3x60 workshop

Milano
Oct. 18, 2024

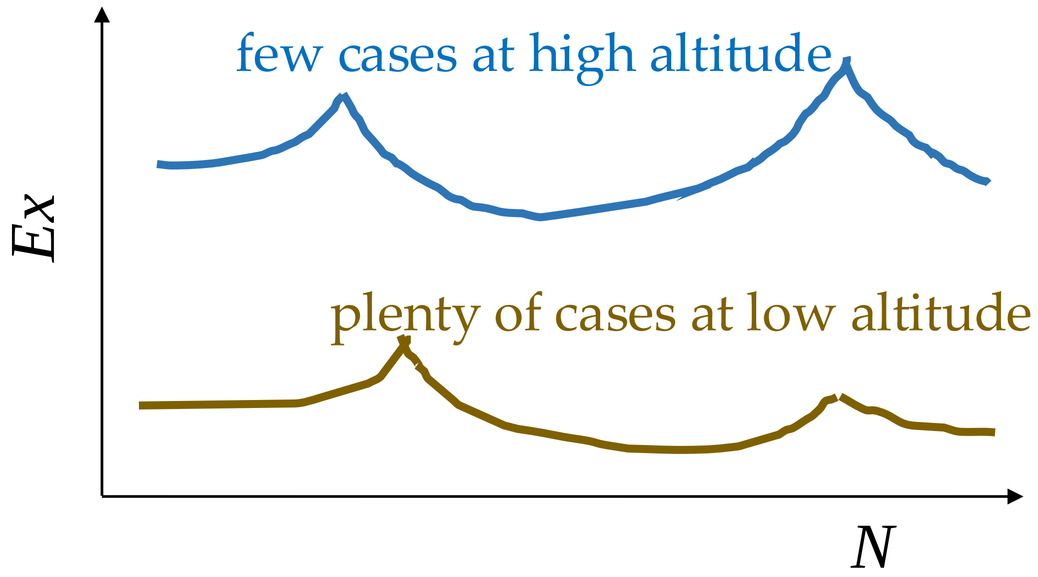
Driving with Ms. Silvia into Isotopic Ridges

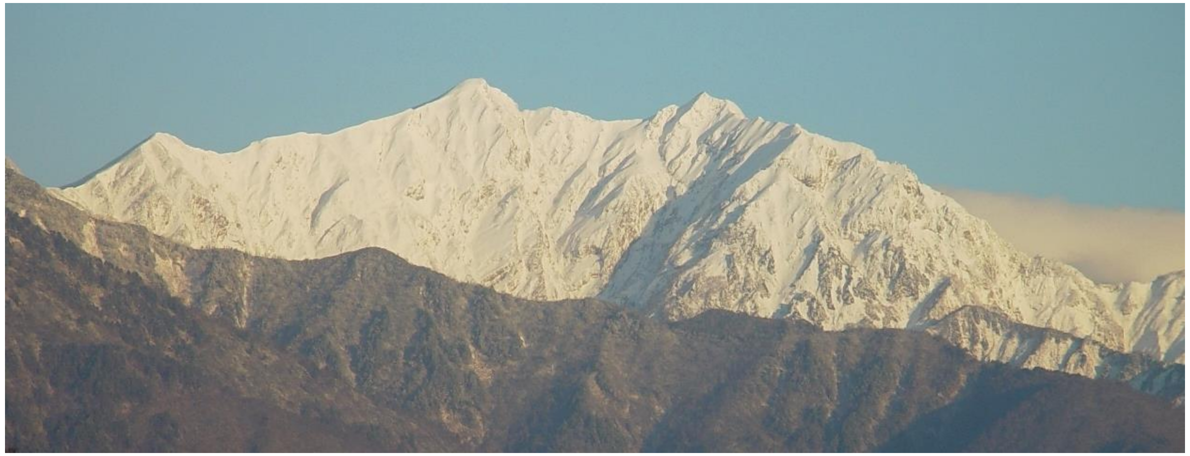
Takaharu Otsuka

Supported by "Program for promoting research on the supercomputer Fugaku", MEXT, Japan (JPMXP1020230411)

What is "Isotopic Ridge" ?

It is rather unexpected to see states of even-even nuclei
- at high excitation energies (~ 4-5 MeV > twice pairing gap)
- with distinct visible characters (such as "shape" or "isomer")
- with low spins (J~0)   [a lot of cases with high spins]
- with systematic appearance in a chain of isotopes





Silvia led and drove us into the exploratory journey hunting for this !

Outline

1. Shell evolution
   Just a brief overview

2. Type II Shell evolution
   A mechanism for shape coexistence illustrated with the example of ^{68}Ni

3. Ni isotopes exhibit an Isotopic Ridge
   An angle to look into structure evolution in 62-78Ni isotopes

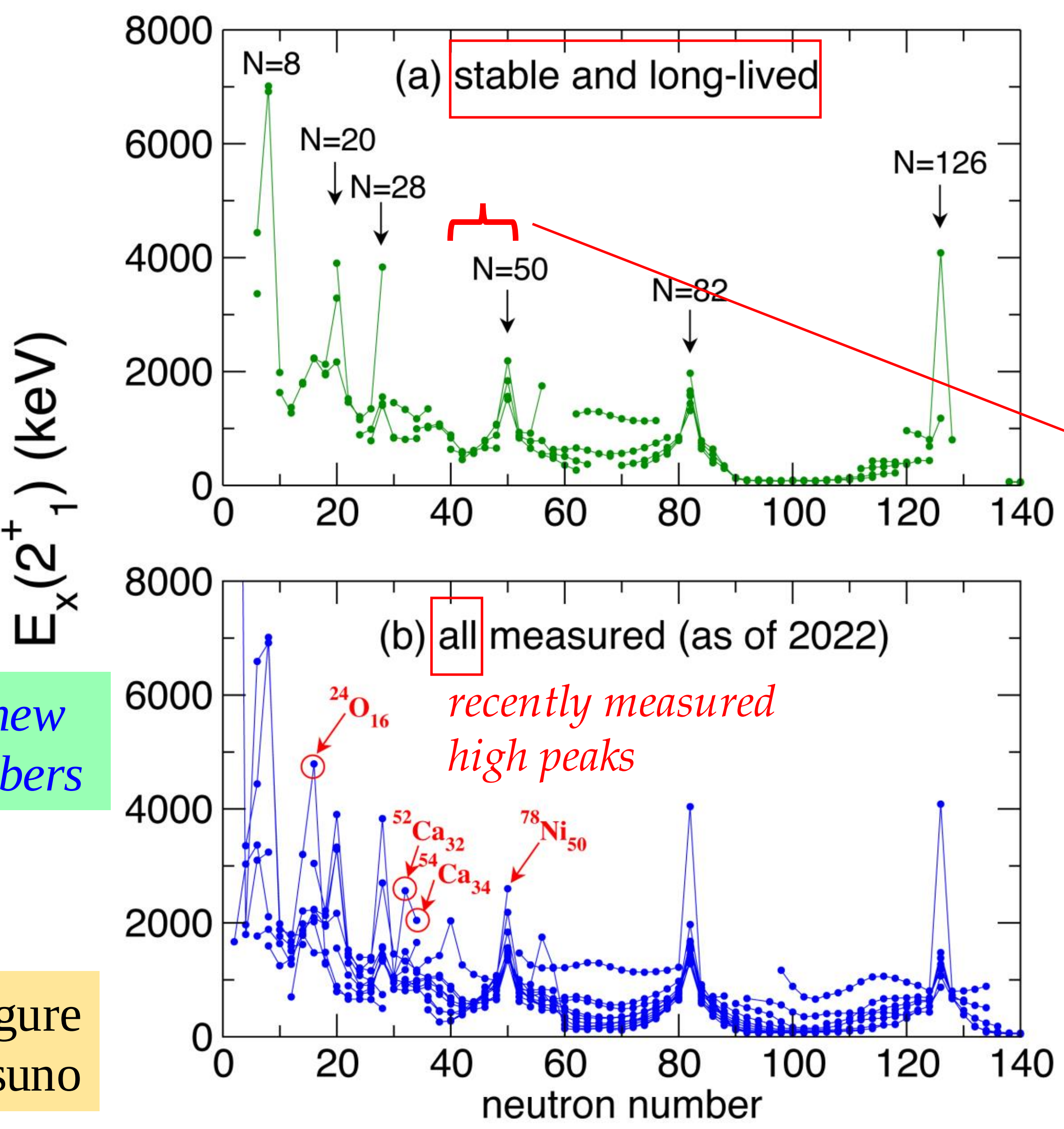
4. Another subject …

Sec. 2 is based on collaboration with Y. Tsunoda (CNS, Tokyo), N. Shimizu (Tsukuba), M. Honma (Aizu) and Y. Utsuno (JAEA). Sec. 3 is based *on collaboration with* Y. Tsunoda (CNS, Tokyo), S. Leoni (Milano), B. Fornel (Krakow), N. Marginean (IFINHH, Bucharest) U.), R. Janssens (North Carolina), and many others.

Sec. 4 is based on collaboration with Y. Tsunoda (CNS, Tokyo), N. Shimizu (Tsukuba), Y. Utsuno (JAEA), T. Abe (Keio U.), H. Ueno (Riken)

We start with observed facts about the nuclear shell structure.

Excitation energies of the lowest excited 2^+ states of even-even nuclei



$E_x(2^+_1)$ is higher at magic numbers.

← "Classical" magic numbers 2, 8, 20, 28, 50, 82, 126 are visible

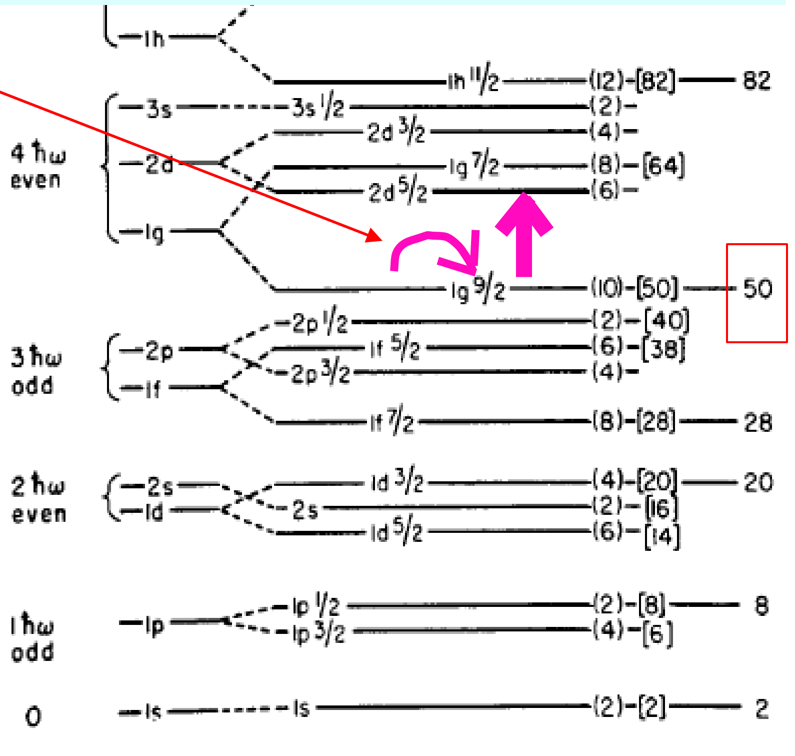


Fig. 7. Realistic level diagram for protons.

Emerging new magic numbers

Courtesy figure by Y. Utsuno

Monopole interaction : angular averaged part of a given interaction

for Central force

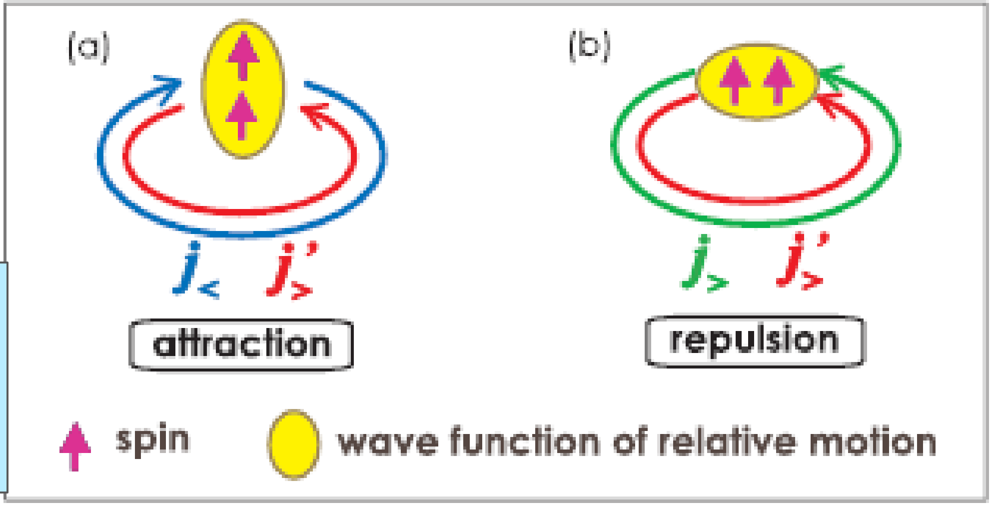
Stronger attraction between single-particle orbits of similar radial wave functions

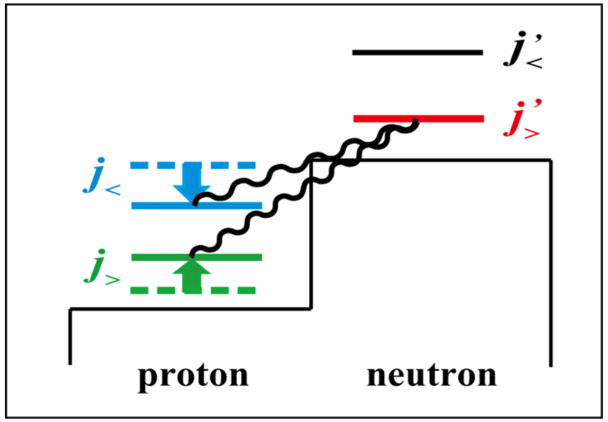
ex.: $f_{7/2} - f_{5/2}$, $g_{9/2} - h_{11/2}$ *cf: Federman-Pittel (1977)*

for Tensor force
(long-range part,
or 1π, 2π exchange)

$$j_> = l + ½$$

$$j_< = l - ½$$





for Three-nucleon force (Δ-hole) : overall repulsive effect

Effects of these monopole interactions can be seen in terms of

Effective Single-Particle Energy (ESPE)

cf: Baranger, Sturm-Watt-Whitehead

Exotic Ca isotopes

$$\hat{\epsilon}^n_j = \epsilon^n_{0;j} + \Sigma_{j'} V^{\rm mono}_{nn}(j, j')\,\hat{n}^n_{j'} + \Sigma_{j'} \tilde{V}^{\rm mono}_{pn}(j', j)\,\hat{n}^p_{j'}$$

