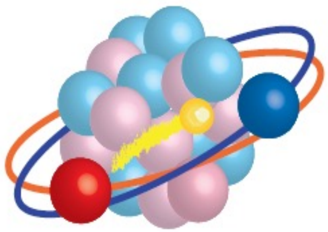


Symposium “Frontiers in Nuclear Structure Theory”
on the occasion of the 90th birthday of Prof. Jan Blomqvist
KTH, Stockholm
May 24 (23-25), 2022

Emerging concepts in nuclear structure based on the shell model (zoom)

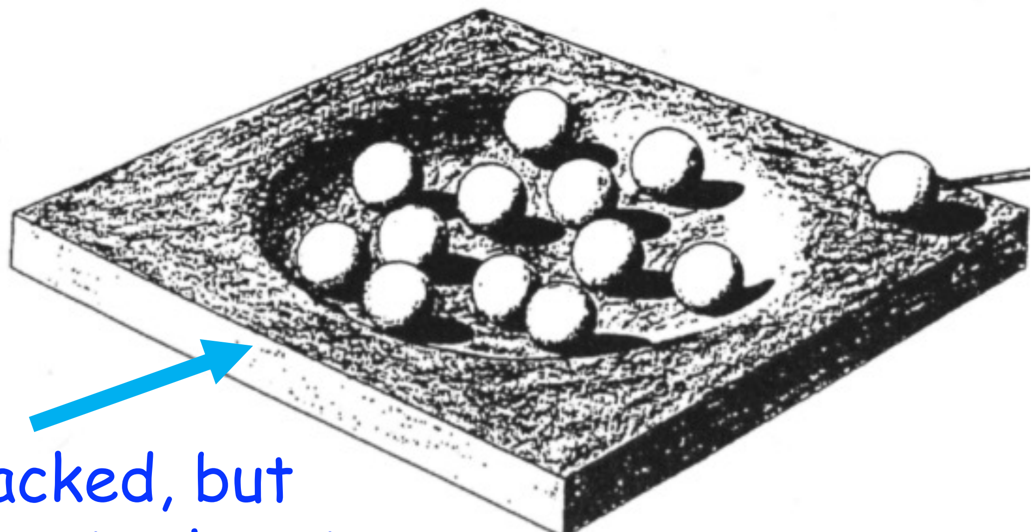
Takaharu Otsuka

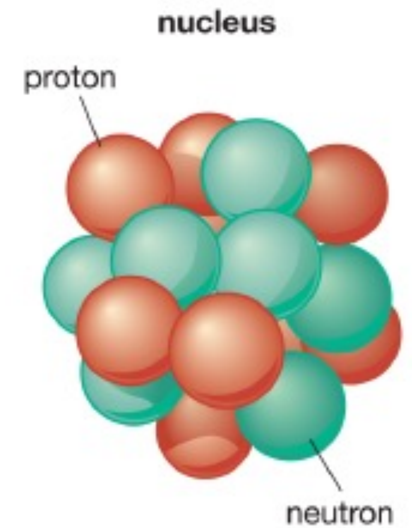
JICFuS 東京大学 THE UNIVERSITY OF TOKYO RIKEN NISHINA CENTER JAEA

This work was supported also by MEXT as “Program for Promoting Researches on the Supercomputer Fugaku” (Simulation for basic science: from fundamental laws of particles to creation of nuclei) and “Priority Issue on post-K computer” (Elucidation of the Fundamental Laws and Evolution of the Universe), and by JICFuS.

In 1940's, the shell structure was excluded/abandoned for atomic nuclei by many physicists.

Compound-nucleus model proposed in 1936 by *Niels Bohr*





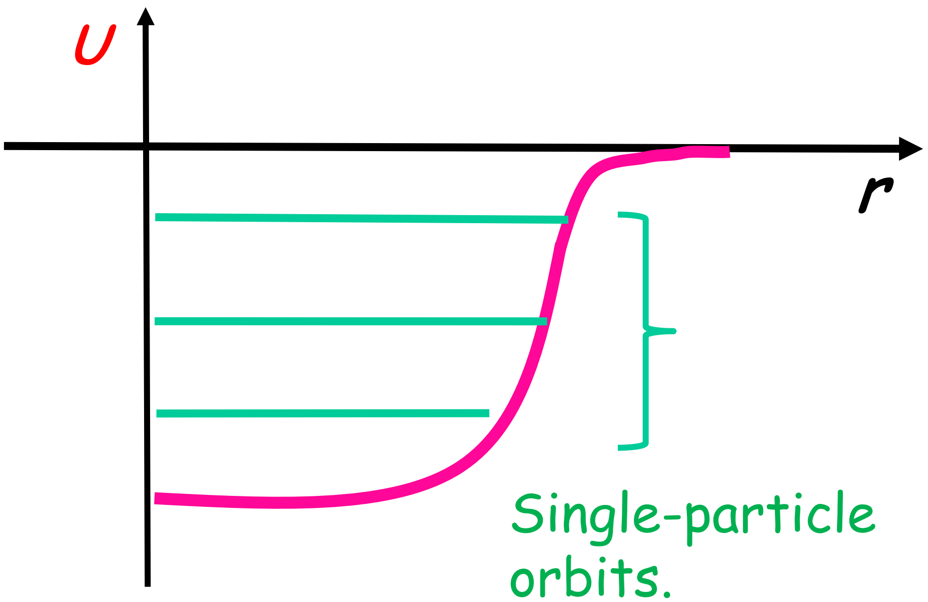
Densely packed, but their motion is chaotic, *i.e.,* no stable orbital motion.

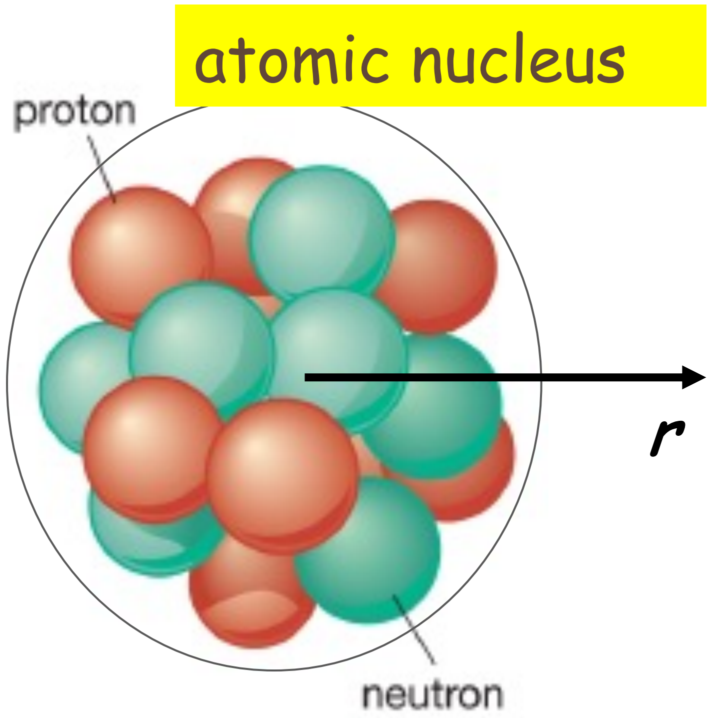
This is the "standard" picture of atomic nuclei in 1940's led by the idea of Niels Bohr inspired by fission etc.

In 1949, Maria Goeppert Mayer and Hans Jensen independently proposed magic numbers and shell model.

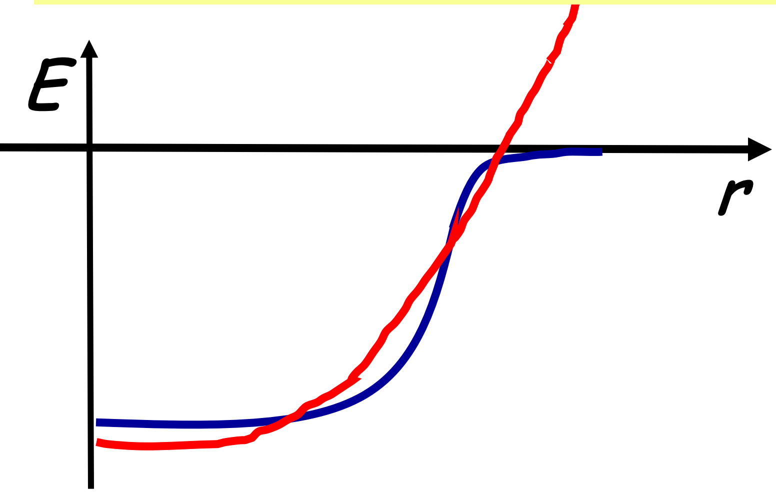
Protons and neutrons form an atomic nucleus confining themselves by a mean potential, U, created by the same protons and neutrons.

The mean potential produces single-particle orbits as eigen solutions of the single-particle motion in the potential.





The mean potential can be approximated by the 3-dimensional Harmonic Oscillator potential.



Eigenvalues of HO potential

spin-orbit coupling

Magic numbers

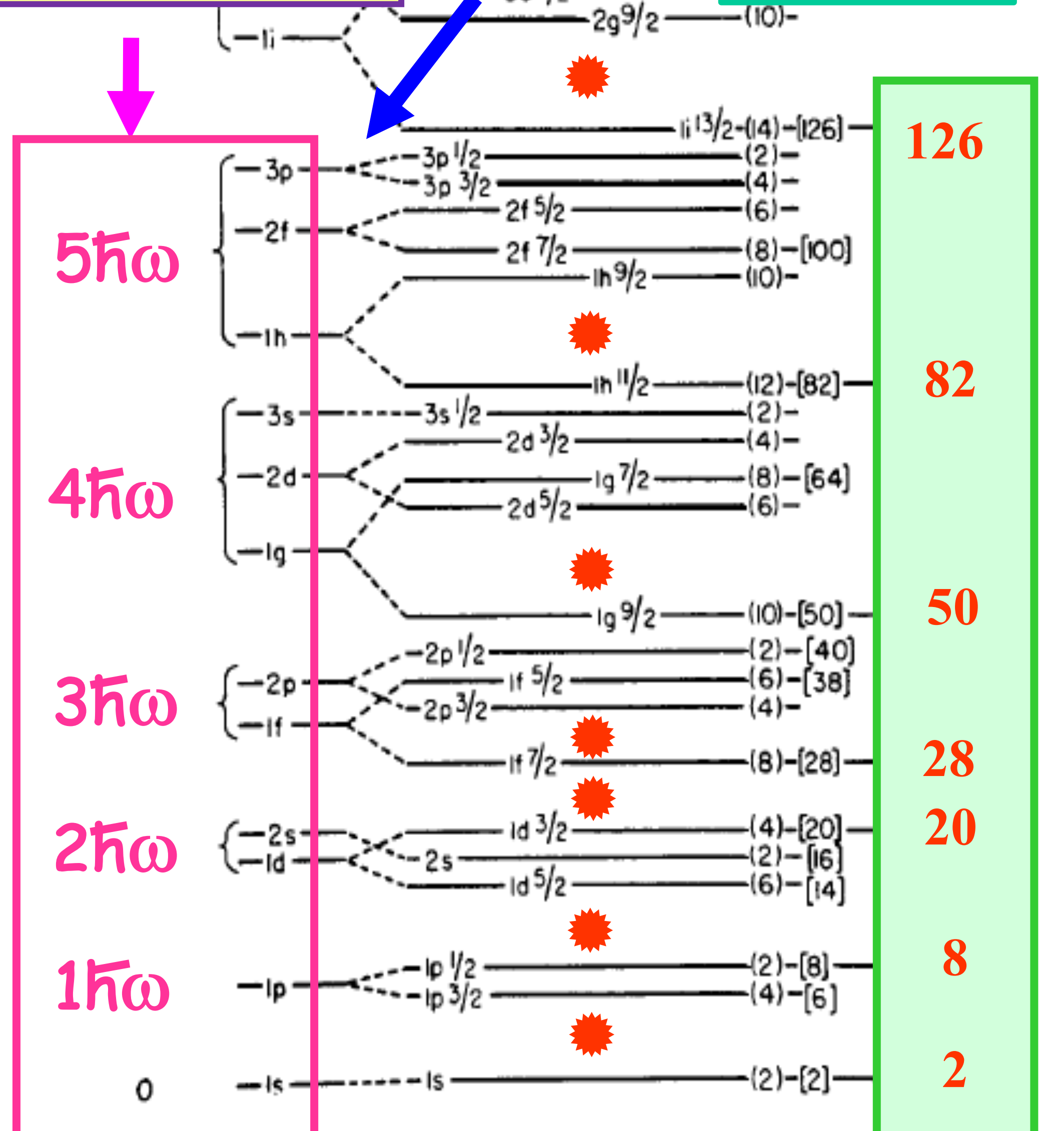
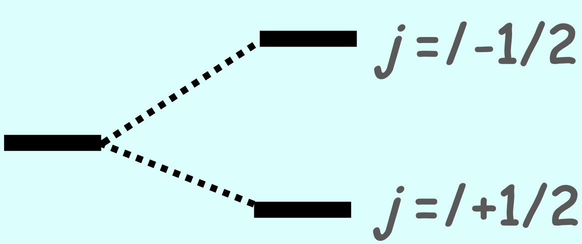


Fig. 7. Realistic level diagram for protons.

+ spin-orbit coupling ($l*s$)



orbital angular momentum l

The shell model meant, in the context of Mayer-Jensen, an Independent Particle Model (IPM) with the Harmonic Oscillator Potential.

Based on this shell structure, the shell model has been evolved to many-body physics with full of correlations originating in nuclear forces, up to so-called *ab initio* calculations.

From the achievements and trends brought in by enormous efforts of many shell-modelists, some concepts seem to have emerged or to be emerging.

Let me overview some of them, with certain my contributions, in this talk.

The contributions of Prof. Jan Blomqvist to the shell model studies ... such as

Atomic masses above ^{146}Gd derived from a shell model analysis of high spin states

Jan Blomqvist, Peter Kleinheinz & Patrick J. Daly

Zeitschrift für Physik A Atoms and Nuclei **312**, 27–41 (1983) | Cite this article

54 Accesses | **72** Citations | Metrics

Abstract

From a shell model analysis of high-spin states in neutron deficient nuclei above ^{146}Gd we have derived the ground state masses of the N=82 and 83 isotones of Eu, Tb, Dy, Ho, and Er. The results can be used to calculate the energies of aligned multiparticle yrast configurations. They also link ten α-decay chains to the nuclei with known masses, providing many new absolute mass values which are compared with predictions. An examination of the two-proton separation energies at N=82 shows an 0.5 MeV break in the nuclear mass surface at Z=64.

The break at Z=64 means a lot in recent shell-model studies of deformed shapes, prolate or triaxial, differentiating Z<64 (e.g. Sm) and Z>64 (e.g. Er) nuclei.

physics

Physics 2022, 4, 258–285.
https://doi.org/10.3390/physics4010018

MDPI

Review

Emerging Concepts in Nuclear Structure Based on the Shell Model

Takaharu Otsuka [1,2,3]

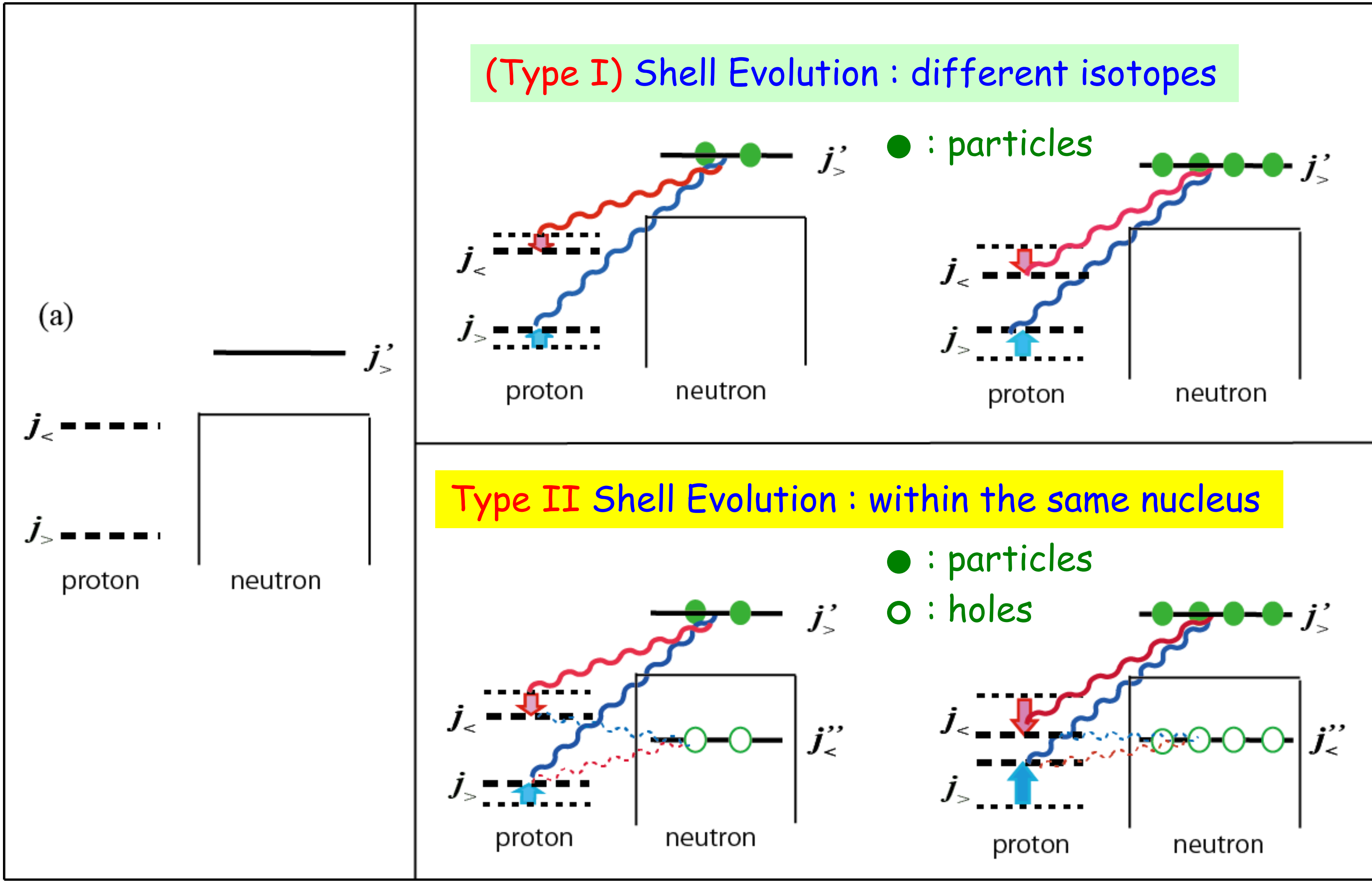
Shell evolution due to the monopole interaction
Type II shell evolution and shape coexistence

