東京大学 THE UNIVERSITY OF TOKYO

CENTER for NUCLEAR STUDY THE UNIVERSITY of TOKYO

NSCL

KU LEUVEN

"Reflections on the atomic nucleus",
University of Liverpool
July 30 (28-30), 2015

Dual quantum liquid picture of nuclei and its implication to reflection asymmetry

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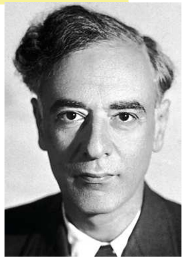
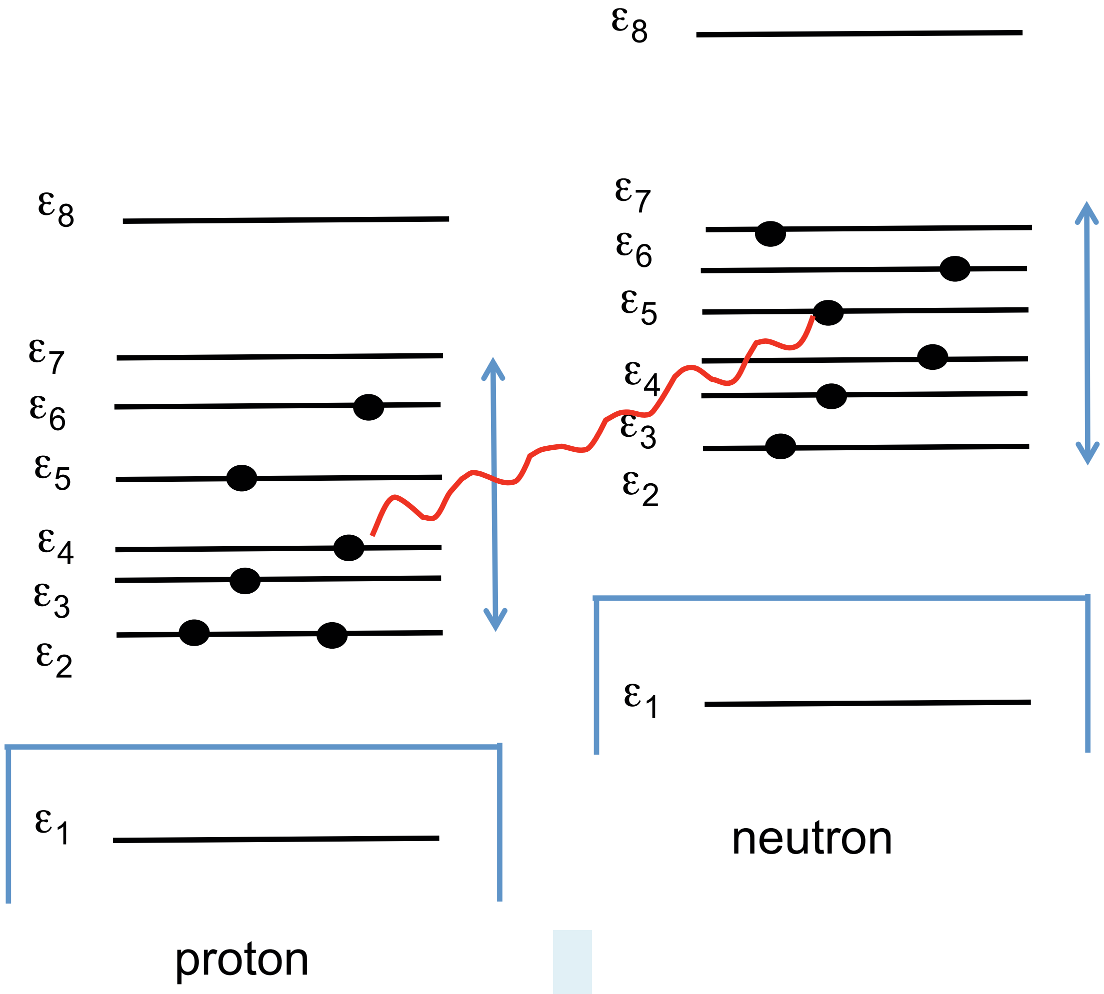
HPCI Strategic Programs for Innovative Research (SPIRE)

Field 5 "The origin of matter and the universe"

The atomic nucleus is a Quantum (Fermi) Liquid (of Landau)

described by
interplay between single-particle energies and "residual" interaction
- in a way like free particles -