Neutron shell structure in Ni isotopes ($f_{7/2}$ fully occupied)

a la Mayer-Jensen

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

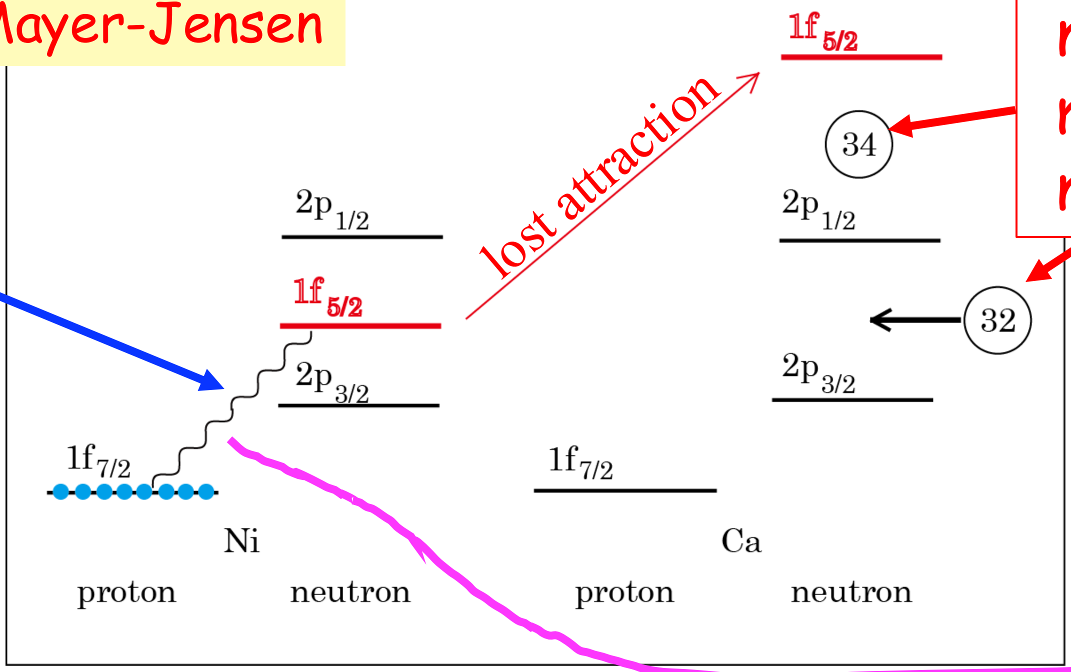
Experiment @ RIBF

12 years after prediction (2001)

strong attraction due to monopole part of tensor force

$f_{7/2}$ $l + 1/2$

$f_{5/2}$ $l - 1/2$



new magic numbers

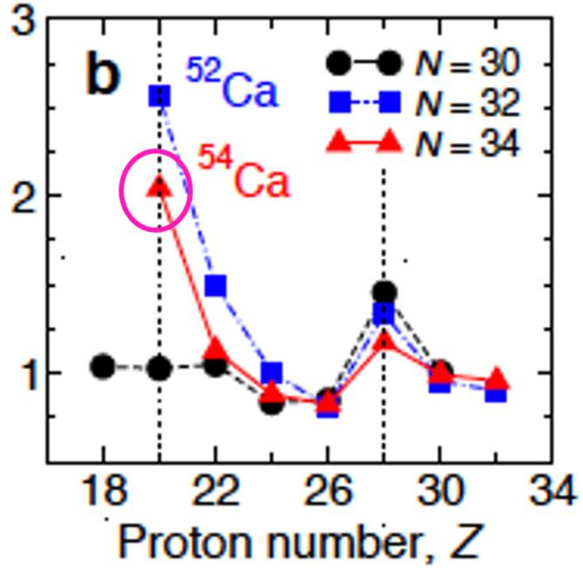
$<\hat{n}^p_{j'}>=8$

$<\hat{n}^p_{j'}>=0$

stable (e.g. ^{56}Ni)

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

excitation energy of the 2+ state



Steppenbeck *et al.* Nature 502 (2013)

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

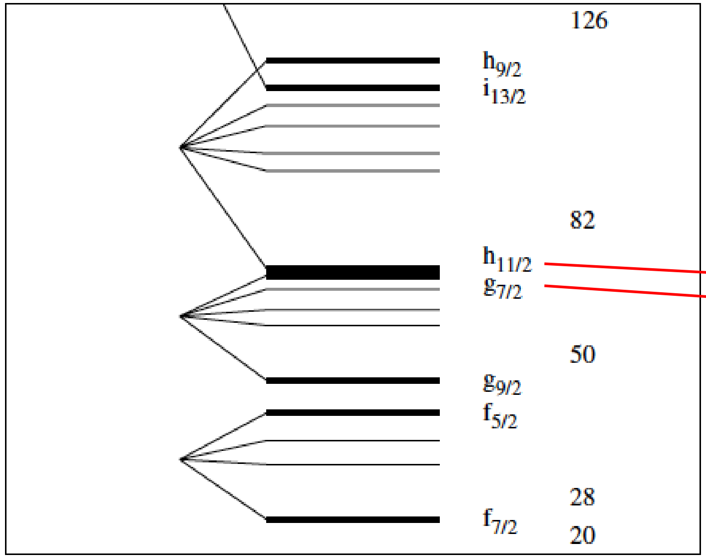
Not limited to magic numbers, … shell structure changes

Probably (one of) the first systematic experimental studies

VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

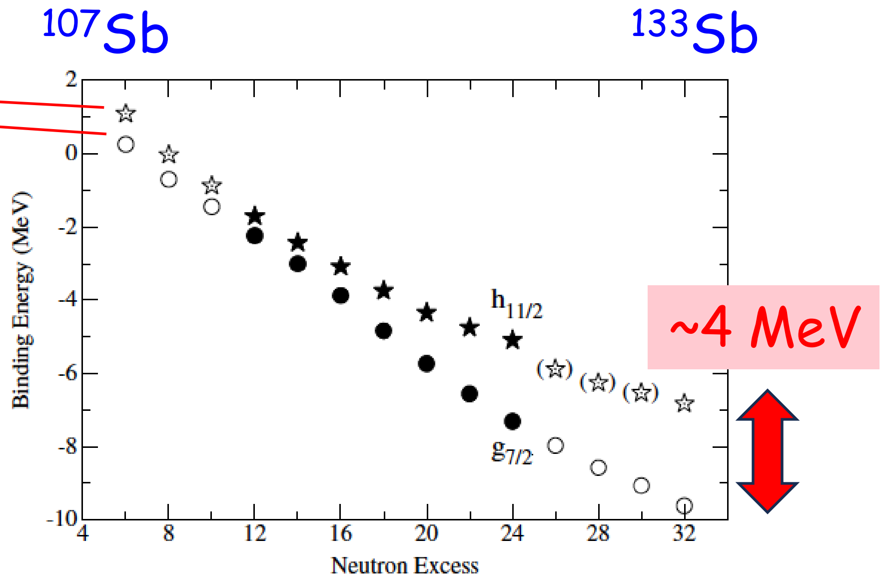
Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

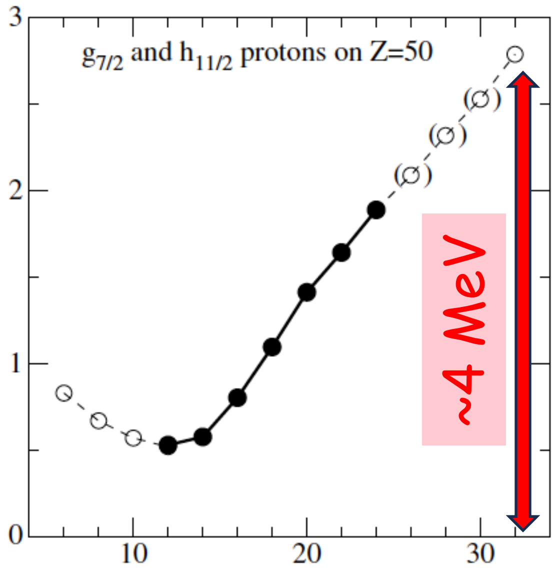
J. P. Schiffer,[1] S. J. Freeman,[1,2] J. A. Caggiano,[3] C. Deibel,[3] A. Heinz,[3] C.-L. Jiang,[1] R. Lewis,[3] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] S. Sinha,[1] and J. S. Thomas[4]



Mayer-Jensen scheme

A question why this widening occurs ?





The shell evolution now occurs almost everywhere on the nuclear chart.

→ one of the major subjects of RI-beam facilities for exotic nuclei

This word did not exist before 2004.

“Shell evolution”* : 0 hit in Google Scholar in 2003
1 2004

~140 hits/year ~2021

*Combine with “atomic nuclei”, to avoid biology, … .

Earlier empirical analyses such as Grawe, Sorlin-Porquet, ….
with different nomenclatures for instance,“orbital migration”, …

What about the “shell evolution” mechanism in other nuclear properties ?

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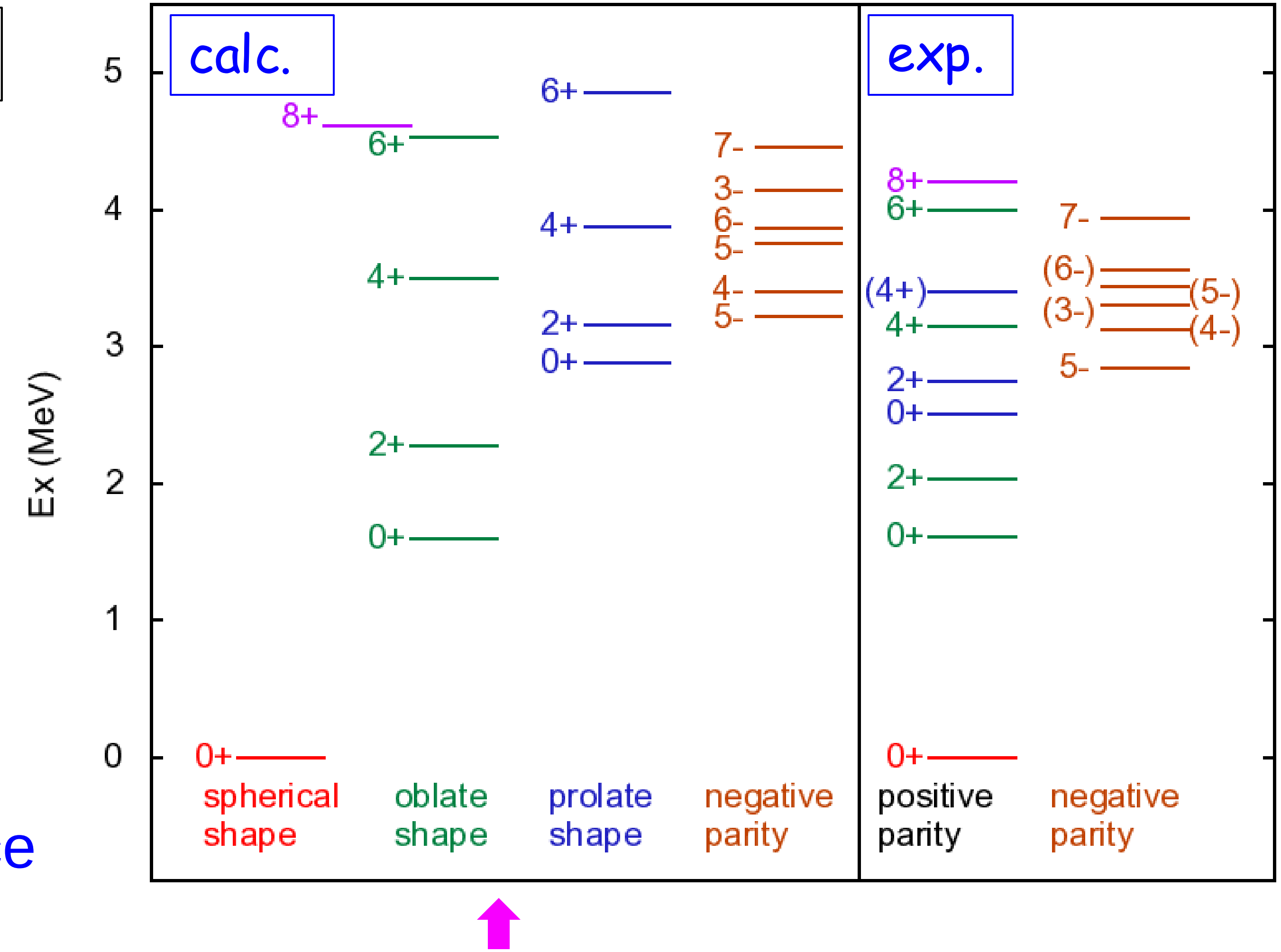
4. Another subject …

