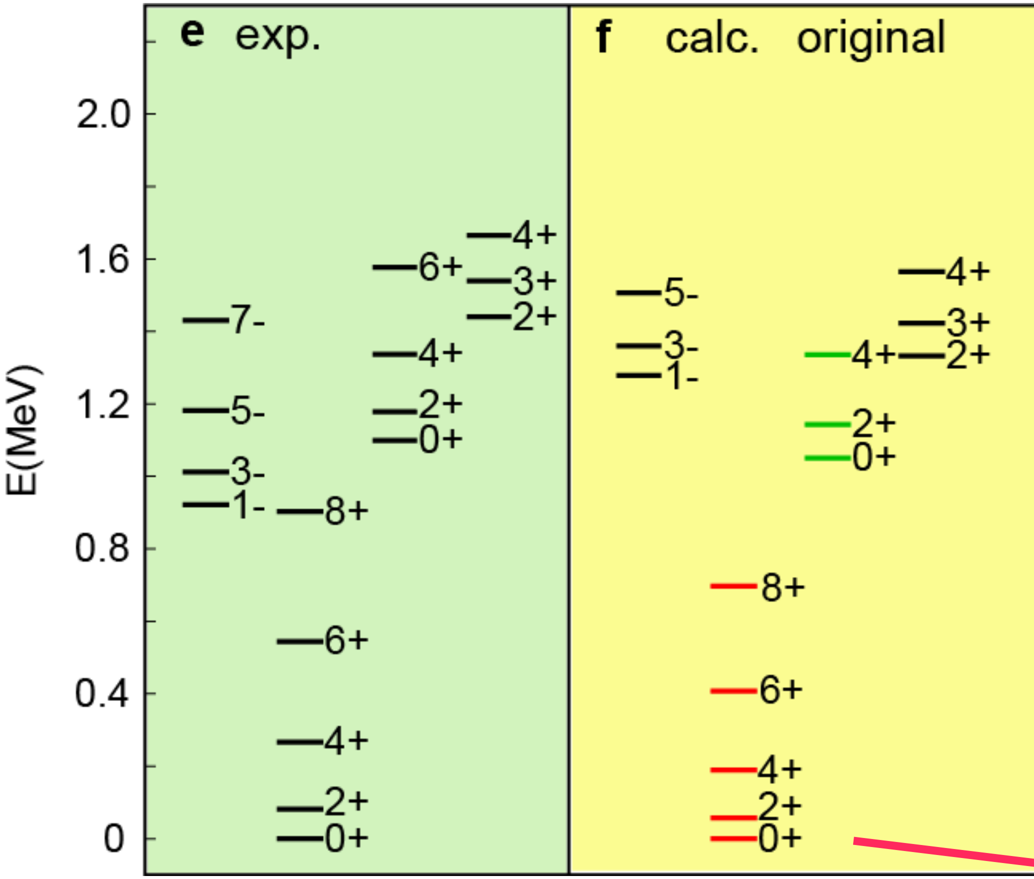


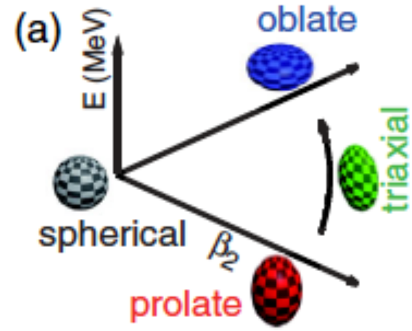
FIG. 1. Systematic changes of the 2_1^+ and 4_1^+ levels in Sm isotopes, as functions of N. (a) Energy levels [25], (b) $B(E2;2_1^+ \to 0_1^+)$ and $B(E2;4_1^+ \to 2_1^+)$ values [25], and (c) spectroscopic electric quadrupole moment of the 2_1^+ state [26].

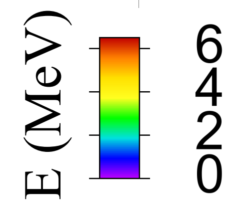
The ground band

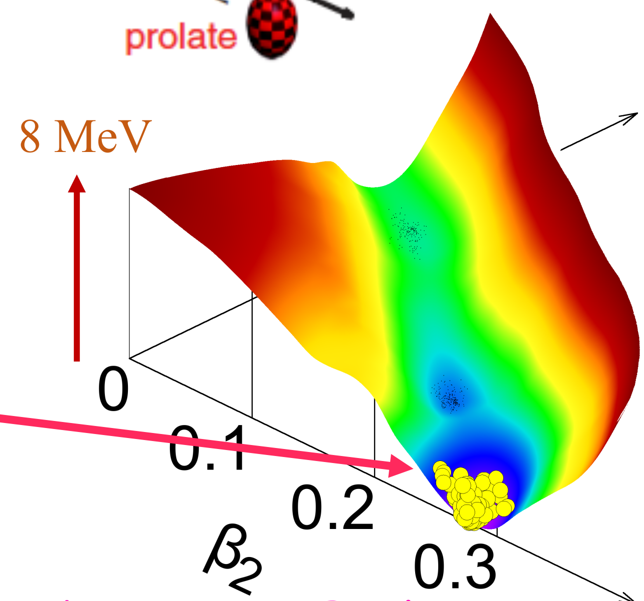
Exp. Calc.



Yellow circles are major components of the CI (MCSM) wave function.





