Nuclear Structure 2016
Knoxville
July 28 (25-29), 2016

Shape coexistence, shape transition and nuclear forces

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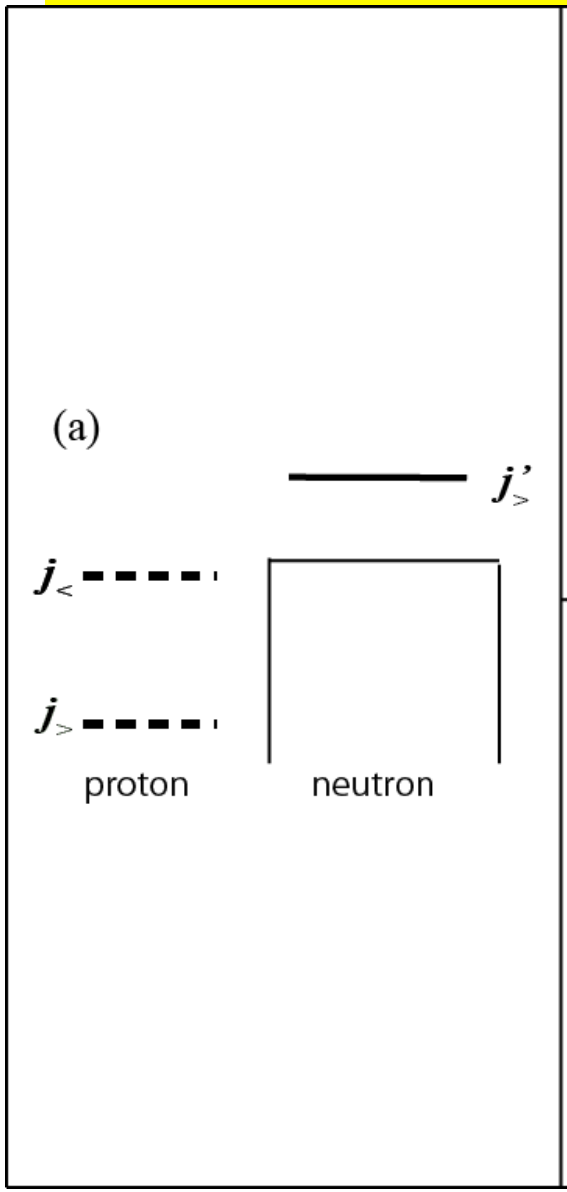
Supported by MEXT and JICFuS as a priority issue (Elucidation of the fundamental laws and evolution of the universe) to be tackled by using Post 'K' Computer

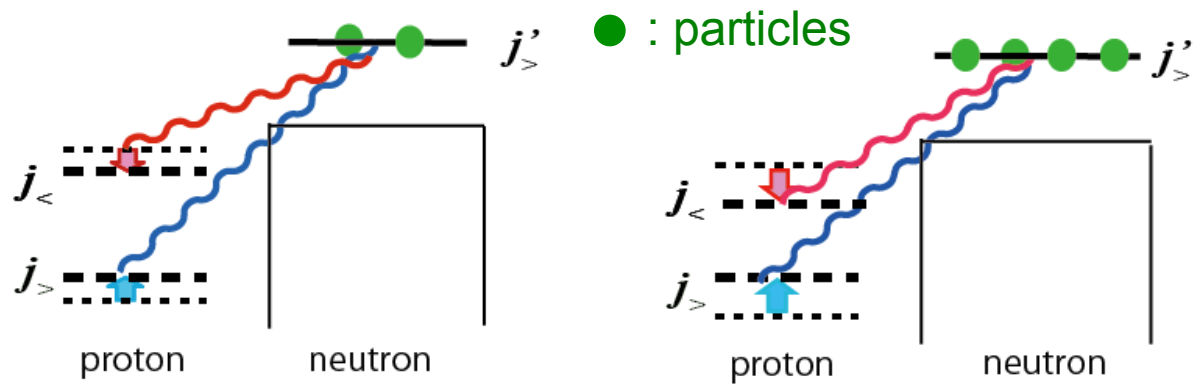
Outline

- Introduction
- Shape coexistence and Type II shell evolution
  - exotic Ni isotopes
- Shape transition including Quantum Phase Transition
  - exotic Zr isotopes
- Summary and Perspectives

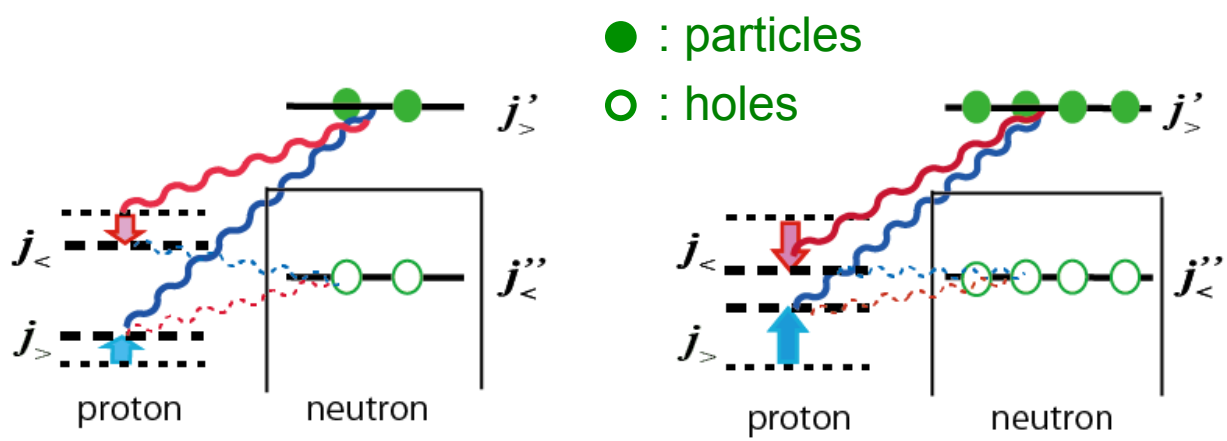
Underlying mechanism : Shell Evolution



Type I Shell Evolution : different isotopes

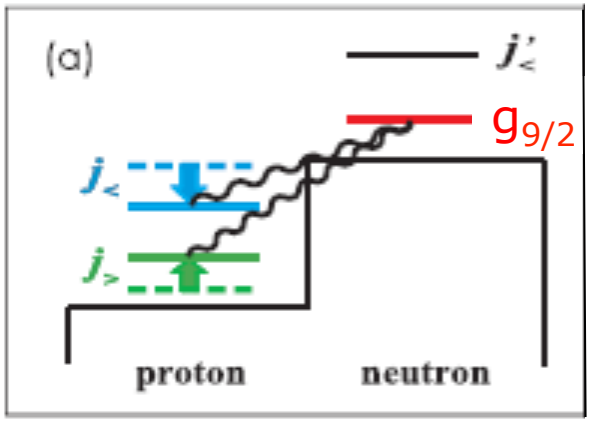


Type II Shell Evolution : within the same nucleus

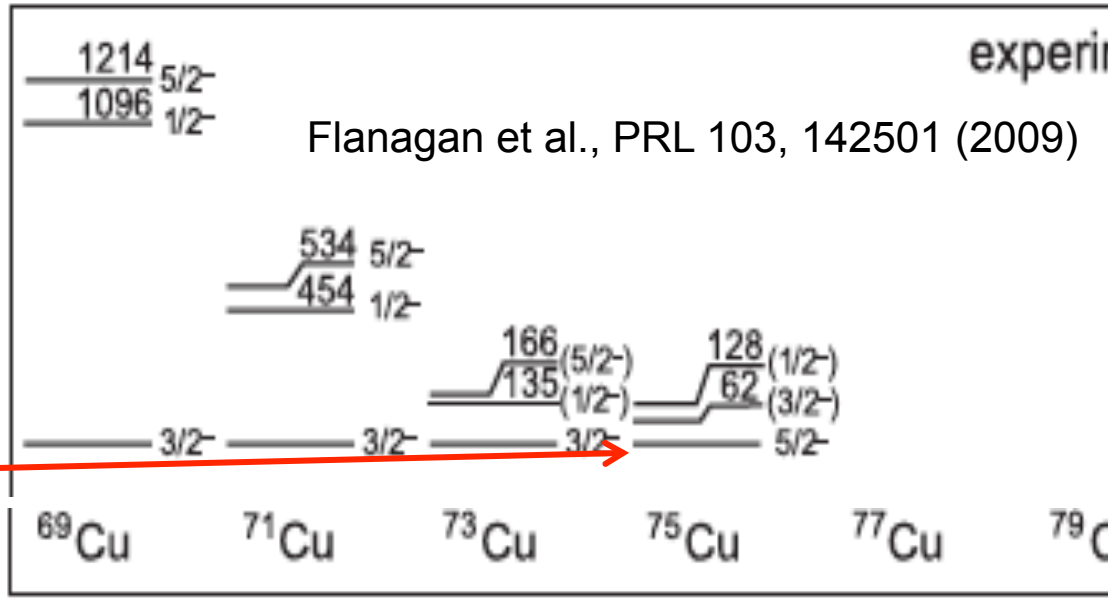


TO and Tsunoda, J. Phys. G: Nucl. Part. Phys. 43 (2016) 024009

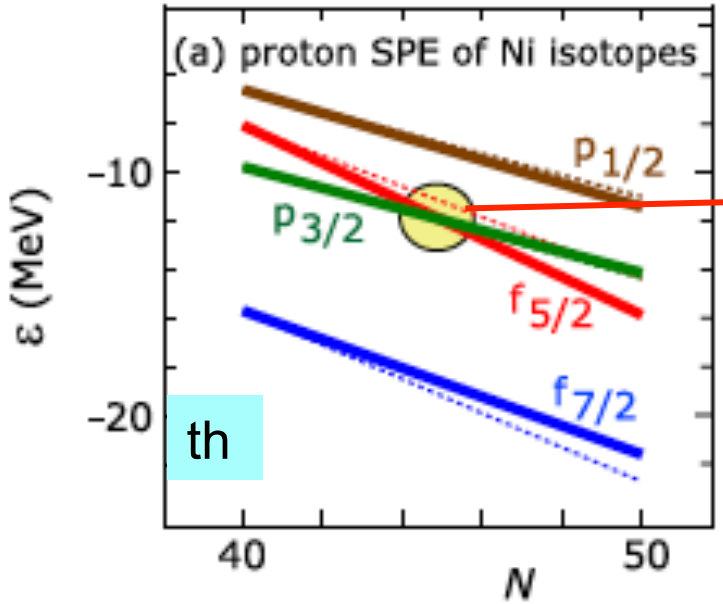
A clean example of tensor-force driven shell evolution



Proton $f_{5/2}$ - $p_{3/2}$ inversion in Cu due to neutron occupancy of $g_{9/2}$



Flanagan et al., PRL 103, 142501 (2009)



Franchoo *et al.*, PRC 64, 054308 (2001)
"level scheme … newly established for ^{71,73}Cu"

TO, Suzuki, *et al*. PRL 95, 232502 (2005) ; PRL 104, 012501 (2010)

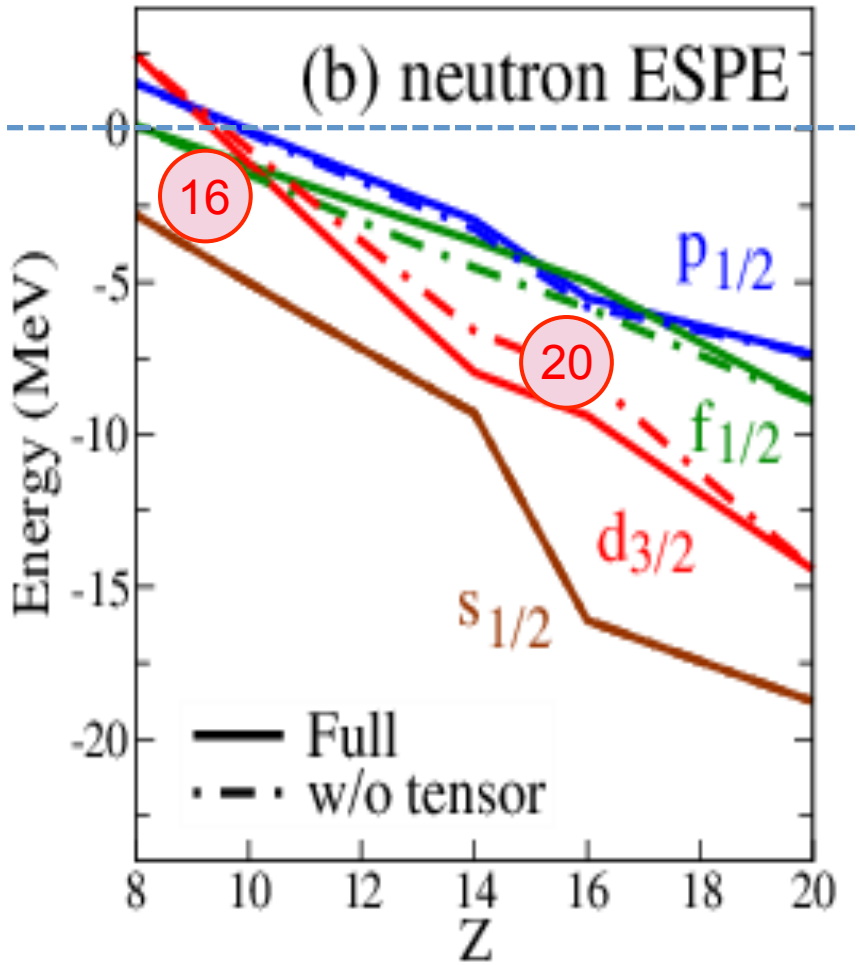
EFT endorses Type I Shell Evolution : Island of Inversion