Energy levels and B(E2) values of Ni isotopes as an example

Description by the Monte Carlo shell model with the A3DA-m Hamiltonian

^{68}Ni

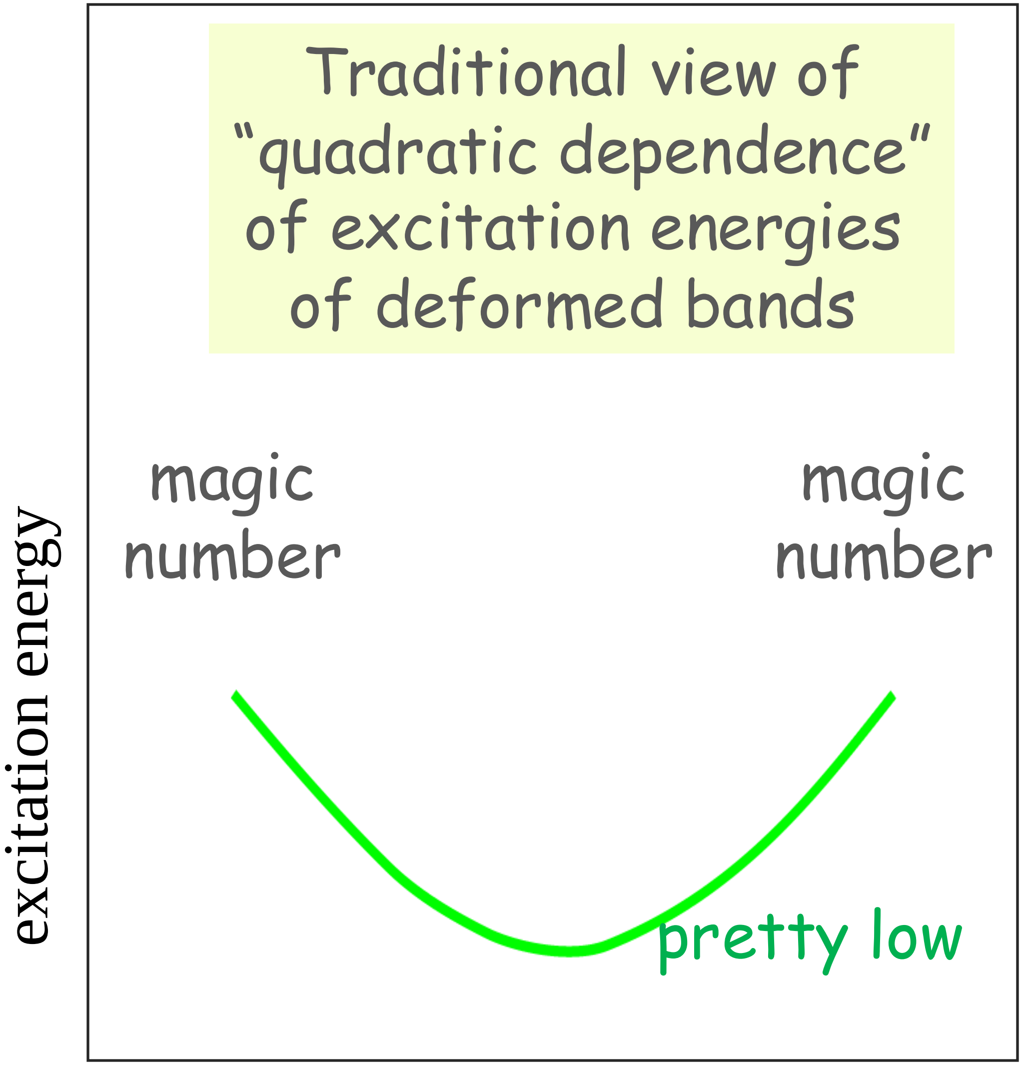


shape coexistence

Calc. : Monte Carlo Shell Model

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

Shape coexistence: traditional view



neutron number, N

Fig. 10 of Heyde & Wood, RMP 83, 1467 (2011)

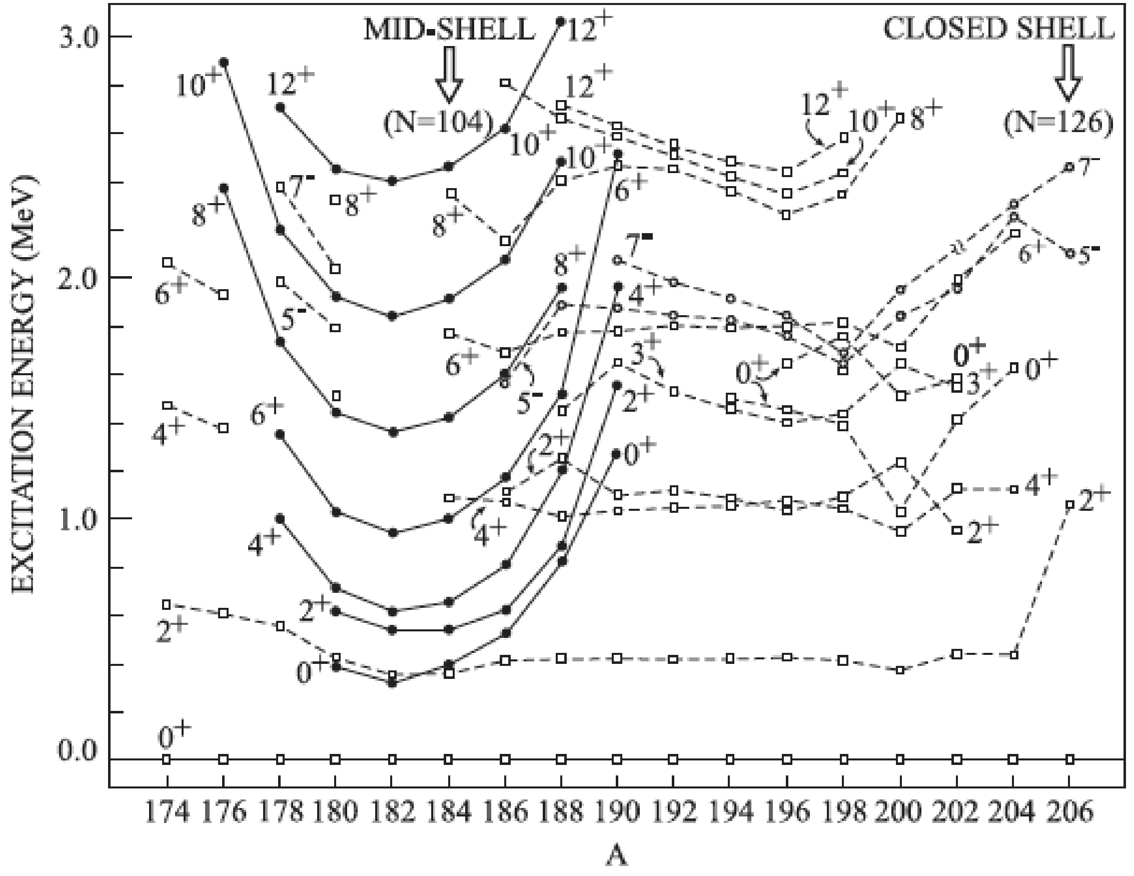
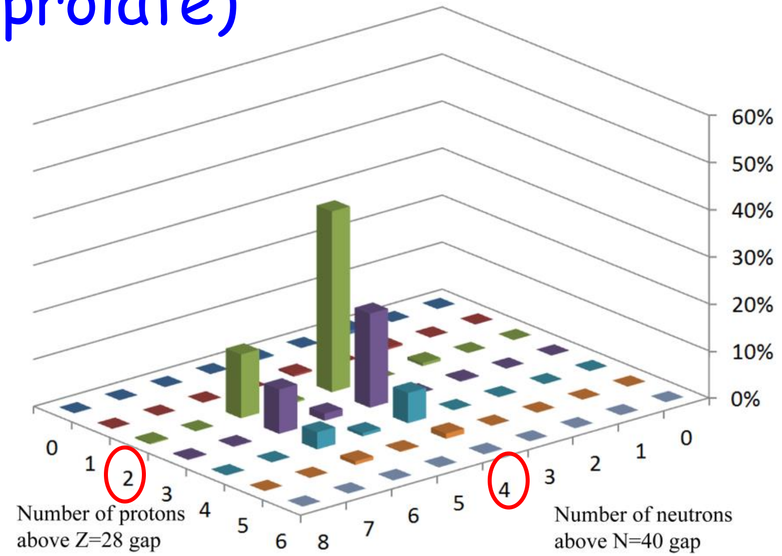


FIG. 10. Systematics of excited states in the even-Hg isotopes. Note the "parabolic intrusion" of the closely spaced bands of states (marked with solid lines) with $J = 0, 2, 4, \ldots$ centered on ^{182}Hg ($N = 102$). The data are taken from Nuclear Data Sheets. Some recent lifetime data can be found in Grahn *et al.* (2009).

Normal and intruder states in ^{68}Ni

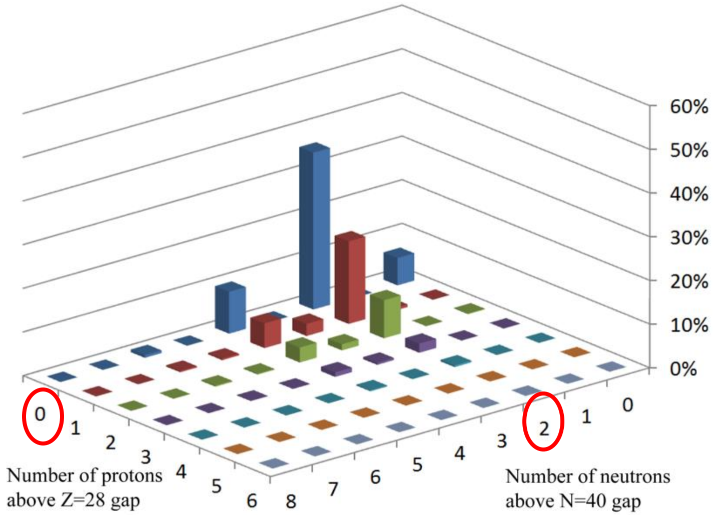
0^+_3 state
(prolate)



6p6h+more excitations

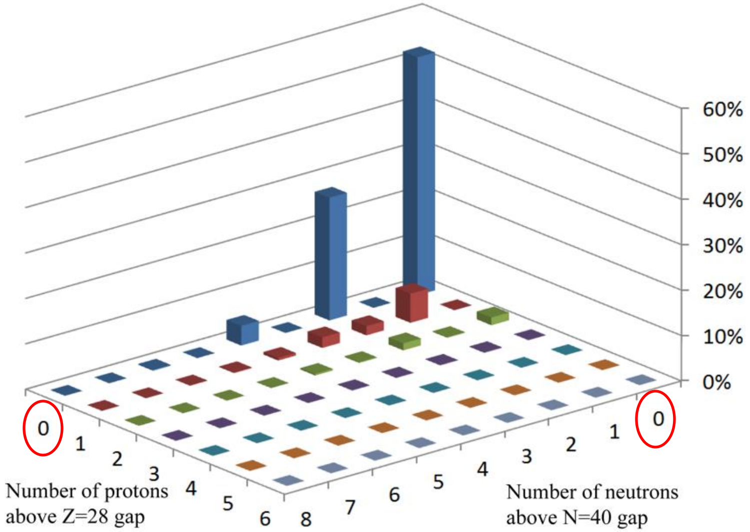
Not 4p4h

0^+_2 state
(oblate)



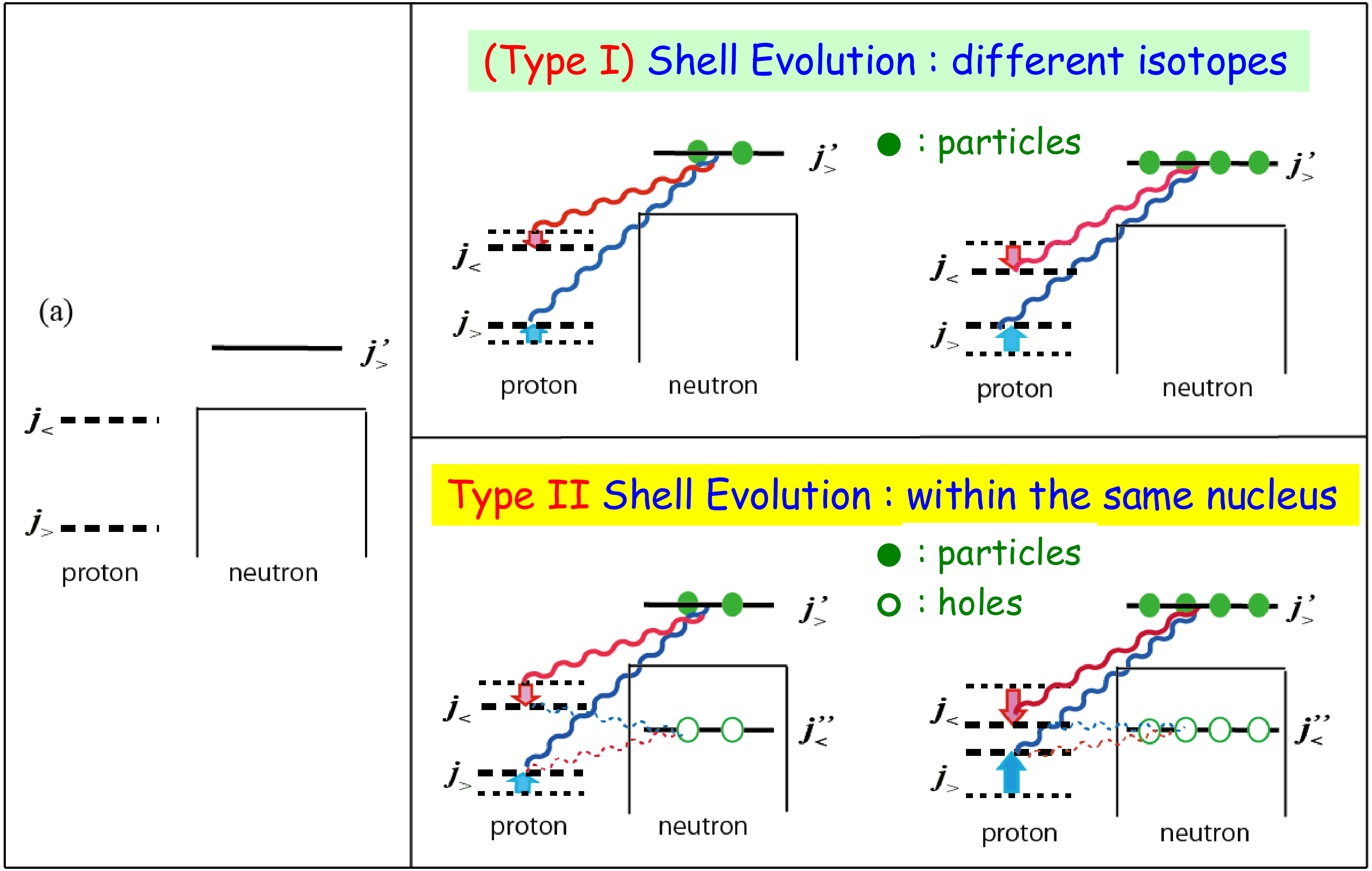
2p2h+more excitations

ground state
(spherical
-> closed shell)



0p0h with 25% mixture of 2p2h excitation over N=40 gap

Non-linear enhancement of p-h excitations due to tensor force



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

Potential energy surface (PES)

Constrained Hartree-Fock calculation for the shell-model Hamiltonian with constraints by β_2 and γ.