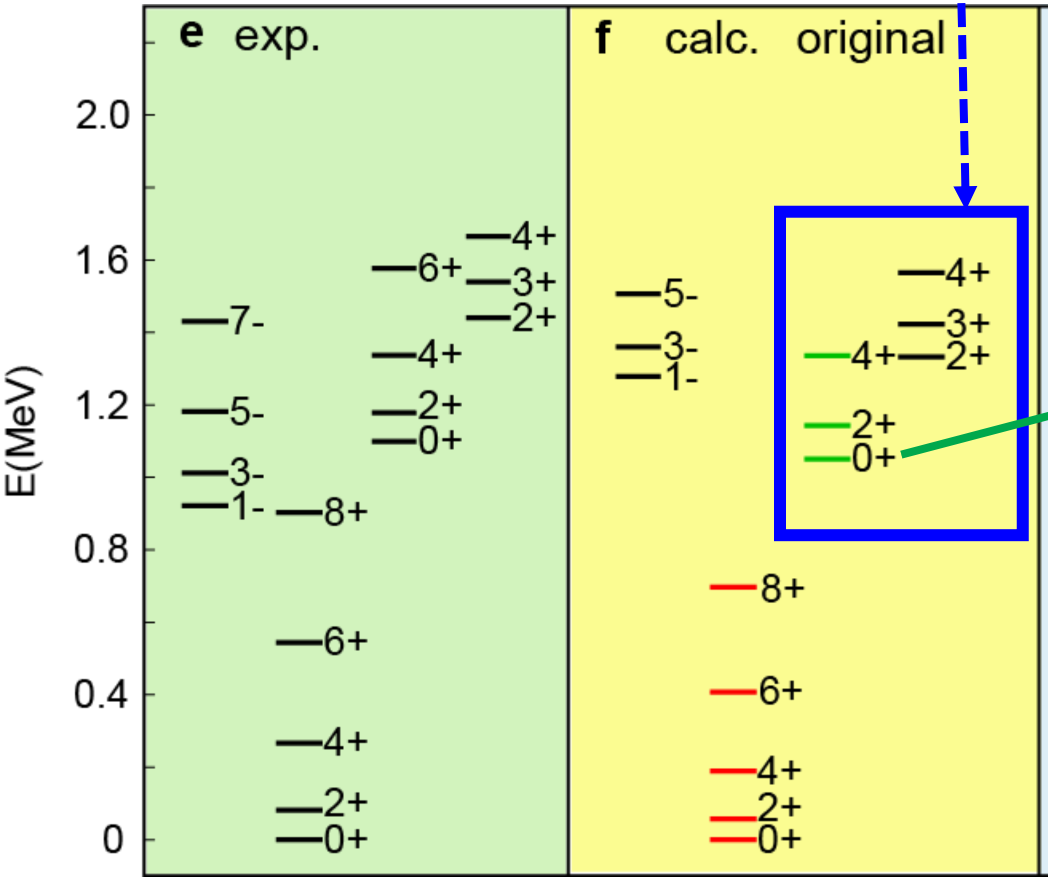


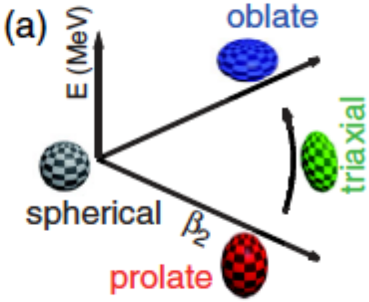
Energy Surface
obtained by constrained Hartree-Fock

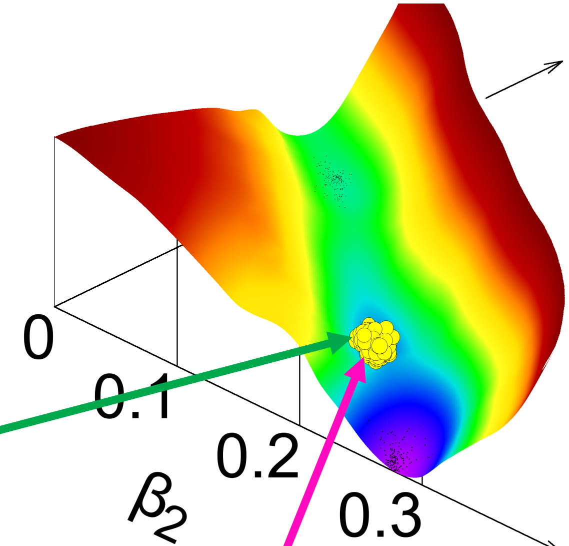
What are those side bands ?

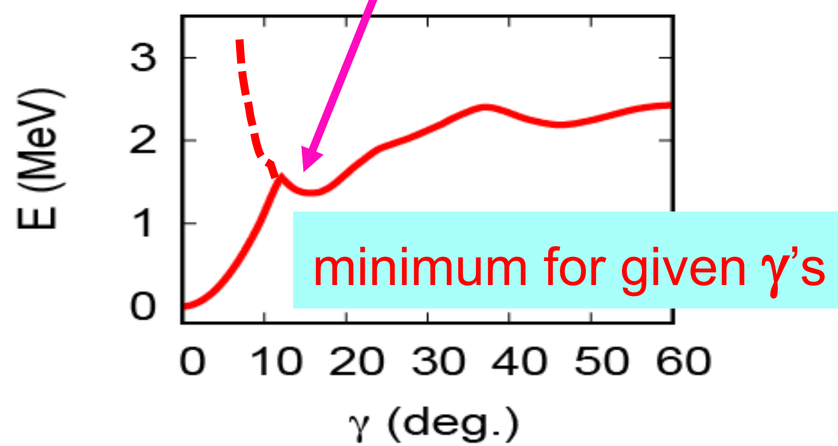
Very different from the traditional view

Exp.　　　　Calc.