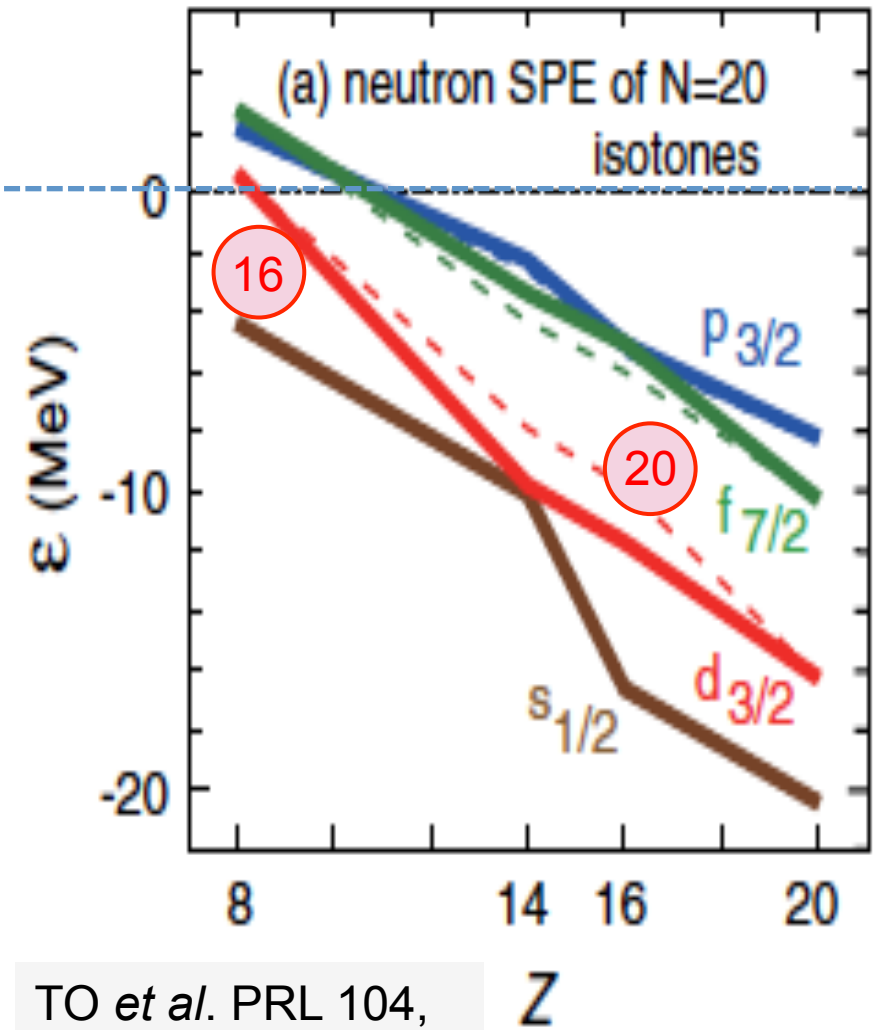
EFT + 3NF + EKK

EKK : In-medium effect beyond G-matrix

Tsunoda *et al*. submitted, arXiv

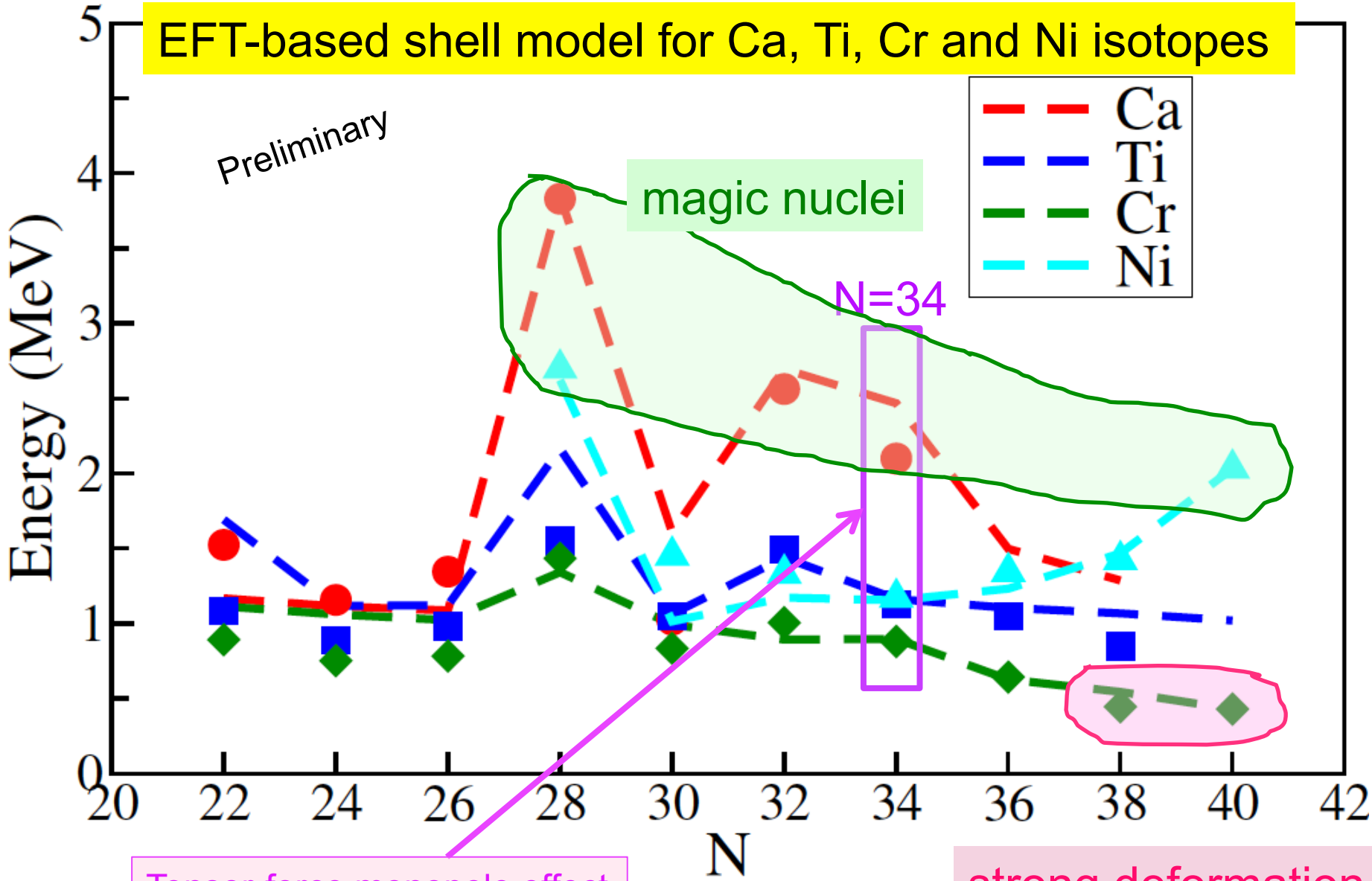
VMU : central force + meson exchange tensor force





TO *et al*. PRL 104, 012501 (2010)

EFT-based shell model for Ca, Ti, Cr and Ni isotopes



Tensor-force monopole effect as predicted by TO *et al*, PRL 87, 082502 (2001)

strong deformation

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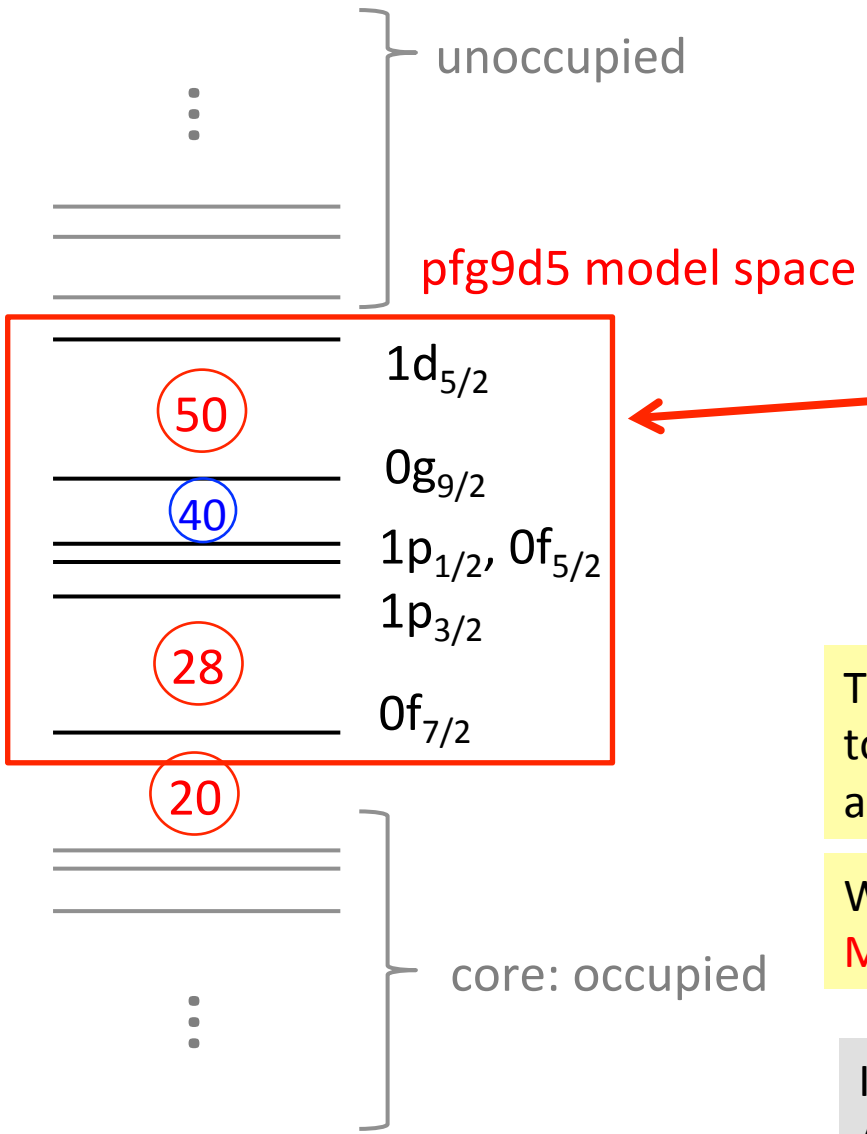
  - exotic Ni isotopes

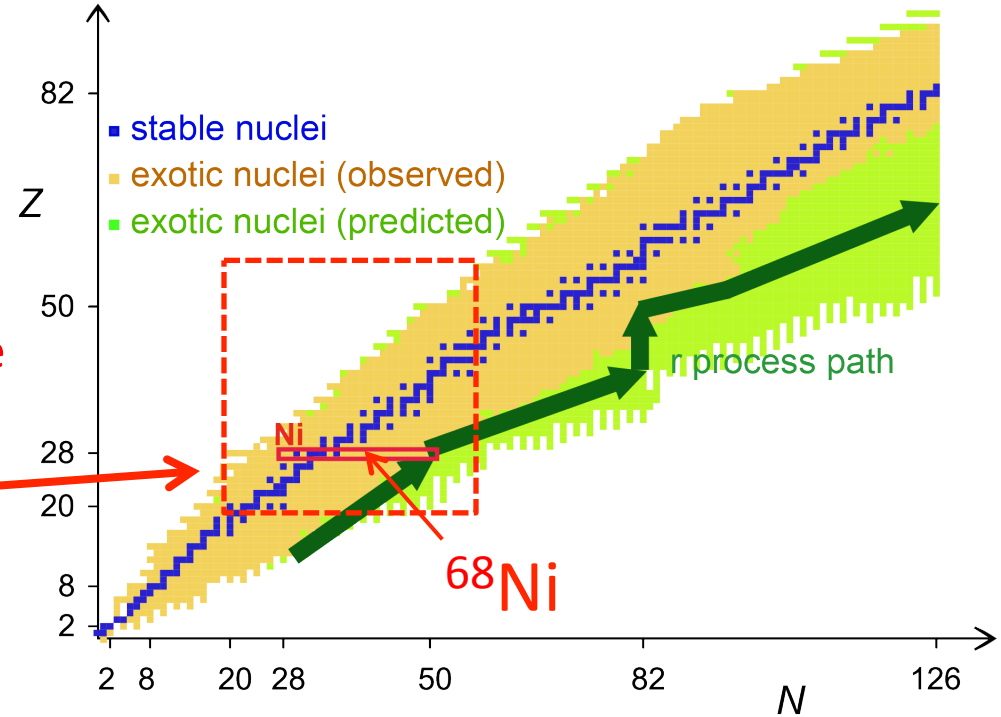
- Shape transition including Quantum Phase Transition
  - exotic Zr isotopes