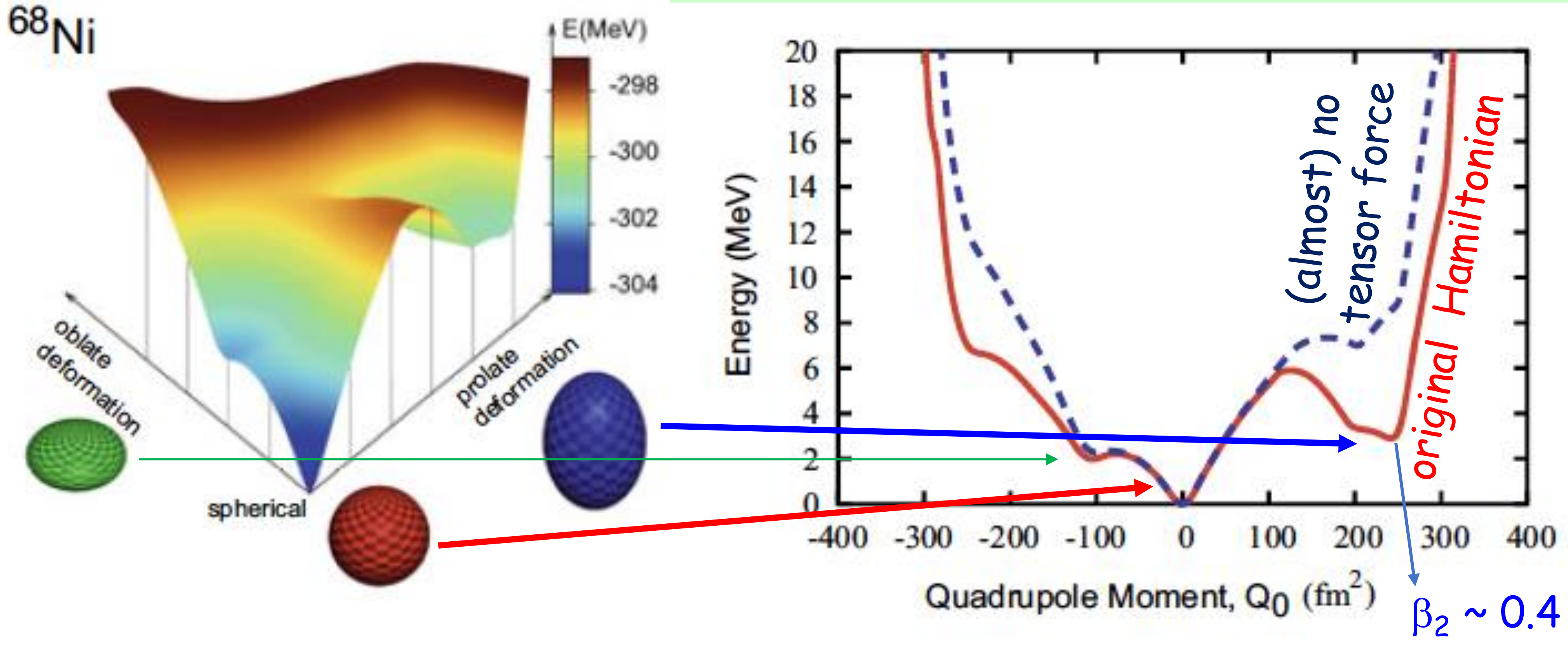
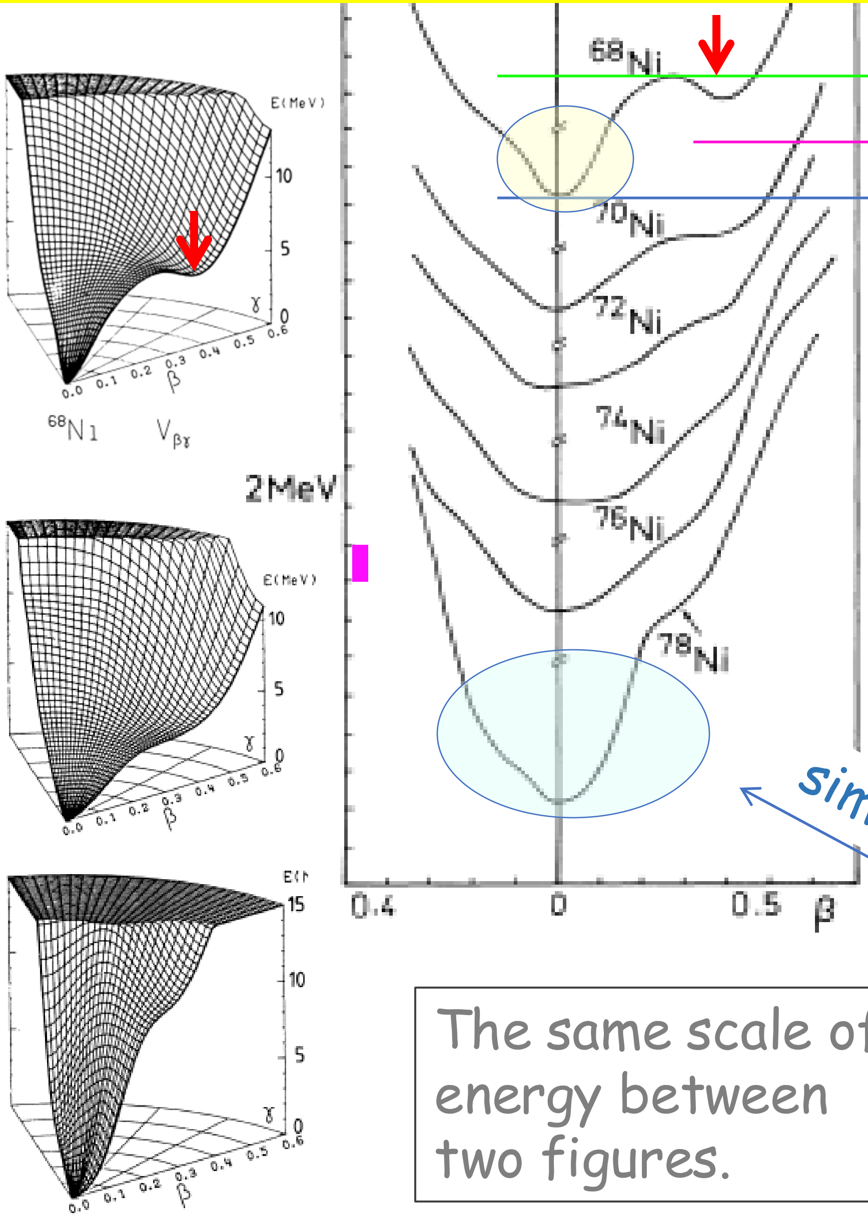


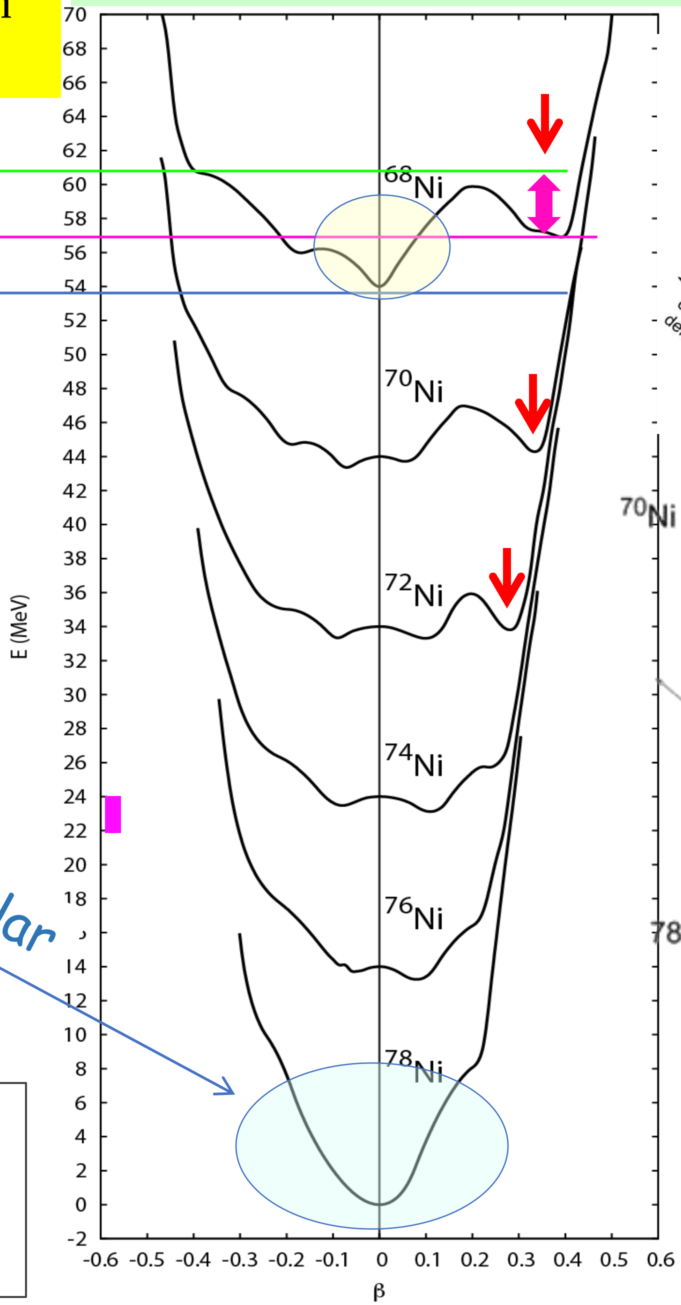
Fig. 17 (left) Potential energy surface (PES) of ^{68}Ni. (Taken from Fig. 5 of Otsuka and Tsunoda 2016). (right) PES of ^{68}Ni for axially symmetric shapes. The solid line shows the PES of the full Hamiltonian, whereas the dashed line is the PES with practically no tensor force contribution. (Taken from Fig. 6 of Otsuka and Tsunoda 2016)

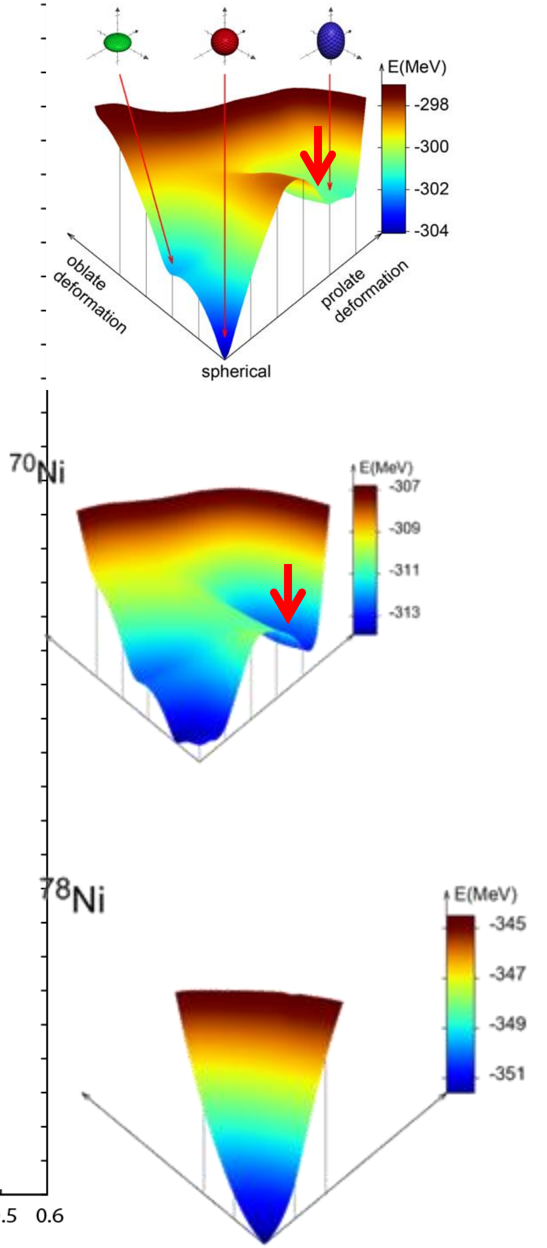
Bohr-model calc. by HFB with **Gogny** force, Girod, Dessagne, Bernes, Langevin, Pougheon and Roussel, PRC 37,2600 (1988)

Present with full monopole effects



similar





The same scale of energy between two figures.