Triaxiality dominance in heavy nuclei as a consequence of the self-organization due to the monopole-quadrupole interplay
←→ traditional prolate dominance picture

New neutron dripline mechanism due to the monopole-quadrupole interplay, exemplified for F, Ne, Na and Mg isotopes
besides the traditional mechanism with single-particle nature

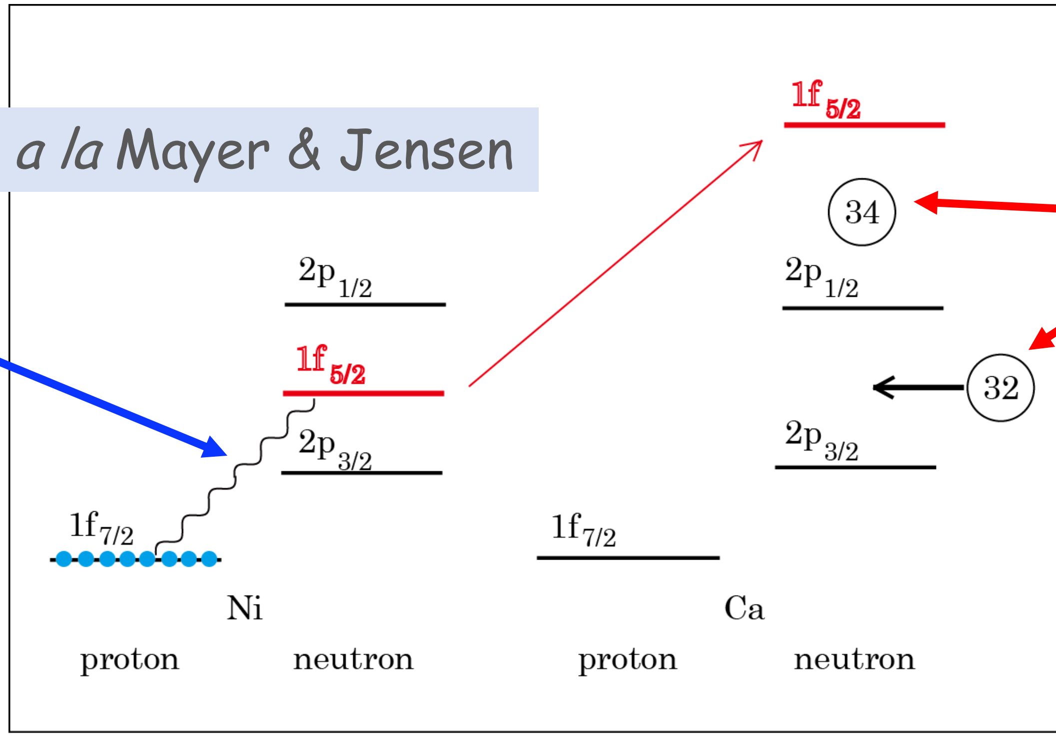
Fully *ab initio* calculations clarify alpha clustering ground and Hoyle states of ^{12}C (not included in the above paper)

Shell Evolution due to the tensor force



TO and Y. Tsunoda, J. Phys. G: Nucl. Part. Phys. 43 (2016) 024009 shell structure for neutrons in Ni isotopes ($f_{7/2}$ fully occupied)

N=34 magic number appears if proton $f_{7/2}$ becomes vacant (Ca) ($f_{5/2}$ becomes less bound)



strong attractive effect due to tensor force

$f_{7/2}$ $j_>$

$f_{5/2}$ $j_<$

new magic numbers

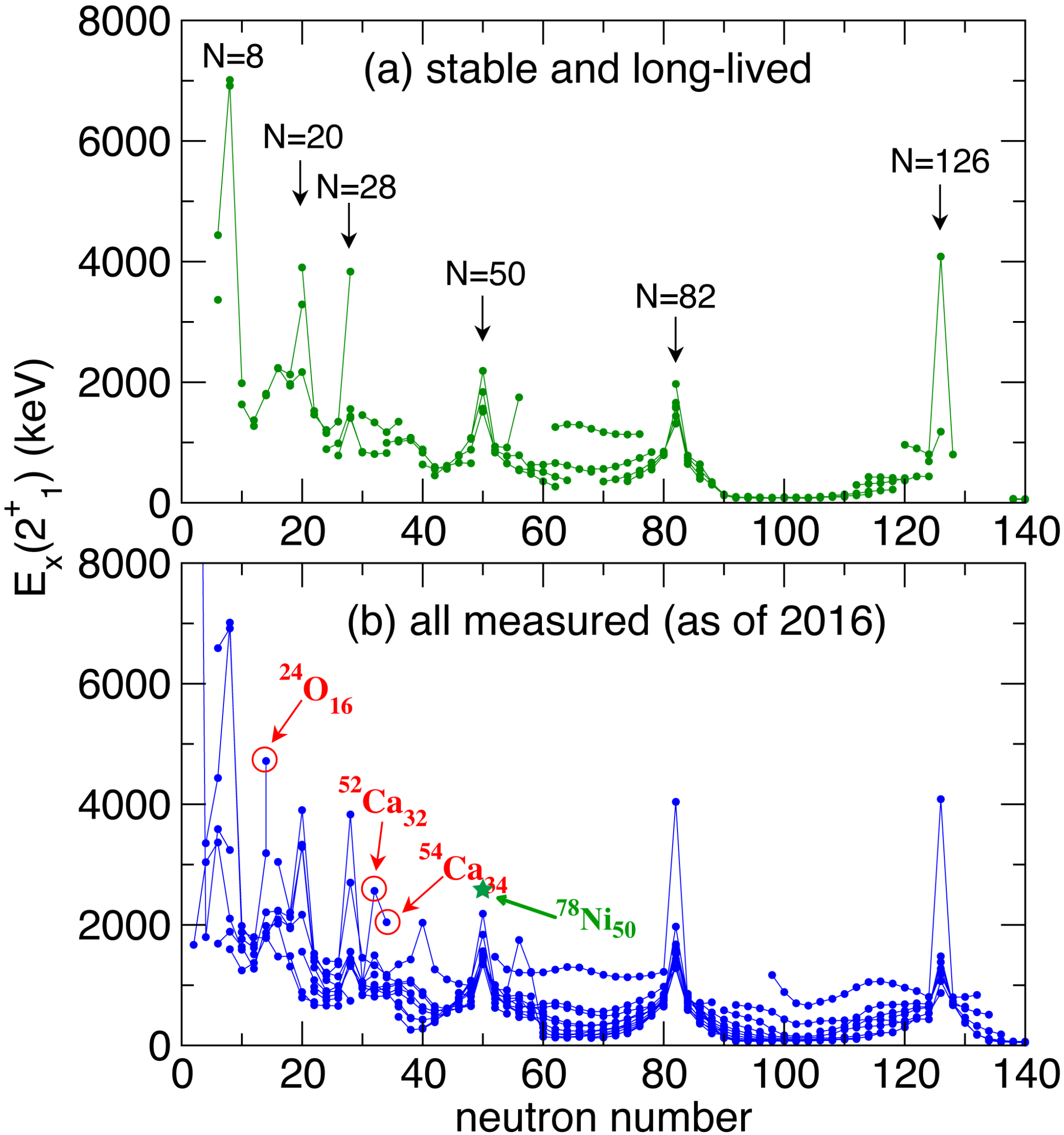
missing attraction

stable (e.g. ^{58}Ni)
a la Mayer-Jensen

exotic
(neutron-rich, e.g. ^{54}Ca)

TO and Tsunoda,
J. Phys. *G* 43, 024009 (2016)

Excitation energy of the lowest excited 2+ state for even-even nuclei



Magic numbers
2, 8, 20, 28, 50, 82, 126
are visible

More magic numbers
16, 32*, 34*, 40**, ...
are visible, while ^{78}Ni is verified as doubly magic

* not present in Mayer-Jensen

** HO magic number

Reference

REVIEWS OF MODERN PHYSICS, VOLUME 92, JANUARY–MARCH 2020

Evolution of shell structure in exotic nuclei

by T. Otsuka, A. Gade, O. Sorlin, T. Suzuki and Y. Utsuno

CONTENTS

Energy levels and B(E2) values of Ni isotopes

Description by the A3DA-m Hamiltonian

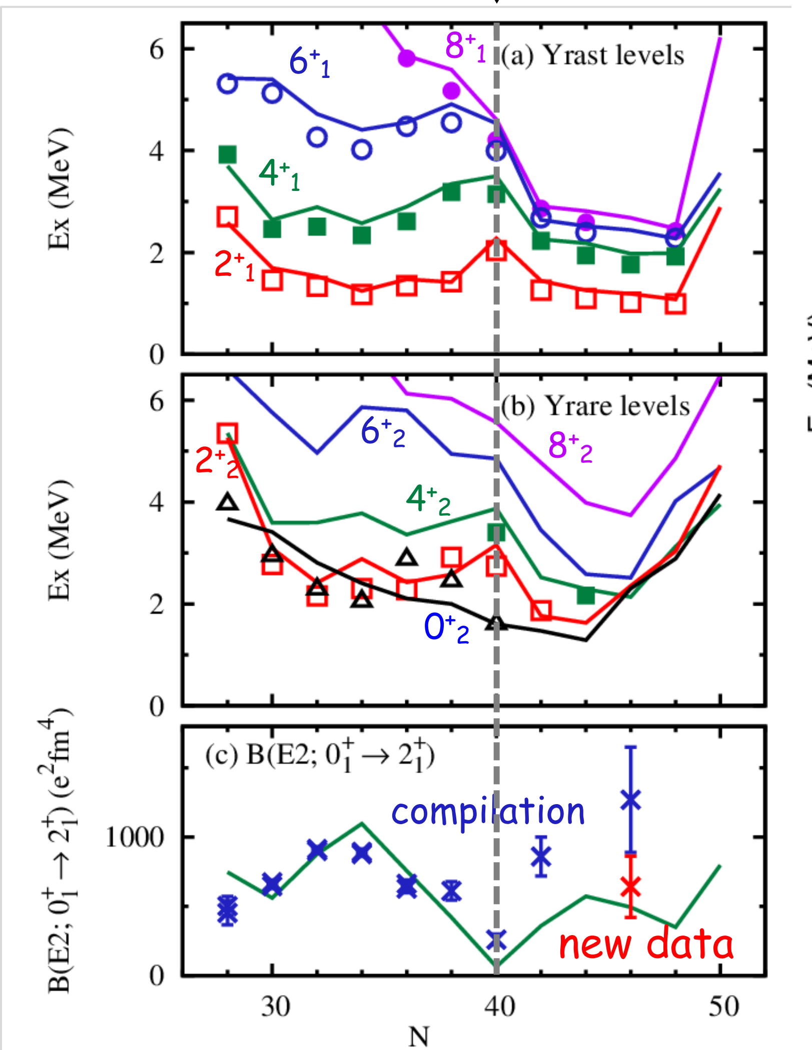
× exp.

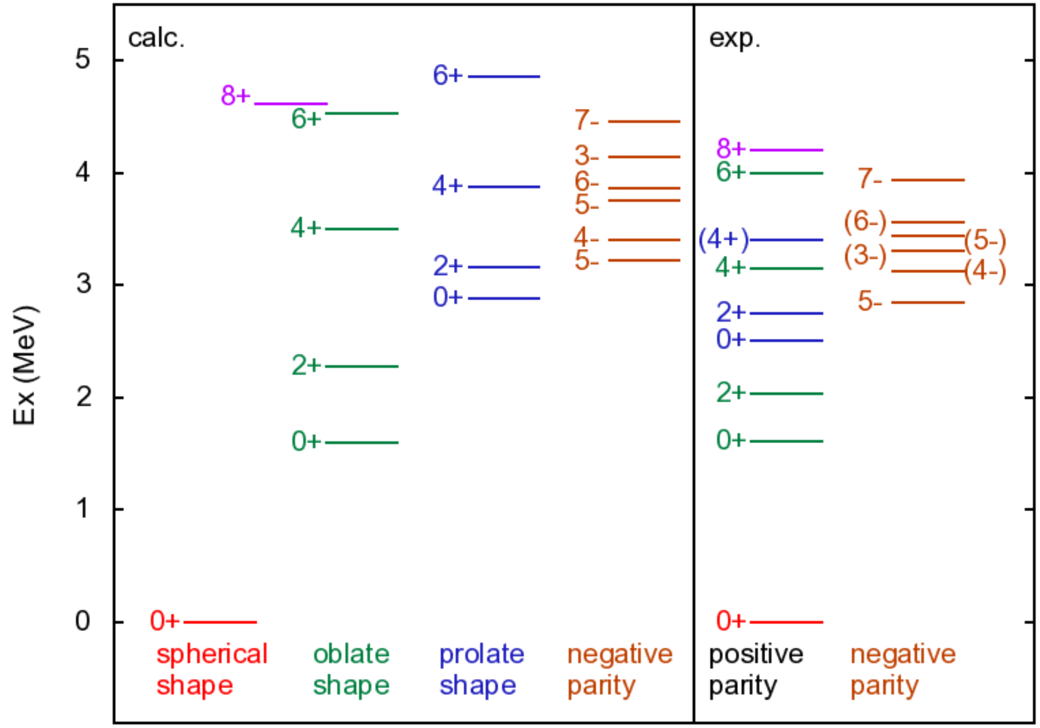
— calc.

Shape coexistence in ^{68}Ni

^{68}Ni

calc. exp.