- Summary and Perspectives

MCSM calculation on Ni isotopes

Y. Tsunoda *et al.*, PRC89, 031301(R) (2014)



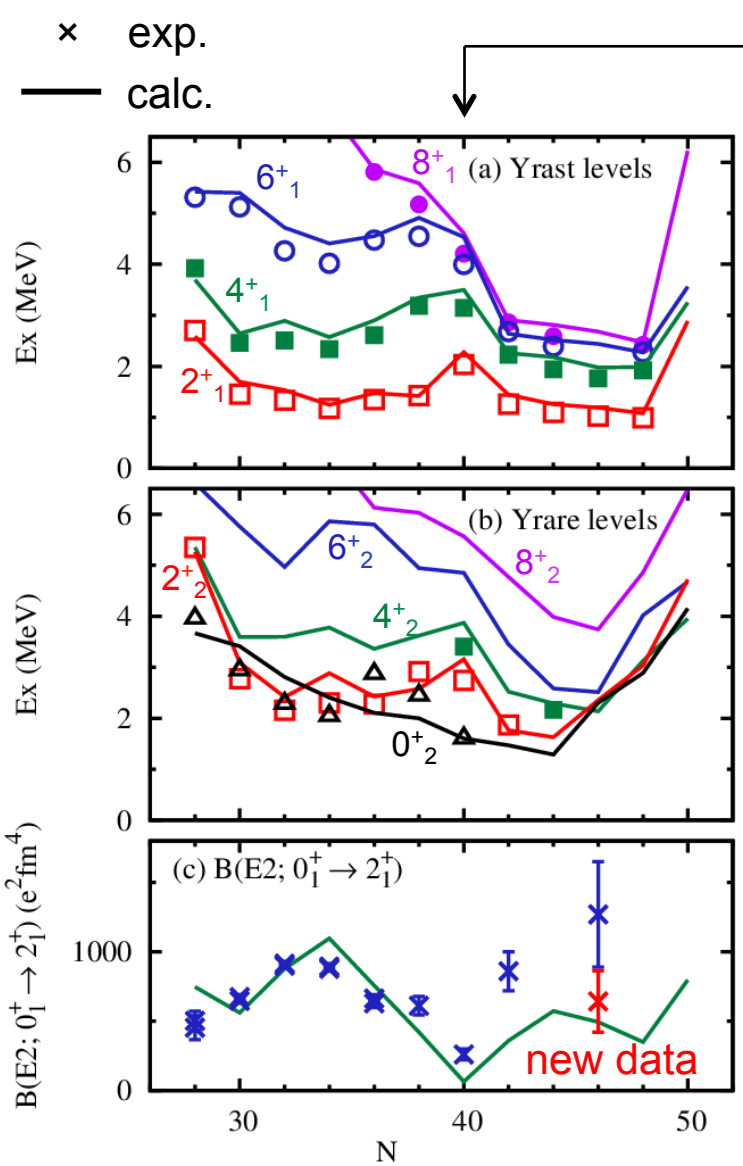


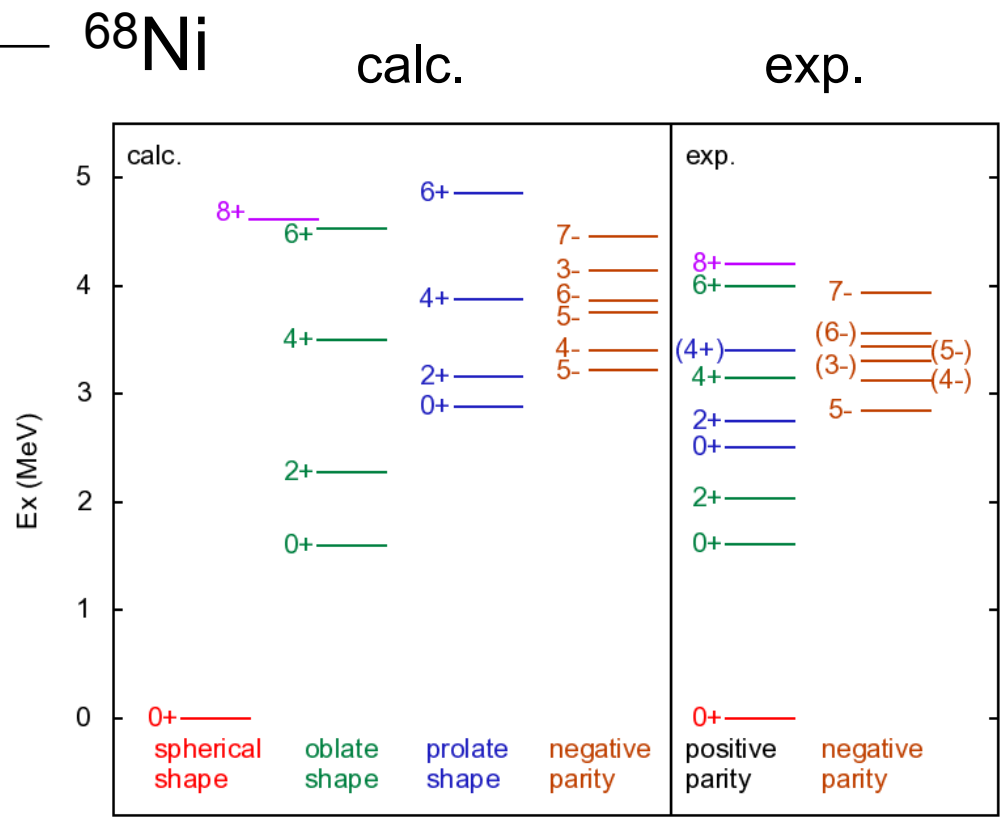
This model space is wide enough to discuss how magic numbers 28, 50 and semi-magic number 40 are retained/broken

We performed Monte Carlo Shell Model (MCSM) calculations

Interaction:
A3DA interaction is used with minor corrections

Energies and B(E2) of Ni isotopes





- Experimental values are reproduced by the same Hamiltonian
- Shape coexistence in ^{68}Ni

e.g. Flavigny et al., PRC 91, 034310 (2015)

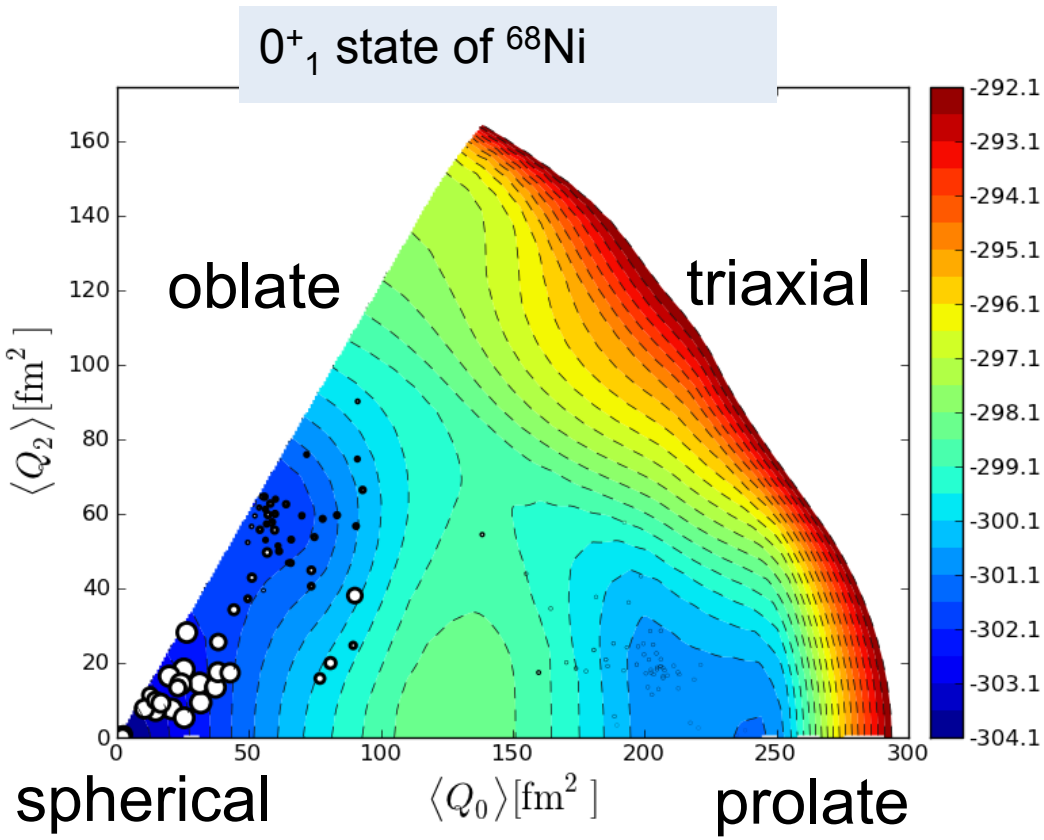
MCSM basis vectors on Potential Energy Surface

eigenstate

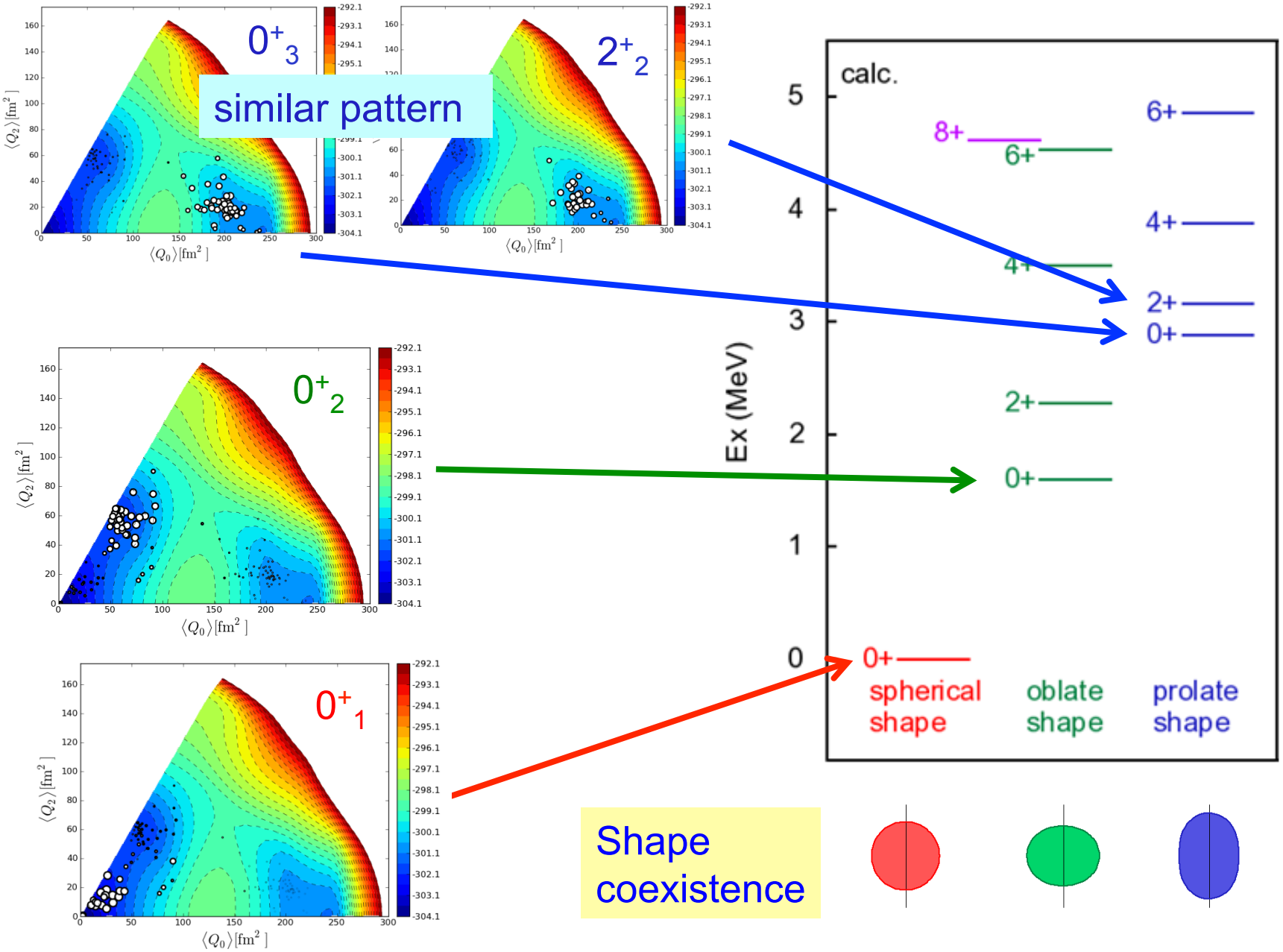
$$\Psi = \sum_i c_i P[J^\pi] \Phi_i$$

Slater determinant
-> intrinsic deformation

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

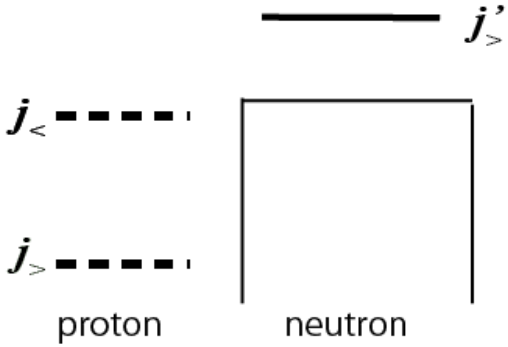


Can be used for the anatomy of band structure

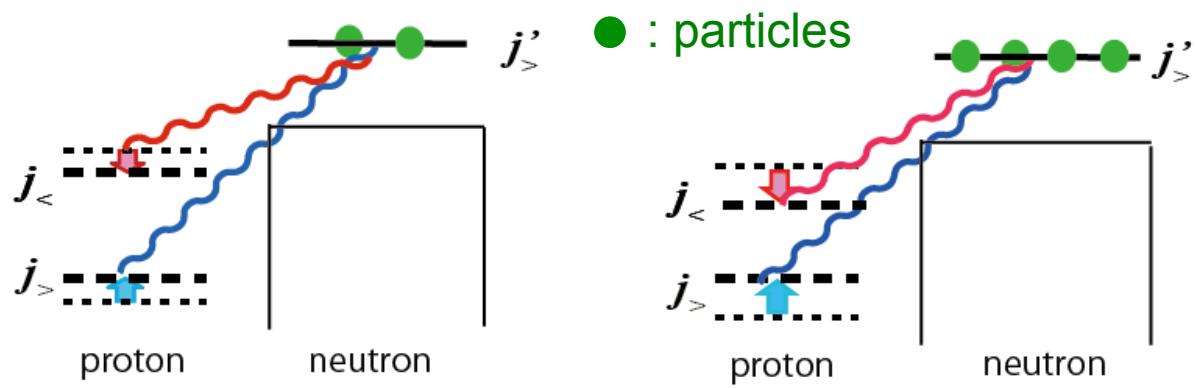


Let's move on to Type II Shell Evolution

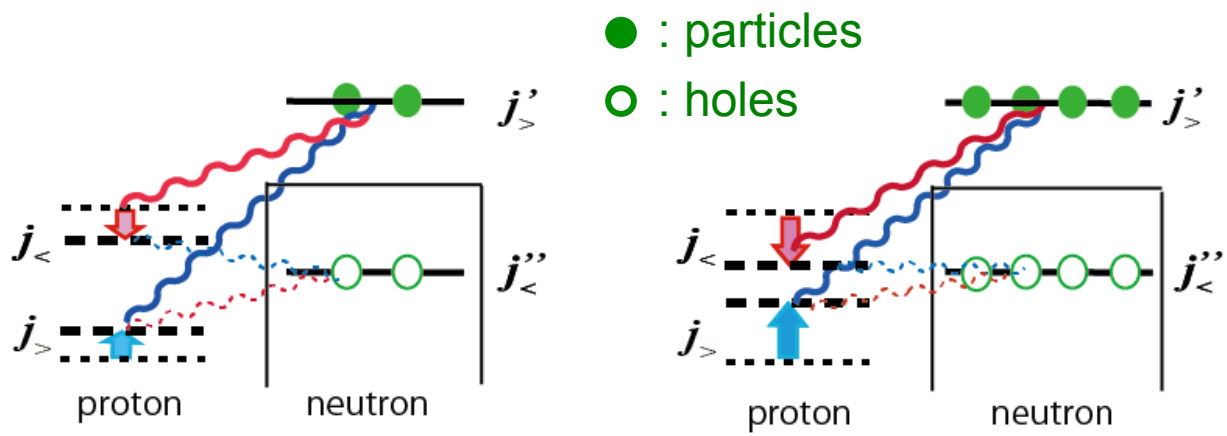
TO and Tsunoda, J. Phys. G: Nucl. Part. Phys. 43 (2016) 024009