Another key underlying mechanism

Monopole interaction

A component of effective *NN* interaction

Effects can be expressed as $v(j, j') \, n_j \; n_{j'}$ （ j, j' : orbits）

Effective Single-Particle Energy (ESPE)

$v(j, j') < n_j > \; n_{j'}$ ➡ change of the energy of the orbit **j'**

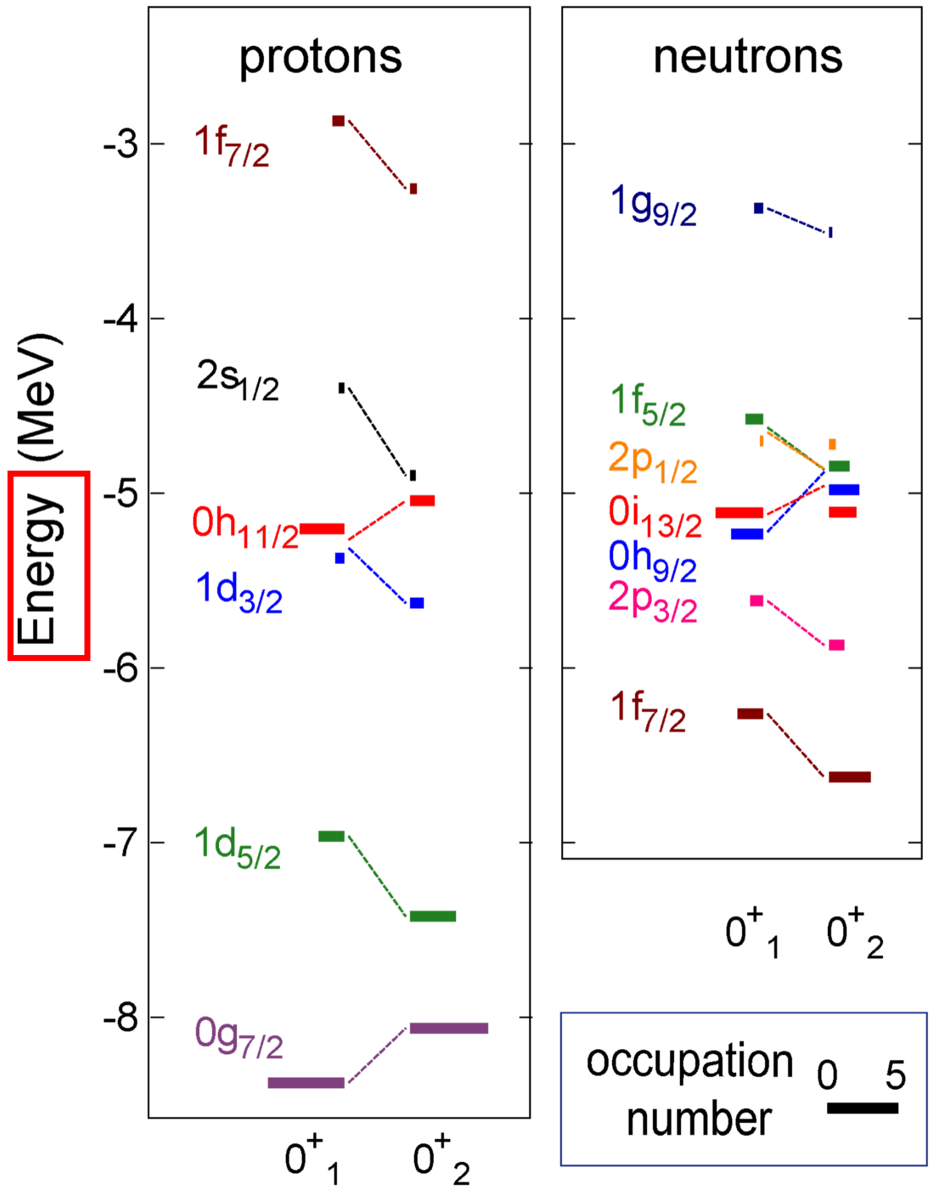
Expectation value with respect to the relevant many-body state

$v(j, j')$ shows strong **j** and **j'** dependences

→ pattern of single-particle energies (shell structure) changes depending on occupation numbers of orbits