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Shape coexistence with known lowest excitation energy within Ni isotopes

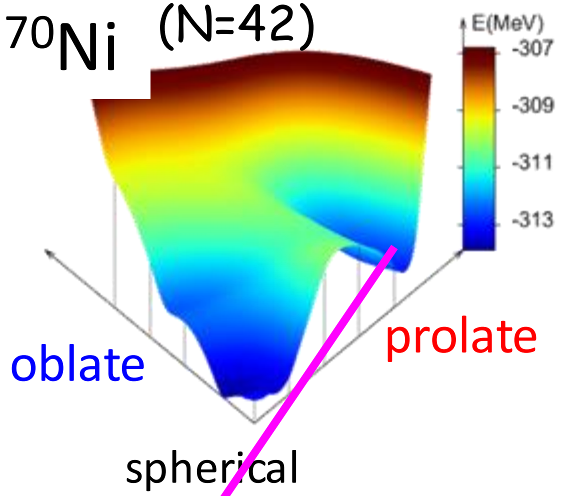
Physics Letters B 765 (2017) 328–333

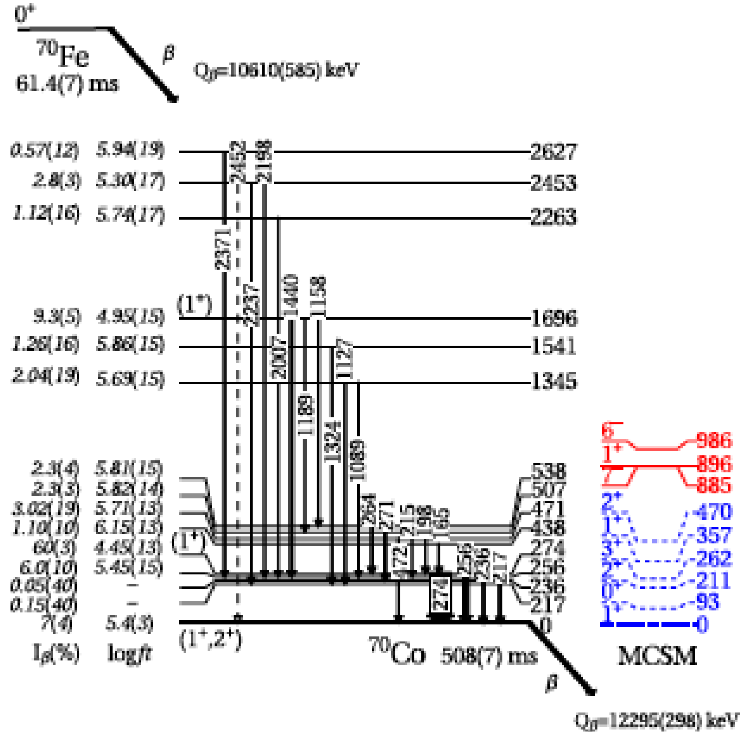
Type II shell evolution in $A = 70$ isobars from the $N \geq 40$ island of inversion

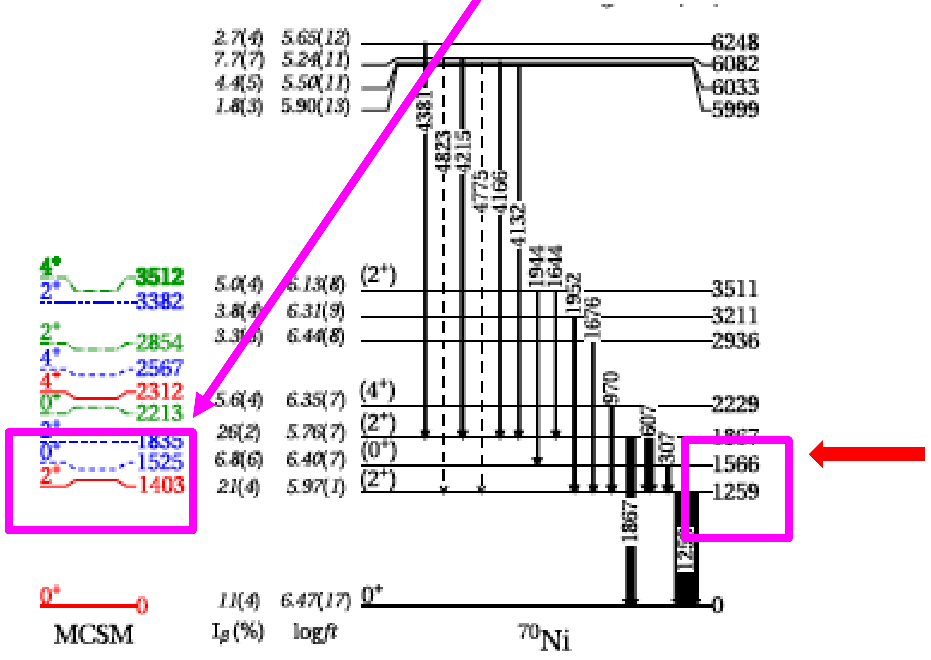
A.I. Morales[a,b,*], G. Benzoni[a], H. Watanabe[c,d], Y. Tsunoda[e], T. Otsuka[f,g,h], S. Nishimura[d], F. Browne[i,d], R. Daido[j], P. Doornenbal[d], Y. Fang[j], G. Lorusso[d], Z. Patel[k,d], S. Rice[k,d], L. Sinclair[l,d], P.-A. Söderström[d], T. Sumikama[m], J. Wu[d], Z.Y. Xu[f,d], A. Yagi[j], R. 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

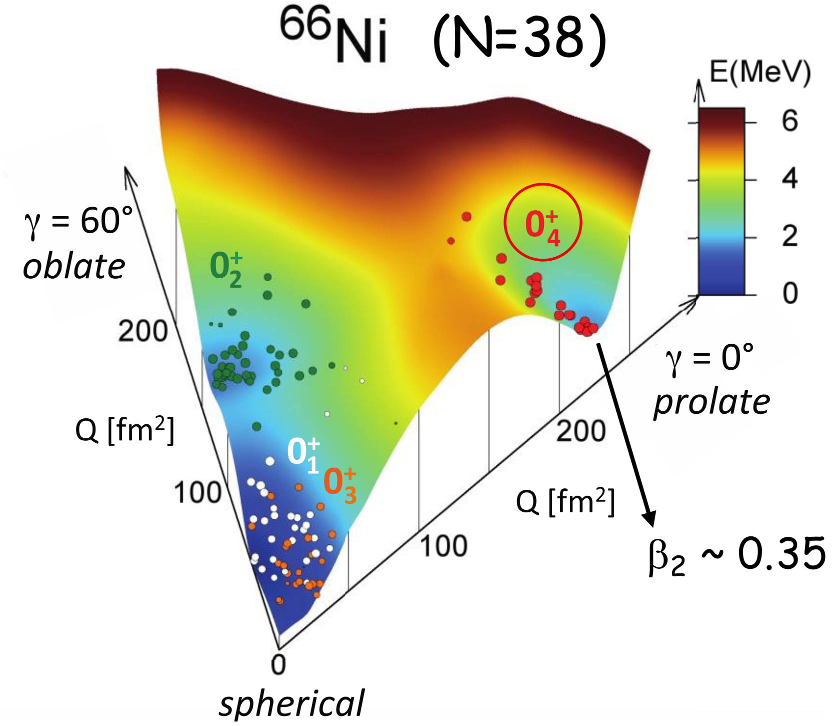
^{70}Ni (N=42)

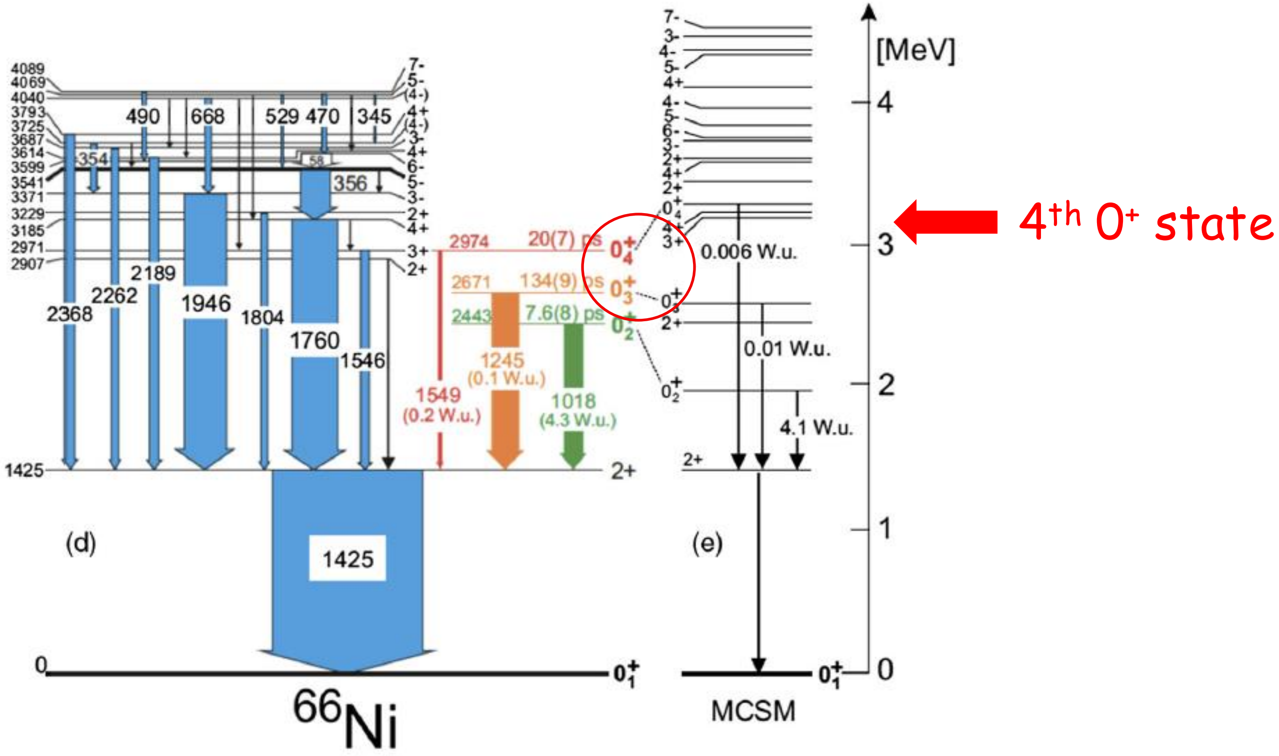






What happens in the other side of the magic number *N* =40





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]

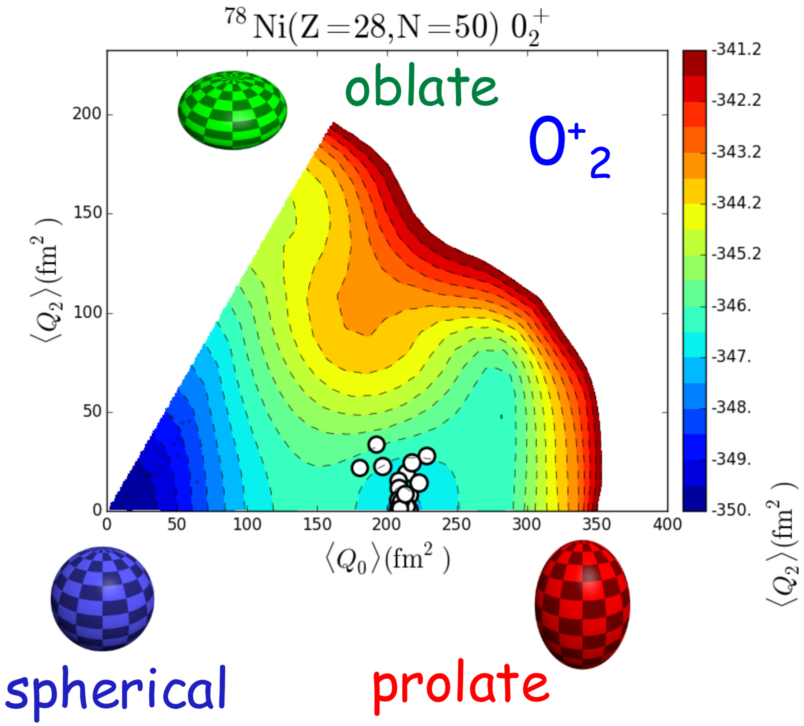
Identification of nuclear shape by T-plot of MCSM

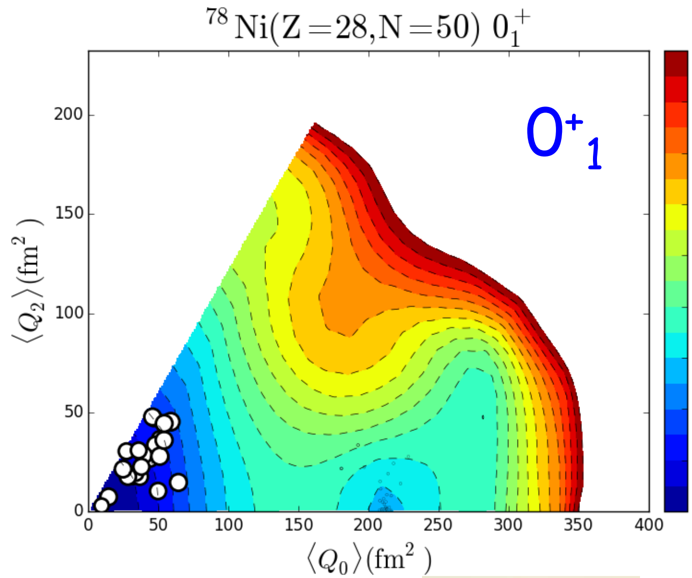
- Location of circle: shape
  quadrupole deformation of unprojected MCSM basis vector

- Area of circle: importance
  overlap probability between each projected basis vector and the eigen wave function

- Potential energy surface (PES) is calculated by Constrained HF for the same interaction

T-plot of 0^+ states of ^{78}Ni (Z=28, N=50)





angular-momentum, parity projection

Slater determinant

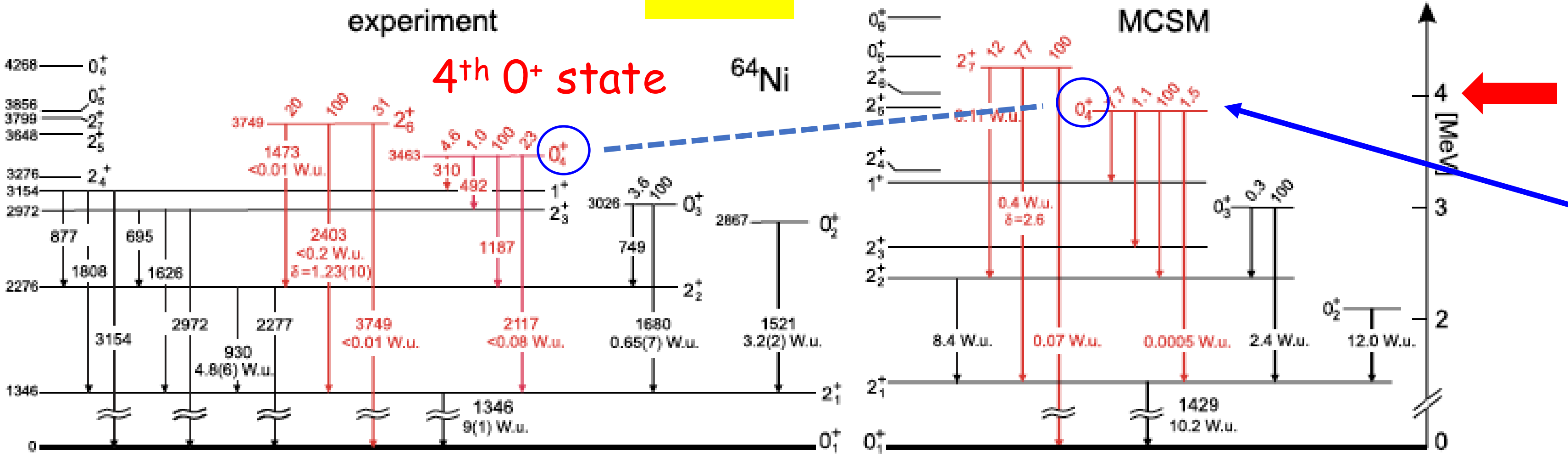
$$|\Psi\rangle = \sum_n f_n P^{J\pi}|\psi_n\rangle$$

