東京大学
THE UNIVERSITY OF TOKYO

KU LEUVEN

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Gross Properties of Nuclei and Nuclear Excitations
Neutron star mergers: From gravitational waves to nucleosynthesis
Hirschegg, Austria
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Quantum Self-Organization and its implication in nucleosynthesis

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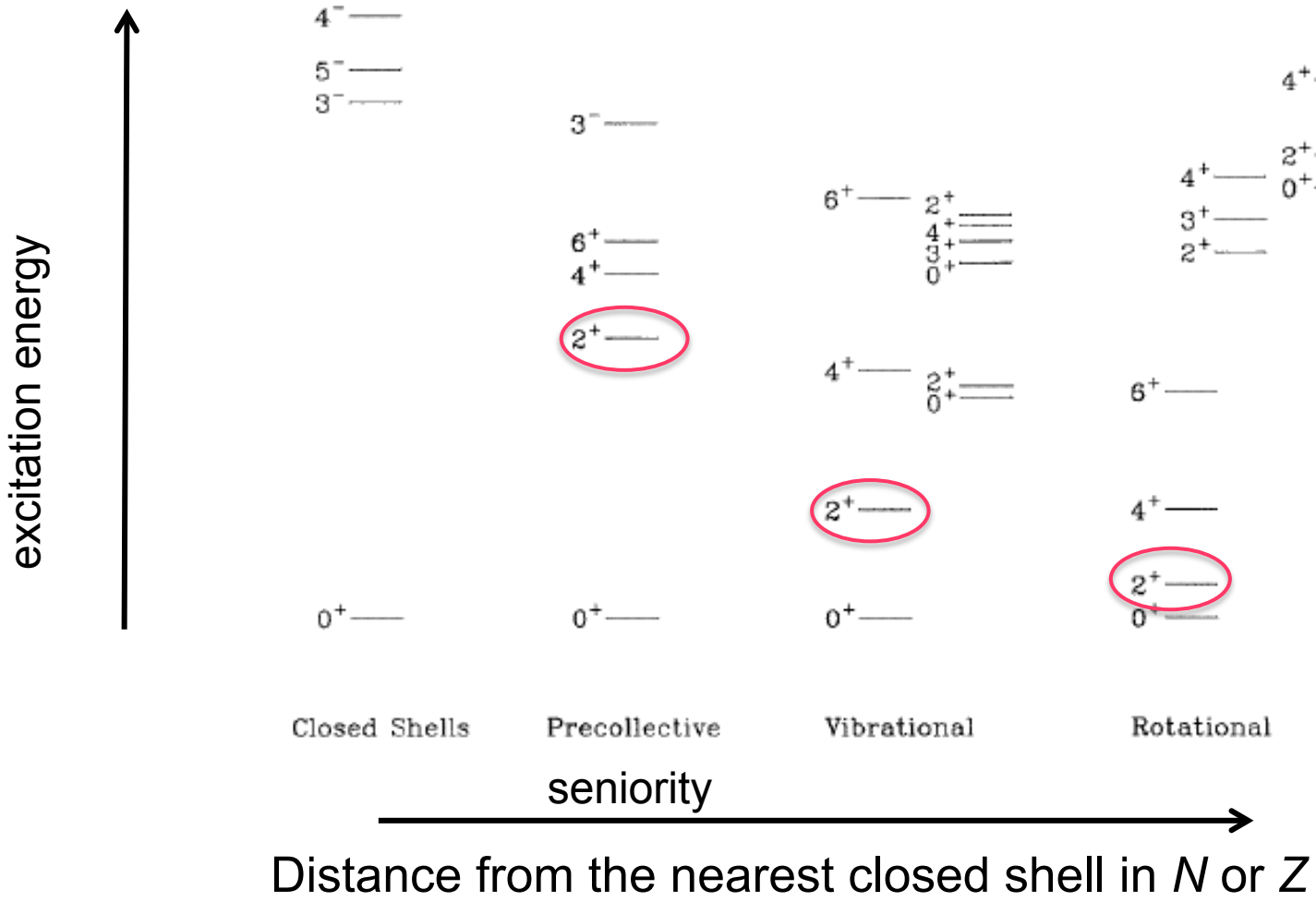
Supported by MEXT and JICFuS as a priority issue (Elucidation of the fundamental laws and evolution of the universe) to be tackled by using Post 'K' Computer

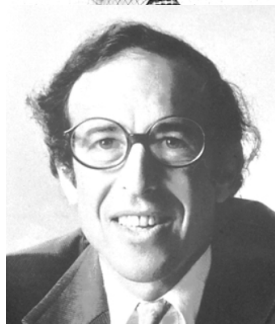
Outline

- Nuclear shapes and quantum phase transition
- Phase Transition in Zr isotopes and Quantum Self-organization
- Implications to nucleosynthesis
- Summary and Perspectives

Schematic picture of shape evolution (sphere to ellipsoid & vice versa)

- gradual changes throughout the nuclear chart –

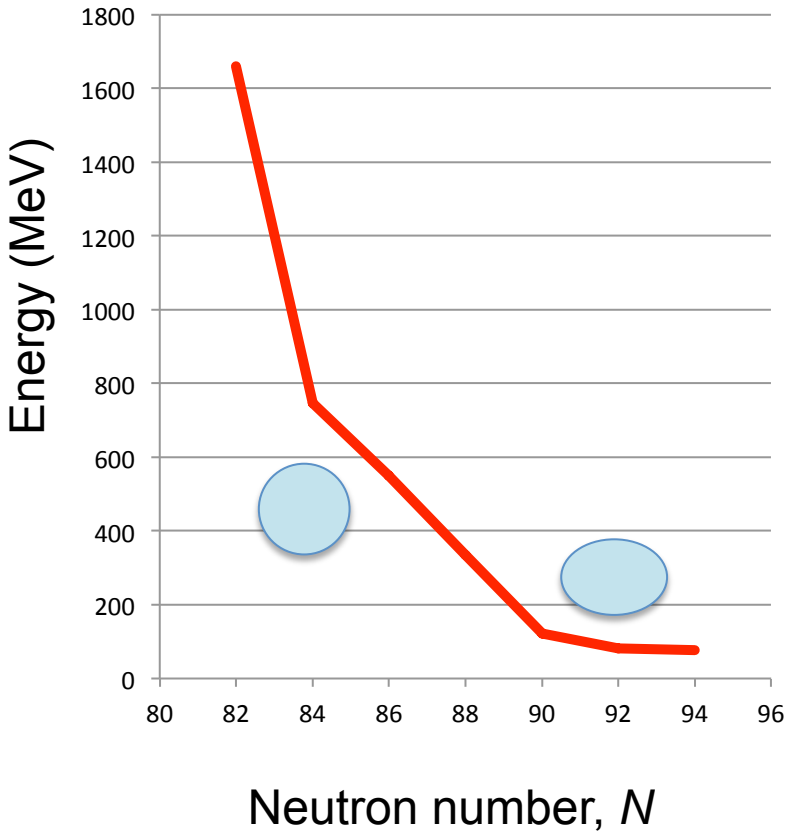




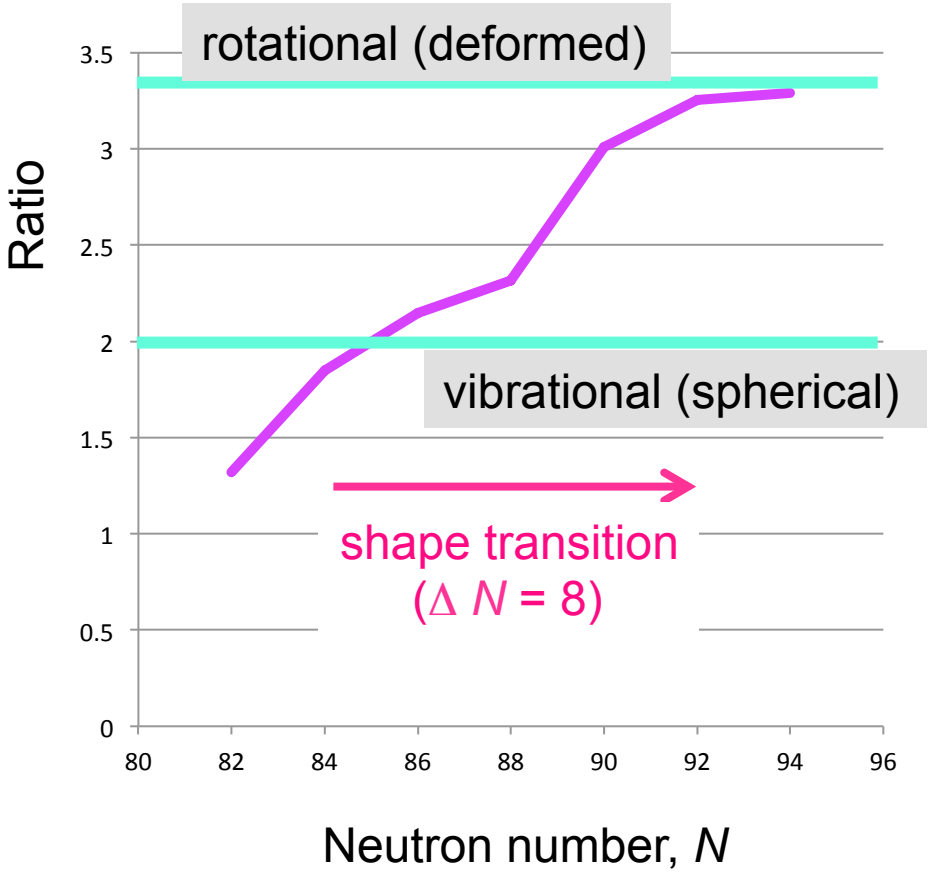
From "Nuclear Structure from a Simple Perspective", R.F. Casten (2001)

2^+ and 4^+ level properties 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* ?

Intuitively, …

This effect becomes larger as the nucleus moves away from the closed shell.

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

resistance power ← for instance, pairing force

Assumed to be a constant, for a moment.

We come back to this point later !

The quadrupole force is a part of nuclear forces.