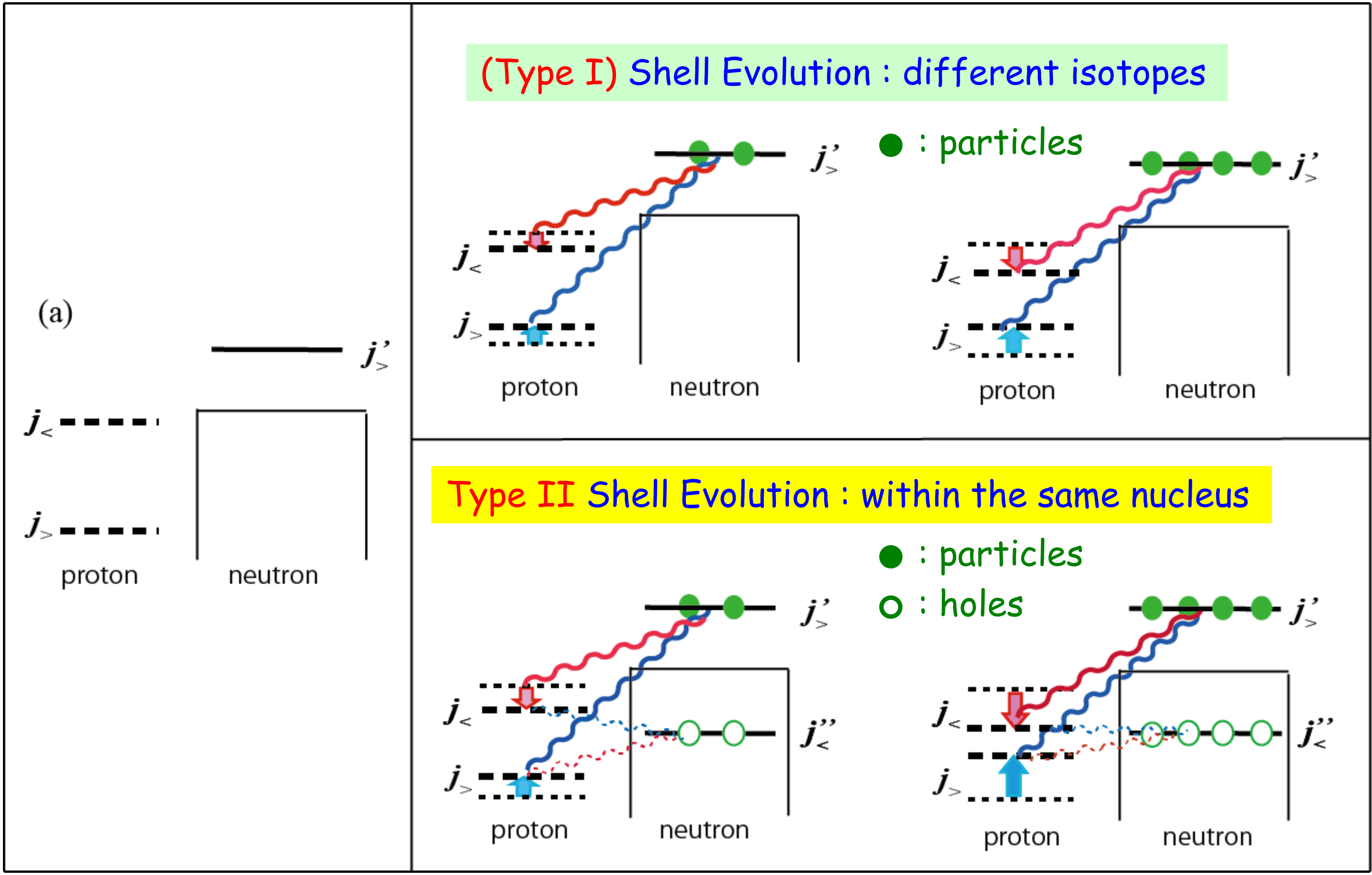


Calc. : Monte Carlo Shell Model

Figures:

Y. Tsunoda, TO, Shimizu, Honma and Utsuno, PRC 89, 031301 (R) (2014)

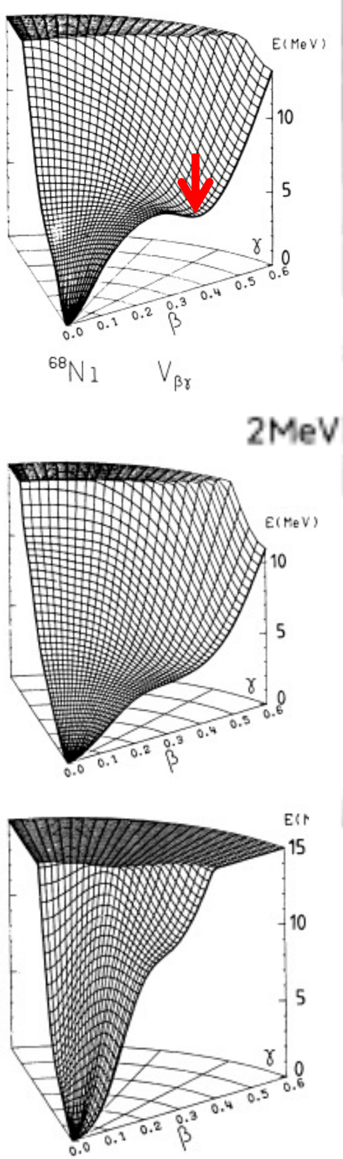
Shell Evolution due to the tensor force

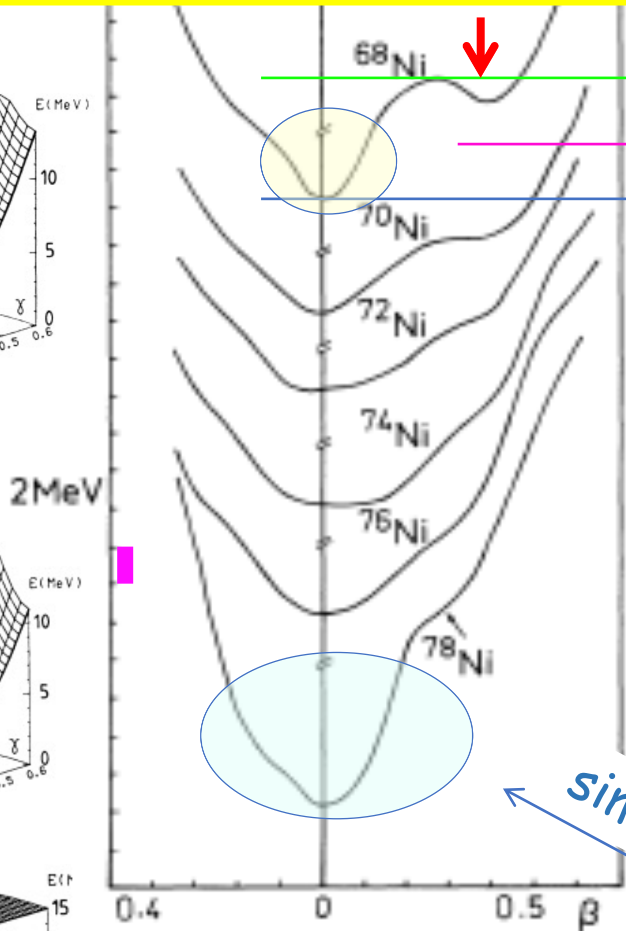


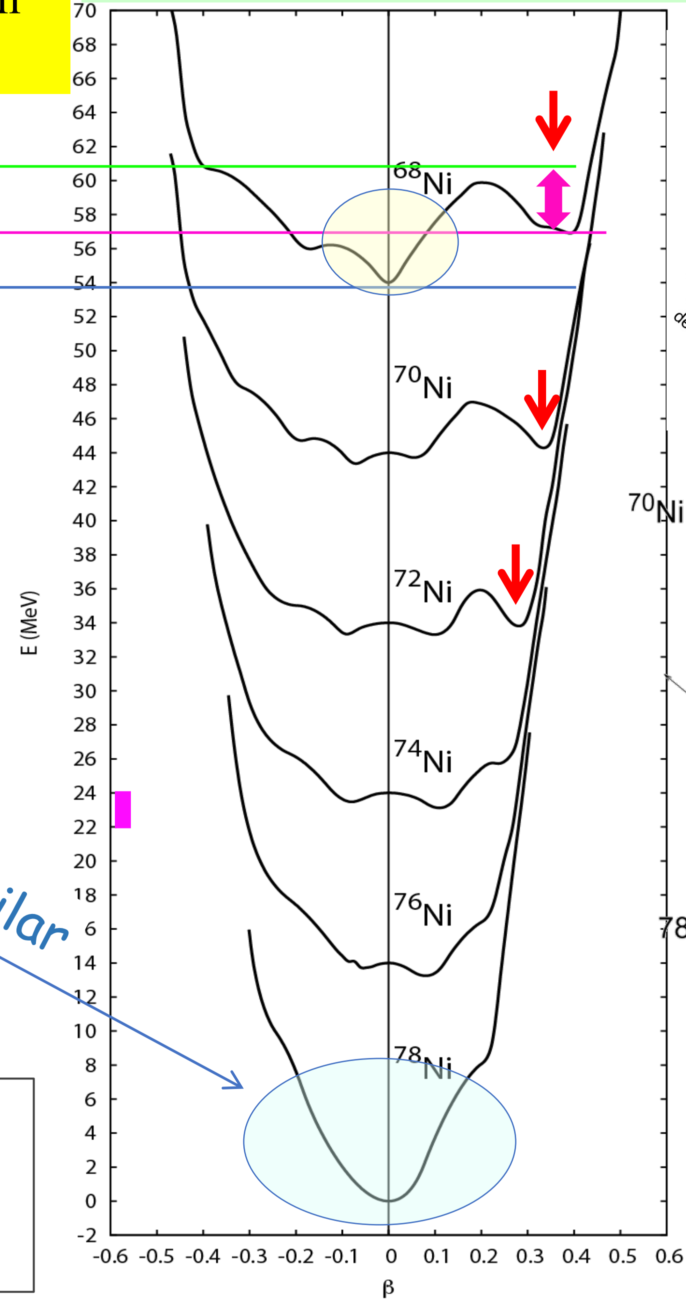
TO and Y. Tsunoda, J. Phys. G: Nucl. Part. Phys. 43 (2016) 024009

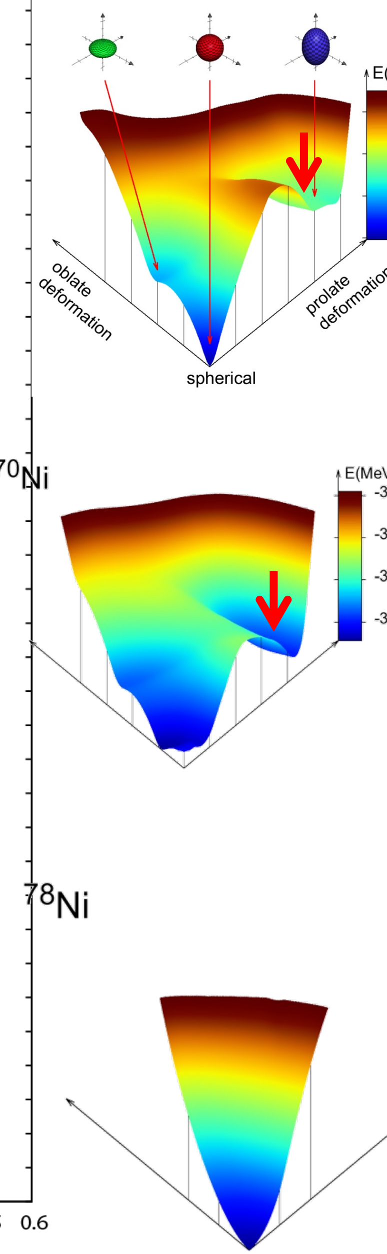
Bohr-model calc. by HFB with **Gogny** force, Girod, Dessagne, Bernes, Langevin, Pougheon and Roussel, PRC 37,2600 (1988)

Present with full monopole effects









similar

The same scale of energy between two figures.

T-plot : visualization of MCSM eigenvector on Potential Energy Surface

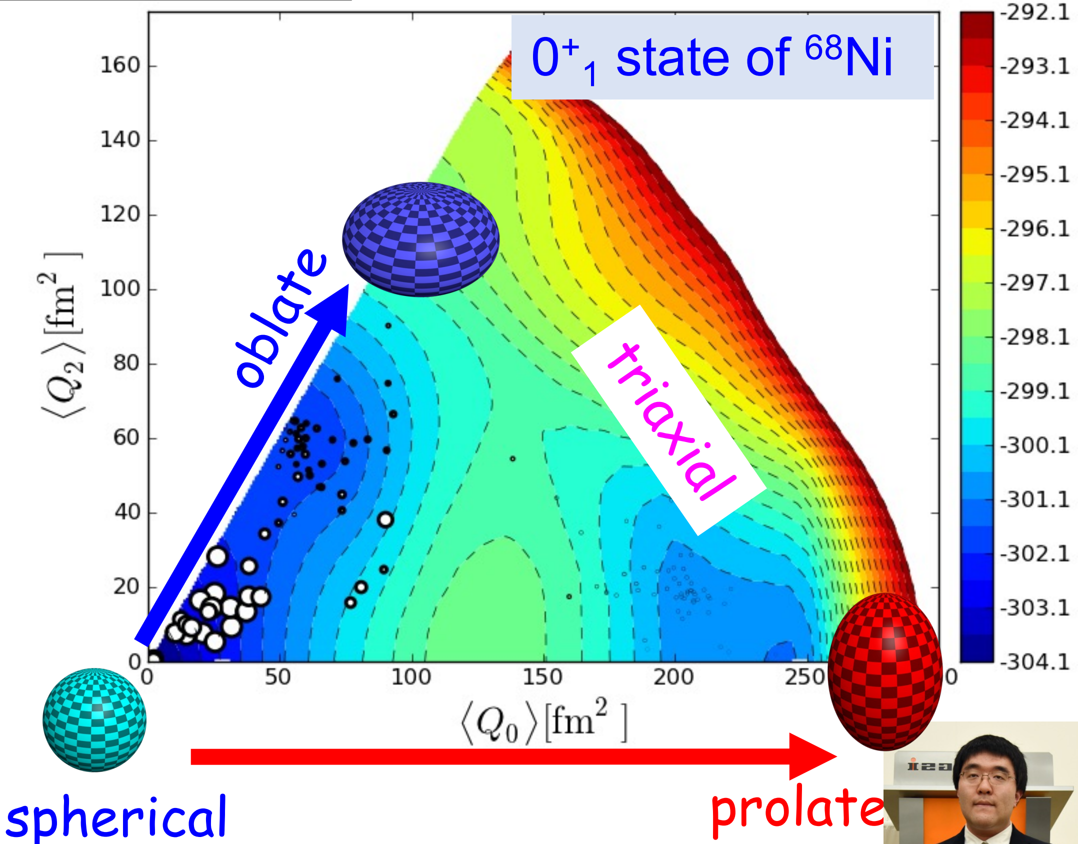
eigenstate $\Psi = \sum_i c_i P[J^\pi] \Phi_i$

amplitude

projection onto J^π

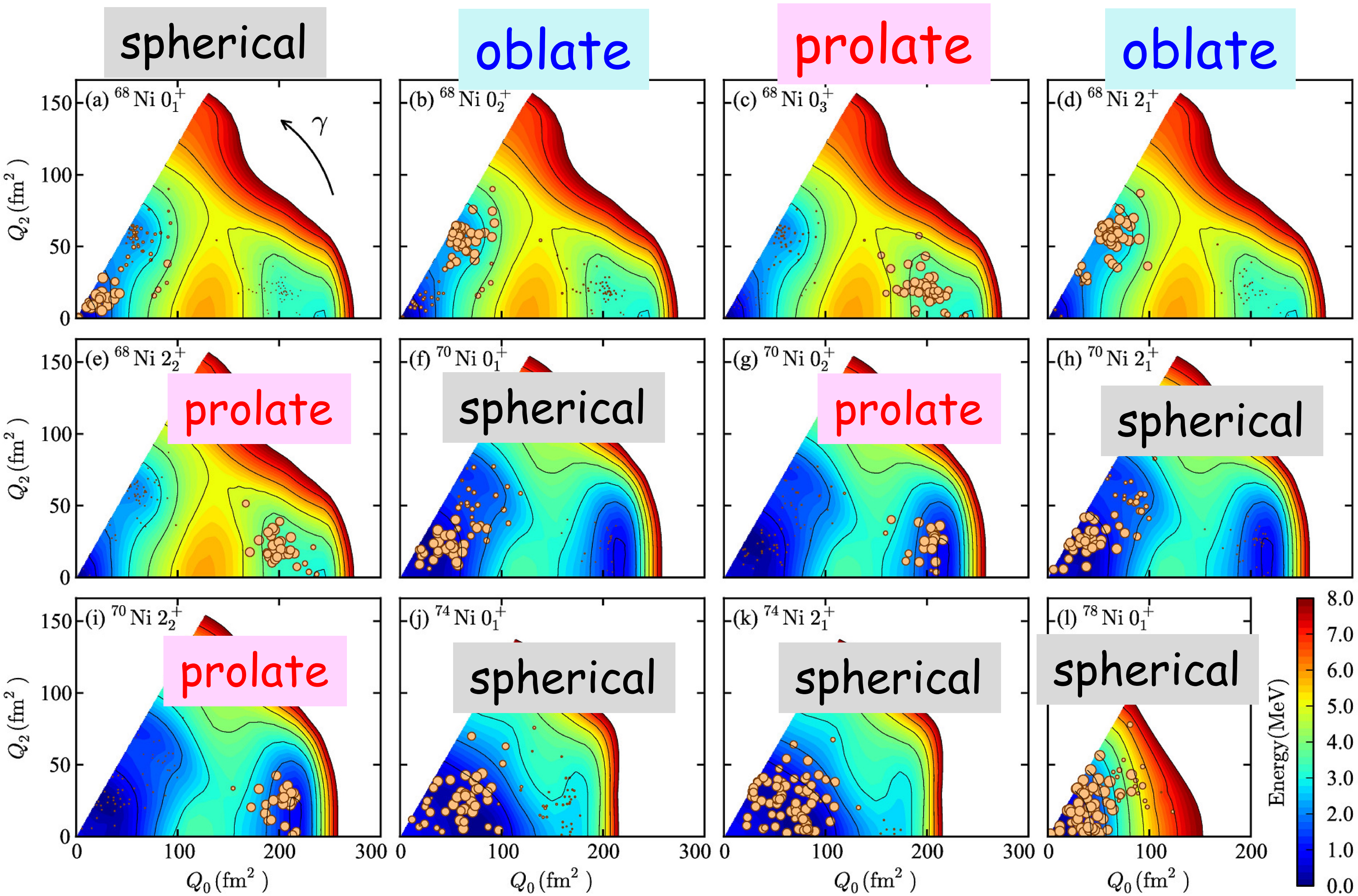
stochastically deformed Slater determinant
→ intrinsic shape