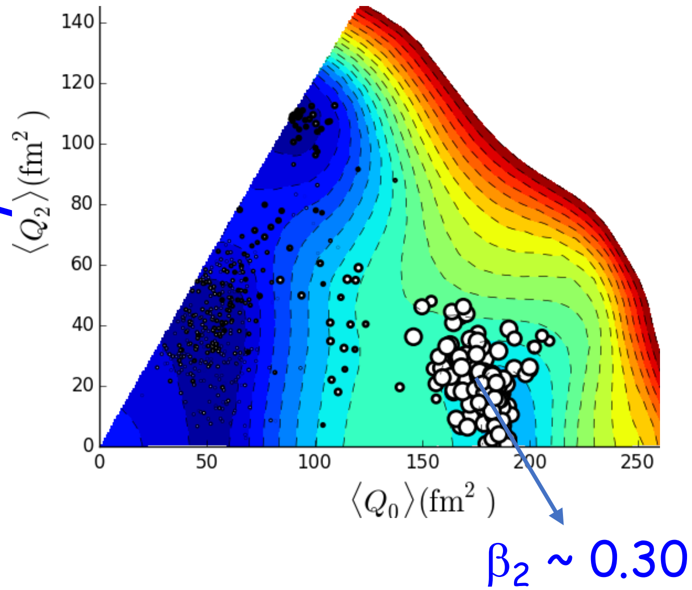
MCSM eigen wave function

MCSM basis vector

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

^{64}Ni (N=36)



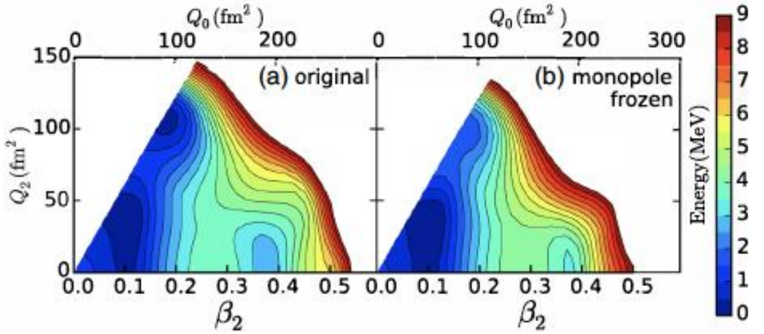


PHYSICAL REVIEW LETTERS 125, 102502 (2020)

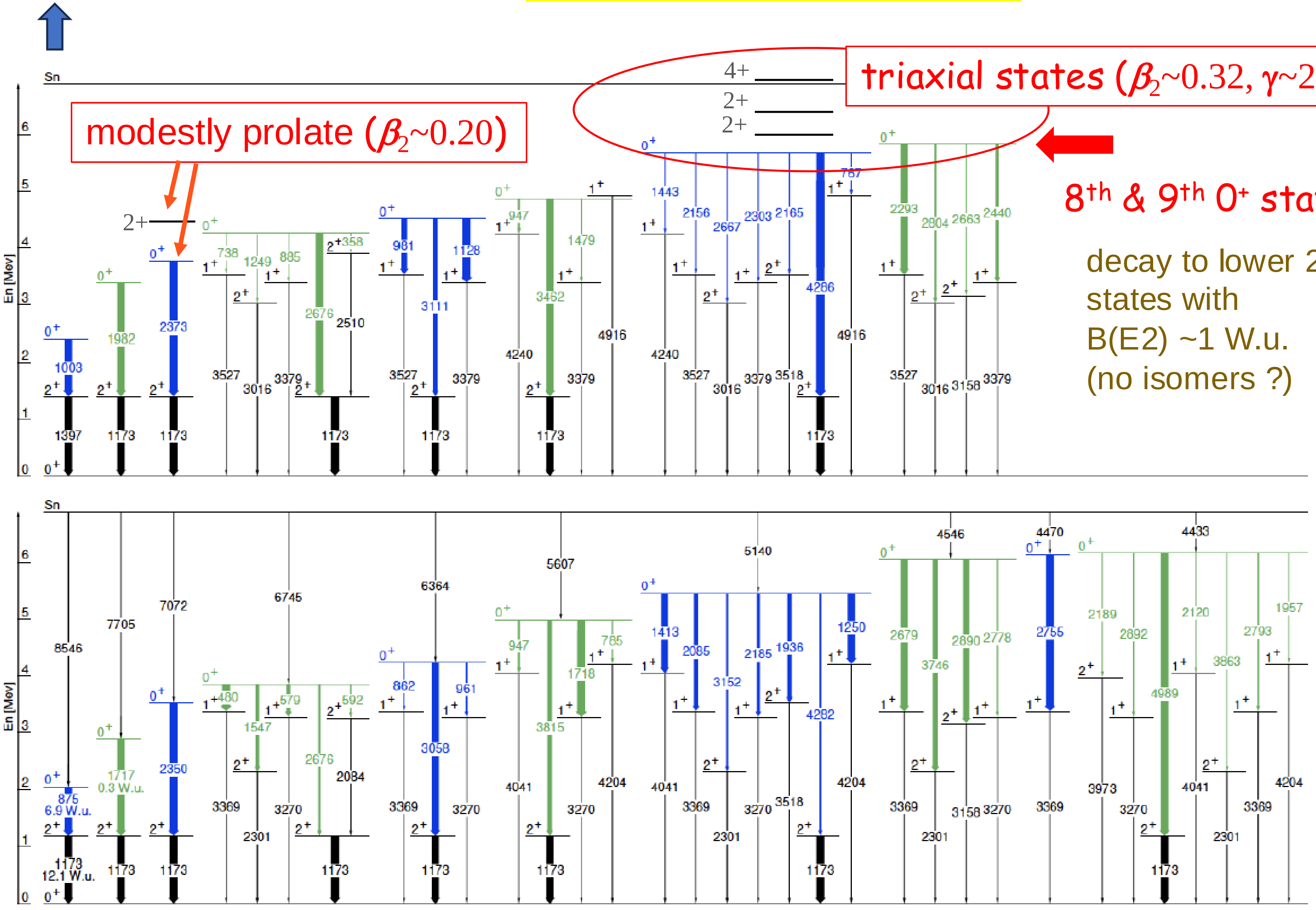
Shape Coexistence at Zero Spin in ^{64}Ni Driven by the Monopole Tensor Interaction

N. Mărginean,[1,*] D. Little,[2,3] Y. Tsunoda,[4] S. Leoni,[5,6,†] R. V. F. Janssens,[2,3,‡] B. Fornal,[7,§] T. Otsuka,[8,9,10,∥] C. Michelagnoli,[11] L. Stan,[1] F. C. L. Crespi,[5,6] C. Costache,[1] R. Lica,[1] M. Sferrazza,[12] A. Turturica,[1] A. D. Ayangeakaa,[13] K. Auranen,[14,¶] M. Barani,[5,6,11] P. C. Bender,[15] S. Bottoni,[5,6] M. Boromiza,[1] A. Bracco,[5,6] S. Călinescu,[1] C. M. Campbell,[16] M. P. Carpenter,[14] P. Chowdhury,[15] M. Ciemała,[7] N. Cieplicka-Oryńczak,[7] D. Cline,[17] C. Clisu,[1] H. L. Crawford,[16] I. E. Dinescu,[1] J. Dudouet,[18] D. Filipescu,[1] N. Florea,[1] A. M. Forney,[19] S. Fracassetti,[5,6,**] A. Gade,[20,21] I. Gheorghe,[1] A. B. Hayes,[22] I. Harca,[1] J. Henderson,[23] A. Ionescu,[1] Ł. W. Iskra,[6] M. Jentschel,[11] F. Kandzia,[11] Y. H. Kim,[11] F. G. Kondev,[14] G. Korschinek,[24] U. Köster,[11] Krishichayan,[3] M. Krzysiek,[7] T. Lauritsen,[14] J. Li,[14,††] R. Mărginean,[1] E. A. Maugeri,[25] C. Mihai,[1] R. E. Mihai,[1] A. Mitu,[1] P. Mutti,[11] A. Negret,[1] C. R. Niţă,[1] A. Olăcel,[1] A. Oprea,[1] S. Pascu,[1] C. Petrone,[1] C. Porzio,[5,6] D. Rhodes,[20,21] D. Seweryniak,[14] D. Schumann,[25] C. Sotty,[1] S. M. Stolze,[14] R. Şuvăilă,[1] S. Toma,[1] S. Ujeniuc,[1] W. B. Walters,[19] C. Y. Wu,[23] J. Wu,[14] S. Zhu,[22] and S. Ziliani[5,6]

[1]*Horia Hulubei National Institute of Physics and Nuclear Engineering—IFIN HH, Bucharest 077125, Romania*



Current edge : ^{62}Ni



^{62}Ni

8th & 9th 0+ states

decay to lower 2+ states with B(E2) ~1 W.u. (no isomers ?)

Theory

MCSM

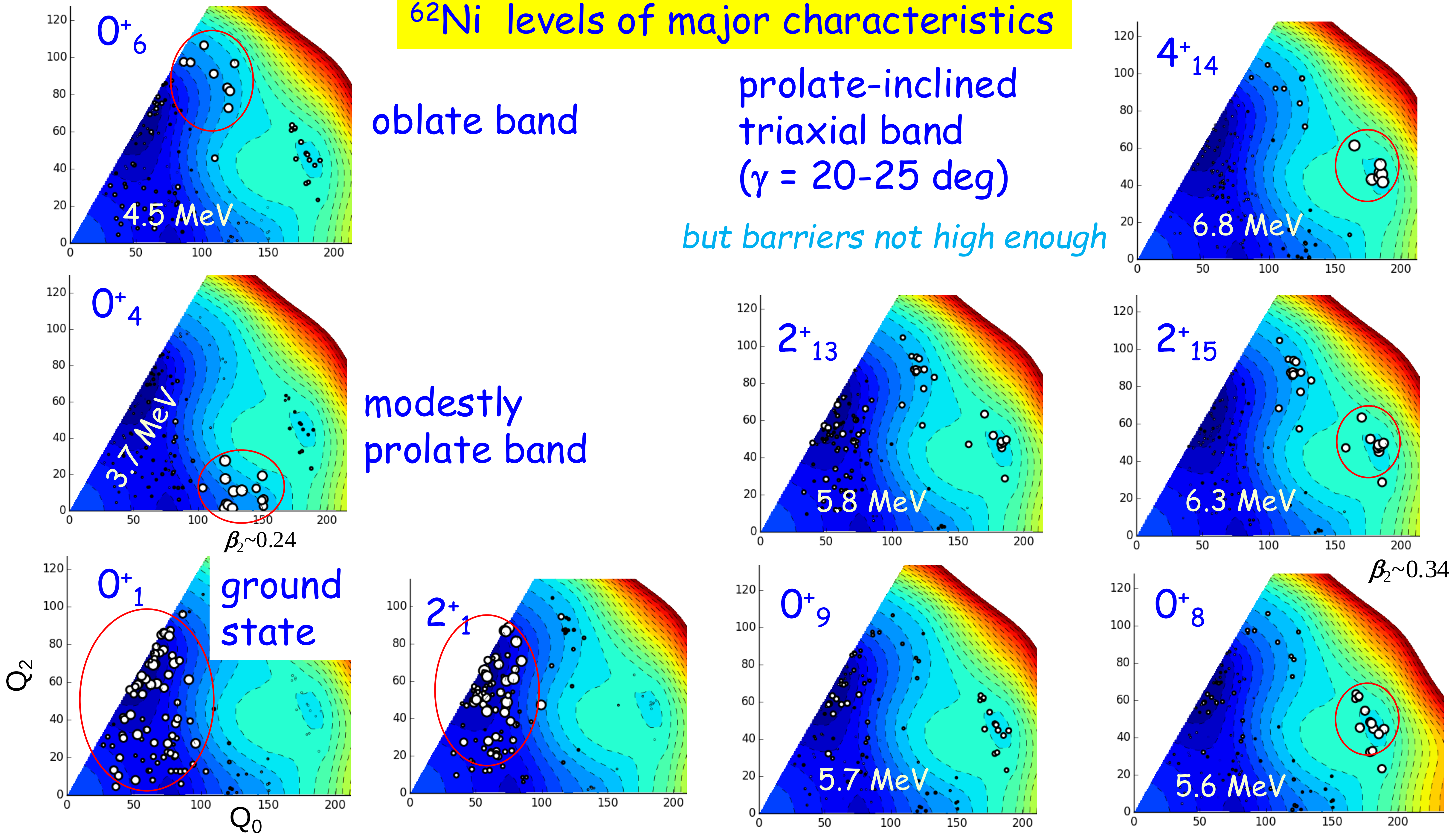
the same A3DA-m interaction

8th & 9th 0+ states

experiment

(n,γ)