Its effect is expressed, for example, in Casten's $N_p N_n$ model, as

$$< \text{quadrupole force} > = \alpha \; N_p \; N_n$$

α : parameter

N_p : number of valence protons

N_n : number of valence neutrons

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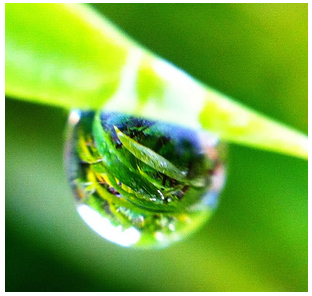
Can the shape transition be a "Phase Transition" ?

Phase Transition :

A macroscopic system can change qualitatively from a stable state (*e.g.* ice for H_2O) to another stable state (*e.g.*, water for H_2O) as a function of a certain parameter (*e.g.*, temperature).

The phase transition implies this kind of phenomena of macroscopic systems consisting of almost infinite number of molecules,
where thermodynamics can be applied.

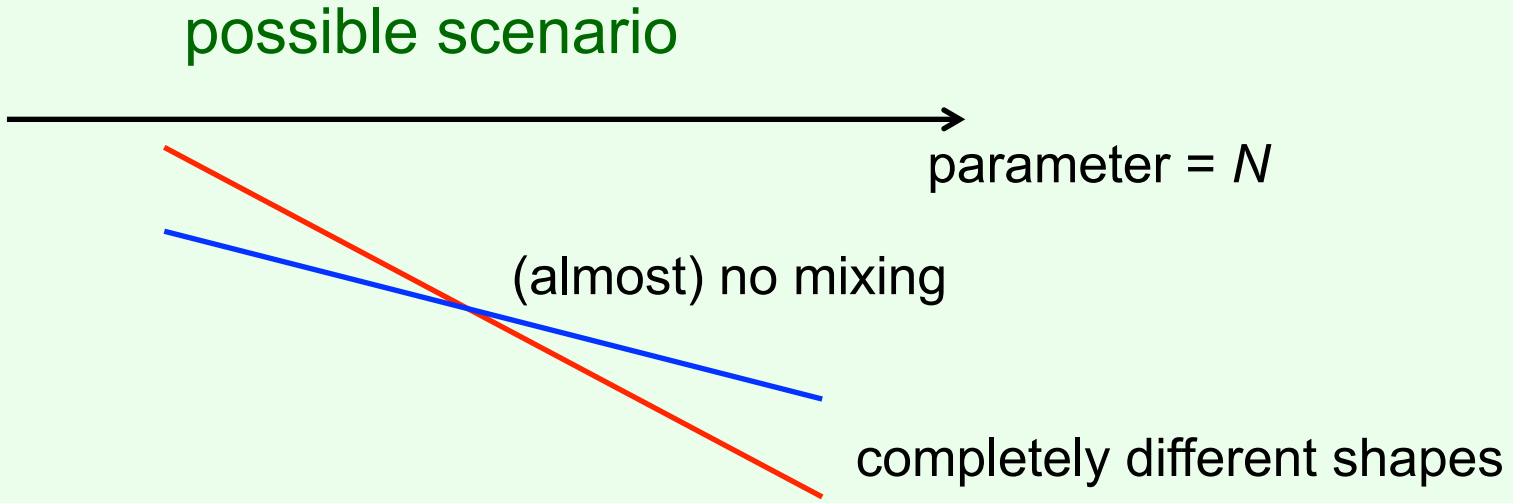


Quantum Phase Transition (QPT)

The concept of the phase transition cannot be applied to microscopic systems as it is. In the QPT, the ground state of a quantum (microscopic) system undergoes abrupt and qualitative change (of order parameter) as a (control) parameter changes.

The shape transition occurs rather gradually.

The usual shape transition may not fulfill the condition being *abrupt*.
Where can we see it ?
If it occurs in atomic nuclei, what is the underlying mechanism ?



Note that sizable mixing occurs usually in finite quantum systems.

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. (cf., Wikipedia)

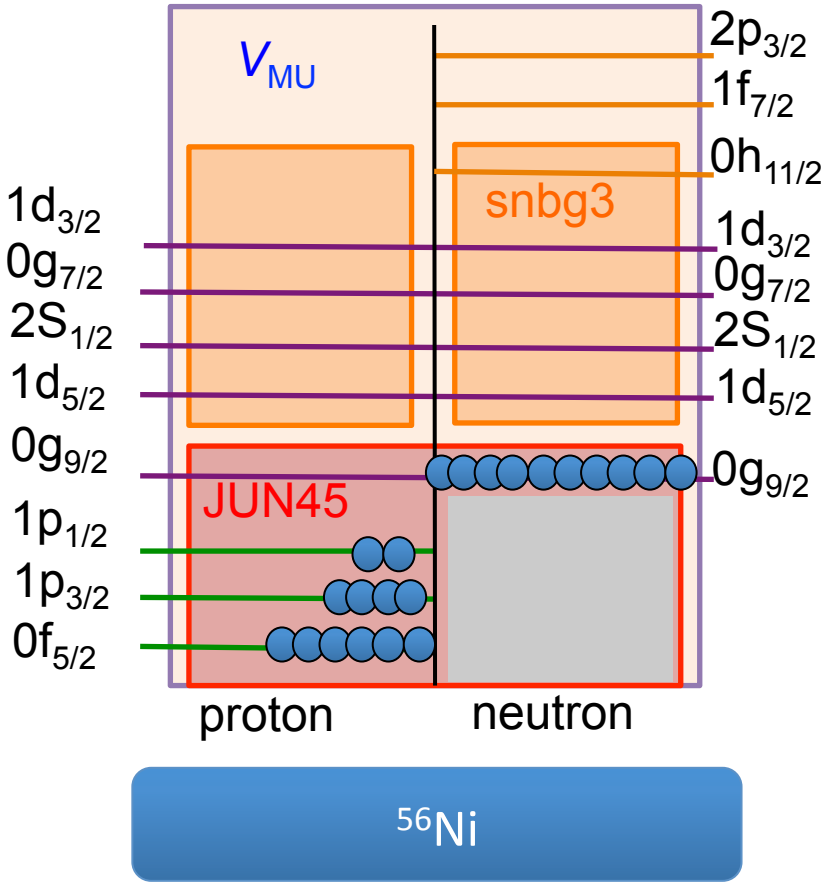
Numerical part of the present work : Monte Carlo Shell Model calculation

- 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)