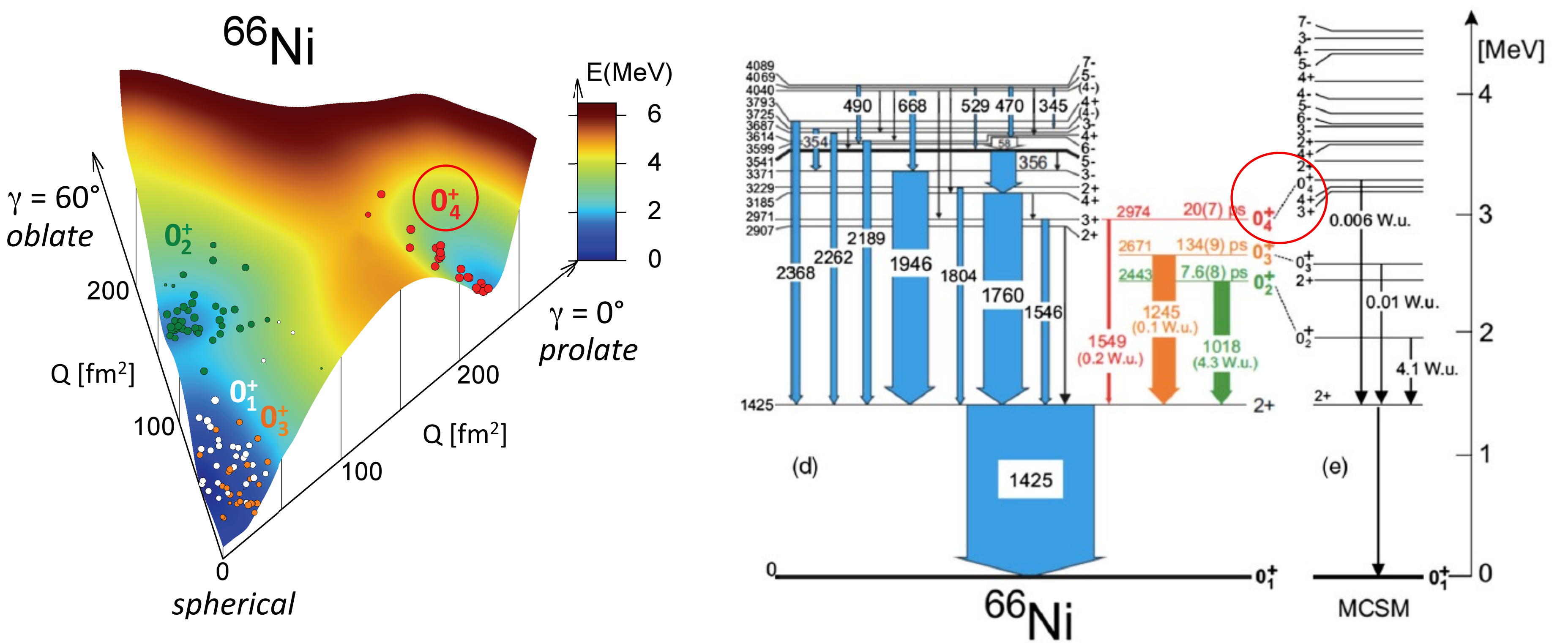
- PES is calculated by CHF for the shell-model Hamiltonian
- Location of circle : quadrupole deformation of unprojected MCSM basis vectors
- Area of circle : overlap probability between each projected basis and eigen wave function



Y. Tsunoda, *et al.*
PRC 89, 031301 (R) (2014)

Evolution of shapes in Ni isotopes





PRL **118**, 162502 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Multifaceted Quadruplet of Low-Lying Spin-Zero States in ^{66}Ni: Emergence of Shape Isomerism in Light Nuclei

S. Leoni,[1,2,*] B. Fornal,[3] N. Mărginean,[4] M. Sferrazza,[5] Y. Tsunoda,[6] T. Otsuka,[6,7,8,9] G. Bocchi,[1,2] F. C. L. Crespi,[1,2] A. Bracco,[1,2] S. Aydin,[10] M. Boromiza,[4,11] D. Bucurescu,[4] N. Cieplicka-Oryǹczak,[2,3] C. Costache,[4] S. Călinescu,[4] N. Florea,[4] D. G. Ghiţă,[4] T. Glodariu,[4] A. Ionescu,[4,11] Ł.W. Iskra,[3] M. Krzysiek,[3] R. Mărginean,[4] C. Mihai,[4] R. E. Mihai,[4] A. Mitu,[4] A. Negreţ,[4] C. R. Niţă,[4] A. Olăcel,[4] A. Oprea,[4] S. Pascu,[4] P. Petkov,[4] C. Petrone,[4] G. Porzio,[1,2] A. Şerban,[4,11] C. Sotty,[4] L. Stan,[4] I. Ştiru,[4] L. Stroe,[4] R. Şuvăilă,[4] S. Toma,[4] A. Turturică,[4] S. Ujeniuc,[4] and C. A. Ur[12]

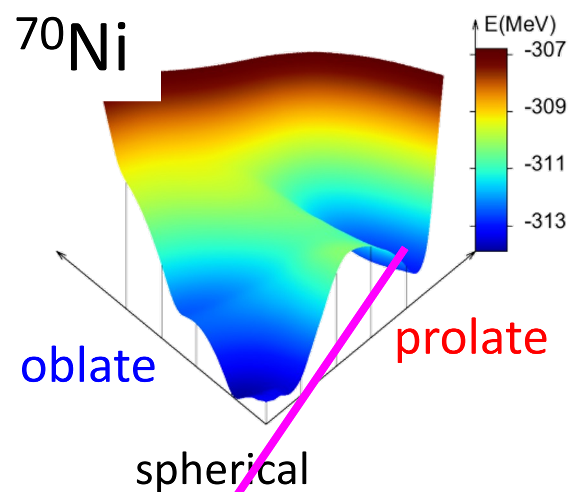
Shape coexistence with a lowest excitation energy

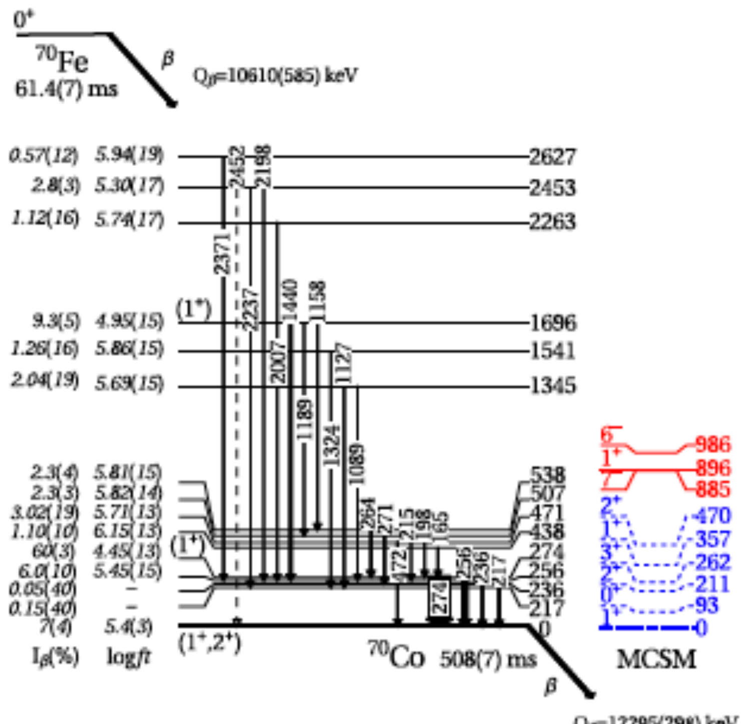
Physics Letters B 765 (2017) 328–333

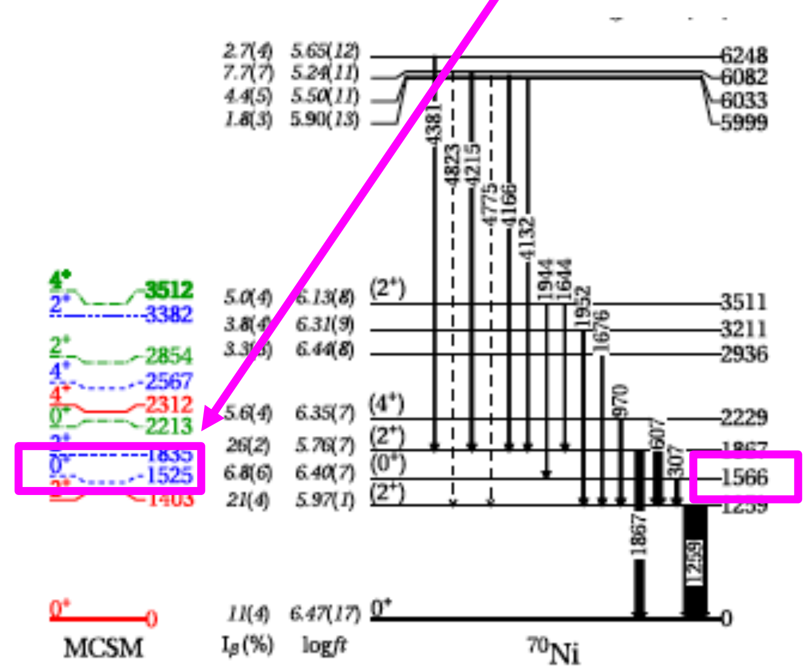
Type II shell evolution in $A = 70$ isobars from the $N \geq 40$ island of inversion

A.I. Morales[a,b,*], G. Benzoni[a], H. Watanabe[c,d], Y. Tsunoda[e], T. Otsuka[f,g,h], S. Nishimura[d], F. Browne[i,d], R. Daido[j], P. Doornenbal[d], Y. Fang[j], G. Lorusso[d], Z. Patel[k,d], S. Rice[k,d], L. Sinclair[l,d], P.-A. Söderström[d], T. Sumikama[m], J. Wu[d], Z.Y. Xu[f,d], A. Yagi[j], R. Yokoyama[f], H. Baba[d], R. Avigo[a,b], F.L. Bello Garrote[n], N. Blasi[a], A. Bracco[a,b], F. Camera[a,b], S. Ceruti[a,b], F.C.L. Crespi[a,b], G. de Angelis[o], M.-C. Delattre[p], Zs. Dombradi[q], A. Gottardo[o], T. Isobe[d], I. Kojouharov[r], N. Kurz[r], I. Kuti[q], K. Matsui[f], B. Melon[s], D. Mengoni[t,u], T. Miyazaki[f], V. Modamio-Hoybjor[o], S. Momiyama[f], D.R. Napoli[o], M. Niikura[f], R. Orlandi[h,v], H. Sakurai[d,f], E. Sahin[n], D. Sohler[q], H. Schaffner[r], R. Taniuchi[f], J. Taprogge[w,x], Zs. Vajta[q], J.J. Valiente-Dobón[o], O. Wieland[a], M. Yalcinkaya[y]

[a] Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy







physics

Physics 2022, 4, 258-285.
https://doi.org/10.3390/physics4010018

MDPI

Review

Emerging Concepts in Nuclear Structure Based on the Shell Model

Takaharu Otsuka [1,2,3]

Shell evolution due to the monopole interaction
Type II shell evolution and shape coexistence

Triaxiality dominance in heavy nuclei as a consequence of the self-organization due to the monopole-quadrupole interplay
←→ traditional prolate dominance picture

New neutron dripline mechanism due to the monopole-quadrupole interplay, exemplified for F, Ne, Na and Mg isotopes
besides the traditional mechanism with single-particle nature

Fully *ab initio* calculations clarify alpha clustering
ground and Hoyle states of ^{12}C (not included in the above paper)

Sm isotopes by Monte Carlo Shell Model

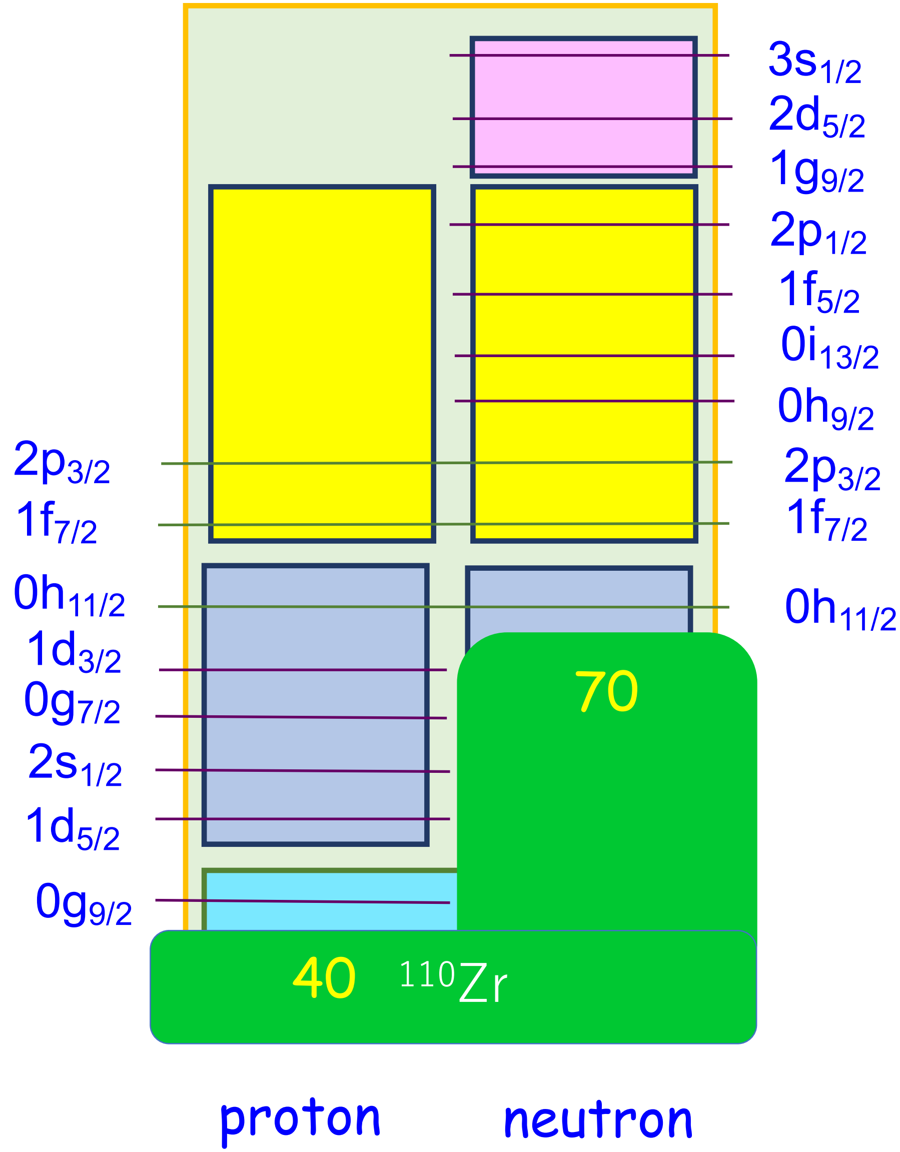
Y. Tsunoda

- 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.

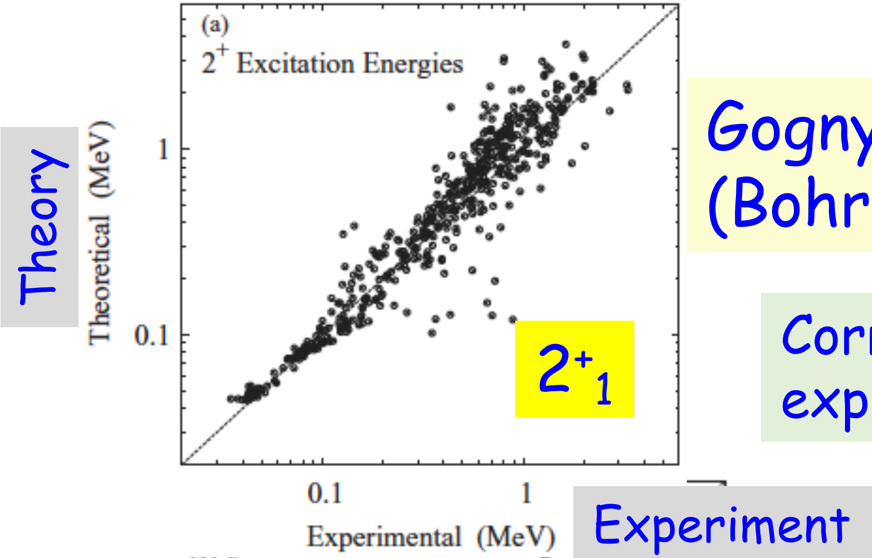


There have been many theoretical approaches, but the description of excited bands are still a challenge.

Gogny -> 5DCH (Bohr-Hamiltonian)

Delaroche et al., PR C 81, 014303 (2010)

Correlations between theoretical & experimental values (scale: logarithmic)



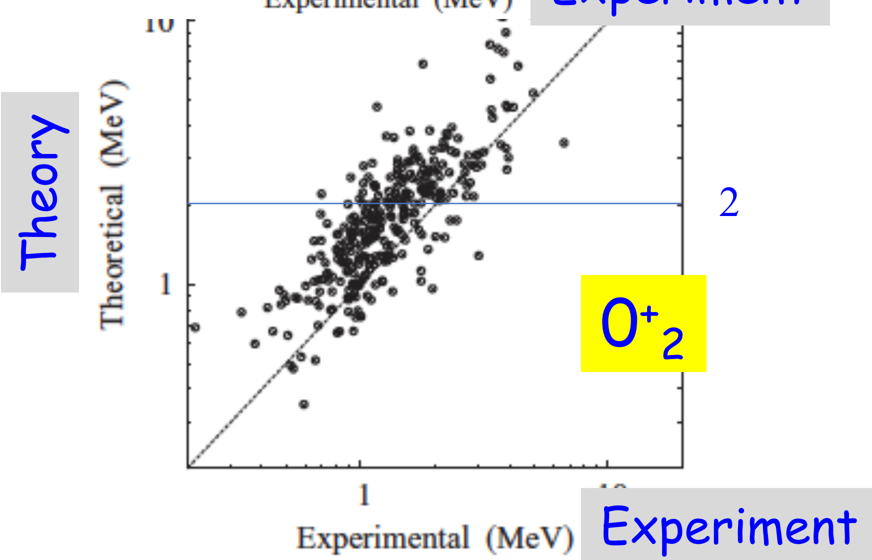


FIG. 20. Excitation energy of the 0_2^+ state compared with experiment [24].