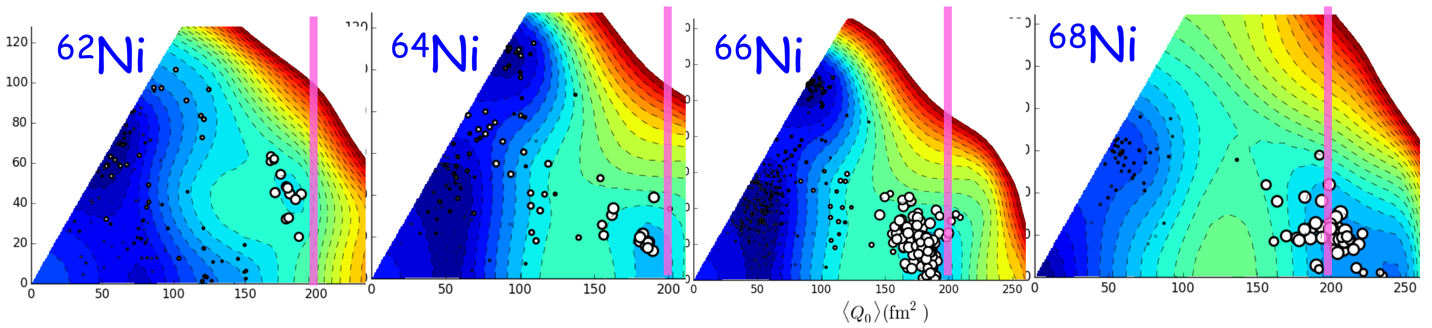
^{62}Ni levels of major characteristics

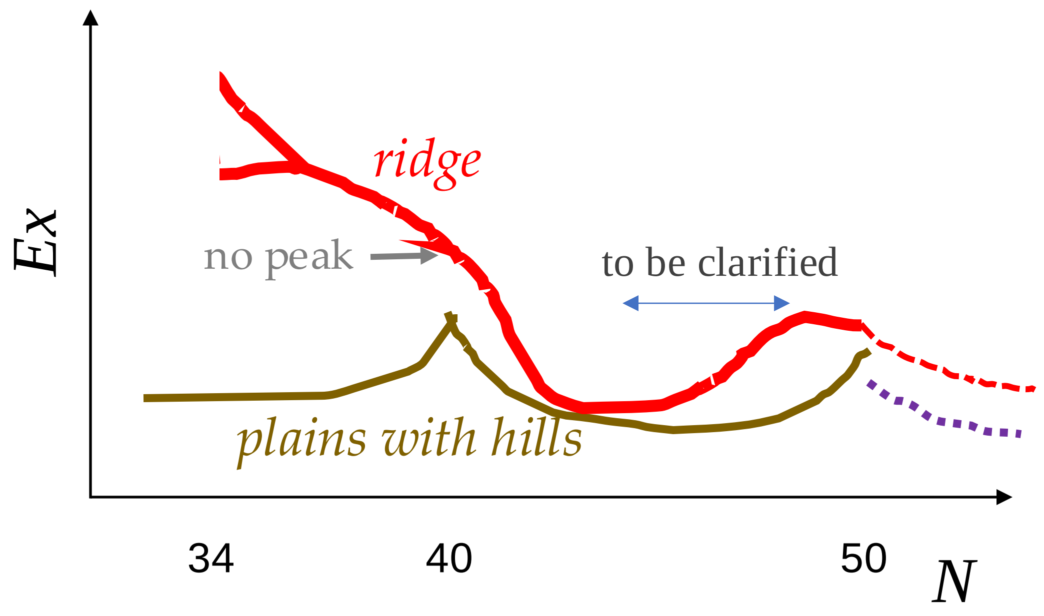


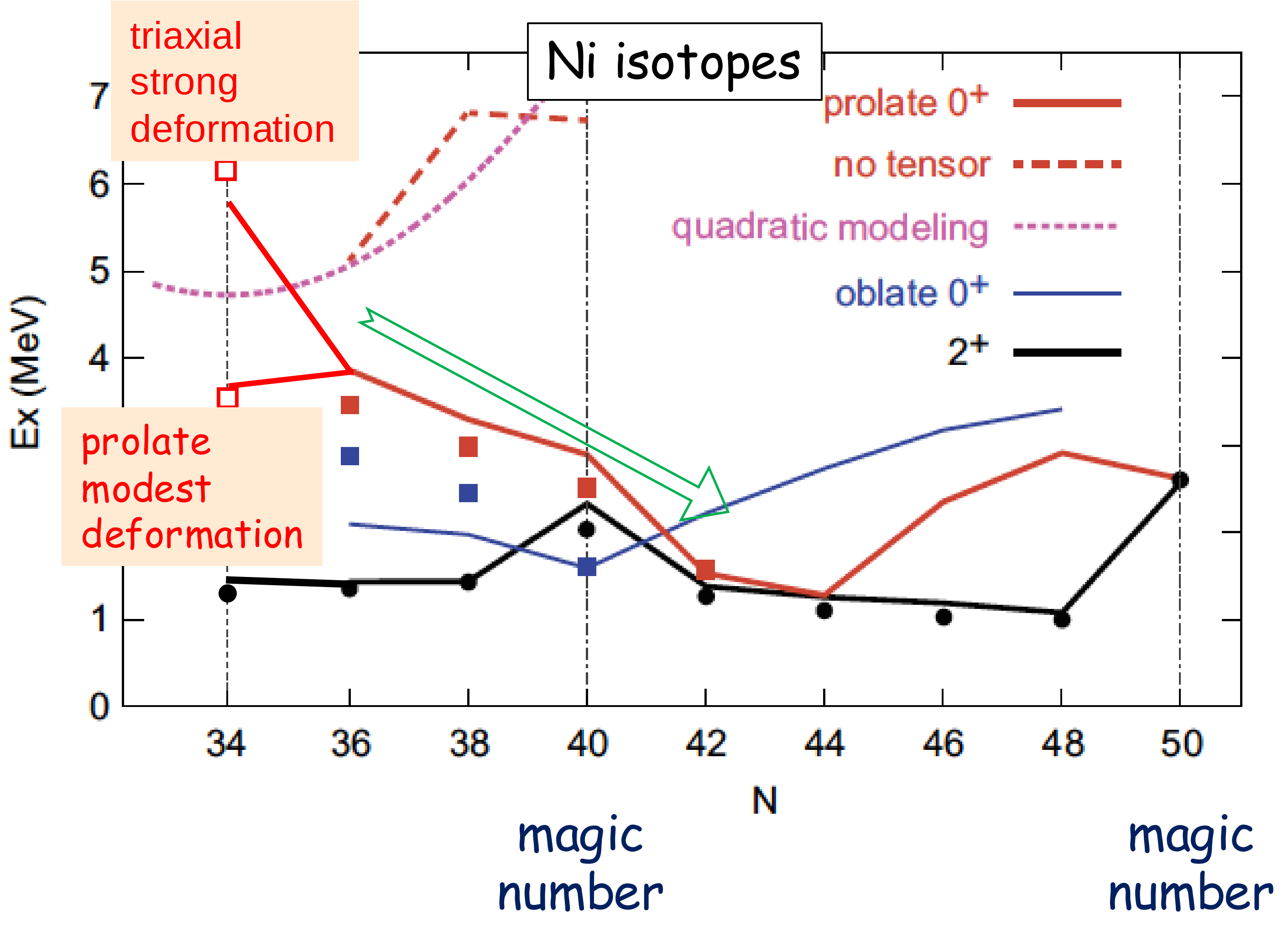
Final picture of "Isotopic Ridge"

Thus, a "ridge" arises for Ni isotopes
with gradually varying deformed shapes.
… splitting at the end, however

Probably, no ridges for Fe or Zn isotopes.
(→ isotopic ridge, if you wish)



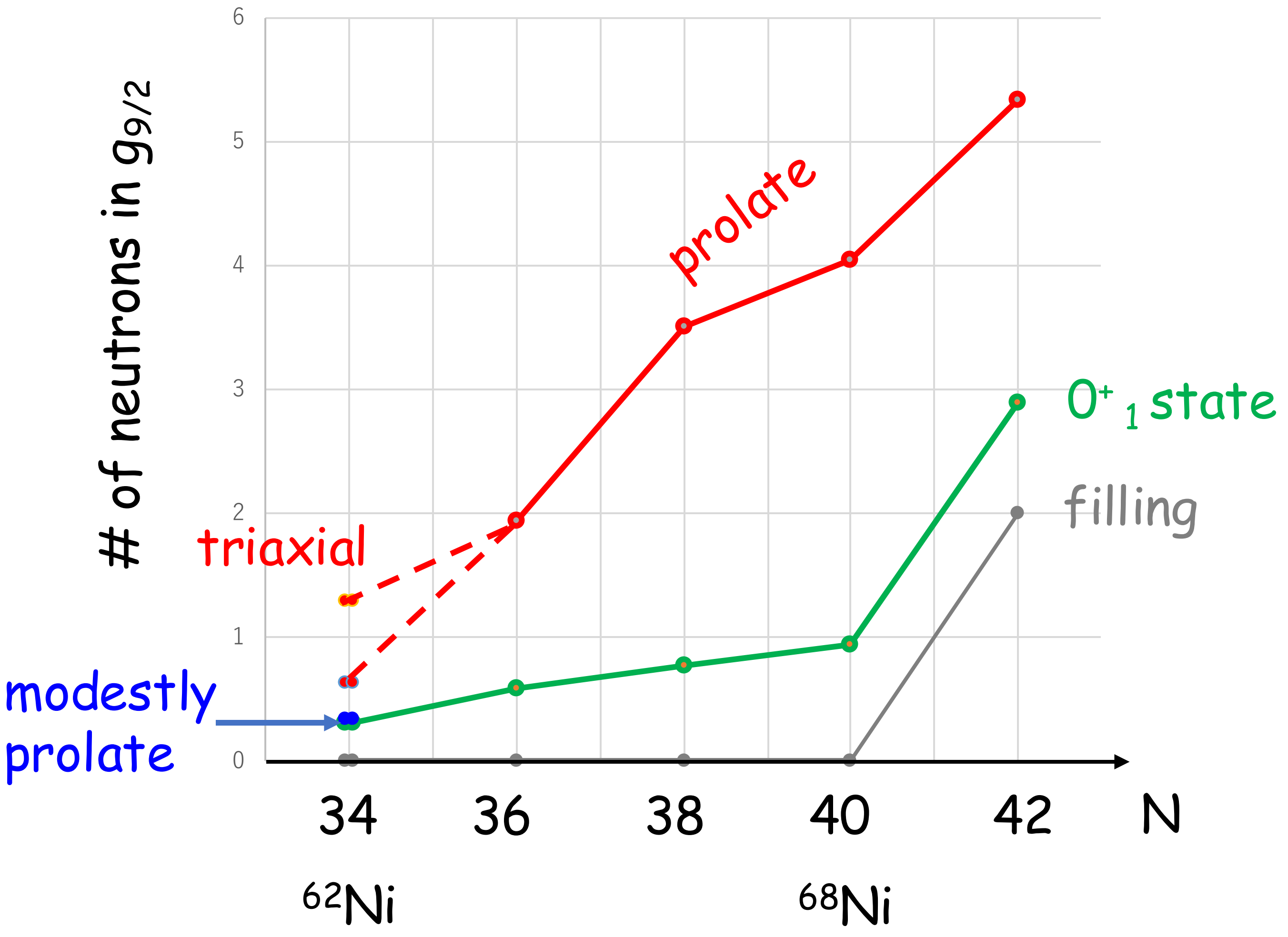




Neutron excitations from pf-shell to $g_{9/2}$ orbital are crucial.

The number of neutrons, or the neutron Fermi energy, directly affects as to how many neutrons are excited to $g_{9/2}$ orbital.

At N=34, the present triaxial states appear with $\beta_2 > 0.34$ with excitations to $g_{9/2}$ orbital.
The middle of pf-shell is at N=30
→ triaxiality may be natural ?
The modestly deformed (β_2~0.2) prolate state appears mostly with the collectivity of pf-shell protons.

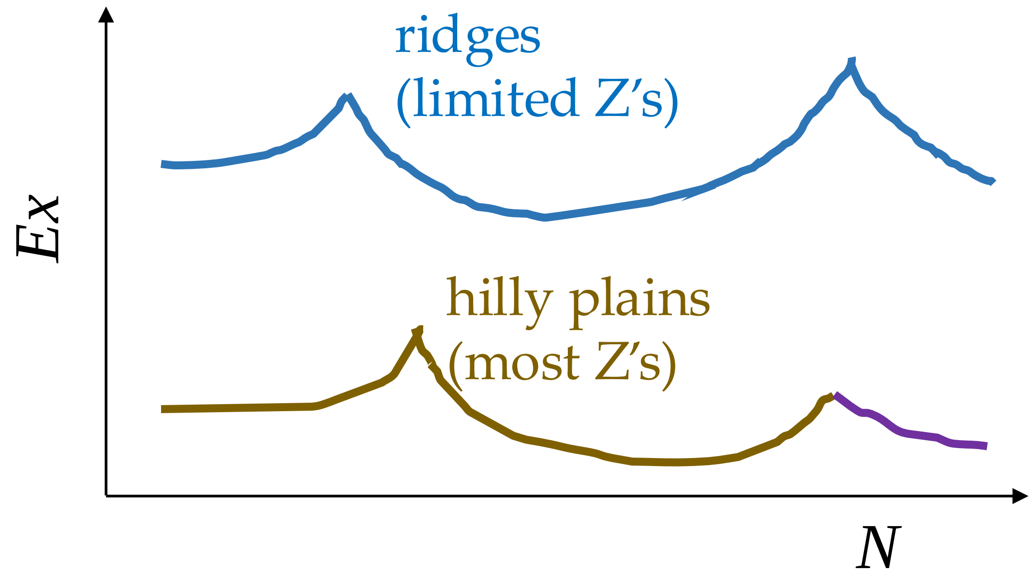


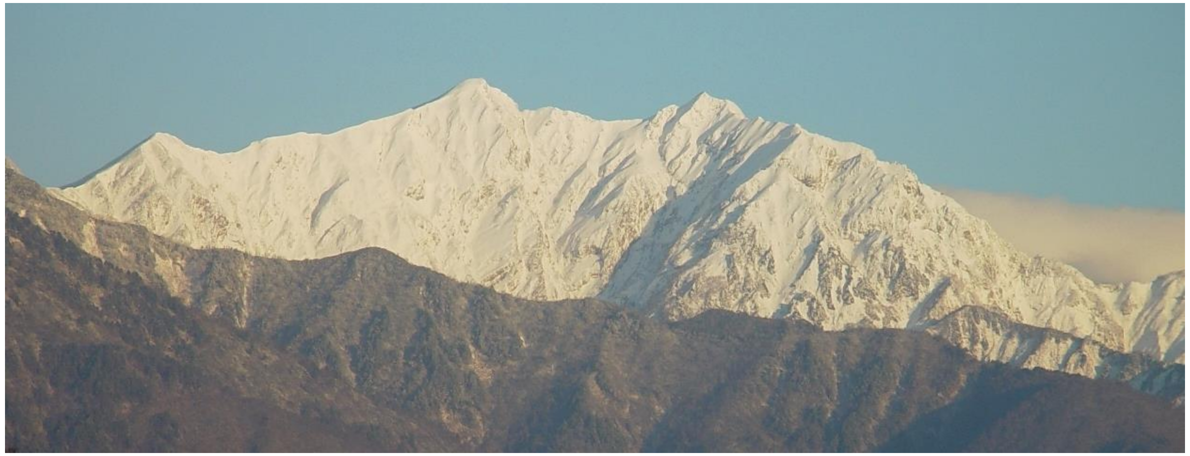
Further exploration for this hidden jewelry is an intriguing project
… thanks for Silvia's strong leadership

Isotopic ridges show up

- at high excitation energies (> twice pairing gap) — because of high-j orbitals
- with distinct visible characters (e.g., shapes) — because of different occup. #
- with low spins (J~0) free from major mixings
- with systematic appearance in an isotopic chain — because of monopole effects

They might give us a gateway to superdeformation.