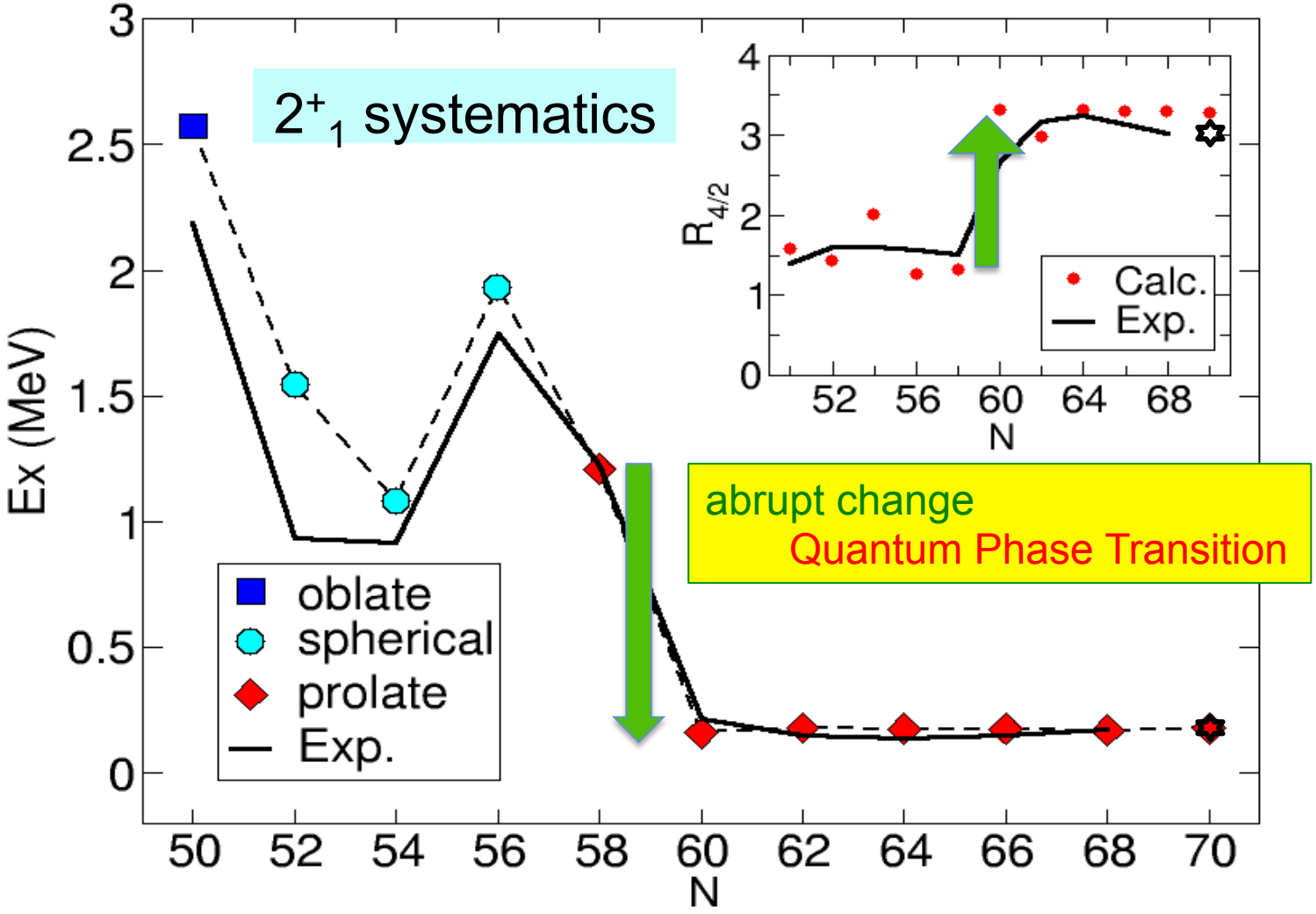


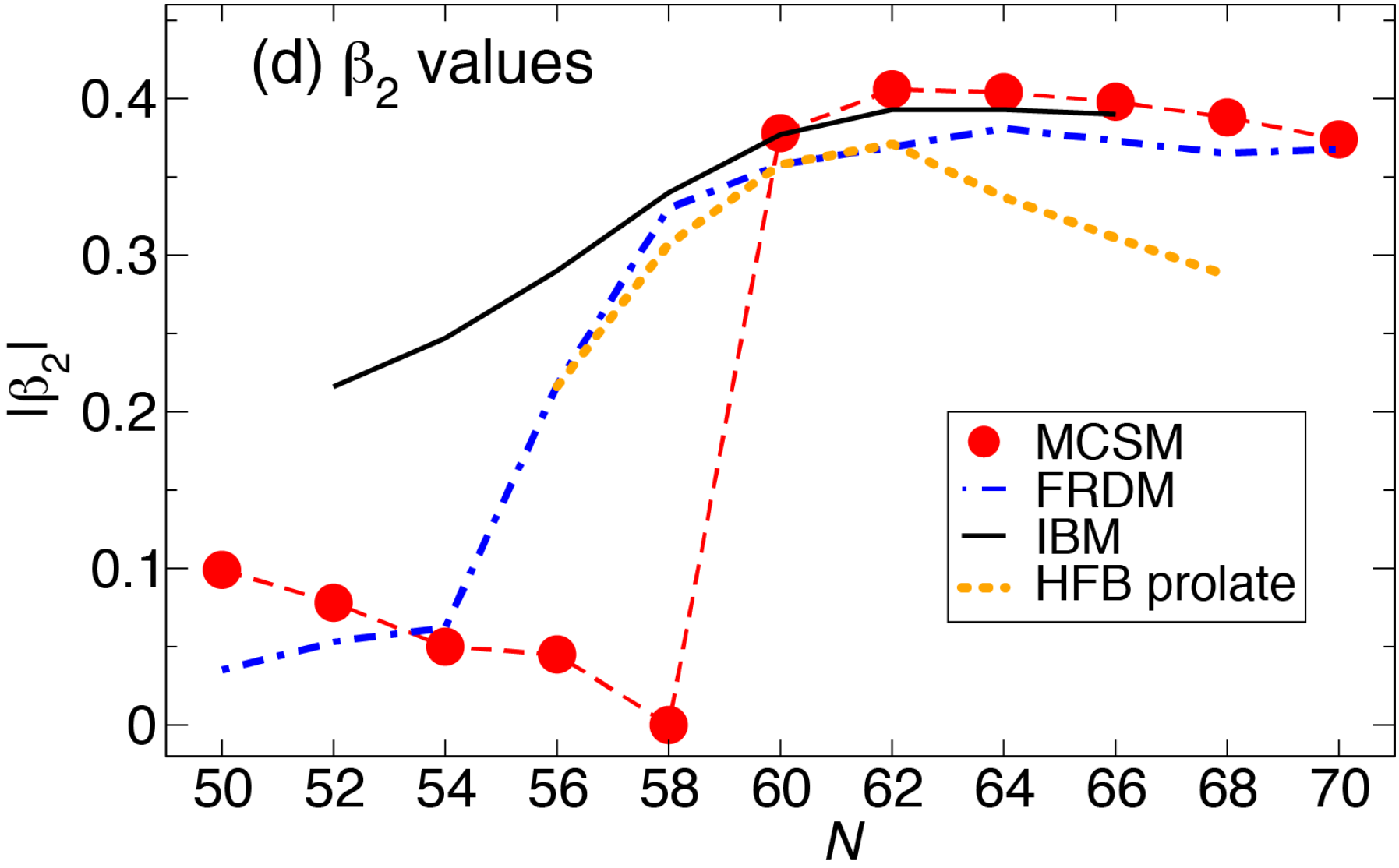
We performed Monte Carlo Shell Model (MCSM) calculations, where the largest case corresponds to the diagonalization of 3.7×10^{23} dimension matrix.

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

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]

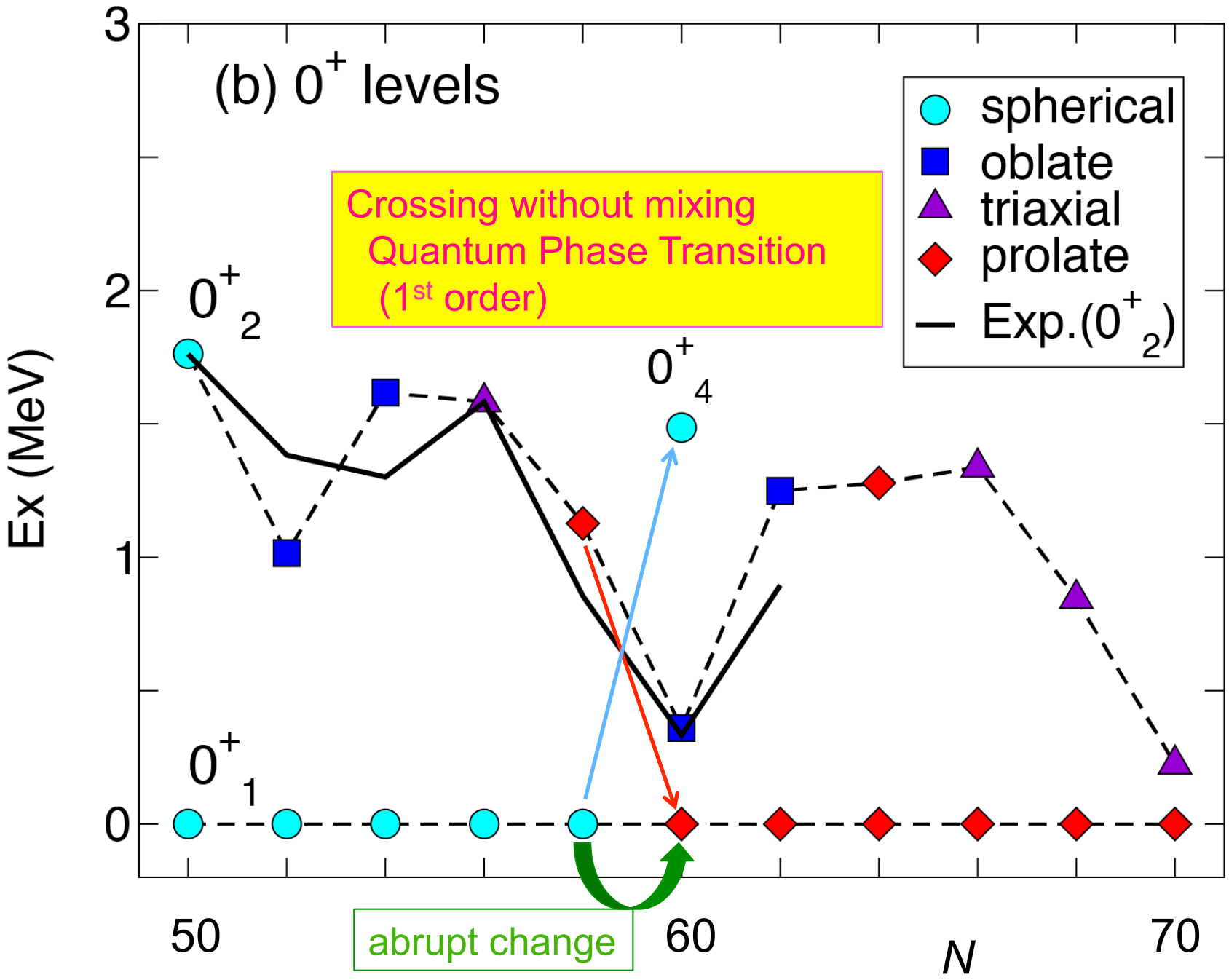




FRDM: S. Moeller et al. At. Data Nucl. Data Tables 59, 185 (1995).

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

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


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

MCSM wave function on Potential Energy Surface (*T-plot*)

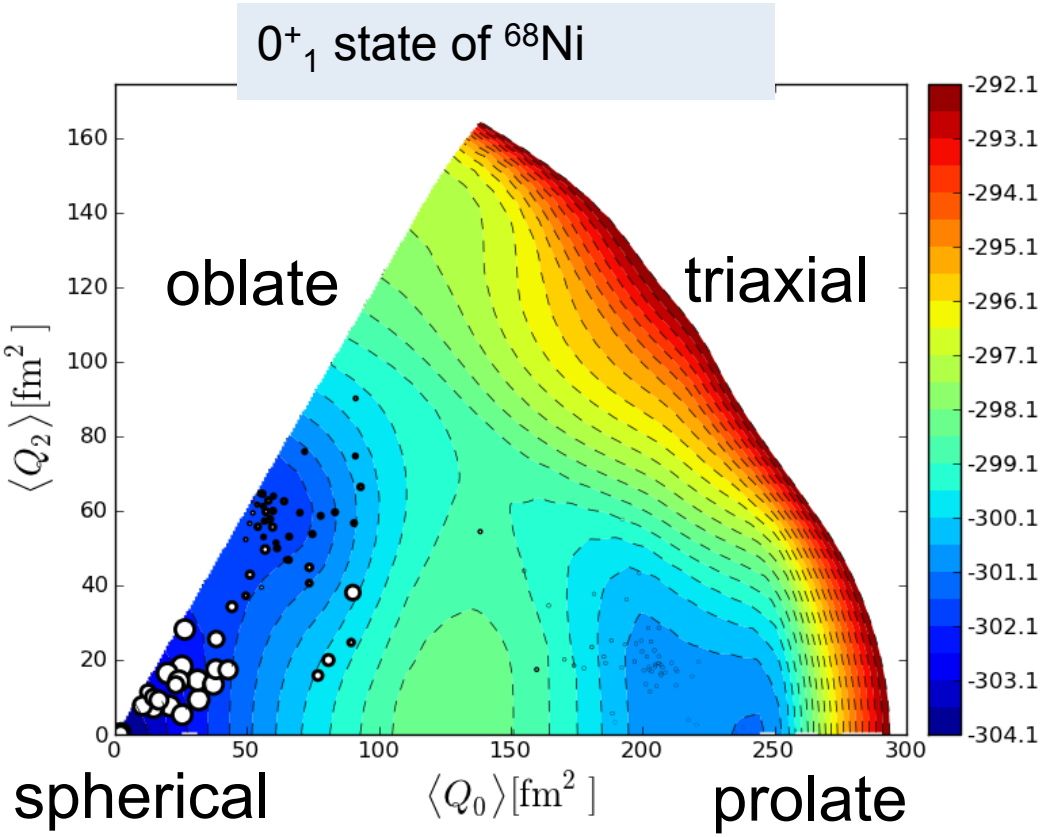
eigenstate $\Psi = \sum_i c_i P[J^\pi] \Phi_i$