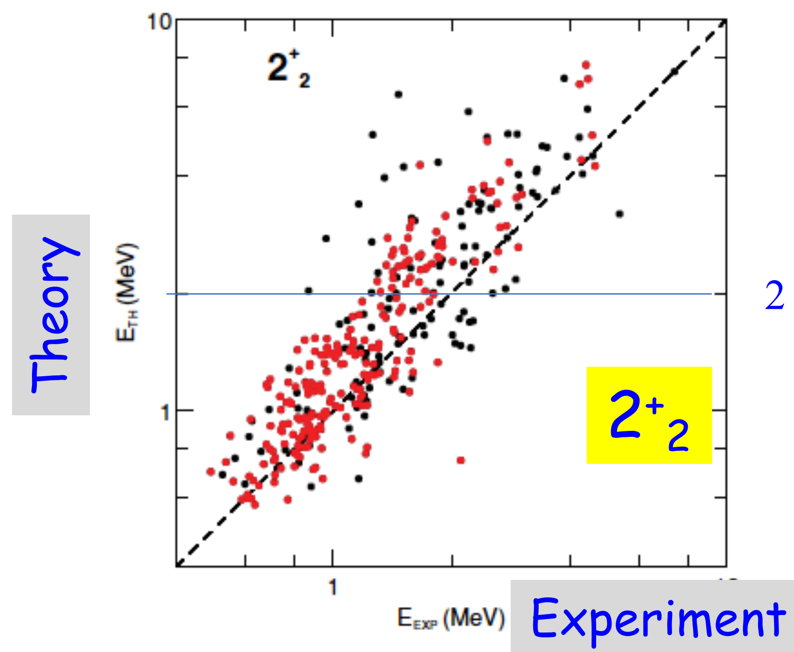


FIG. 19. (Color online) Excitation energy of the second $J = 2$ excitation, comparing 352 nuclei. Experimental data are from Ref. [24]. The 2_γ^+ levels are marked with red color.

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]

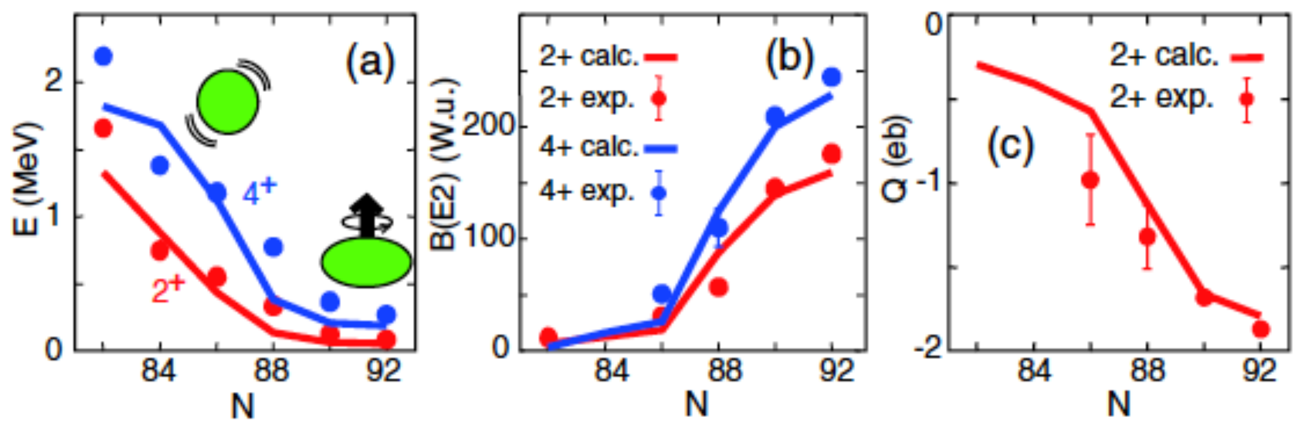
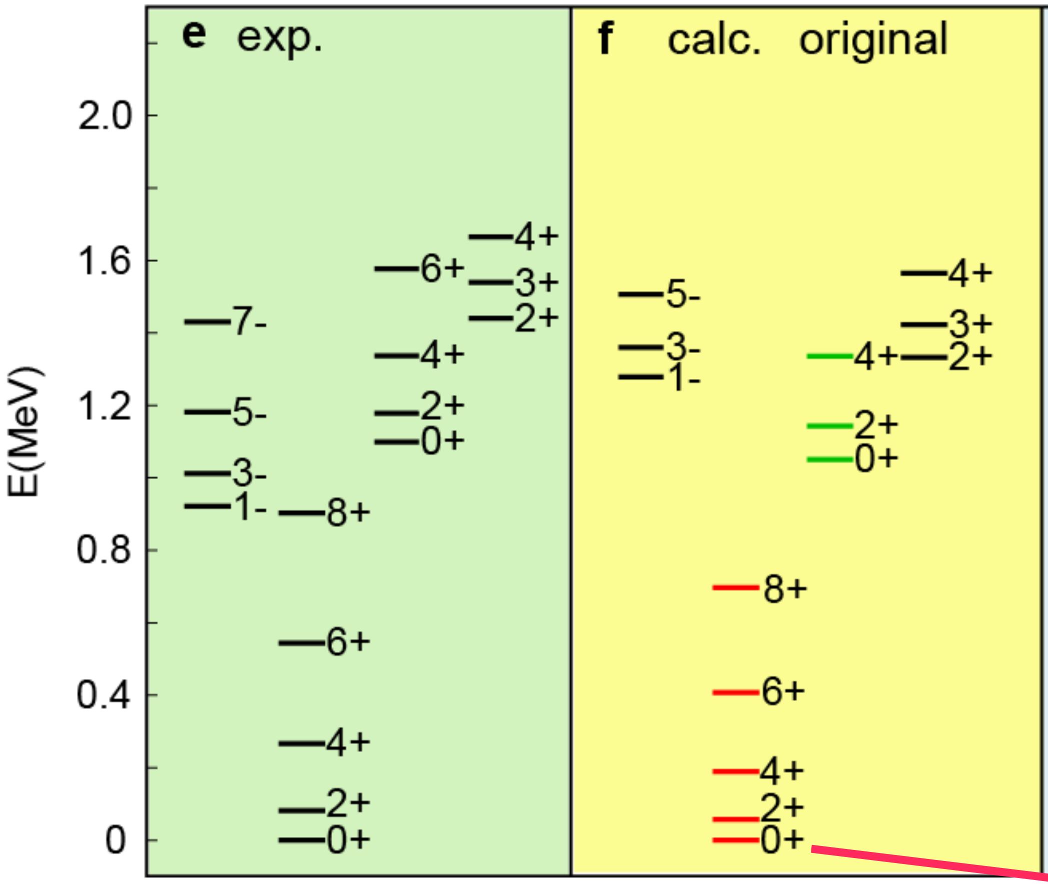
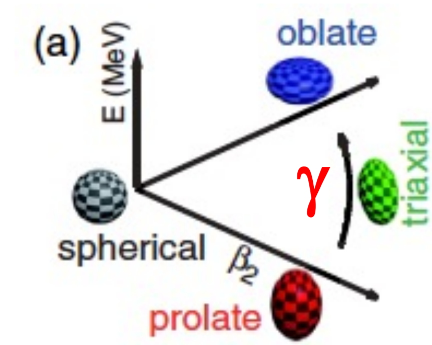


FIG. 1. Systematic changes of the 2_1^+ and 4_1^+ levels in Sm isotopes, as functions of N. (a) Energy levels [25], (b) $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $B(E2; 4_1^+ \rightarrow 2_1^+)$ values [25], and (c) spectroscopic electric quadrupole moment of the 2_1^+ state [26].

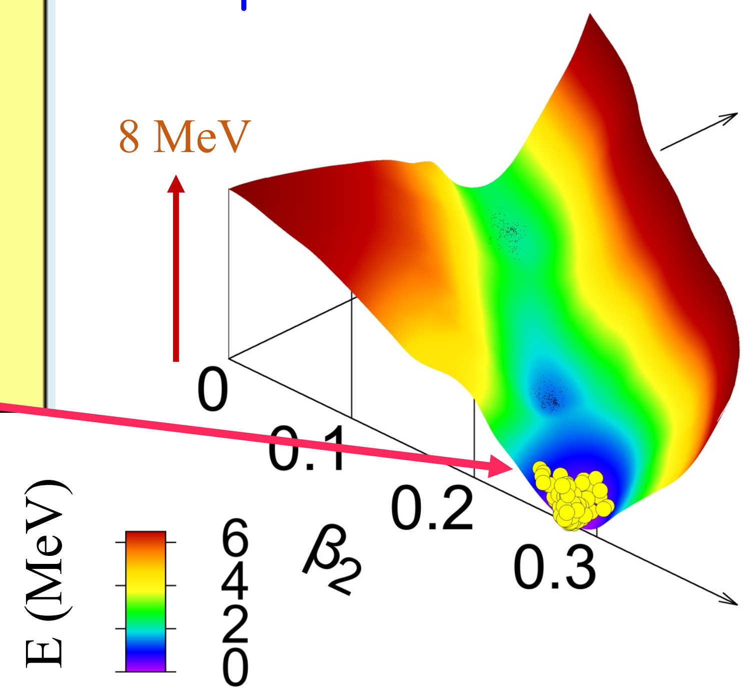
^{154}Sm : ground state

Exp. Calc.





Potential Energy Surface
by Constrained HF
+ T plot

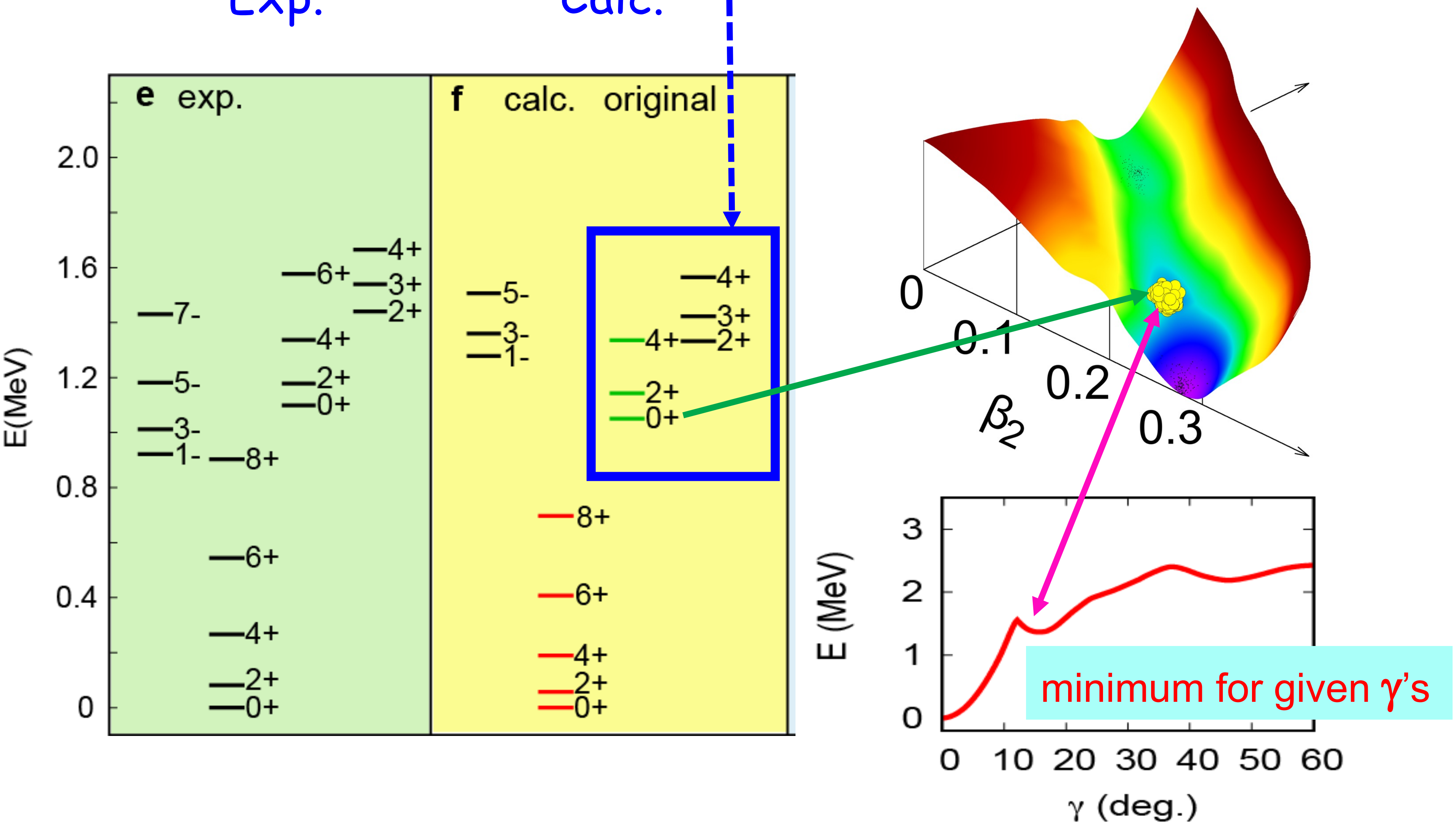


What are those side bands ?

triaxial states
with γ ~ 20 degrees

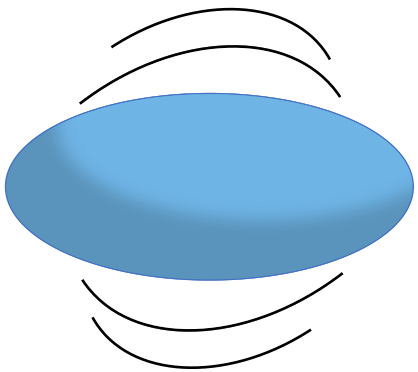
Exp.

Calc.



Aage Bohr
Novel Prize Lecture
(1975)

^{166}Er (Z=68)