Effective Single-Particle Energy (ESPE) and Occupation Number

vertical position *horizontal width*



ground band and "β" band in ^{154}Sm

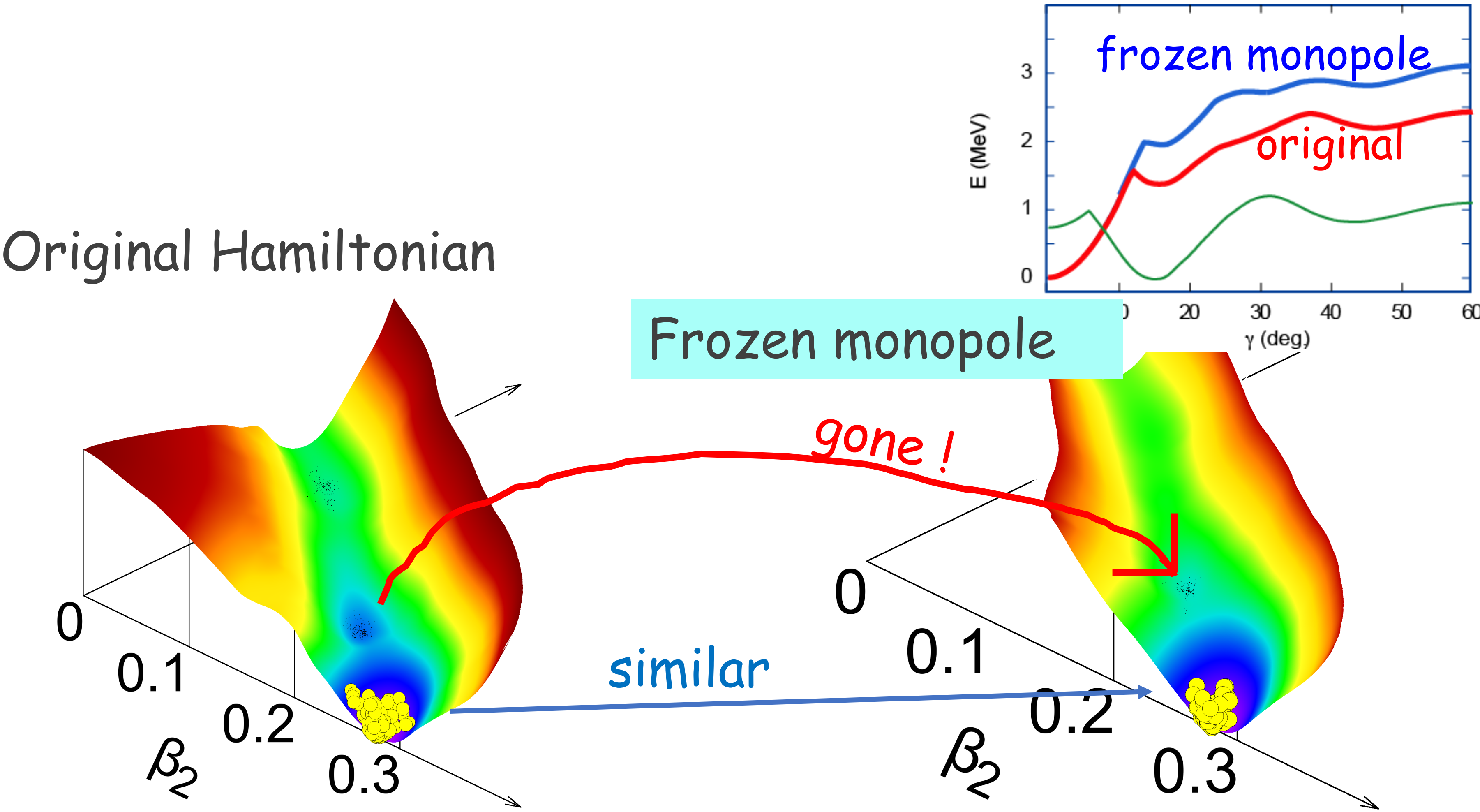
In general,
single-particle energies are optimized effectively, so that each collective band gains more binding energy differently.

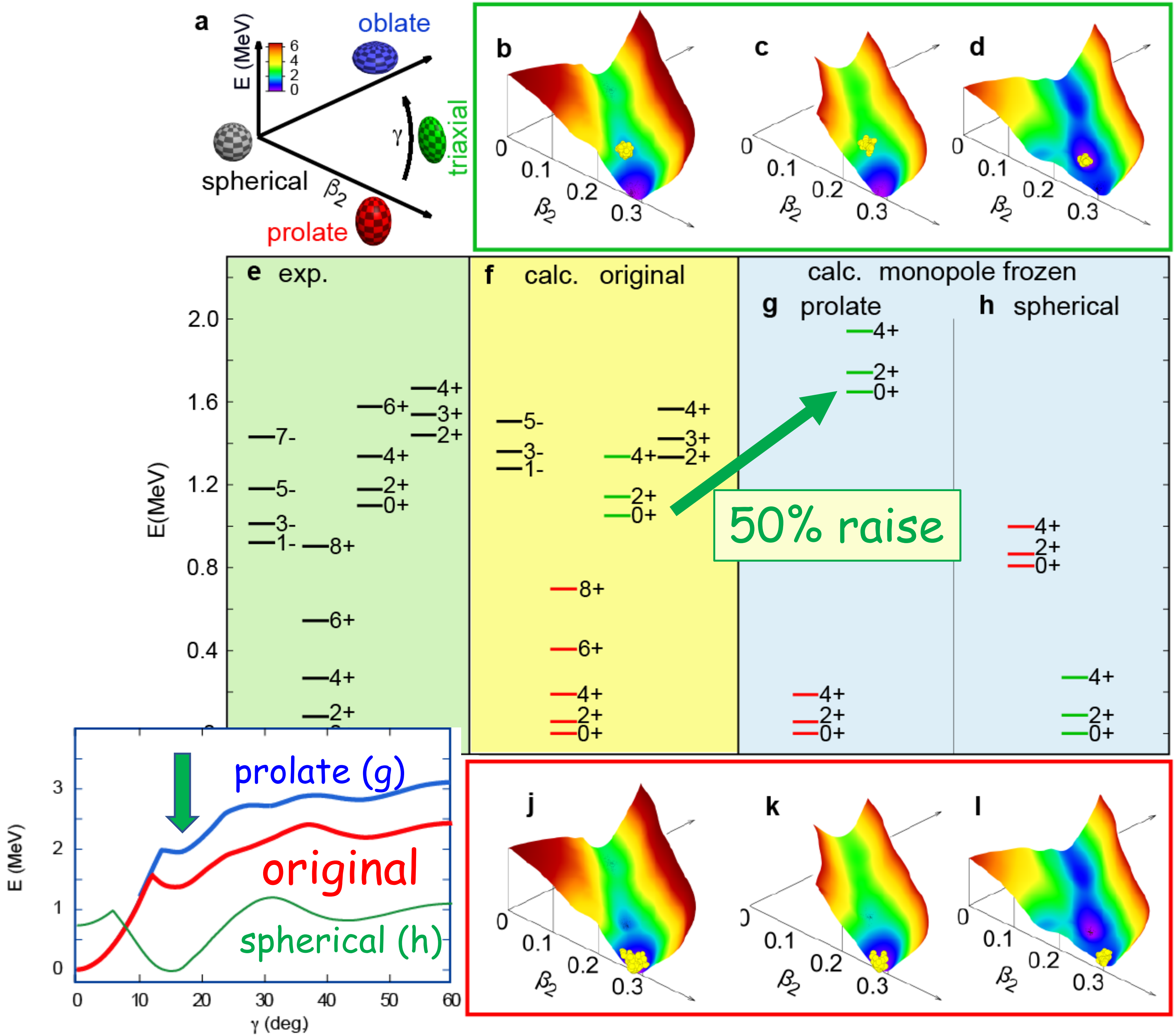
➔ Shell structure tailored to each collectivity

Analysis by Freezing Monopole interaction

Remove monopole component from the *NN* interaction.