Slater determinant → intrinsic deformation

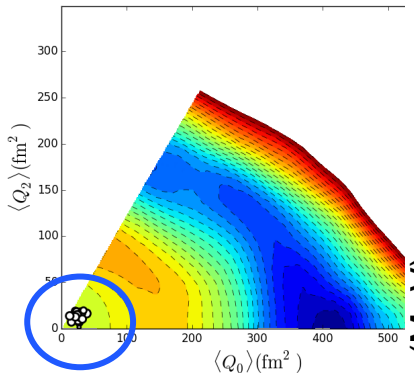
amplitude

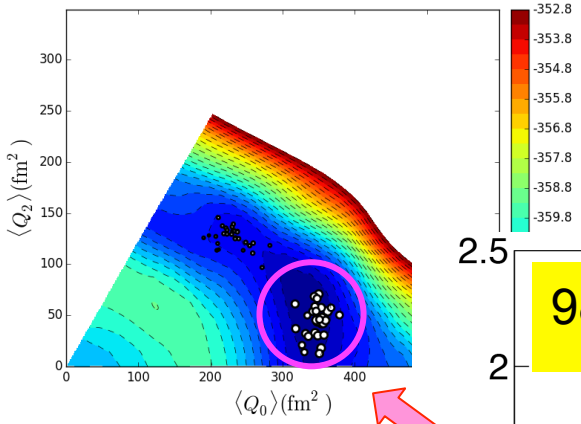
projection on J^π

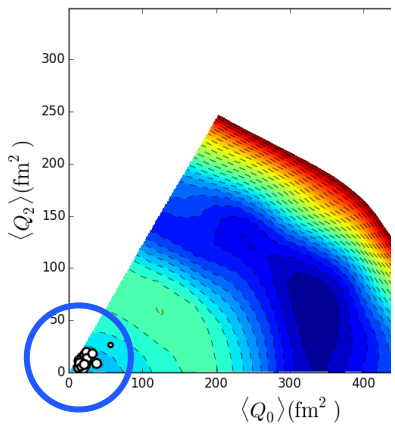
- PES is calculated by CHF
- Location of circle : quadrupole deformation of unprojected MCSM basis vectors
- Area of circle : overlap probability between each projected basis and eigen wave function

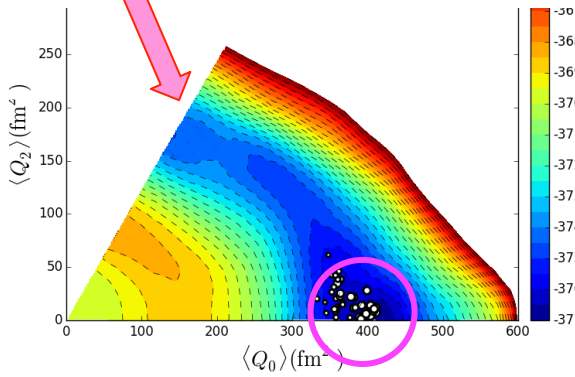


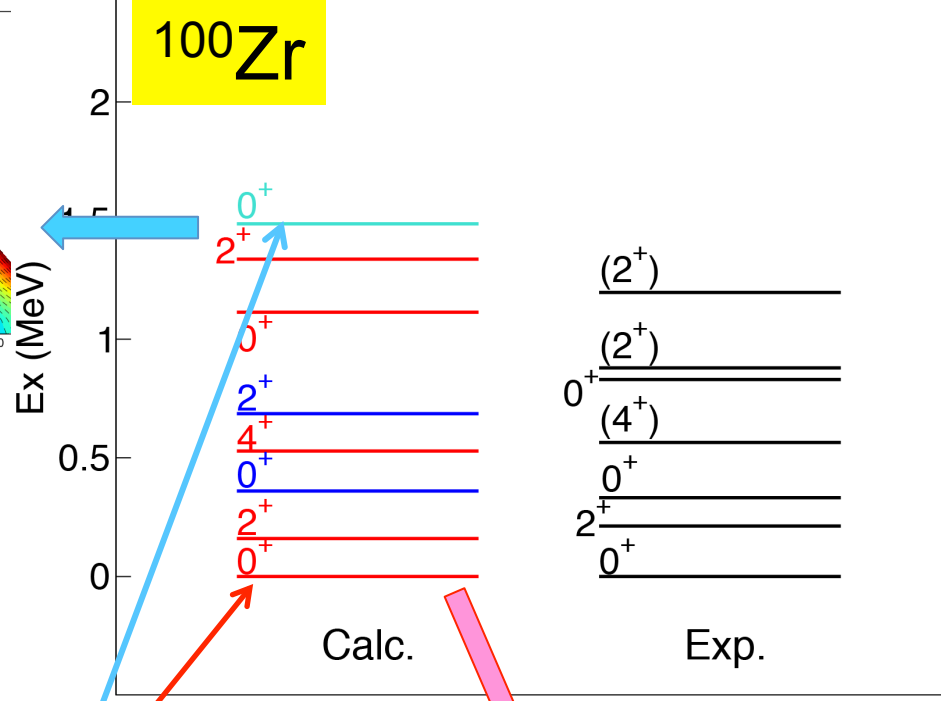
Quantum Phase Transition (1st order) due to crossing without mixing