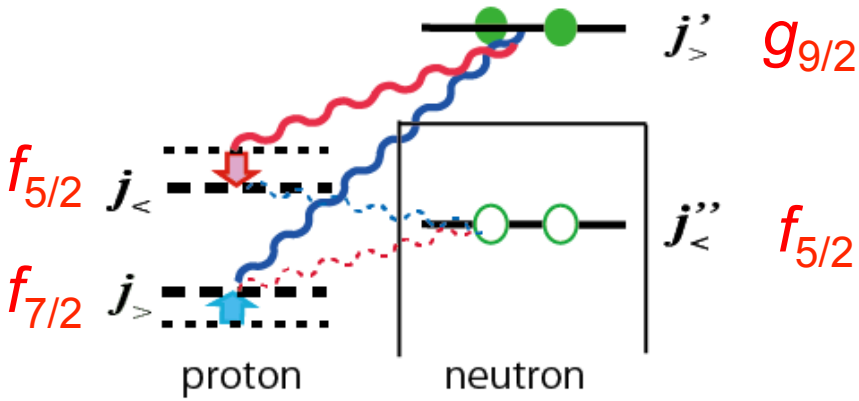
Type I Shell Evolution : different isotopes



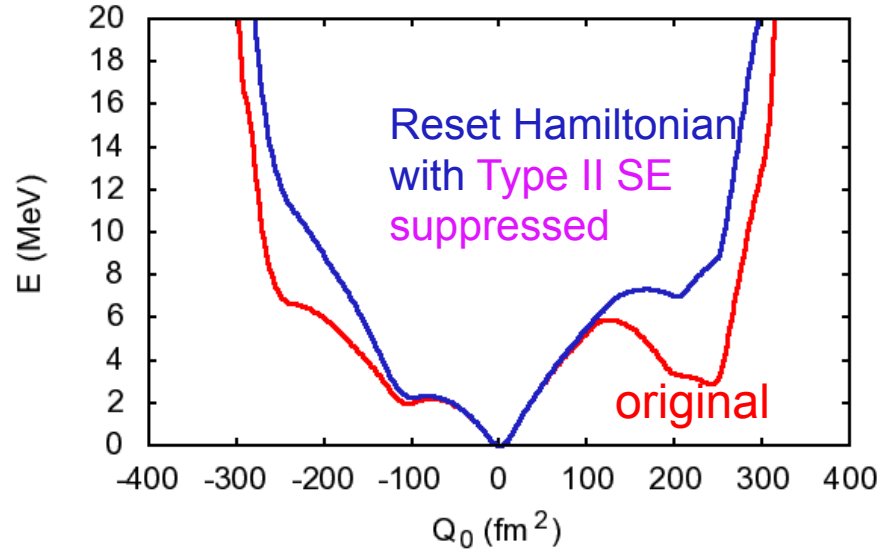
Type II Shell Evolution : within the same nucleus



Type II Shell Evolution in ^{68}Ni (Z=28, N=40)



PES along axially symmetric shape



Spin-orbit splitting reduces quadrupole deformation

(*cf. Elliott's SU(3)*).

weakening of spin-orbit splitting

Type II shell evolution

stronger deformation for protons

-> more neutron p-h excitation

Type II shell evolution can be suppressed by resetting monopole interactions as

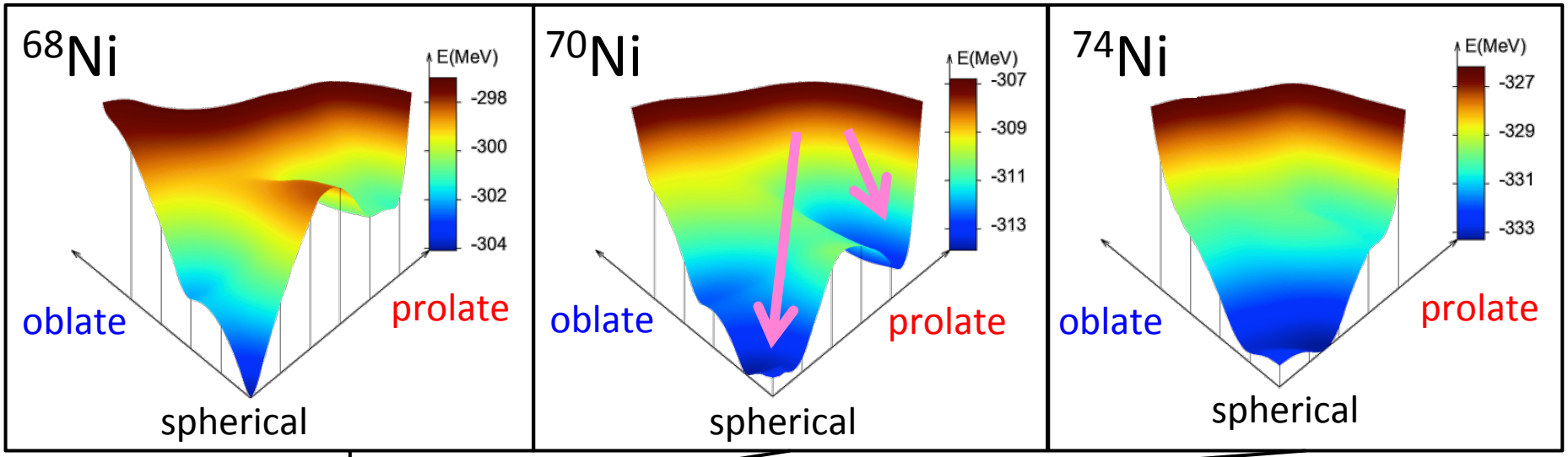
$\pi f_{7/2} - v g_{9/2} = \pi f_{5/2} - v g_{9/2}$

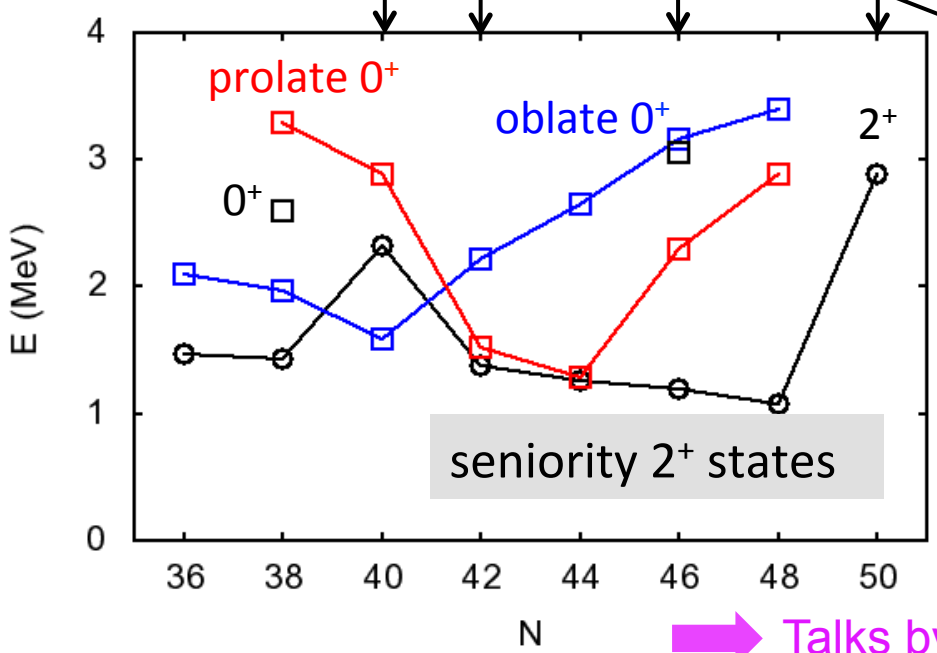
$\pi f_{7/2} - v f_{5/2} = \pi f_{5/2} - v f_{5/2}$

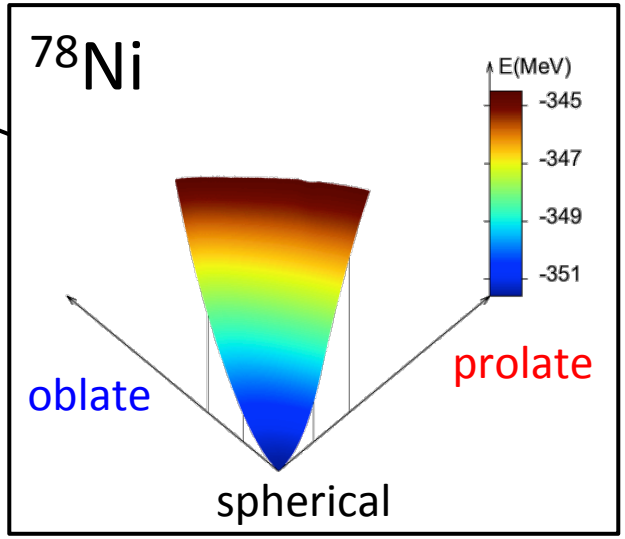
The local minima become much less pronounced.

Shape coexistence is enhanced by type II shell evolution as the same quadrupole interaction works more efficiently.

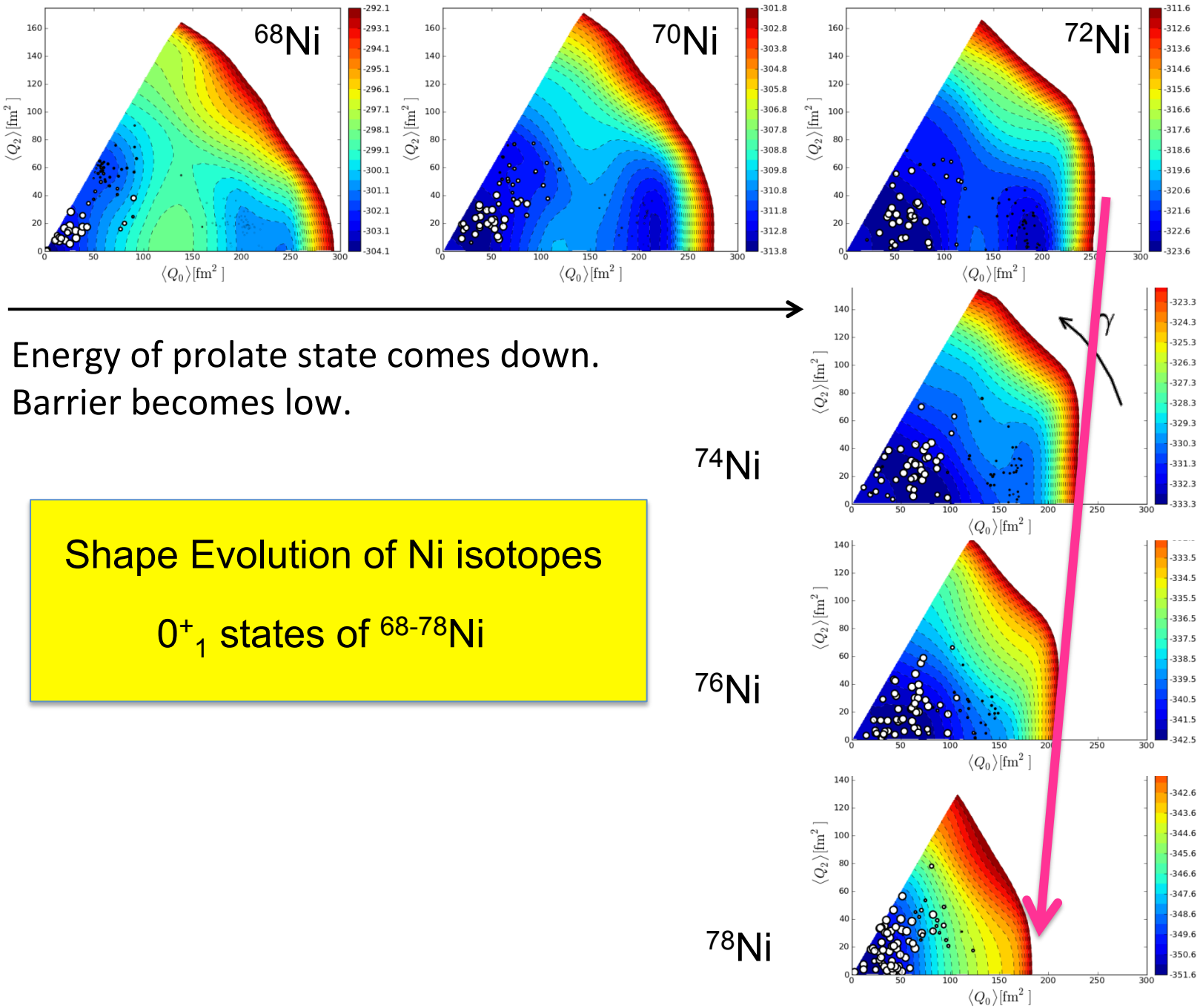
Shape coexistence and evolution of Ni isotopes







Talks by Walters, Recchia and Benzoni



Energy of prolate state comes down.
Barrier becomes low.