Use ESPEs of the original 0^+_1 state as input (bare) SPEs.



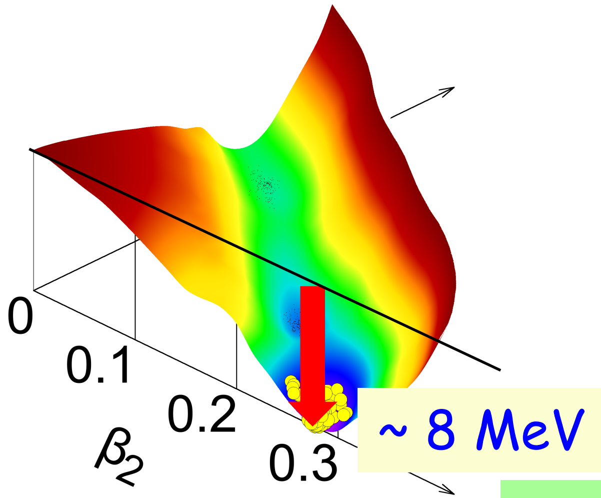


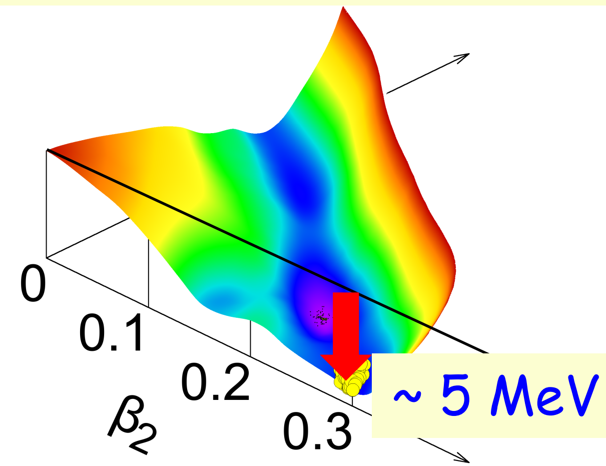
a
E (MeV)
oblate
spherical
triaxial
prolate
b
c
d
e exp.
f calc. original
calc. monopole frozen
g prolate
h spherical
E(MeV)
50% raise
prolate (g)
original
spherical (h)
E (MeV)
γ (deg)
j
k
l

Freezing the monopole interaction,

Original Hamiltonian

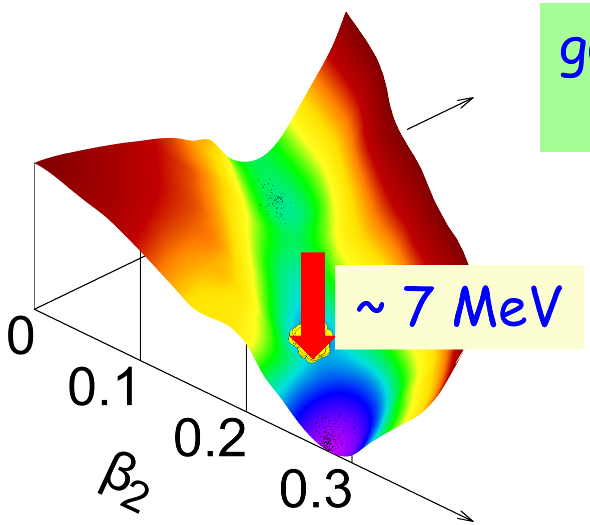
Monopole-frozen at spherical limit

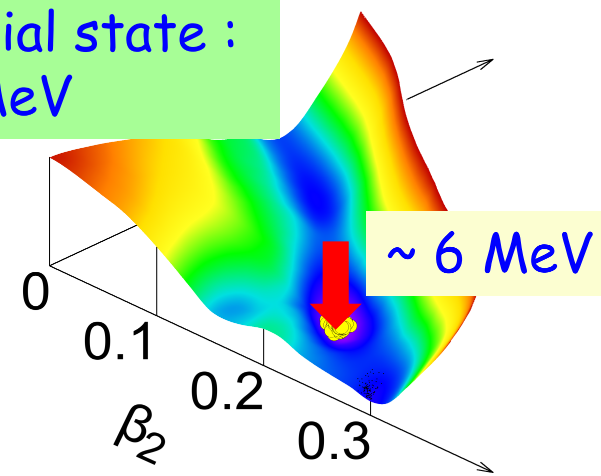




gain for prolate state :
~ 3 MeV

gain for triaxial state :
~ 1 MeV





Optimization of single-particle energies is crucial

The self-organization is a process in natural and social sciences. Some order arises in response to a change of external force (environment) due to the interaction between ingredients.

single-particle energy : resistance against collective mode in general

Combining monopole interaction and occupation pattern, this resistance can be reduced, and a transition disorder → order occurs.