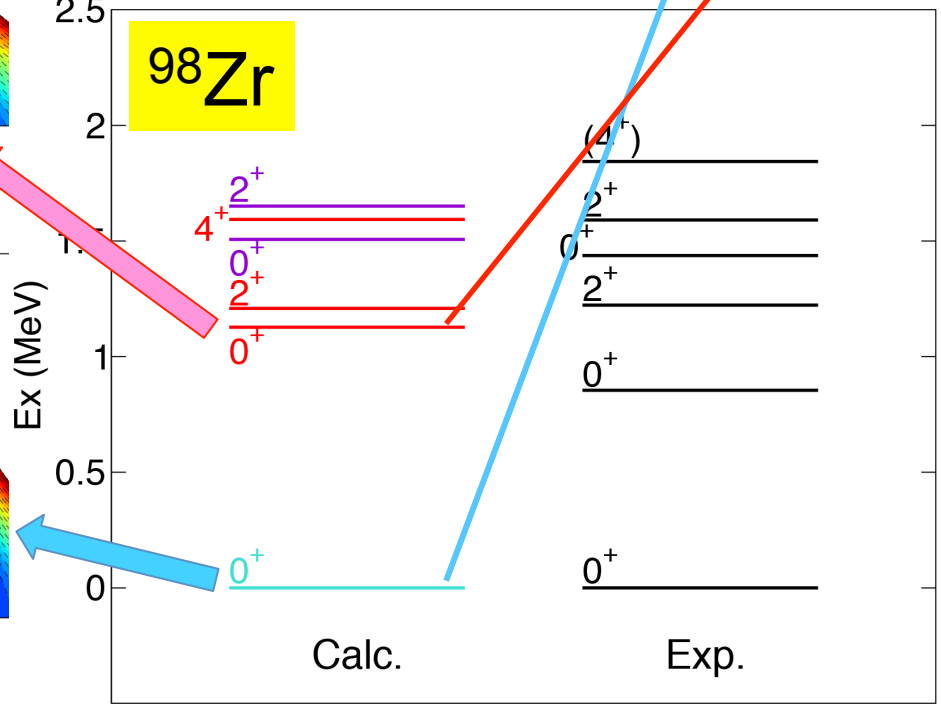


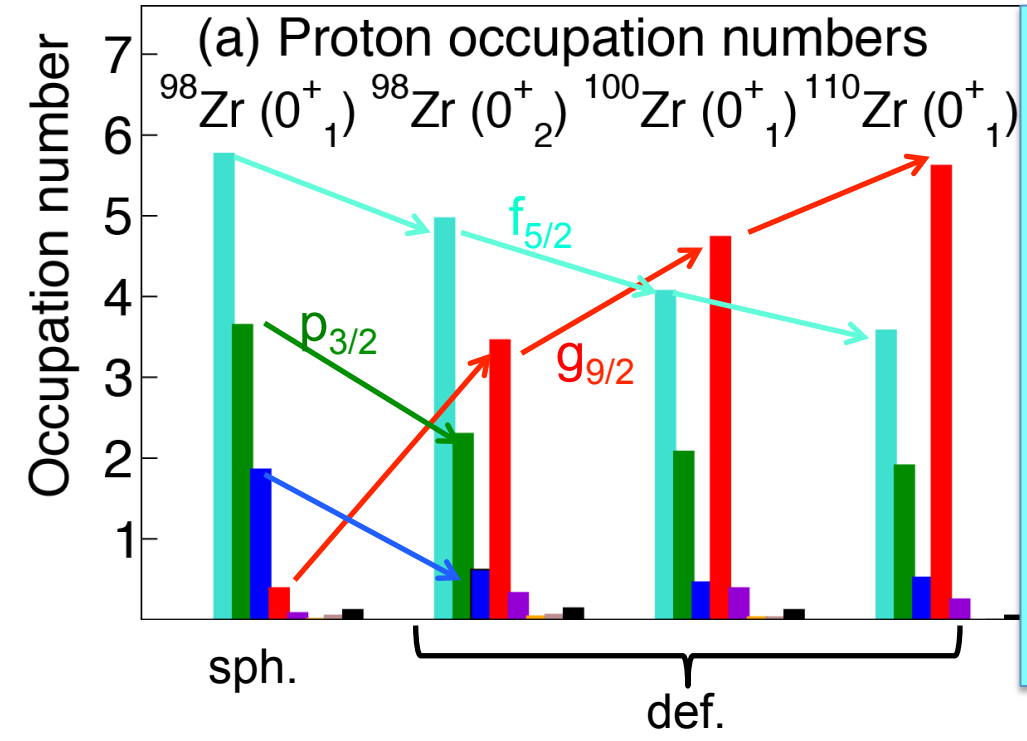


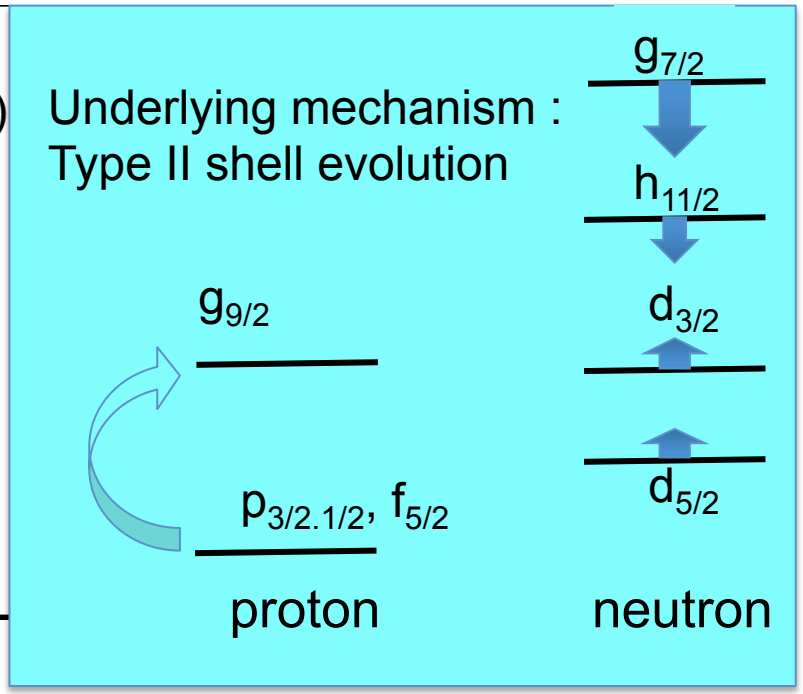


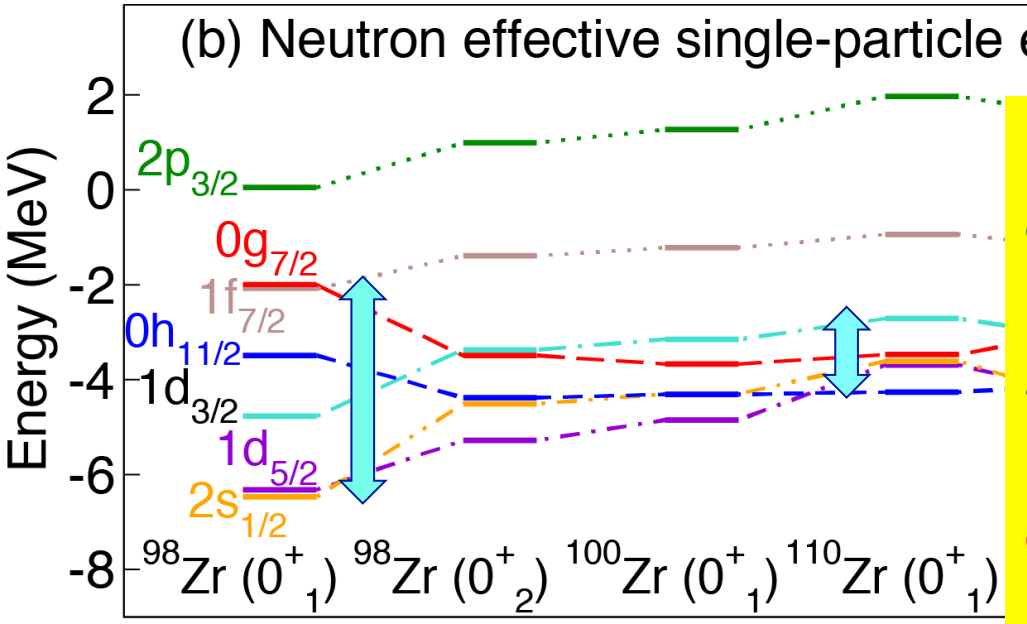








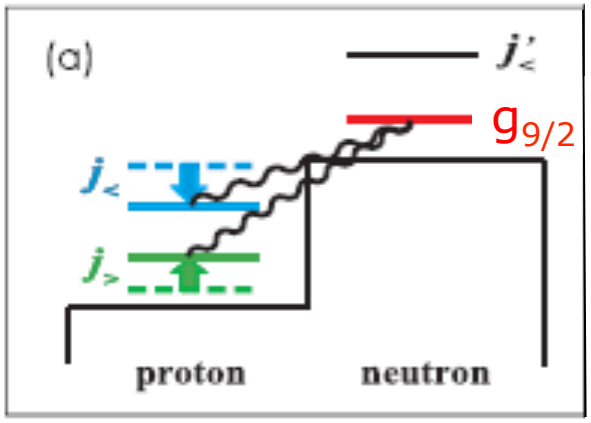




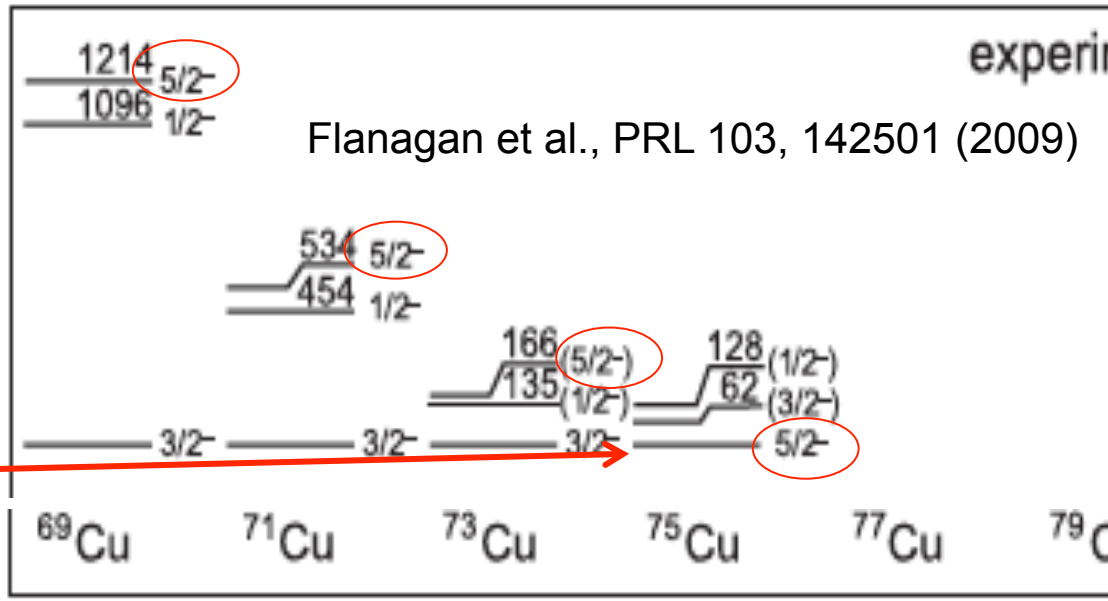
Neutron effective single-particle energies are self-reorganized by nuclear forces (tensor and central) and certain configurations, so as to reduce resistance power against deformation.

- a case of type II shell evolution -

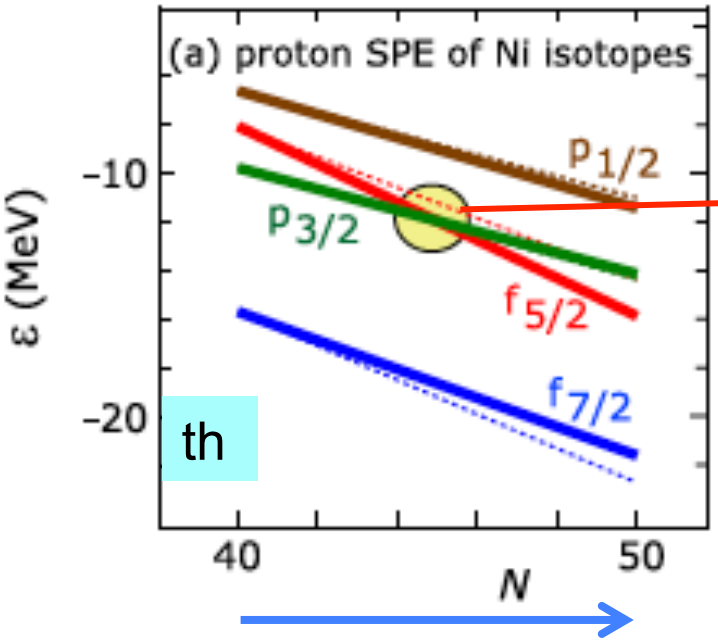
A clean example of tensor-force driven shell evolution



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)



more neutrons in $g_{9/2}$

Franchoo *et al.*, PRC 64, 054308 (2001)

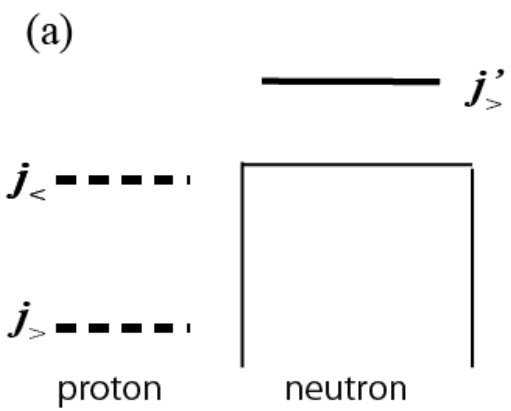
"level scheme … newly established for ^{71,73}Cu"

"… unexpected and sharp lowering of the $\pi f_{5/2}$ orbital"

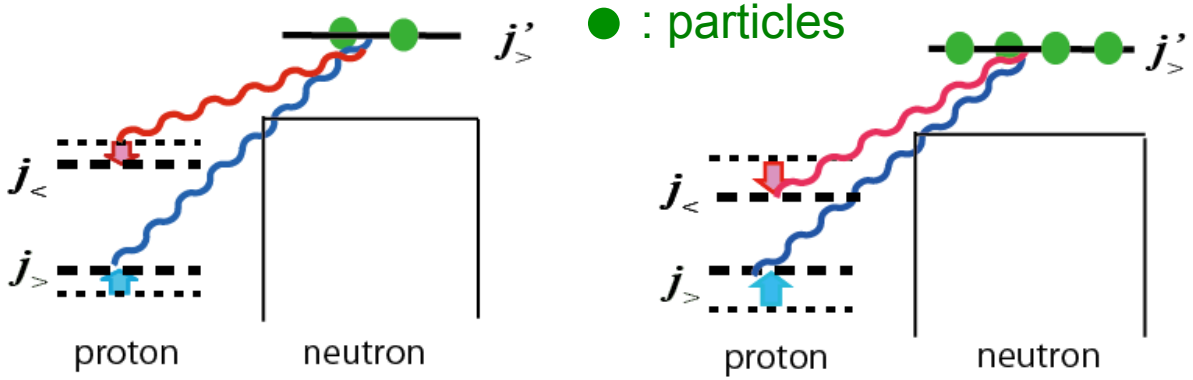
"… ascribed to the monopole term of the residual int. .."