γ-soft deformation
(strong fluctuation in the γ direction)

Shape Evolution of Ni isotopes

0^+_1 states of $^{68\text{-}78}$Ni

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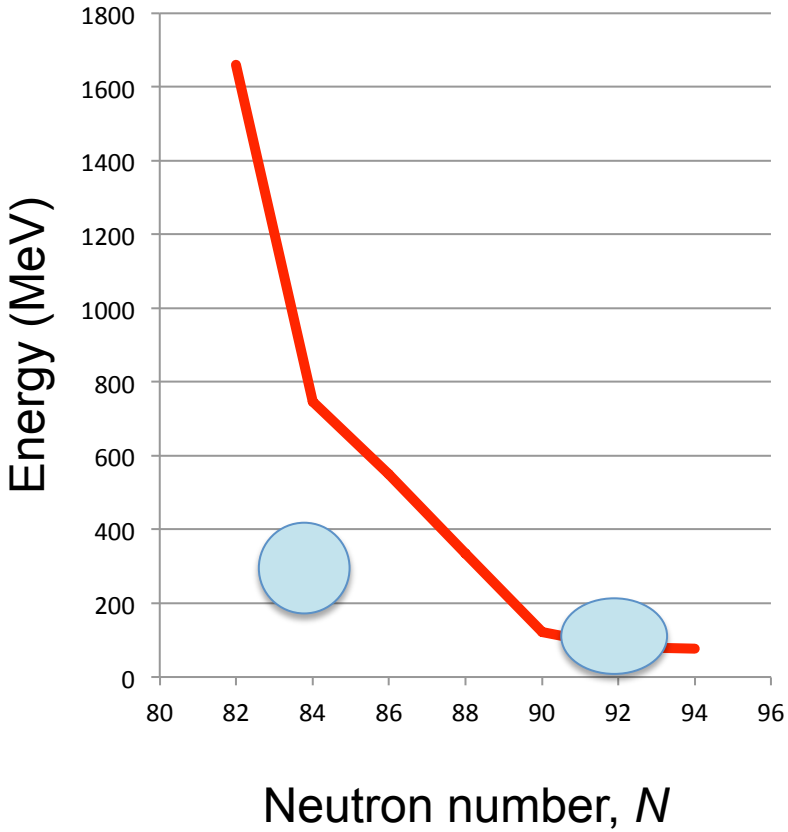
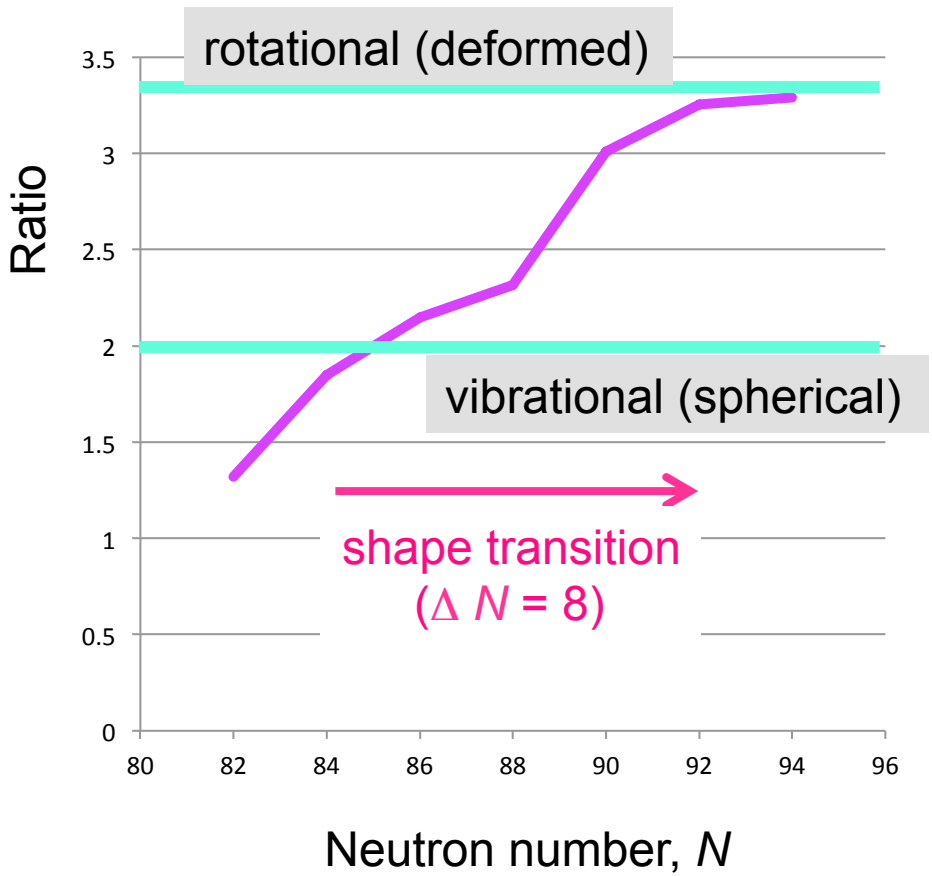
Example : 2^+ and 4^+ levels of Sm isotopes

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



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

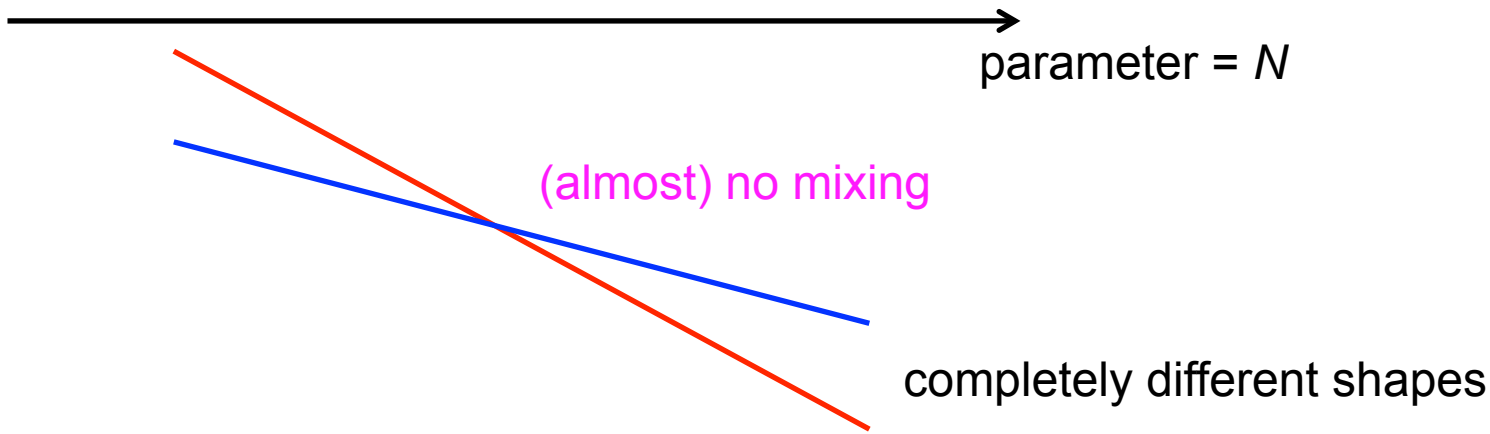


Can this be a kind of *Phase Transition* ?

Can the shape transition be a "Quantum Phase Transition" ?

The definition of Quantum Phase Transition :
an abrupt change in the ground state of a many-body system
by varying a physical parameter at zero temperature

possible scenario



The usual shape transition may not fulfill the condition being *abrupt*.
Where can we see it ?

From earlier works on Zr isotopes…

Federman & Pittel (1979)

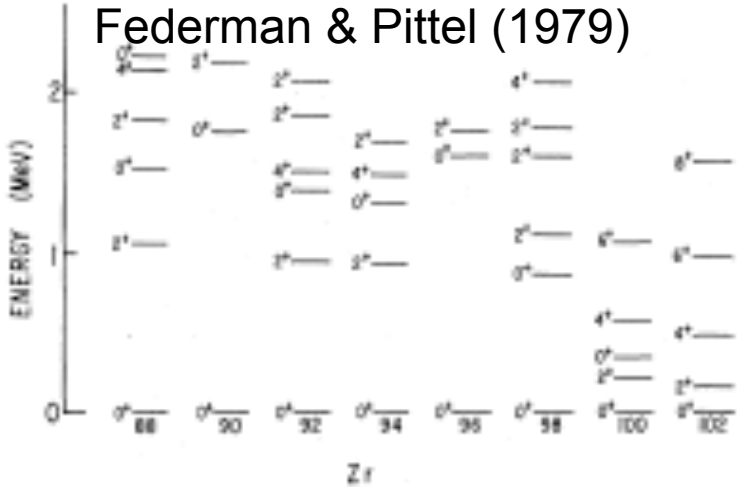


FIG. 2. Experimental spectra of positive-parity energy levels for the Zr isotopes from $N=48$ to $N=62$, from Refs. 1, 13, and 14.

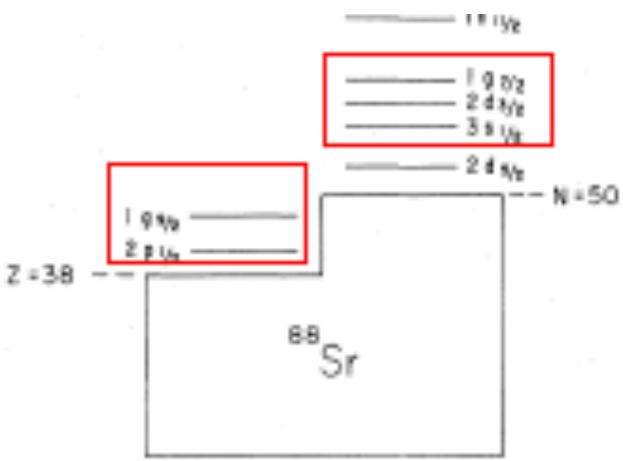


FIG. 3. Single-particle levels appropriate to a description of nuclei in the Zr-Mo region. An ^{88}Sr core is assumed.

Sieja, et al (2009)

In this paper, we perform for the first time a SM study of Zr isotopes in an extended model space $(1f_{5/2}, 2p_{1/2}, 2p_{3/2}, 1g_{9/2})$ for protons and $(2d_{5/2}, 3s_{1/2}, 2d_{3/2}, 1g_{7/2}, 1h_{11/2})$ for neutrons, dubbed hereafter $\pi(r3-g)$, $\nu(r4-h)$.

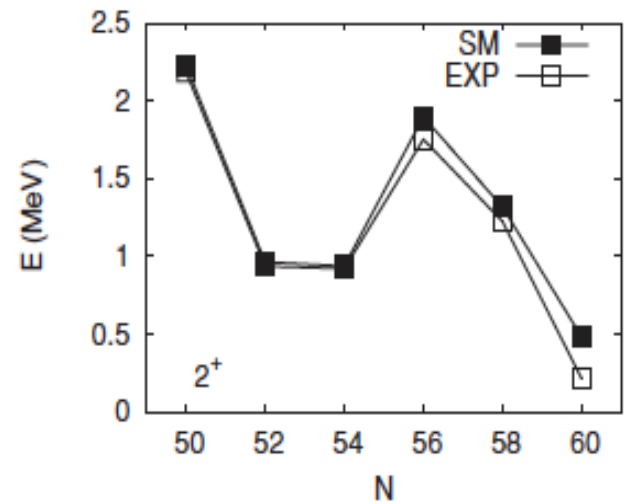


FIG. 12. Systematics of the experimental and theoretical first excited 2^+ states along the zirconium chain.

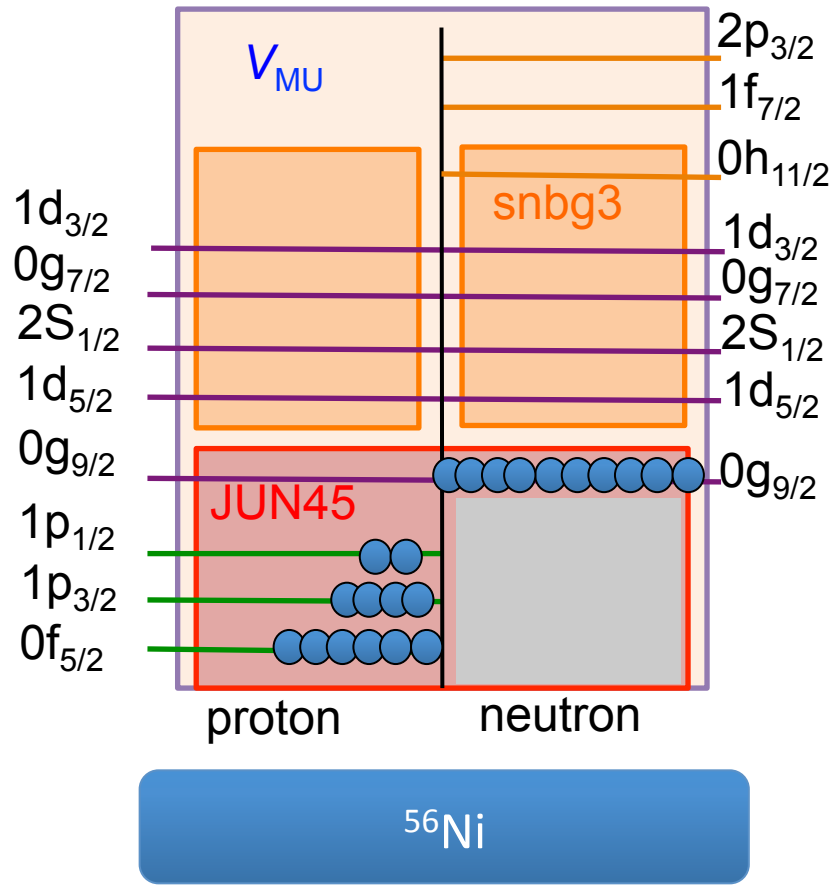
Present work : model space and effective interaction