"order" means tailored effective single-particle energies

Two components of interaction (classification by their functions)

quadrupole interaction : to drive mode (*or* deformation)

monopole interaction : to control resistance

Two kinds of ingredients (protons and neutrons)

- positive feedback between mode and order
- the self-organization evolves purposely

A. Bohr
Novel Prize Lecture

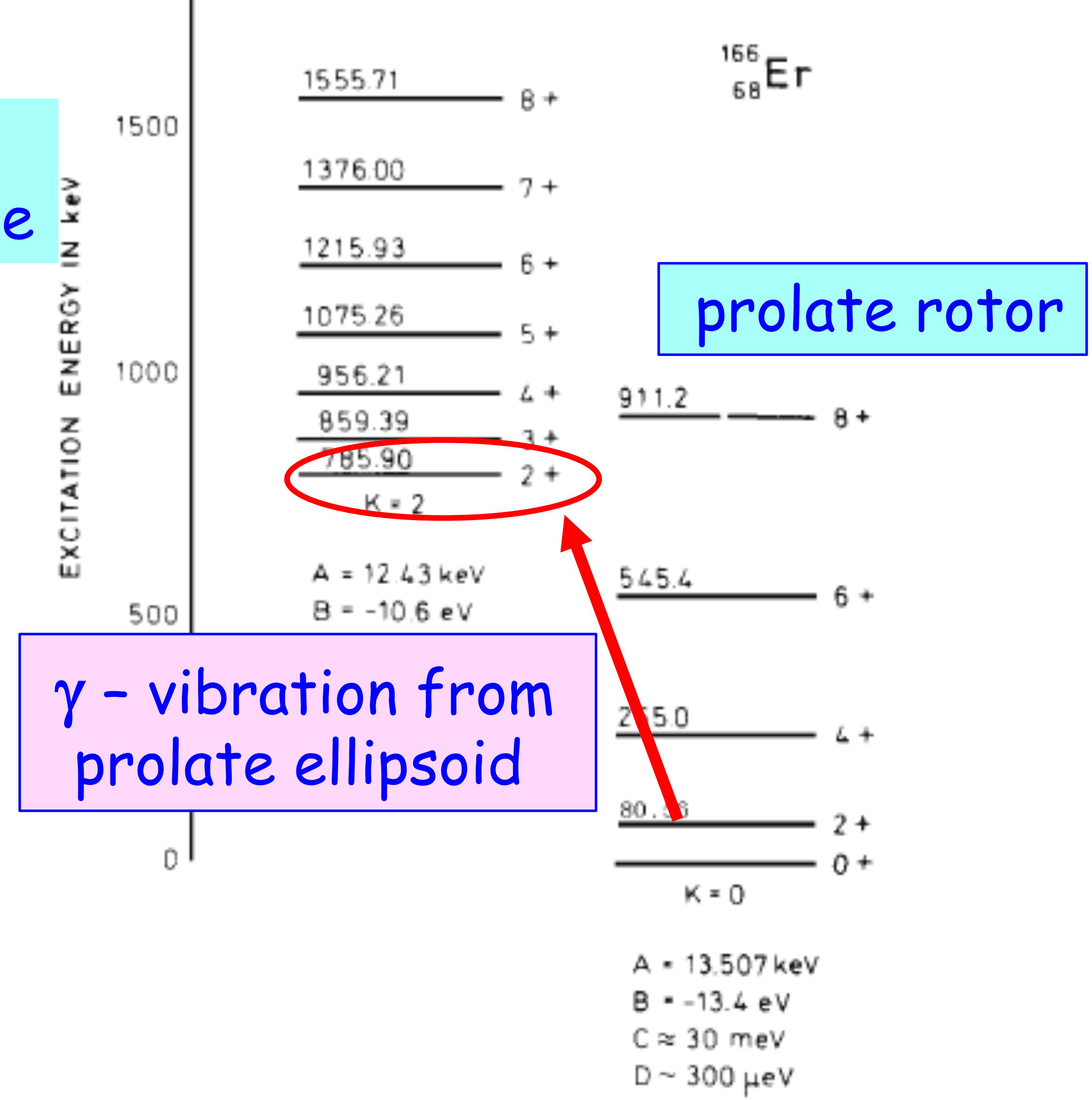


Fig. 9. Rotational bands in ^{166}Er. The figure is from (35) and is based on the experimental data by Reich and Cline (75). The bands are labelled by the component K of the total angular momentum with respect to the symmetry axis. The K = 2 band appears to represent the excitation of a mode of quadrupole vibrations involving deviations from axial symmetry in the nuclear shape.

Bohr & Mottelson, Nuclear Structure II, 1975 (Paper pub. in 1952)

(*The bible for nuclear structure*)

Two possibilities 1. Vibrational mode (likely preferred)

2. Equilibrium shape different from the ground band

Interpretation of the $K\pi = 2+$ excitation ^{166}Er

The low-energy and large $E2$-matrix element for exciting the $K=2$ band suggests that we are dealing with a collective mode involving deviations of the nuclear shape from axial symmetry. (The $B(E2)$ value for exciting the $K=2, I=2$ state is about $28 B_W(E2)$, which is 14 times the appropriate single-particle unit (see p. 549).) Such a collective mode could have the character of a vibration around an axially symmetric equilibrium or might be associated with an equilibrium shape deviating from axial symmetry.