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

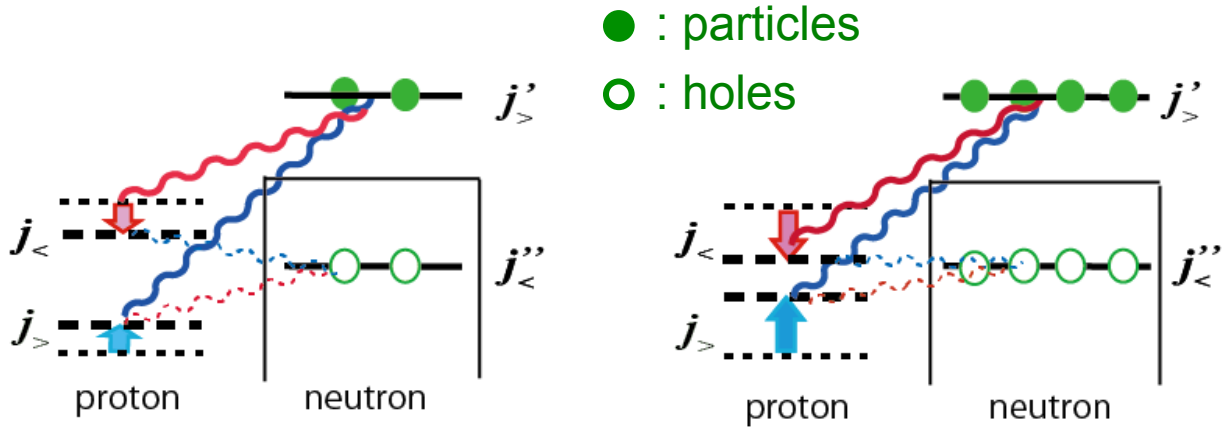
Shell Evolution - from Type I to Type II -



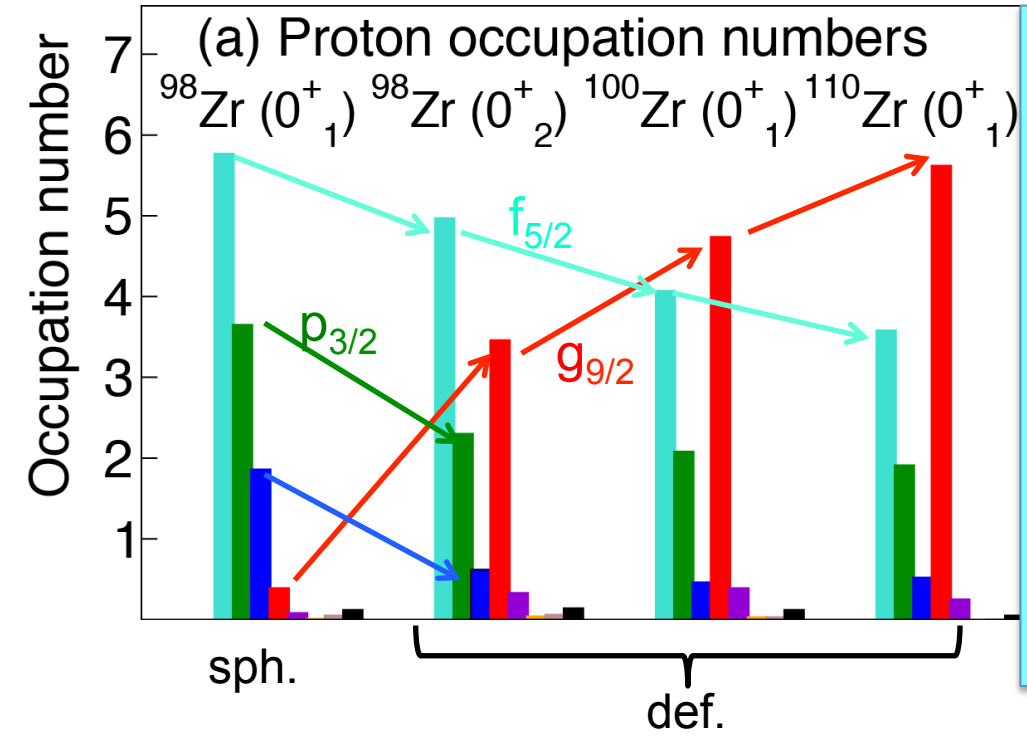
Type I Shell Evolution : different isotopes

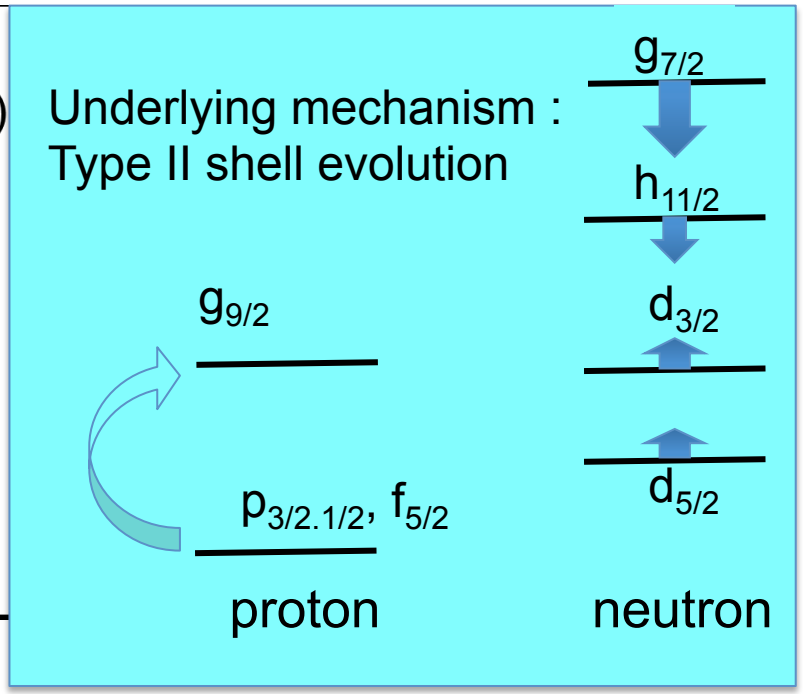


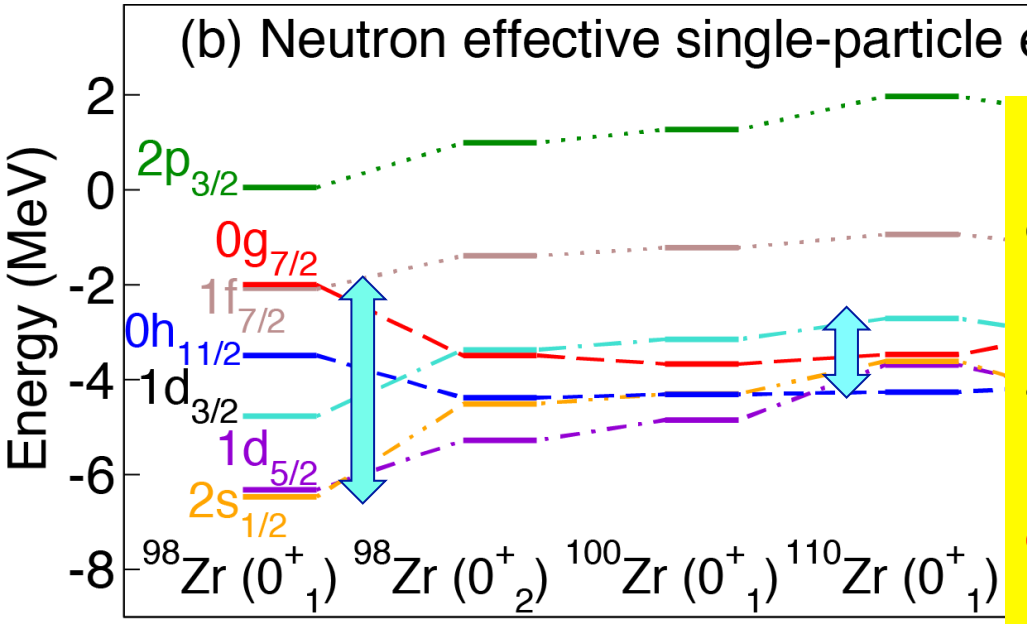
Type II Shell Evolution : within the same nucleus



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







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 -

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

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).

Quantum Self Organization

Type I and II shell evolutions are simpler examples

Next page : spherical single-particle energies are often treated being constant

Woods-Saxon potential

Parameters are constant within a given nucleus

Nilsson model Hamiltonian

"*Nuclear structure II*" by Bohr and Mottelson

deformed nuclei, is obtained by a simple modification of the harmonic oscillator (Nilsson, 1955; Gustafson *et al.*, 1967),

$$H = \frac{\mathbf{p}^2}{2M} + \tfrac{1}{2}M\left(\omega_3^2 x_3^2 + \omega_\perp^2 (x_1^2 + x_2^2)\right) + v_{ll}\hbar\omega_0(\mathbf{l}^2 - \langle \mathbf{l}^2 \rangle_N) + v_{ls}\hbar\omega_0(\mathbf{l}\cdot\mathbf{s}) \qquad (5\text{-}10)$$

quadrupole deformed field

spherical field

constant within a region

$$\langle \mathbf{l}^2 \rangle_N = \tfrac{1}{2}N(N+3)$$

Figure	Region	$-v_{ls}$	$-v_{ll}$
5-1	N and $Z < 20$	0.16	0
5-2	$50 < Z < 82$	0.127	0.0382
5-3	$82 < N < 126$	0.127	0.0268
5-4	$82 < Z < 126$	0.115	0.0375
5-5	$126 < N$	0.127	0.0206

Table 5-1 Parameters used in the single-particle potentials of Figs. 5-1 to 5-5.