gamma vibration

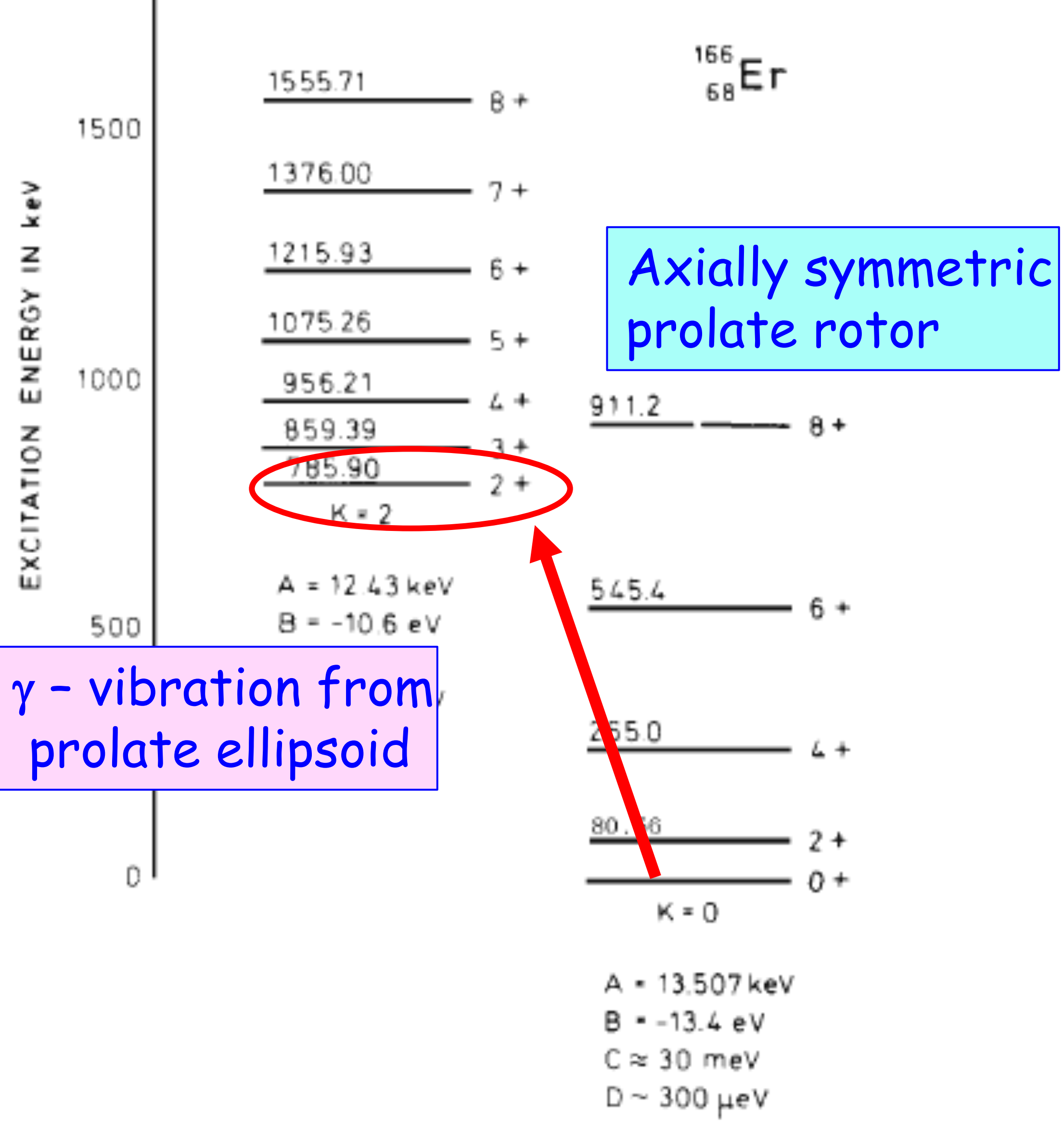
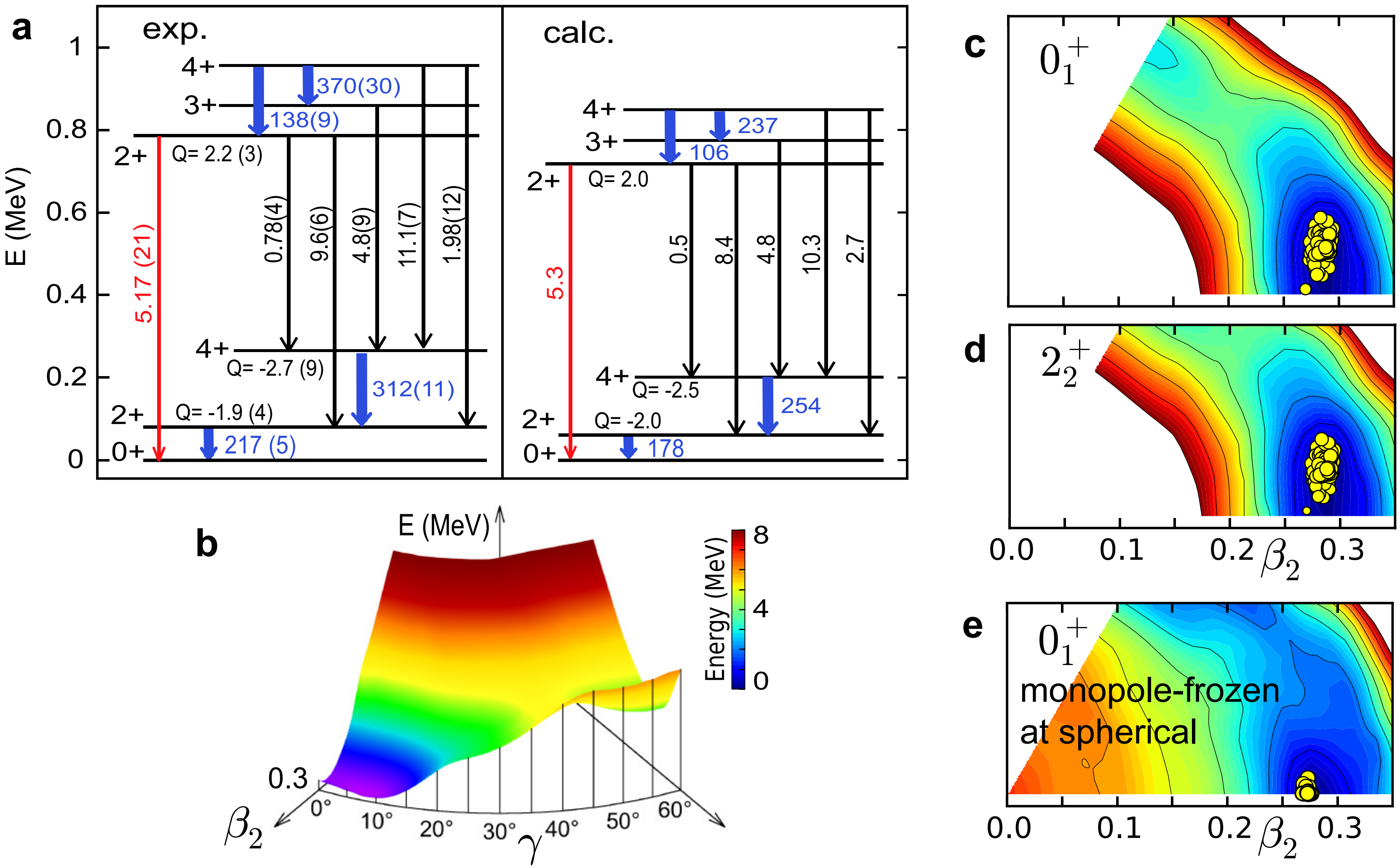


Fig. 9. Rotational bands in ^{166}Er. The figure is from (35) and is based on the experimental data by Reich and Cline (75). The bands are labelled by the component K of the total angular momentum with respect to the symmetry axis. The K = 2 band appears to represent the excitation of a mode of quadrupole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

Question to Gamma-vibration picture by Aage Bohr

MCSM result



Self organization

Single-Particle Energies on top of the inert core : disorder

Effective Single-Particle energies optimized (or tailored) to the eigenstate of interest by the monopole interaction : order

- This optimization is not perfect but yields sizable effects.

- The quadrupole interaction : mode driving force
  The monopole interaction : resistance control force
      The SPE generally works against any particular collective mode.

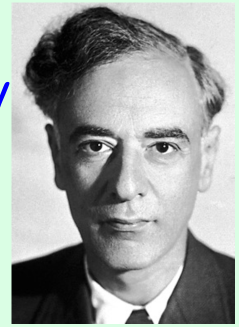
The collective rotational bands of heavy nuclei seem to show triaxiality in virtually all nuclei, in ground and/or side bands, in contrast to the traditional picture of axial symmetry + vibration (a la Aage Bohr).

This monopole-quadrupole interplay seems to be important also to the neutron driplines.

Two major phases: Sm-like and Er-like separated by Z=64 gap

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

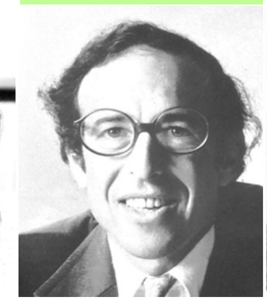
Atomic nucleus is a quantum Fermi liquid :
The nucleus is composed of almost free nucleons interacting weakly via residual forces in a (solid) (mean) potential like a solid "vase".



Landau

The shape of atomic nucleus can be described by the deformation of the "vase", a la Nilsson model (next page).

A. Bohr



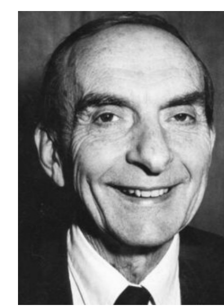
Mottelson

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

physics
Physics 2022, 4, 258-285.
https://doi.org/10.3390/physics4010018
MDPI

Review

Emerging Concepts in Nuclear Structure Based on the Shell Model

Takaharu Otsuka [1,2,3]

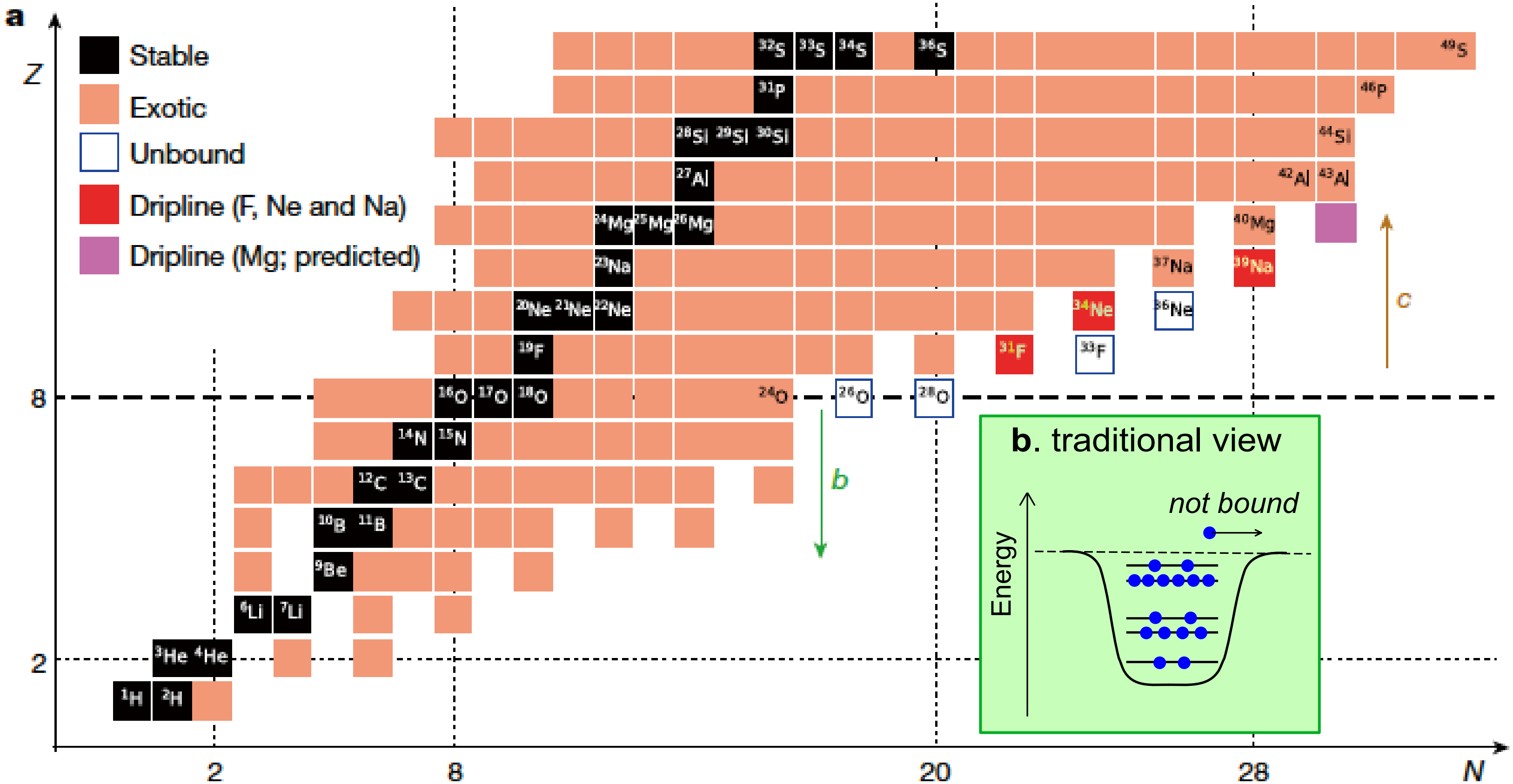
Shell evolution due to the monopole interaction
Type II shell evolution and shape coexistence

Triaxiality dominance in heavy nuclei as a consequence of the self-organization due to the monopole-quadrupole interplay
←→ traditional prolate dominance picture

New neutron dripline mechanism due to the monopole-quadrupole interplay, exemplified for F, Ne, Na and Mg isotopes
besides the traditional mechanism with single-particle nature

Fully *ab initio* calculations clarify alpha clustering ground and Hoyle states of ^{12}C (not included in the above paper)

Neutron driplines and its traditional view



nature

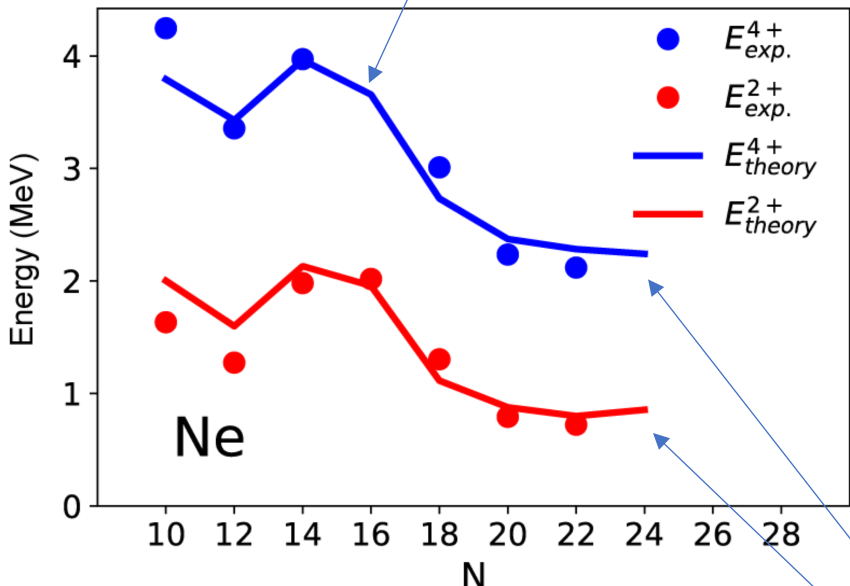
Article | Published: 04 November 2020

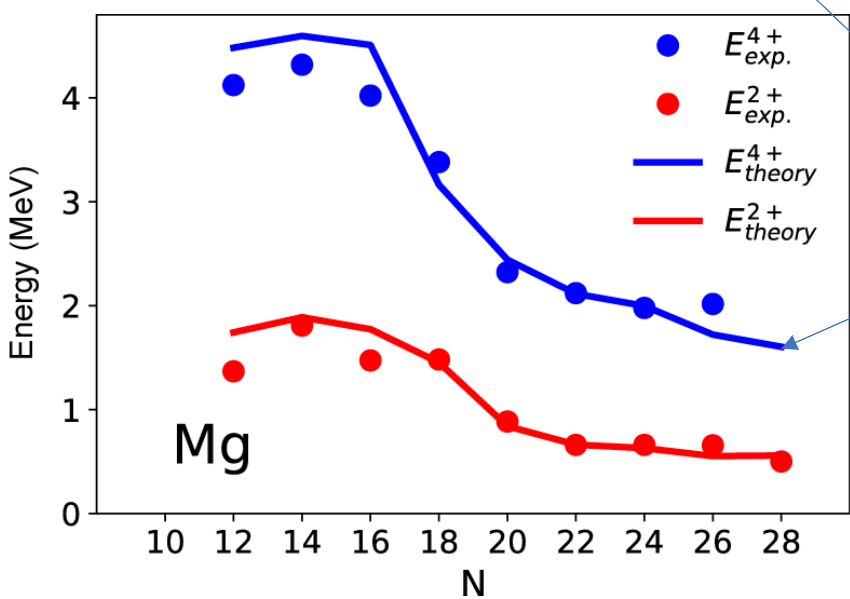
The impact of nuclear shape on the emergence of the neutron dripline

Naofumi Tsunoda, Takaharu Otsuka, Kazuo Takayanagi, Noritaka Shimizu, Toshio Suzuki, Yutaka Utsuno, Sota Yoshida & Hideki Ueno

Nature **587**, 66–71(2020) | Cite this article

Ne and Mg systematics



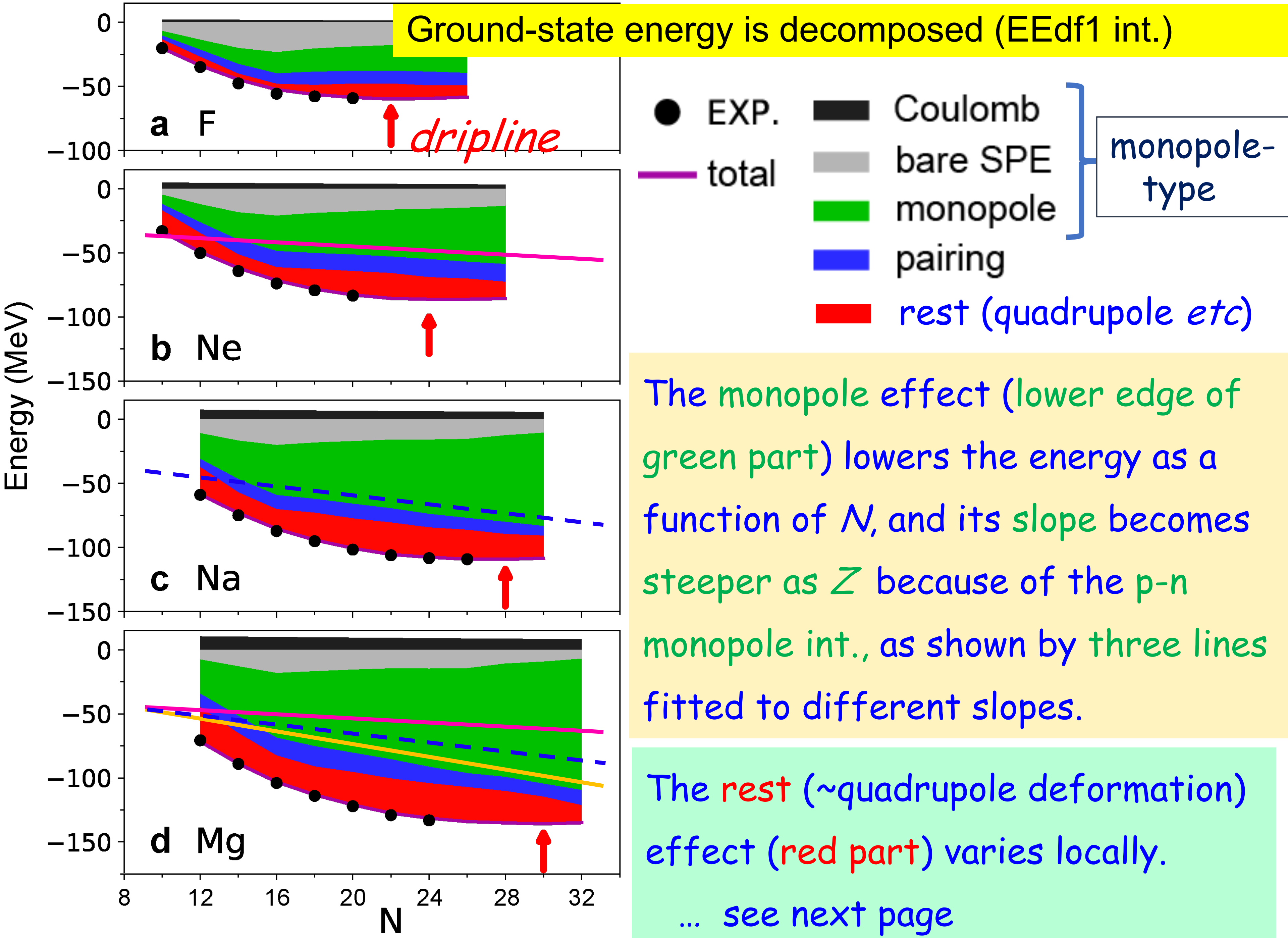


We use the EEdf1 interaction derived from the N3LO chiral EFT interaction + Fujita-Miyazawa three-nucleon force.