Nobel lecture by A. Bohr (1975) next page

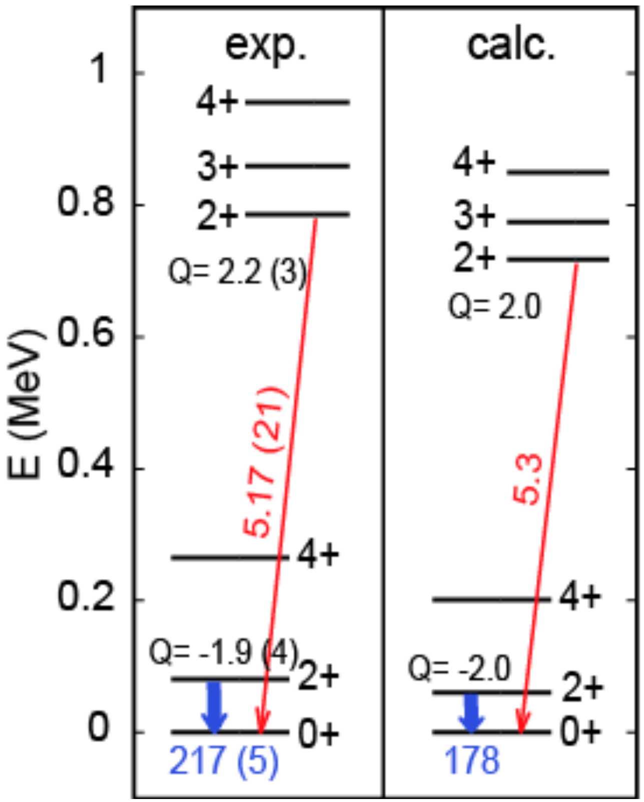
Only the possibility 1. was mentioned for ^{166}Er.

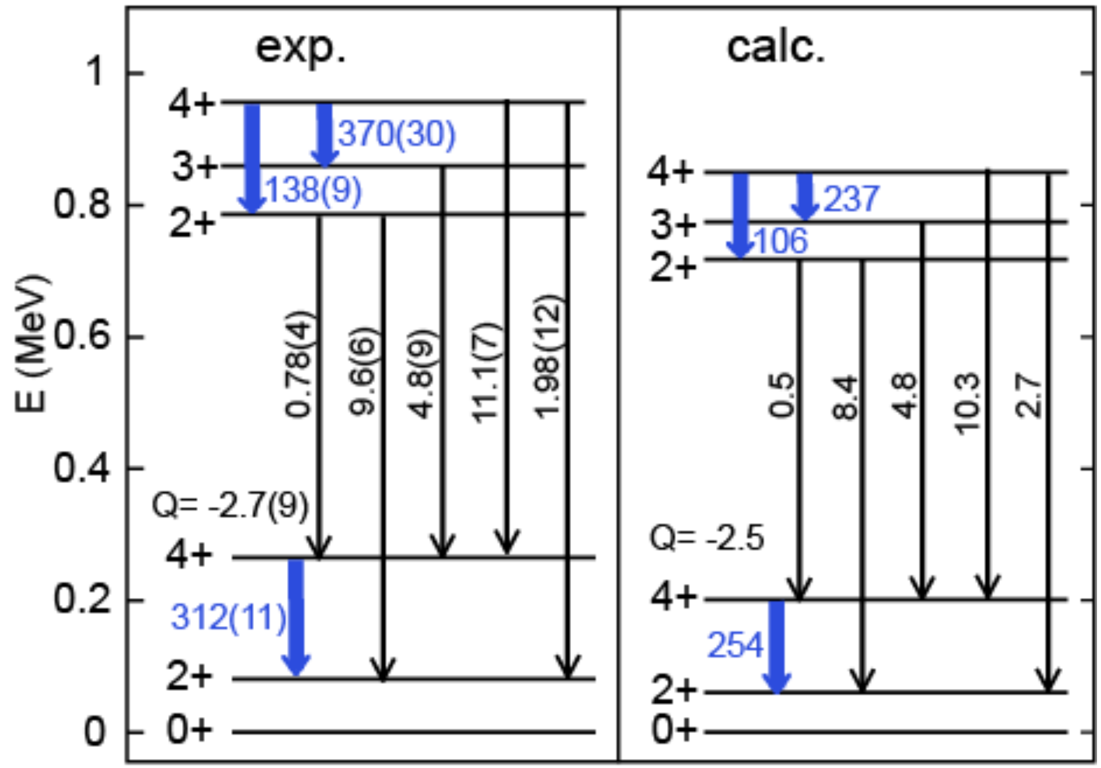
No (serious) discussions on the possibility 2 for half a century.