Spin-orbit force

A= 68 1.28

A=100 1.12

A=186 0.91

$(\mathbf{l}\cdot\mathbf{s})$

Intuitively speaking,

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

resistance power ← pairing force

single-particle energies

Analogy to electric current,

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

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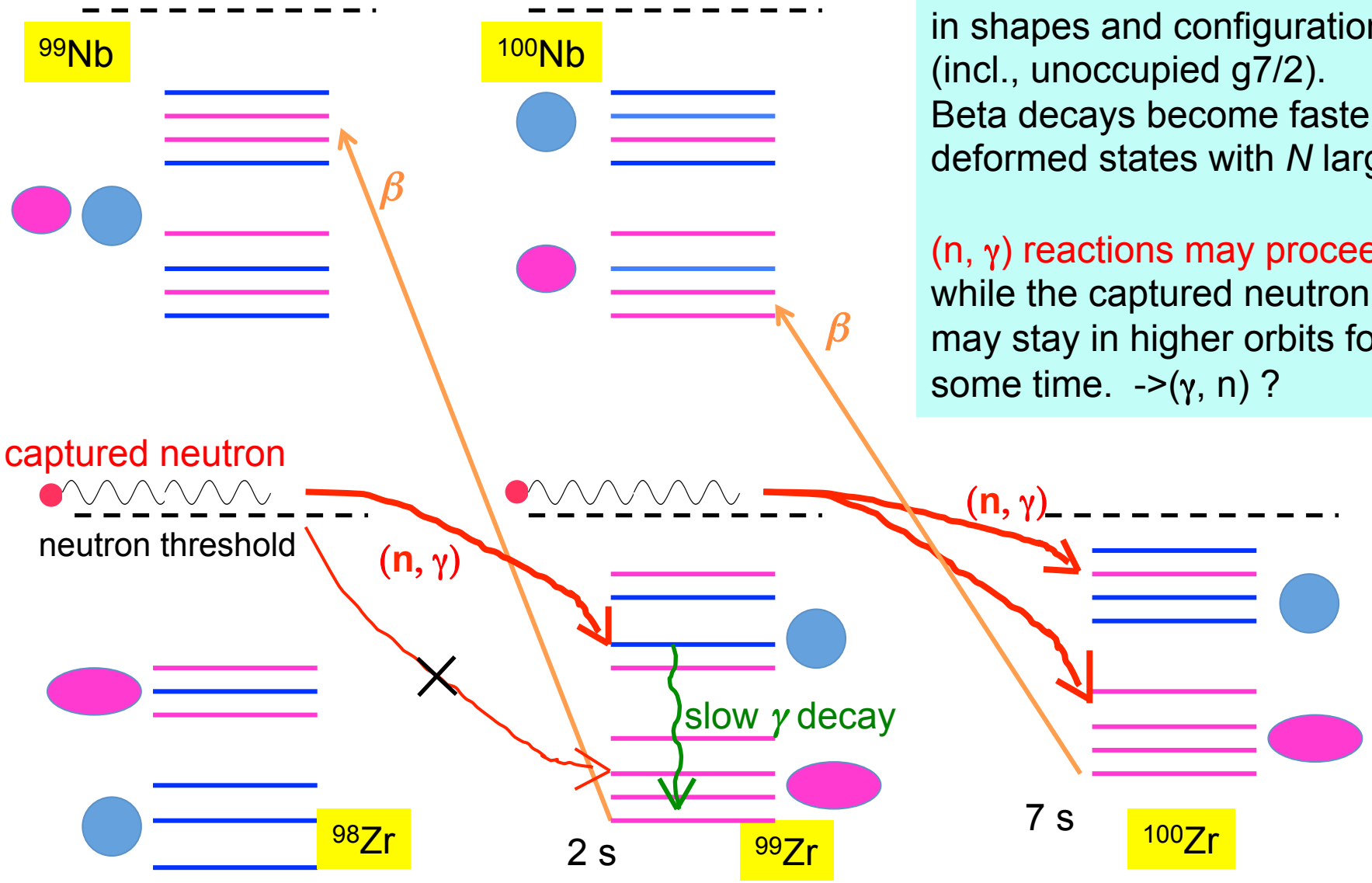
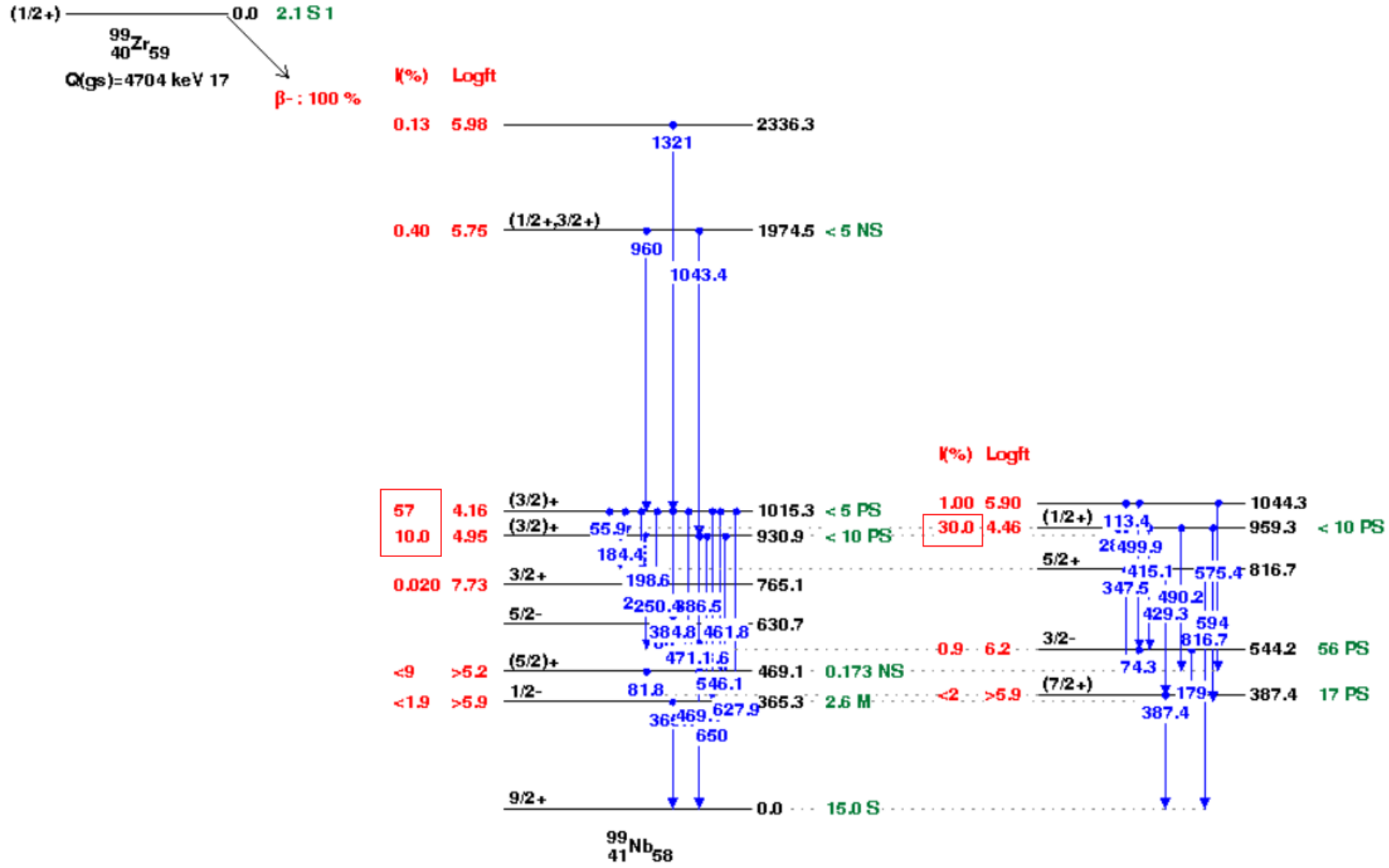
What is the possible implications to nucleosynthesis ?

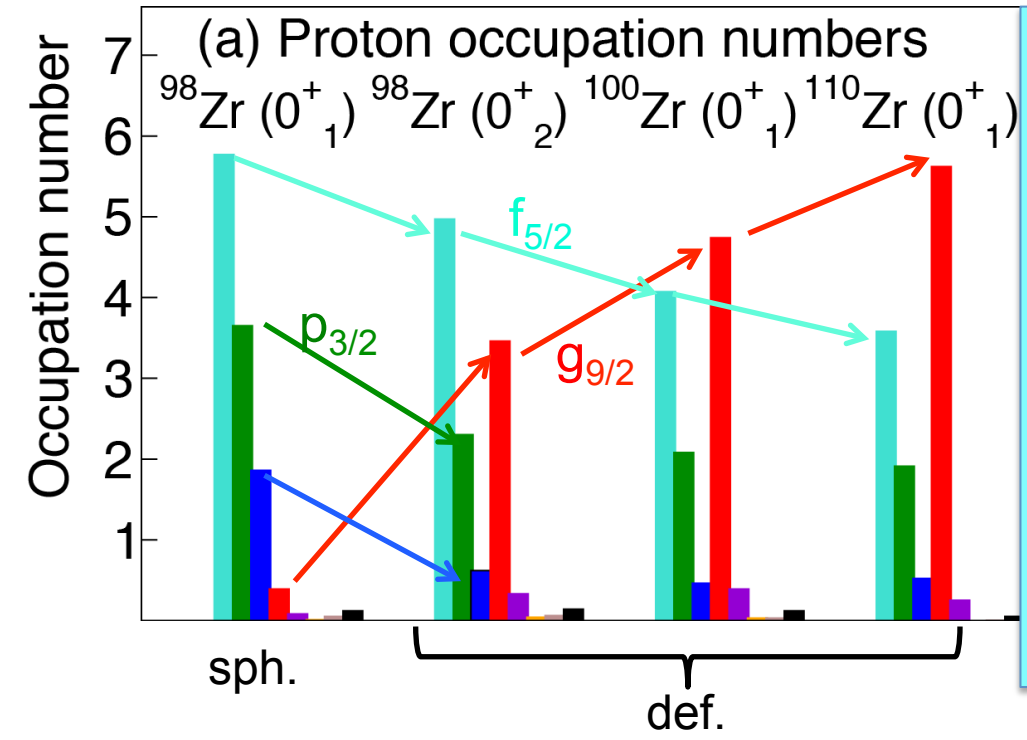
A preliminary conceptual scheme.