PHYSICAL REVIEW C **94**, 034301 (2016)

Single-particle and collective excitations in ^{62}Ni

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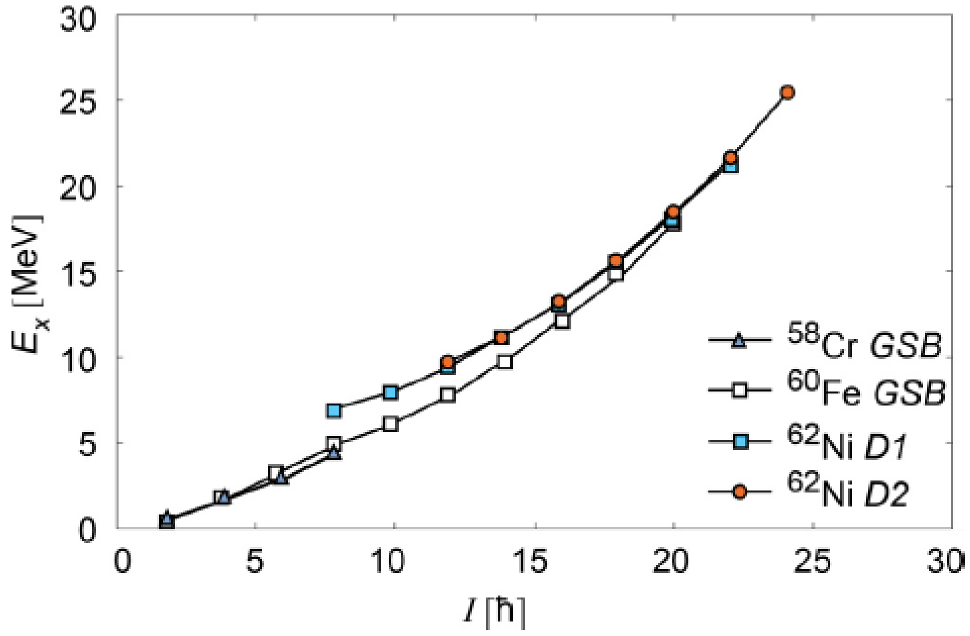

FIG. 4. Excitation energy versus spin for the two collective bands observed in the present measurement and for the ground-state bands in ^{58}Cr [25] and ^{60}Fe [27]. See text for details.

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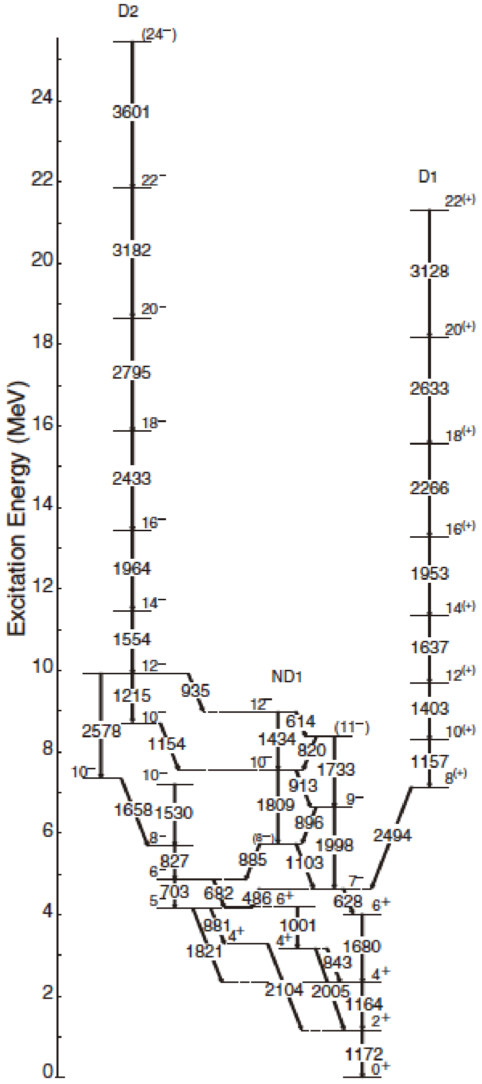


FIG. 2. Level scheme of ^{62}Ni deduced in the present work. The states are labeled with their spin and parity.

Outline

1. Shell evolution
   Just a brief overview

2. Type II Shell evolution
   A mechanism for shape coexistence illustrated with the example of ^{68}Ni

3. Ni isotopes exhibit th an Isotropic Ridge
   An angle to look into structure evolution in 62-78Ni isotopes

4. Another subject …

Before I finish, let me mention recent developments about shapes and rotations of atomic nuclei.

1. Rotational excitation energy proportional to $J(J+1) - K^2$ is derived in quantum many-body framework, without resorting to the quantization of the free rotation of classical rigid body.

2. Triaxial deformation occurs in virtually all deformed nuclei, because it gives more binding energy than axially symmetric shapes. → "**basic triaxiality**" It is not a fluctuation. The ground band of ^{154}Sm is an example, while side bands show shape coexistence with γ.

3. Stronger triaxiality occurs due to tensor (monopole) or central (hexadecupole) forces in some nuclei, at least in the ground bands of 13 rare-earth nuclei, such as ^{166}Er, ^{164}Dy, ^{158}Gd. → "**prominent triaxiality**"

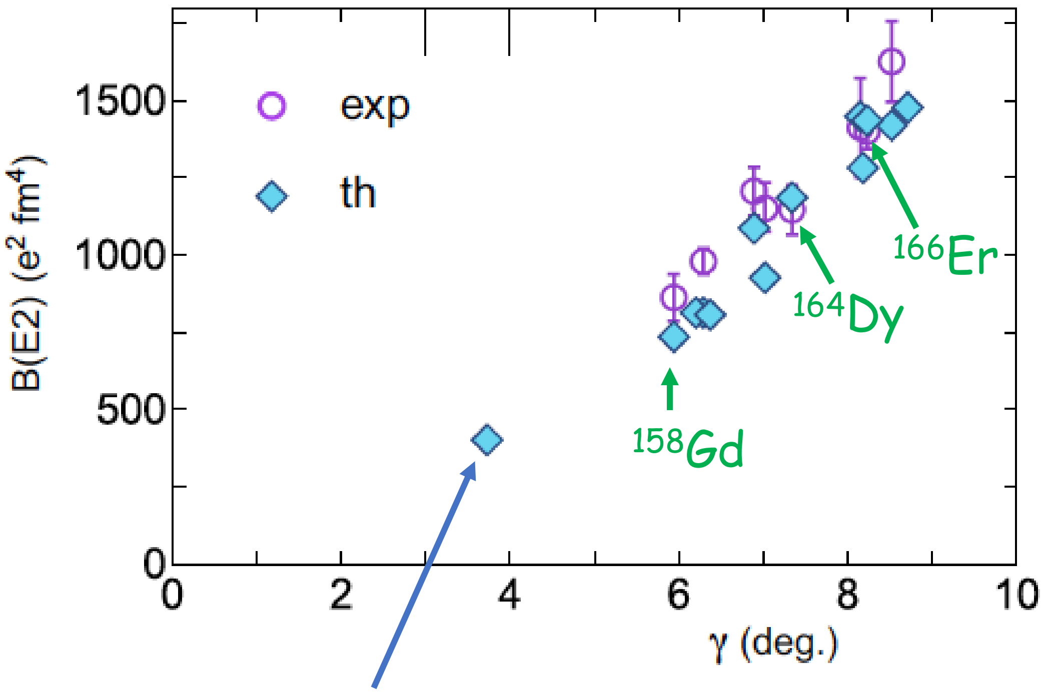
We need Silvia's great initiative again for this challenging and exciting subject !

Reference: **Prevailing Triaxial Shapes in Atomic Nuclei and a Quantum Theory of Rotation of Composite Objects** arXiv:2303.11299v6 [nucl-th]

T. Otsuka,[1,2,3,4,*] Y. Tsunoda,[5,6] N. Shimizu,[6,5] Y. Utsuno,[7,5] T. Abe,[8,2] and H. Ueno[2]

Systematic behaviors by MCSM (QVSM)

B(E2; 0^+_1 -> 2^+_{gamma})



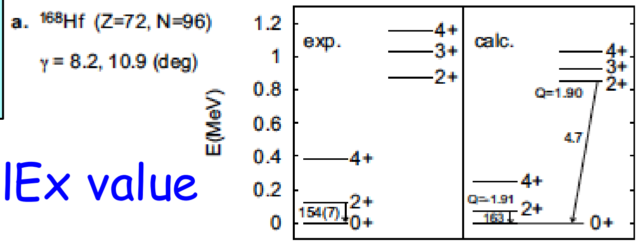
B(E2) from 2^+ at Ex~2.7 MeV of ^{154}Sm

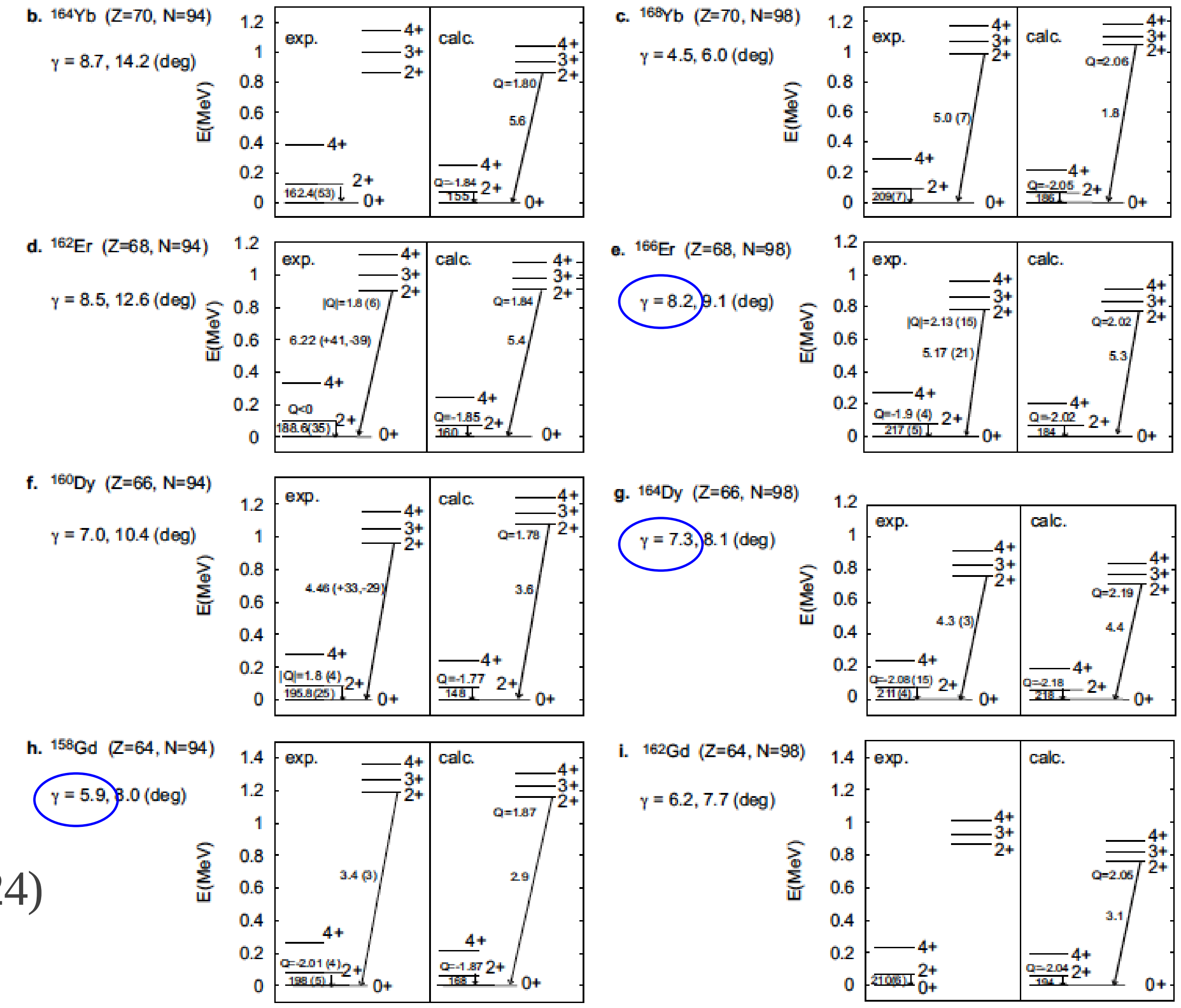
γ = 3.7 deg (^{154}Sm)

supported by a recent GDR (Kleemann *et al.*, 2024) experiment (γ = 5.0 +- 1.4 deg)

Levels, B(E2)'s and Q-moments

γ ~ Multiple CoulEx value





Happy 60^{th} birthday for Franco, Gianluca, Silvia
and
be active like a dragon

2024 is the year of Dragon,
those 60, 72 years old
belong to this

Kaihou, Yushou (1533-1615), Ken-Nin Ji, Kyoto

海北友松作「双龍図襖絵」建仁寺　（写真撮影は講演者）