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

  known effective interactions

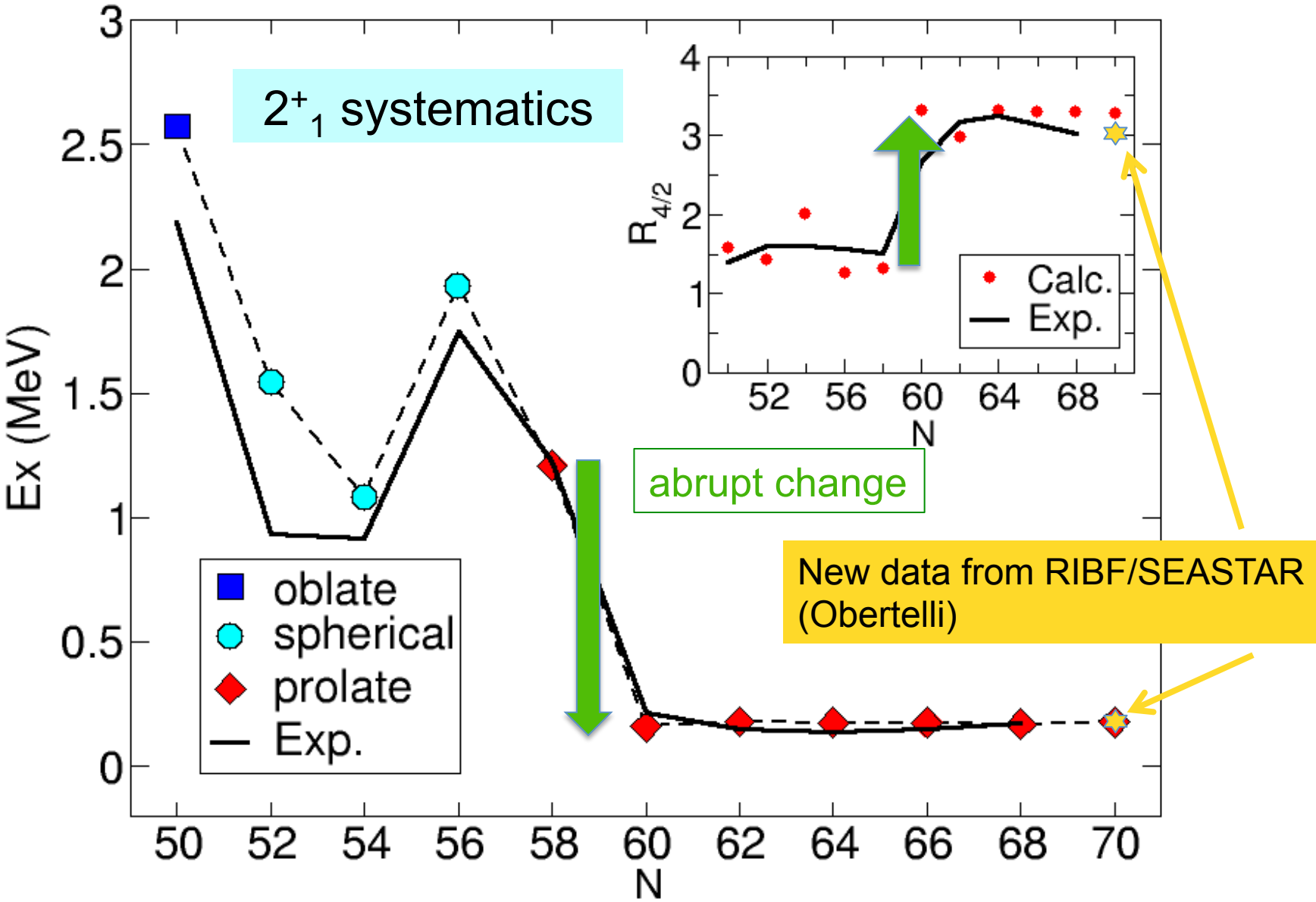
  + minor fit for a part of
  T=1 TBME's

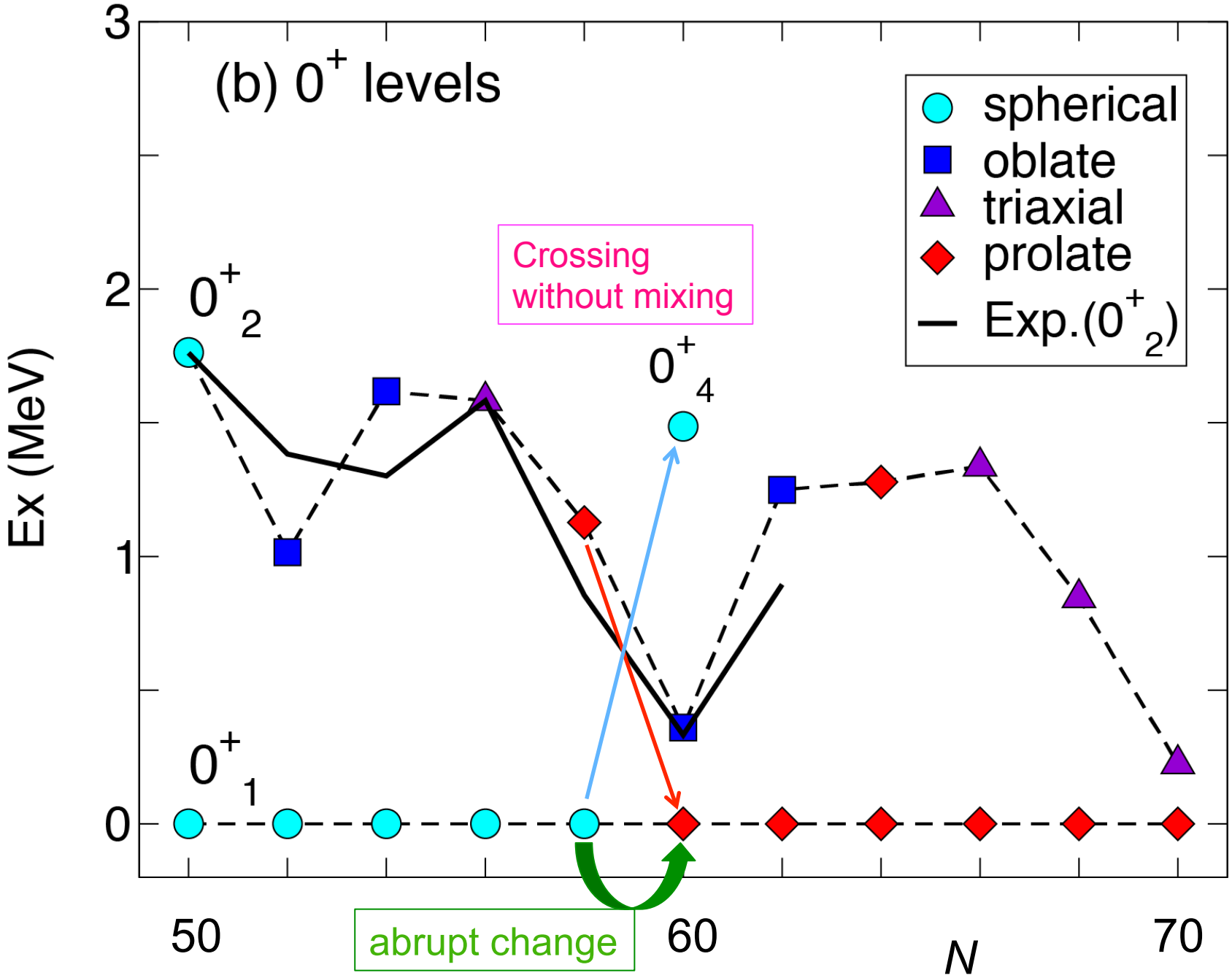
  Nucleons are excited fully
  within this model space
  (no truncation)



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

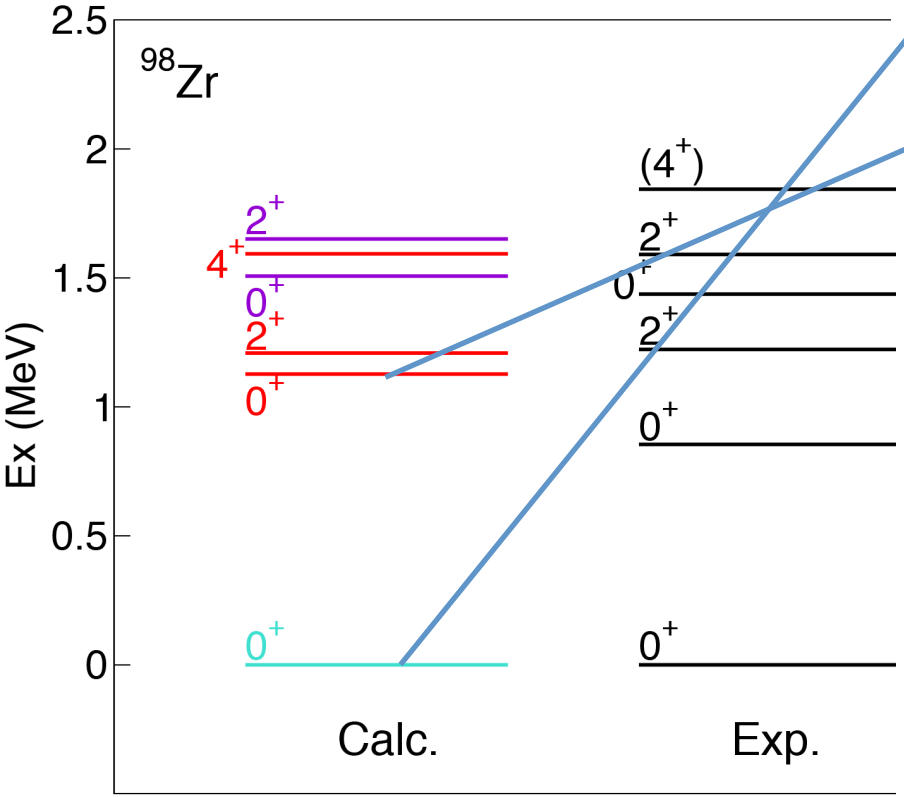
Togashi, Tsunoda, TO *et al*. submitted, also in arXiv

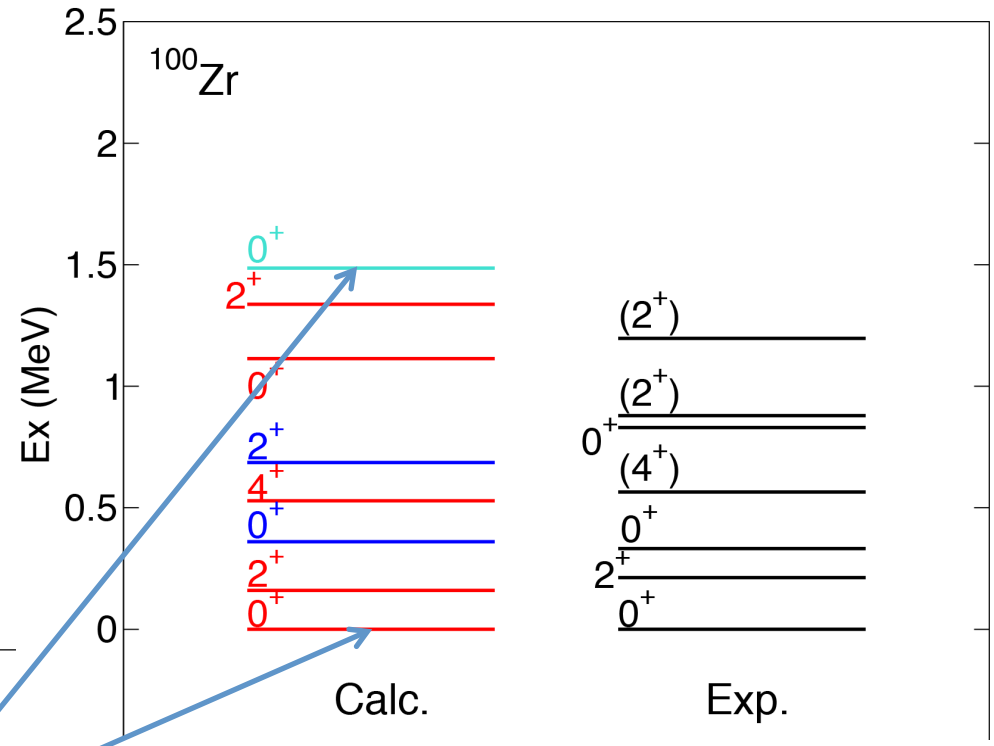

2+1 systematics
Ex (MeV)
N
oblate
spherical
prolate
Exp.
R4/2
Calc.
Exp.
abrupt change
New data from RIBF/SEASTAR
(Obertelli)