The EEdf1 Hamiltonian appears to be reasonable up to N~28 for Z=9-12.

Levels do not exist as bound states, because their energies are above the threshold of neutron emission.

Ground-state energy is decomposed (EEdf1 int.)



The monopole effect (lower edge of green part) lowers the energy as a function of *N*, and its slope becomes steeper as *Z* because of the p-n monopole int., as shown by three lines fitted to different slopes.

The rest (~quadrupole deformation) effect (red part) varies locally.

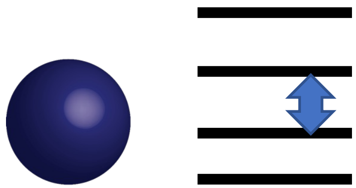
… see next page

Decomposition of the Hamiltonian

monopole part

bare SPE $\sum \epsilon_i a_i^+ a_i$

monopole $\sum_{i,j} V_{\rm mono}^{ab} a_i^+ a_j^+ a_j a_i$ $\quad V_{\rm mono}^{ab} = \sum_J \frac{(2J+1)\langle ab|V|ab\rangle_J}{2J+1}$

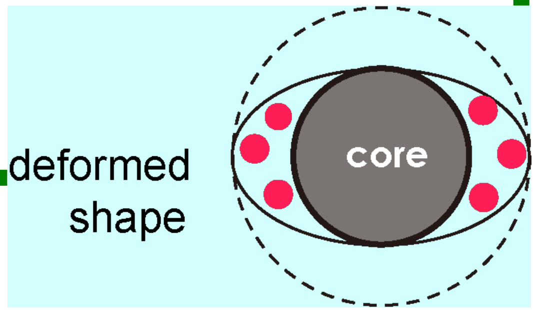


monopole: shift of SPE

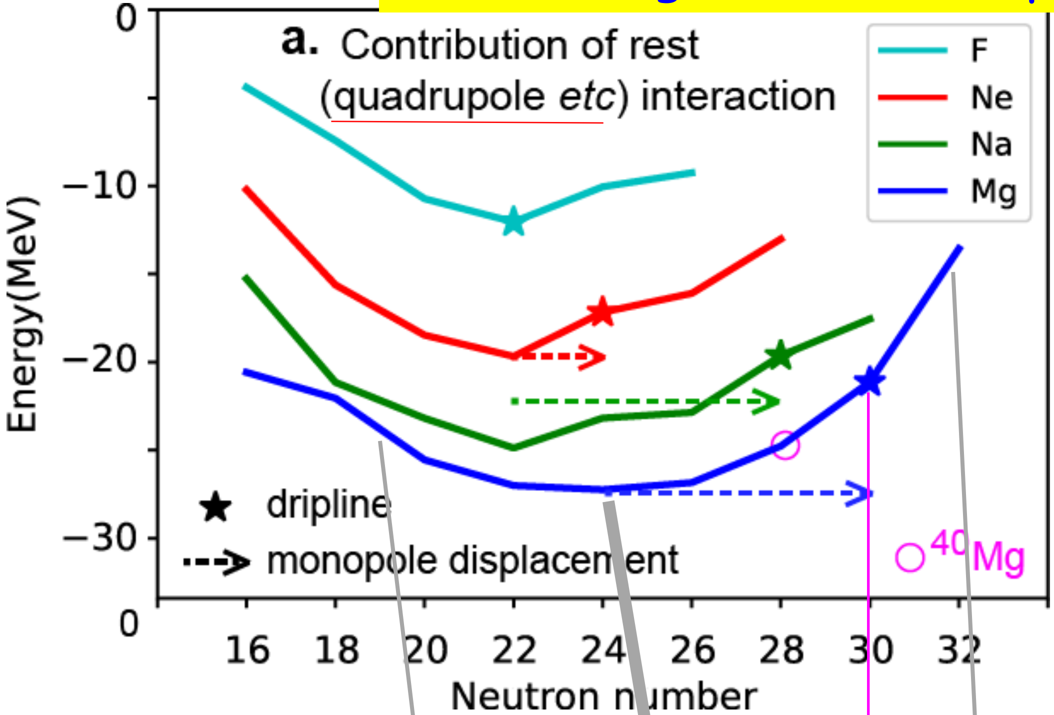
multipole part

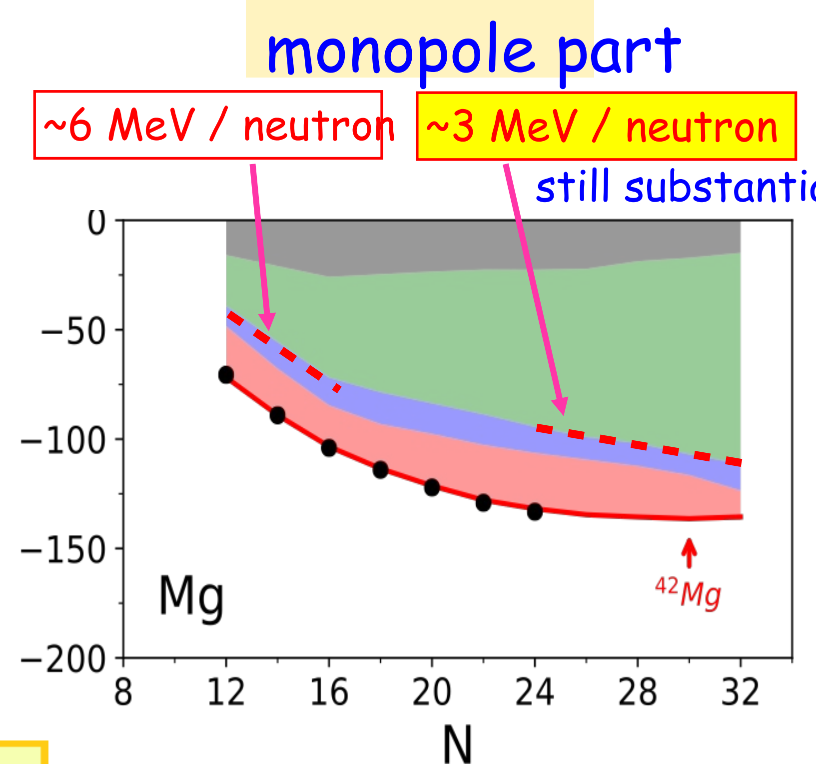
pairing J=0 nn + pp pairing correlations

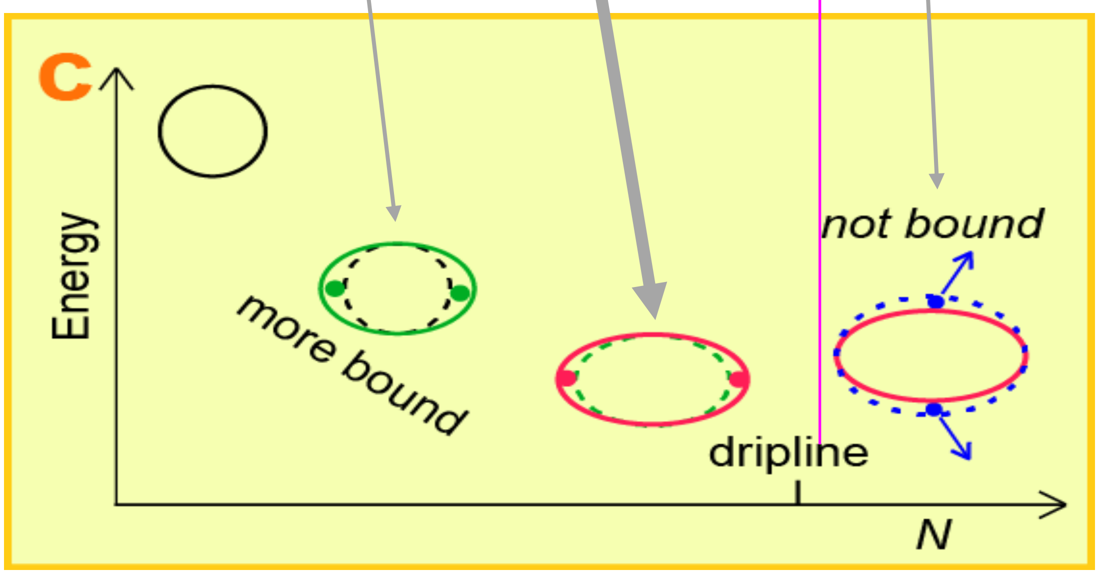
rest quadrupole deformation, *etc*



Two driving forces: example from Mg isotopes



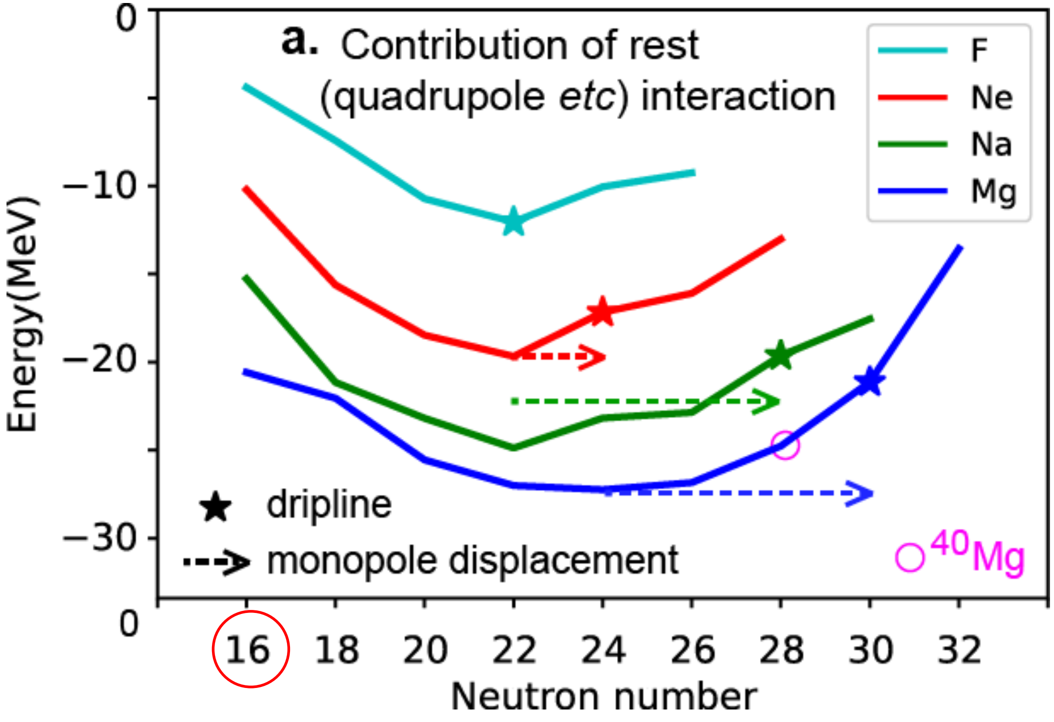


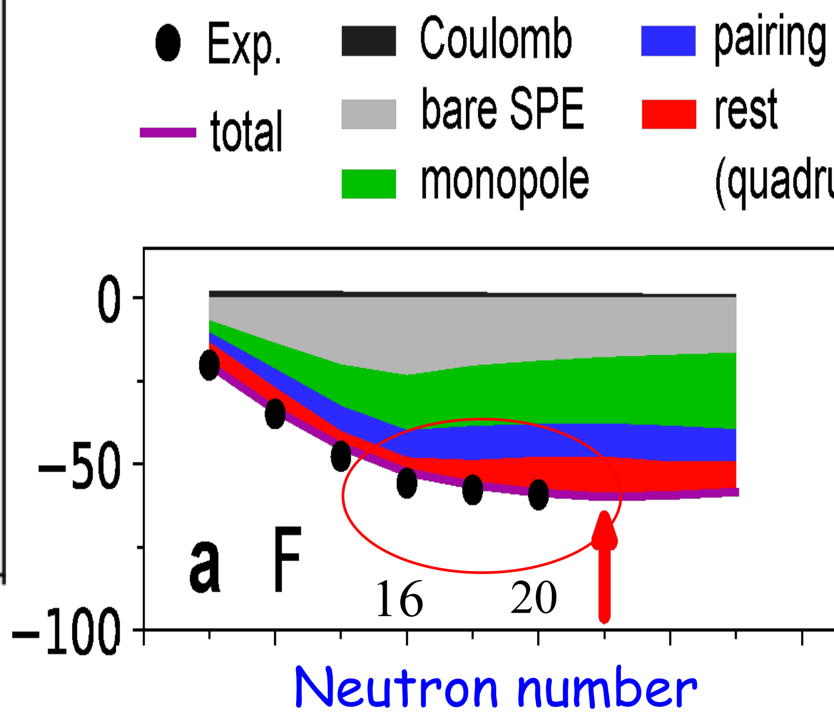


The rest (mainly deformation energy) part is saturated at N=24.

The monopole effects compensate it, and pushes the dripline away (dashed arrows).

Dripline of F isotopes



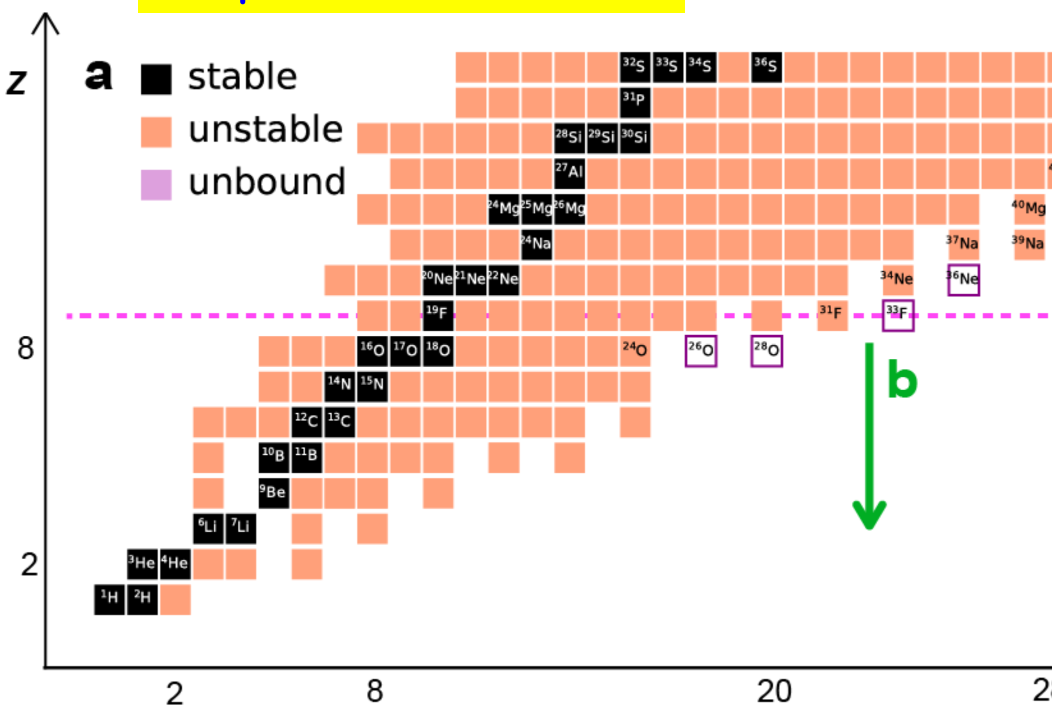


Monopole effect (edge of green part) becomes weaker for N > 16 in F isotopes. It even decreases because of high-lying d3/2 (see gray edge).