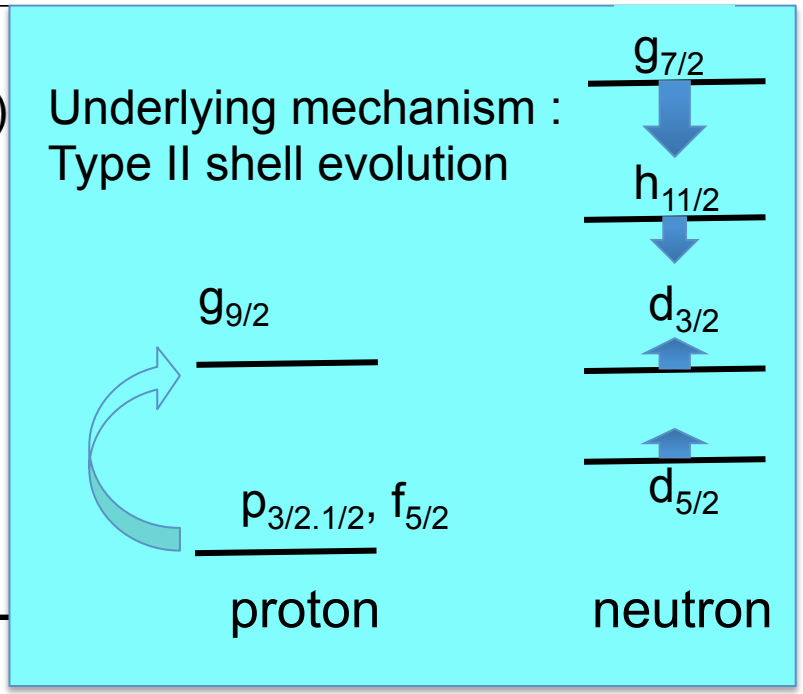


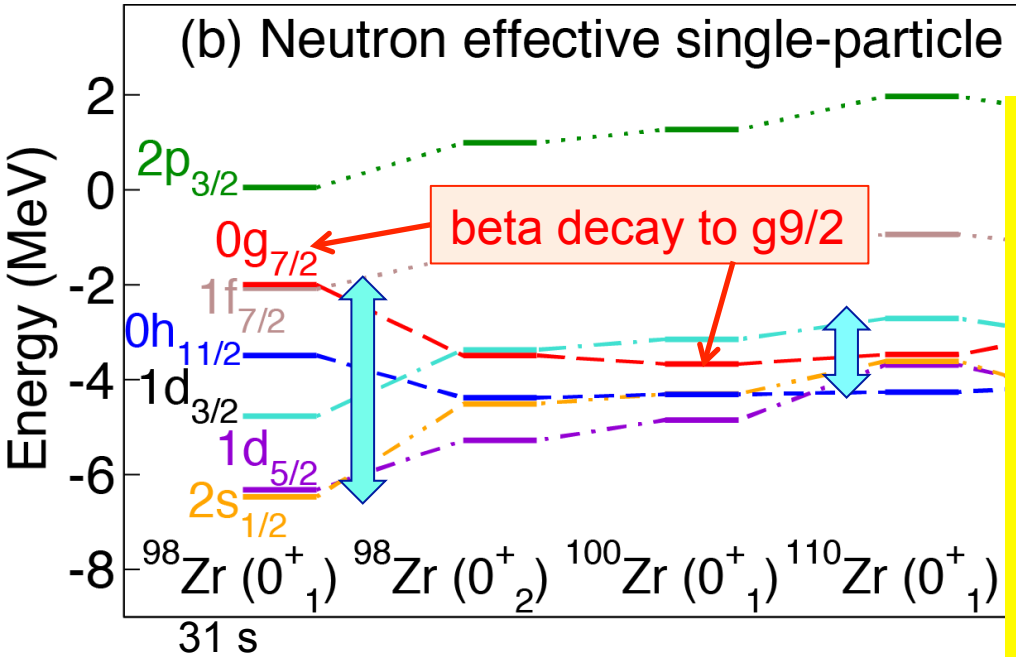
Beta decays can be delayed due to differences in shapes and configurations (incl., unoccupied g7/2). Beta decays become faster for deformed states with *N* larger.

(n, γ) reactions may proceed, while the captured neutron may stay in higher orbits for some time. ->(γ, n) ?


(1/2+)
0.0
2.1 S 1
99 40 Zr 59
Q(gs)=4704 keV 17
β- : 100 %
I(%)
Logft
0.13
5.98
2336.3
1321
0.40
5.75
(1/2+,3/2+)
1974.5
< 5 NS
960
1043.4
57
4.16
(3/2)+
1015.3
< 5 PS
10.0
4.95
(3/2)+
930.9
< 10 PS
55.9
184.4
0.020
7.73
3/2+
198.6
765.1
250.4
886.5
5/2-
384.8
461.8
630.7
471.1
6
(5/2)+
469.1
0.173 NS
<9
>5.2
546.1
81.8
1/2-
<1.9
>5.9
365.3
2.6 M
627.9
469.
650
9/2+
0.0
15.0 S
99 41 Nb 58
I(%)
Logft
1.00
5.90
1044.3
30.0
4.46
(1/2+)
113.4
959.3
< 10 PS
499.9
5/2+
415.1
575.4
816.7
347.5
490.2
429.3
594
816.7
0.9
6.2
3/2-
544.2
56 PS
74.3
<2
>5.9
(7/2+)
179
387.4
17 PS
387.4

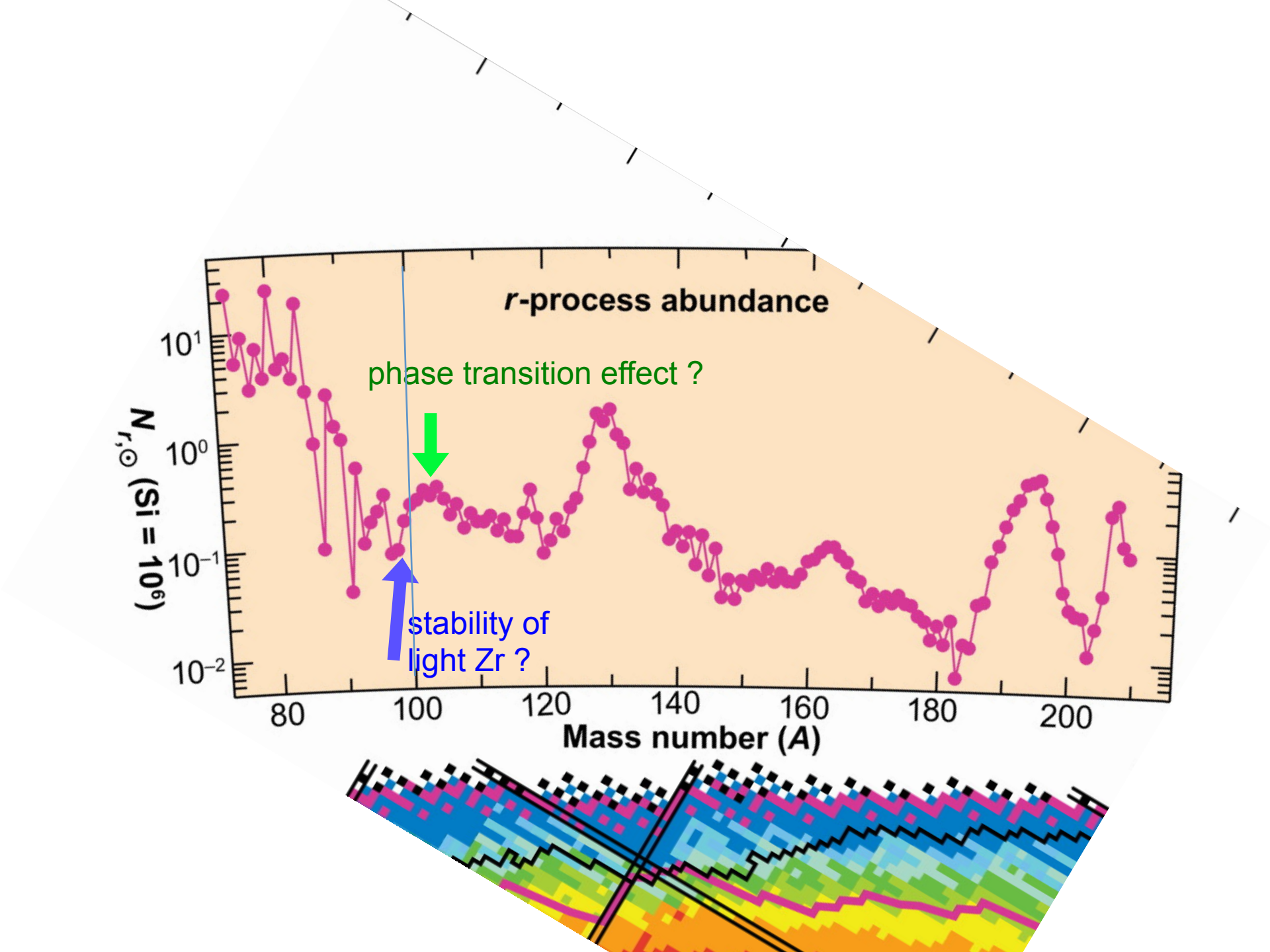






Neutron effective single-particle energies are self-reorganized by nuclear forces (tensor and central) and certain configurations, so as to reduce resistance power against deformation.

- a case of type II shell evolution -


r-process abundance
phase transition effect ?
stability of
light Zr ?
$N_{r,\odot}$ (Si = 10^6)
10^1
10^0
10^{-1}
10^{-2}
80
100
120
140
160
180
200
Mass number (A)

Summary and Perspectives

- The atomic nuclei are not like a simple rigid vase containing almost free nucleons.
- Nuclear forces are rich enough to change single-particle energies for each eigenstate. Type I and II shell evolutions are simple cases.

  → shape coexistence, quantum phase transition in shapes, *super def, octupole excitations, fission*, *etc*.
- More generally, single particle energies can be self-organized, because of (i) two quantum liquids (protons and neutrons),

  (ii) two major force components :

  e.g., quadrupole interaction : to drive deformation

  monopole interaction : to control resistance
- Nucleosynthesis can be affected around the phase transition

  example : certain shift of abundance to higher A ?

  (n, γ) populates higher levels but not lowest states,

  beta decay from higher levels, more delay in beta decay, …