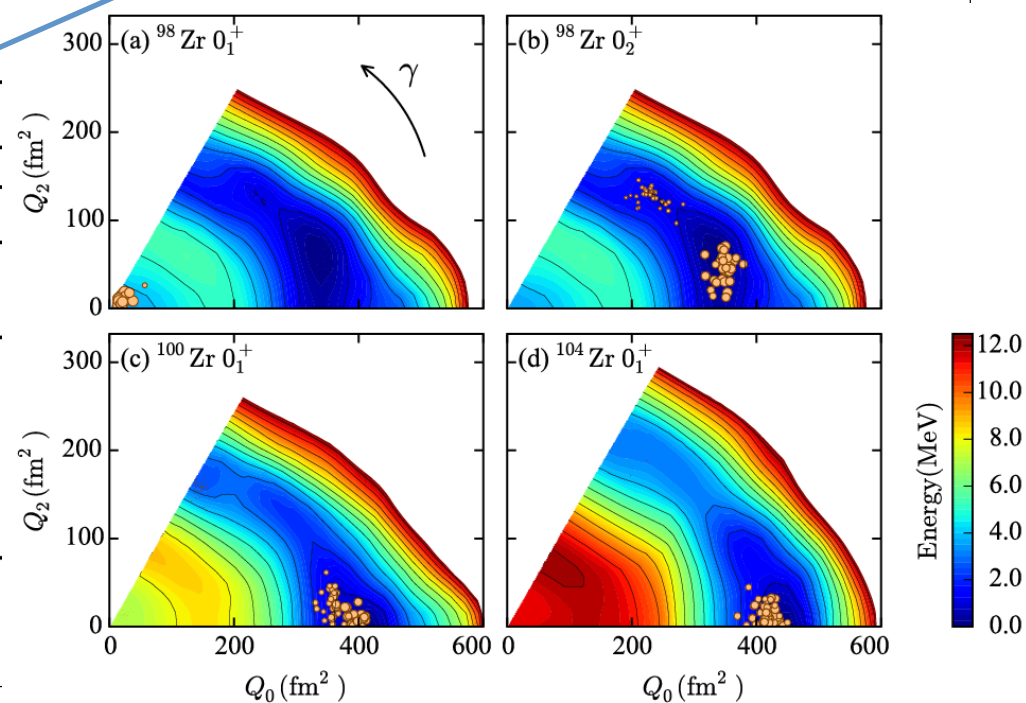

(b) 0+ levels
spherical
oblate
triaxial
prolate
Exp.(0+2)
Crossing
without mixing
0+2
0+4
0+1
abrupt change
Ex (MeV)
N
0
1
2
3
50
60
70

Detailed level schemes

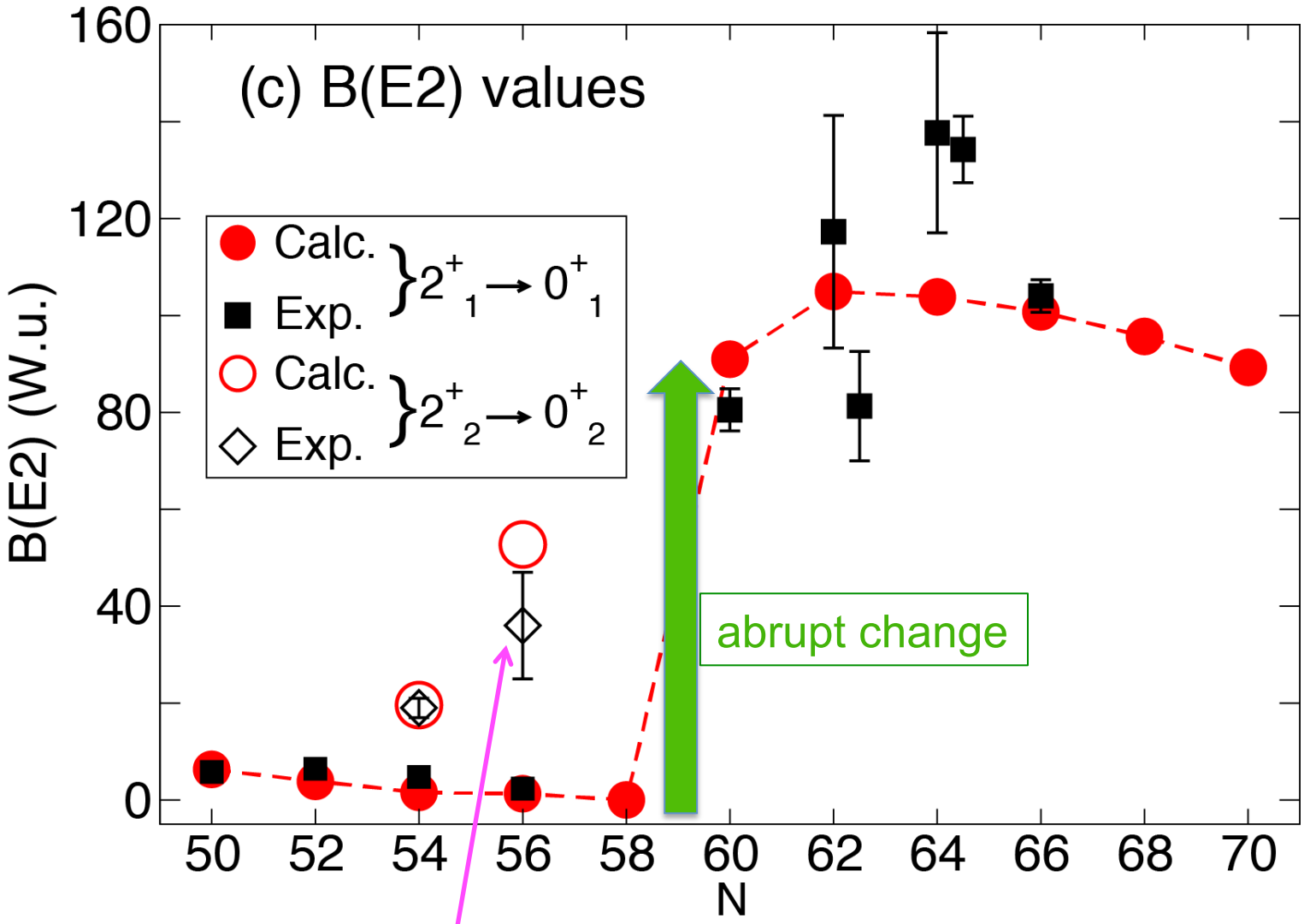
Where is the spherical 0+ state gone ?





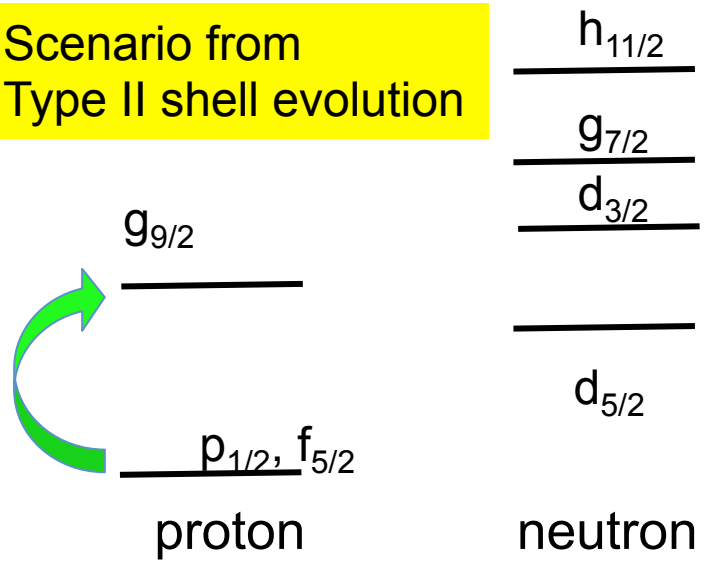


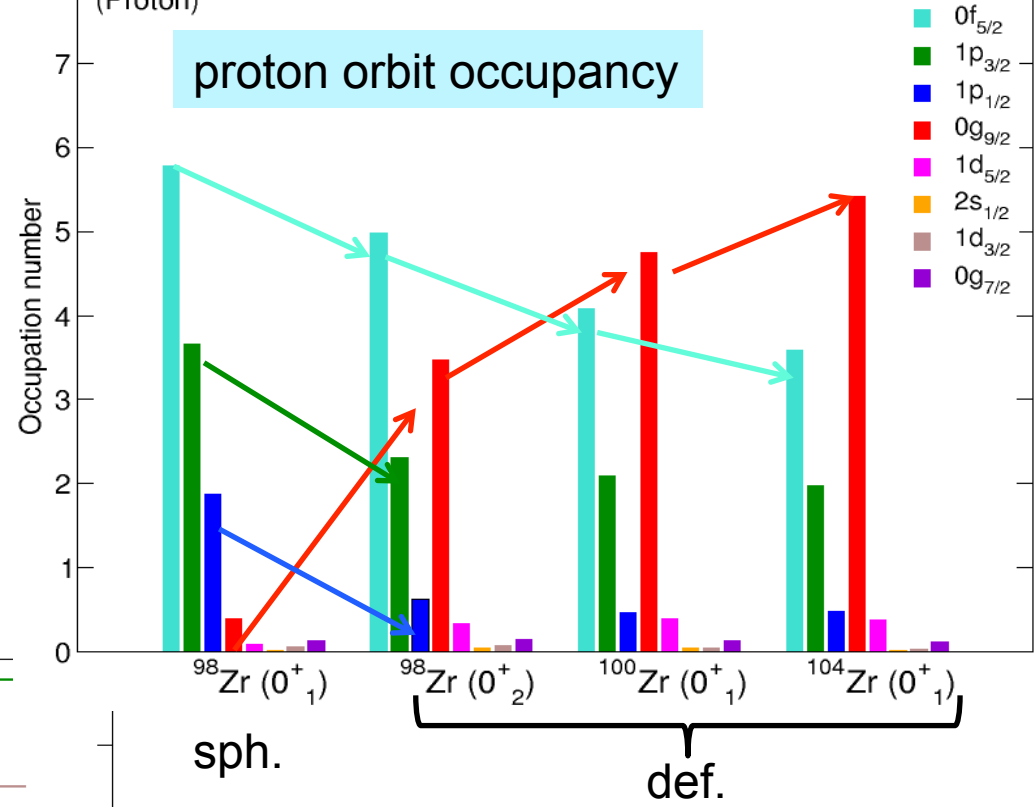
B(E2; 2^+ -> 0^+) systematics

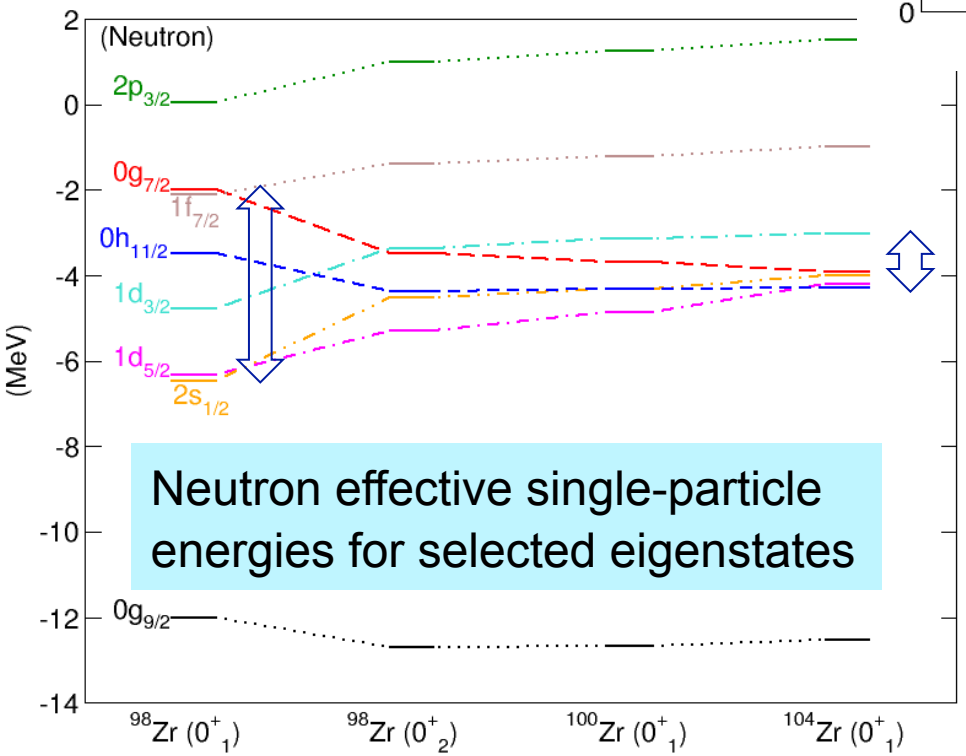


New data from Darmstadt, Kremer *et al.* for 2^+_2 -> 0^+_2

Scenario from
Type II shell evolution



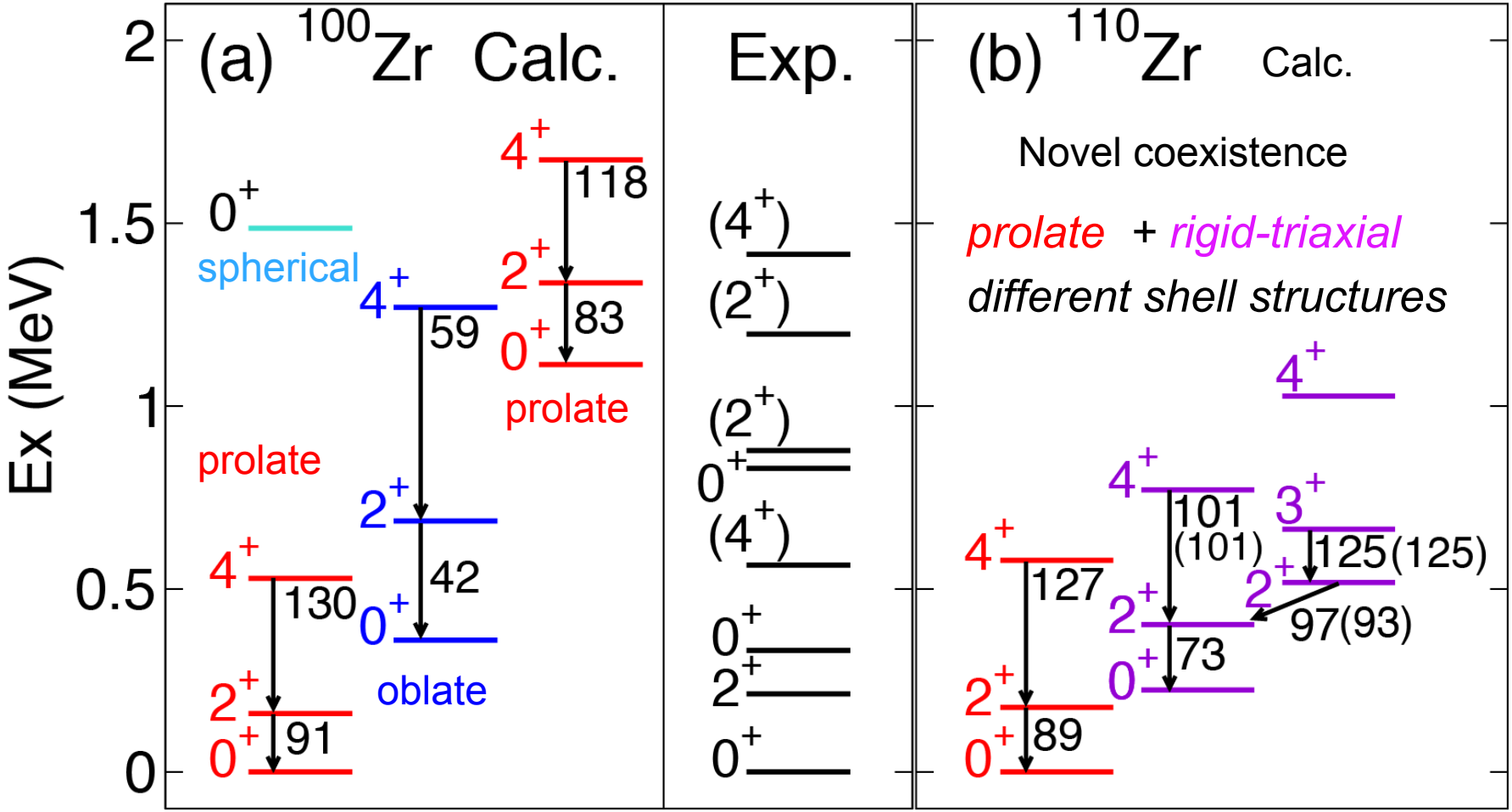




Neutron effective single-particle energies for selected eigenstates

Neutron effective single-particle energies are self-reorganized by nuclear forces (tensor and central) and certain configurations, so as to reduce resistance power against deformation.