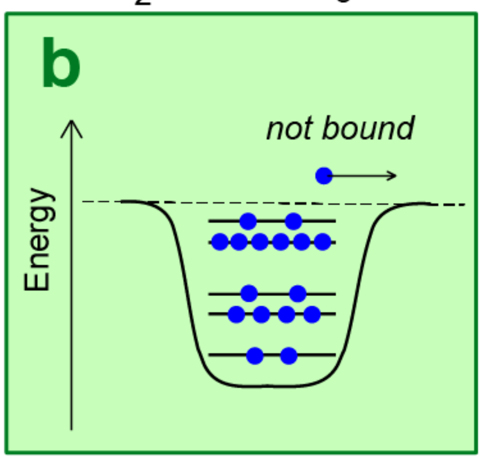
If there were no "rest" (~ quadrupole deformation) effect (red part), the dripline would be at N = 16, which is the same as oxygen isotopes.

Loose binding phenomena may be seen (?), in contrast to Ne, Na or Mg.

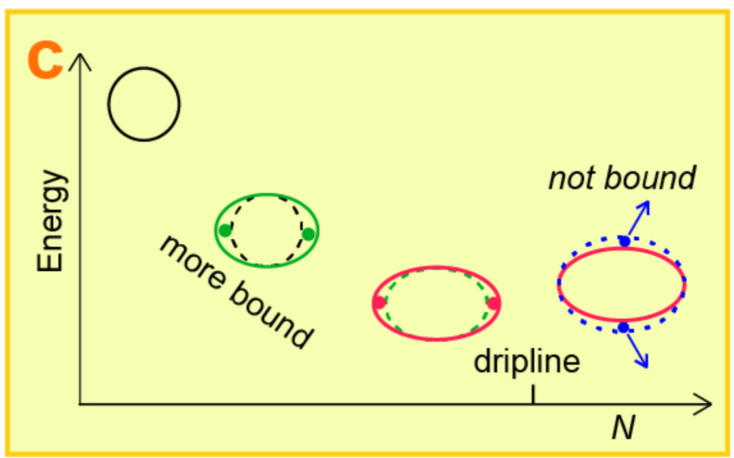
Dripline mechanisms



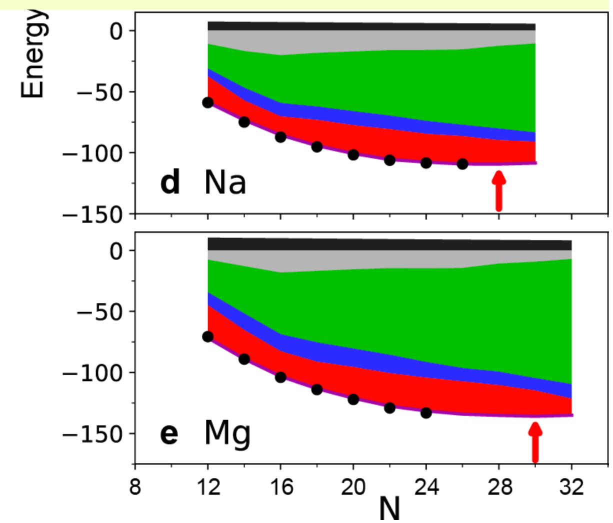
Neutron driplines are due to two mechanisms: one has single-particle origin (b), while the other new one (c) is due to the interplay of monopole and deformation energies. They may appear alternatively as Z increases.



Traditional (vague) view
-> extreme: neutron halo



New view



Intermedaite case: ^{22}C

Suzuki, O, Yuan & Alahari,

physics

Physics 2022, 4, 258-285.
https://doi.org/10.3390/physics4010018

MDPI

Review

Emerging Concepts in Nuclear Structure Based on the Shell Model

Takaharu Otsuka [1,2,3]

Shell evolution due to the monopole interaction

Type II shell evolution and shape coexistence

Triaxiality dominance in heavy nuclei as a consequence of the self-organization due to the monopole-quadrupole interplay

←→ traditional prolate dominance picture

New neutron dripline mechanism due to the monopole-quadrupole interplay, exemplified for F, Ne, Na and Mg isotopes

besides the traditional mechanism with single-particle nature

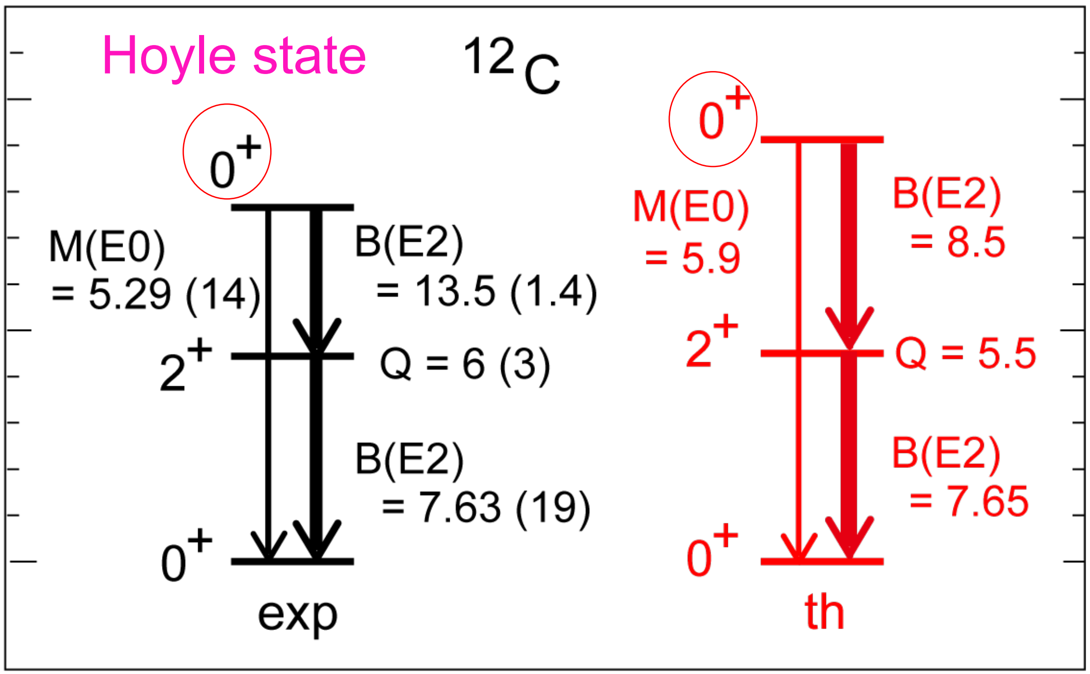
Fully *ab initio* calculations clarify alpha clustering ground and Hoyle states of ^{12}C (not included in the above paper)

Energy level & transition strength of ^{12}C

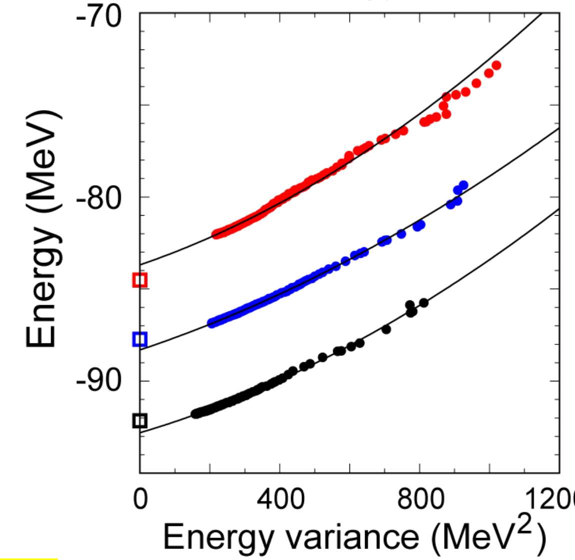
ab initio no-core MCSM + Daejeon 16 interaction (Shirokov et al.)
based on chiral EFT (Machleidt-Entem, 2011)

correlation effects are explicitly treated
(no medium correction needed)

charges protons 1e
neutrons 0e



convergence pattern as functions of energy variance

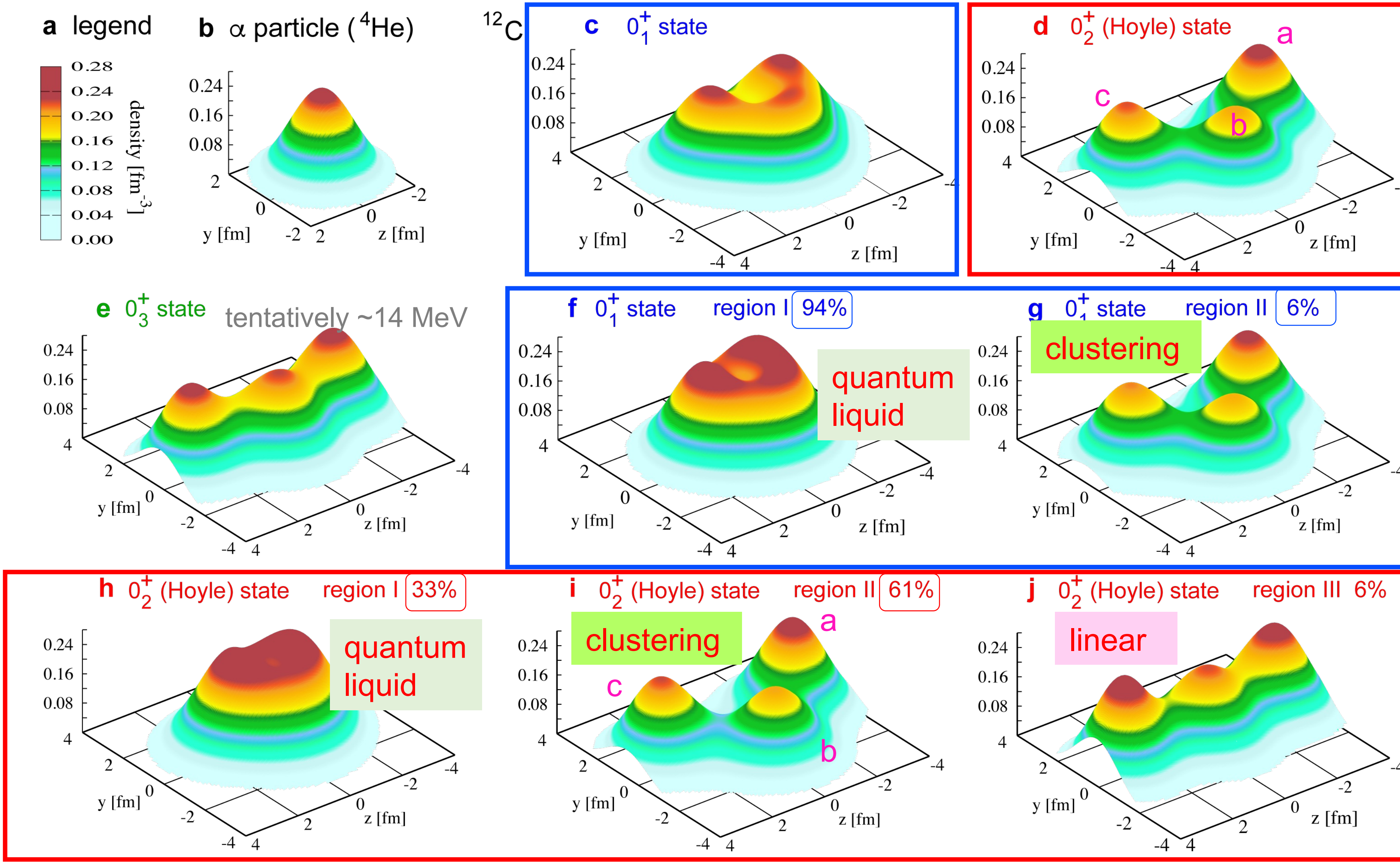


Strong deformation (β_2~0.6, oblate) in the 0^+_1 and 2^+_1 states can now be described from *first principles*.

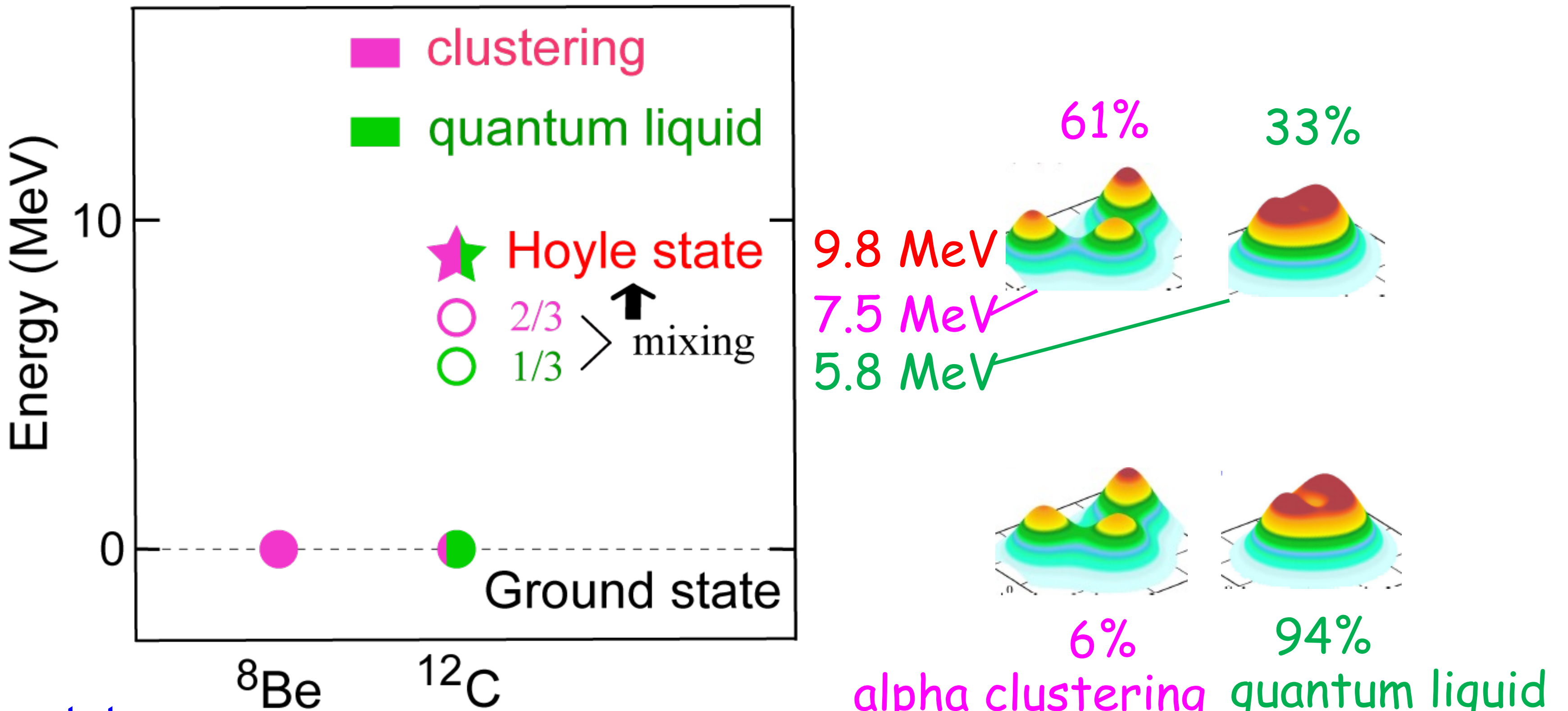
Stringent test for the Daejeon 16 interaction and the present No-Core MCSM.

Nucleon densities in the body-fixed frame

after proper orthogonalization



From ^{8}Be to ^{12}C, and the crossover in the ground & Hoyle states of ^{12}C



Hoyle state

The mixing occurs also due to the orthogonality to the ground state.

The mixing pushes the Hoyle state upwards by ~3 MeV (repulsive effect).

Ground state :

the mixing matrix element is ~ -3 MeV (attractive effect) with 6% (ampl. ~ 0.24) alpha clustering. →alpha decay, alpha knockout

Main features

Nuclear forces favor both quantum liquid and alpha cluster with different binding energies

Transition between them is not a phase transition but a crossover (no intermediate situation, but they can mix as components)

Alpha cluster emerges without threshold effect (←→Ikeda diagram)

Hoyle state ~ 2/3 triangular clusters + 1/3 quantum liquid.

What is crucial is probably shorter range parts of nuclear forces, which has been "uninvited guest" to nuclear structure physics

nature COMMUNICATIONS 13, 2234 (2022) *open access*

α-Clustering in atomic nuclei from first principles with statistical learning and the Hoyle state character

T. Otsuka[1,2,3✉], T. Abe[2,4], T. Yoshida[4,5], Y. Tsunoda[4], N. Shimizu[4], N. Itagaki[6], Y. Utsuno[3,4], J. Vary[7], P. Maris[7] & H. Ueno[2]

Summary

The emerging concepts include

- shell evolution in exotic nuclei described by the monopole interaction,
- shape coexistence due to type II shell evolution clarified by T-plot,
- self-organization in shape deformation and prevailing triaxiality,
- new dripline mechanism.

The monopole-quadrupole interplay is a common key.

- alpha clustering has recently been clarified by fully ab initio calculations. It may be in well-bound state (cf, alpha decay); crossover features; importance of almost bare *NN* interaction

Happy 90th Birthday

to

Professor Jan Blomqvist