^{166}Er : ground and K=2$^+$ bands

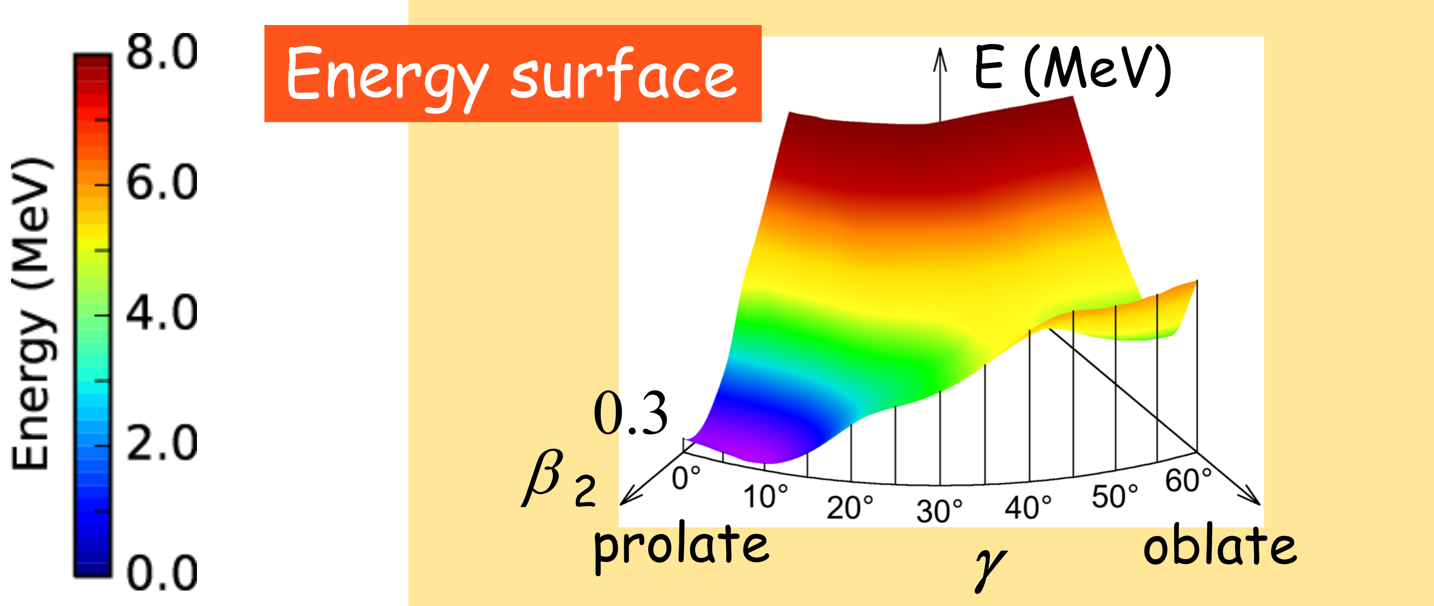
In Bohr-Mottelson' picture

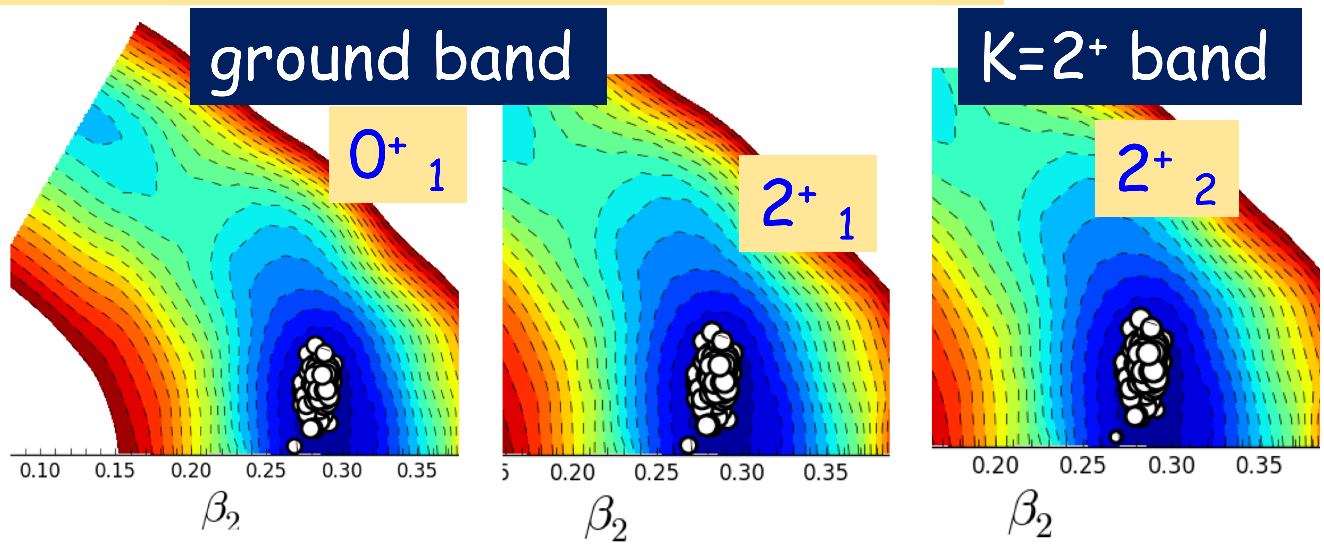
γ-vibration because of relatively strong E2 transition



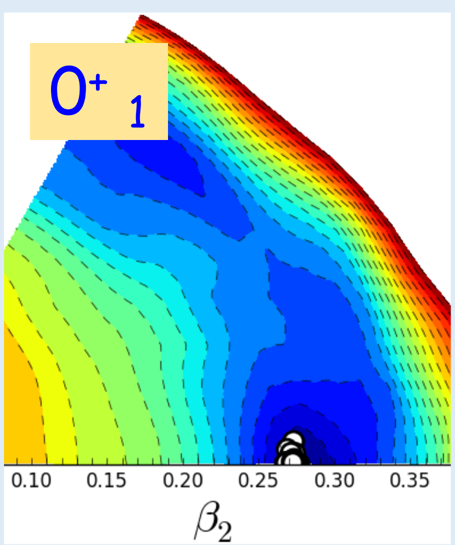


Resemblance to Davydov-Filippov model





Monopole frozen at spherical limit
→ prolate 0^+_1



All these states belong to a "gamma-wide" potential minimum with substantial fluctuations, due to the present interplay.

Summary

Landau's Fermi Liquid picture in its most naïve expression may not be the whole story for atomic nuclei.

Nuclear forces are rich enough to optimize (tailor) single-particle energies to each eigenstate (especially for collective-mode states), as referred to as quantum self-organization. It produces sizable effects with

(i) two quantum fluids (protons and neutrons),
(ii) two major forces : *e.g.*, quadrupole interaction to drive mode
monopole interaction to control resistance

Their effects can be coherent in many-body systems.

It sheds light on the β/γ vibration model, a leading idea for ~70 years.

Prospects

- diversity in the appearance: Ni, Zr and Hg (staggering) …
- greater importance for heavier nuclei due to more orbits and particles (more rooms for optimization) → superheavy nuclei & fission ?
- application of this idea to hadrons, atoms, molecules, …

Can there be a resistance-control force ?