- a case of type II shell evolution -



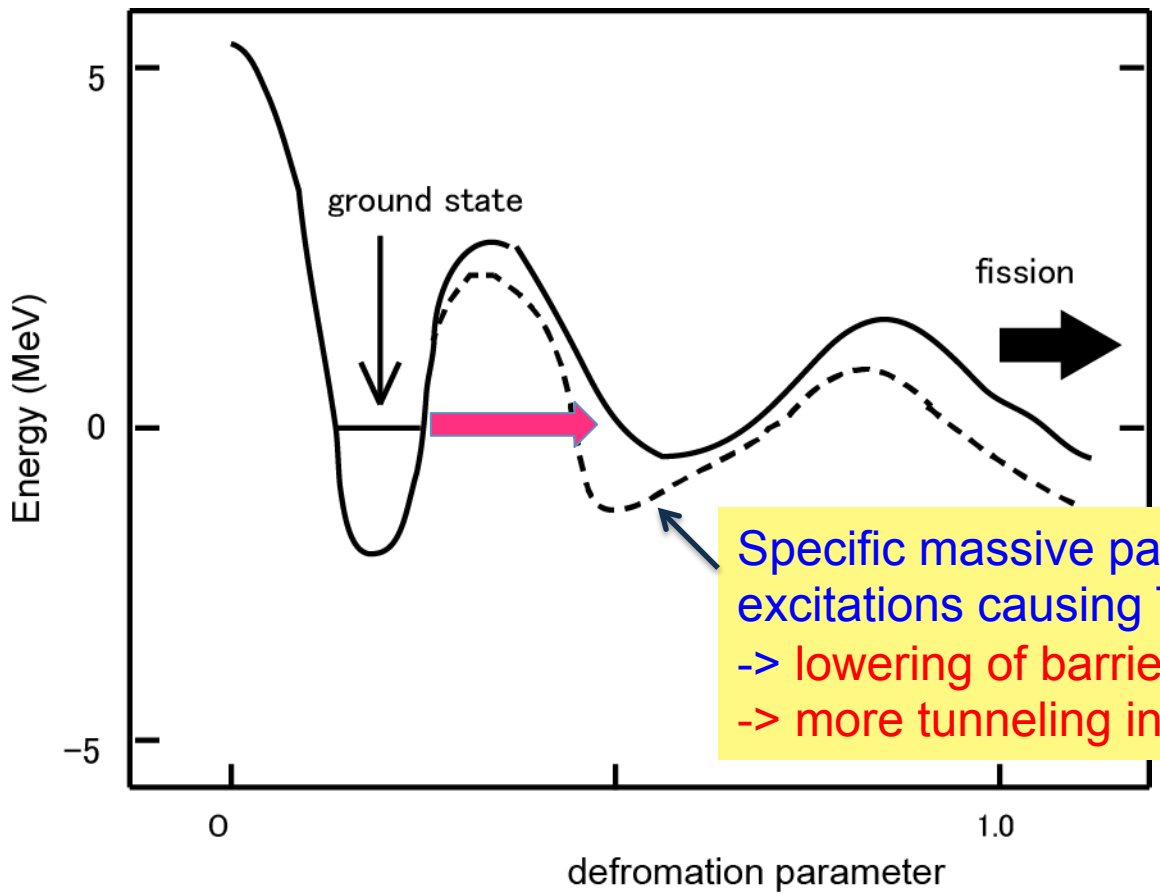
( ) : Rigid-triaxial rotor with gamma=28 degrees normalized at $2^+_2 \rightarrow 0^+_2$

Summary and Perspectives

- MCSM has been applied to Ni and Zr, with a visualization of the intrinsic shape by T-plot. The largest case corresponds to 3.7 x 10^{23} dim.
- Type II shell evolution can change the softness or resistance to deformation, and can play a crucial role in forming nuclear shapes.
- In Ni isotopes, strongly prolate deformed states come down in $^{70\text{-}72}$Ni as well developed shape coexistence. However, they do not become ground states, and go up in heavier ones. ^{78}Ni is a good magic nucleus with magic index (closed-shell probability) 75%.
- In Zr isotopes, the shape change can be a quantum phase transition (abrupt qualitative change in the ground state as a function of parameter) as a result of the crossing of two very different phases of $\beta_2 \sim 0.0$ and 0.4.
- Predictions on ^{78}Ni and ^{110}Zr agree well with experiments performed later.
- Effective single particle energies can be self-reorganized through monopole effects with occupation patterns favorable to stronger deformation. Sr isotopes may show similar feature.
- Relevance to other deformation-related phenomena like fission (next page),… ?

Fission and Type II shell evolution

There could be a general mechanism to increase fission probability.



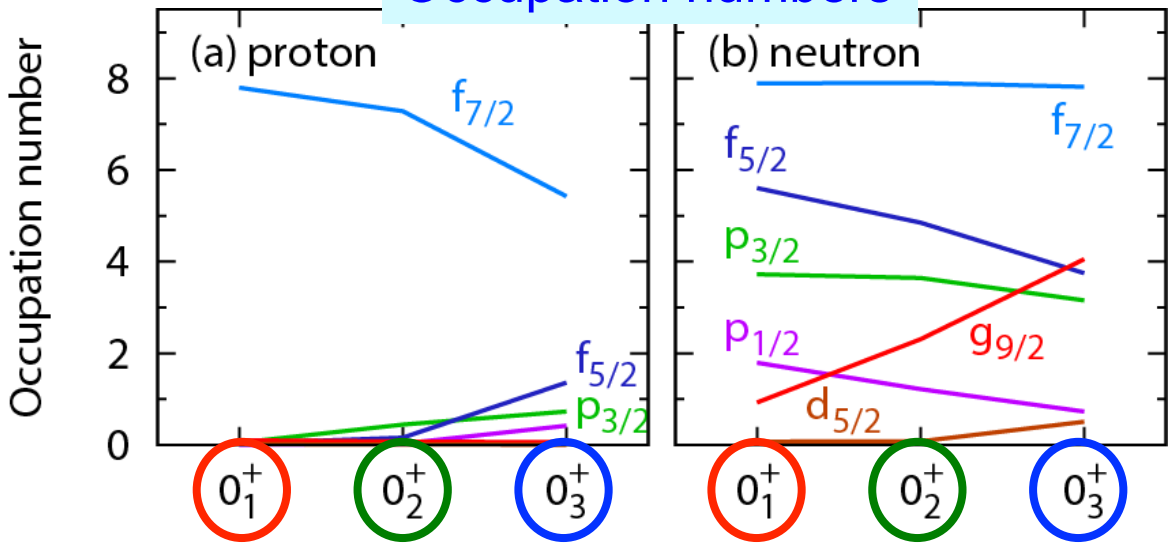
Specific massive particle-hole excitations causing Type II shell evolution
-> lowering of barrier and minimum
-> more tunneling in any kind

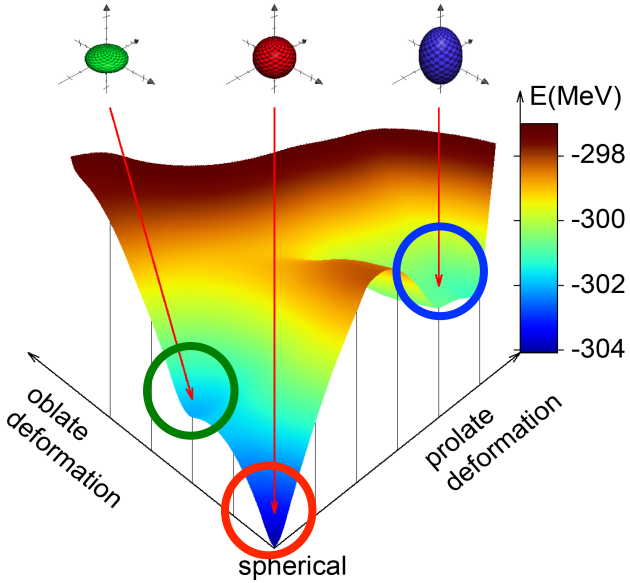
The suppression of this mechanism → the *Island of Stability ?*

Collaborators

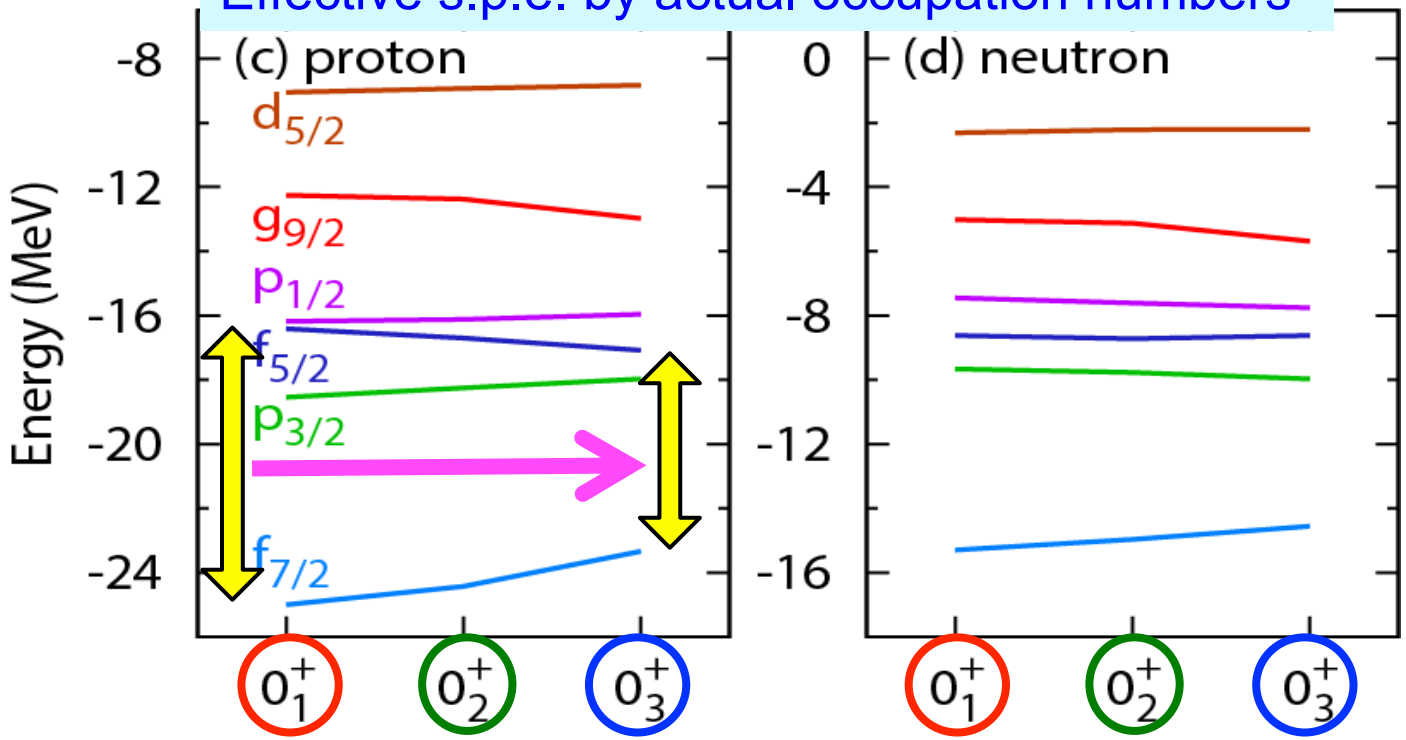
- Yusuke Tsunoda (CNS, Tokyo)
- Tomoaki Togashi (CNS, Tokyo)
- Naofumi Tsunoda (CNS, Tokyo)
- Noritaka Shimuzu (CNS, Tokyo)
- Kazuo Takayanagi (Sophia Univ.)
- Toshio Suzuki (Nihon Univ.)
- Morten Hjorth-Jensen (MSU/Oslo)
- Michio Honma (Aizu)
- Yutaka Utsuno (JAEA)

Occupation numbers





Effective s.p.e. by actual occupation numbers



0^+ state

1st — modest correlations

2nd — 2p-2h

3rd — 6p-6h