For most of states, there may have been Ansatz that

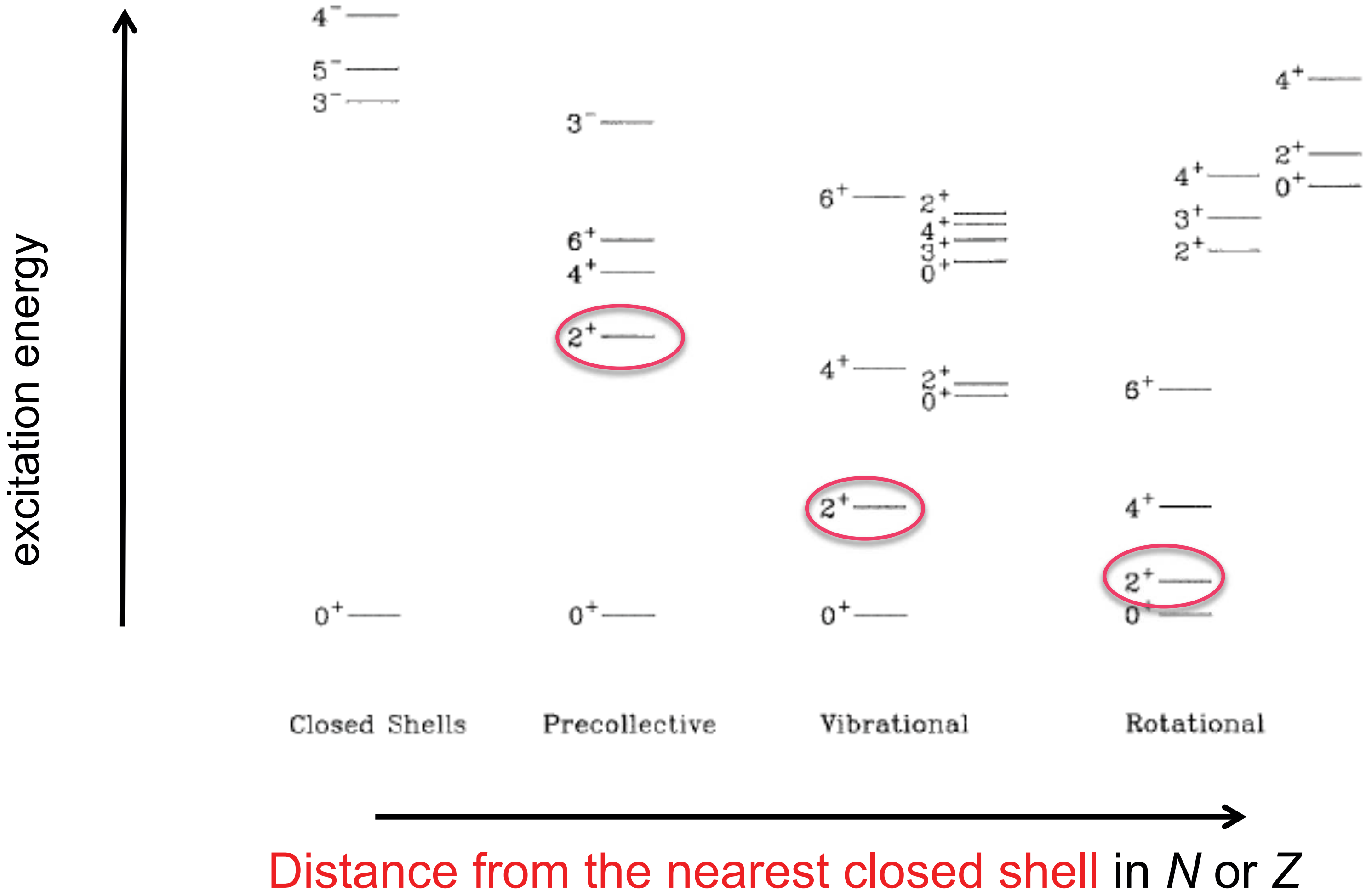
Spherical single particle energies remain basically unchanged.
-> spherical part of *Nilsson model*

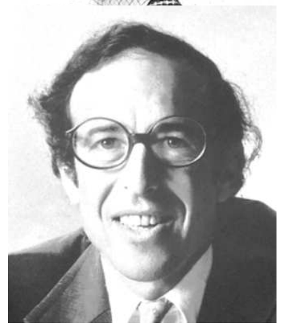
Correlations originating in nuclear forces (residual interaction) produce various features, including shape evolution and shape coexistence.

Schematic picture of shape evolution (sphere to ellipsoid)

- monotonic pattern throughout the nuclear chart –

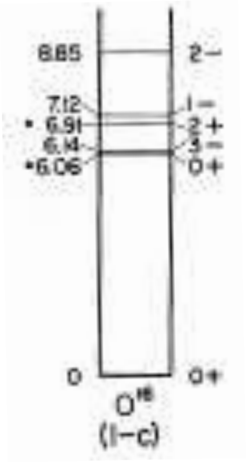
one "shape" per one nucleus in many stable nuclei



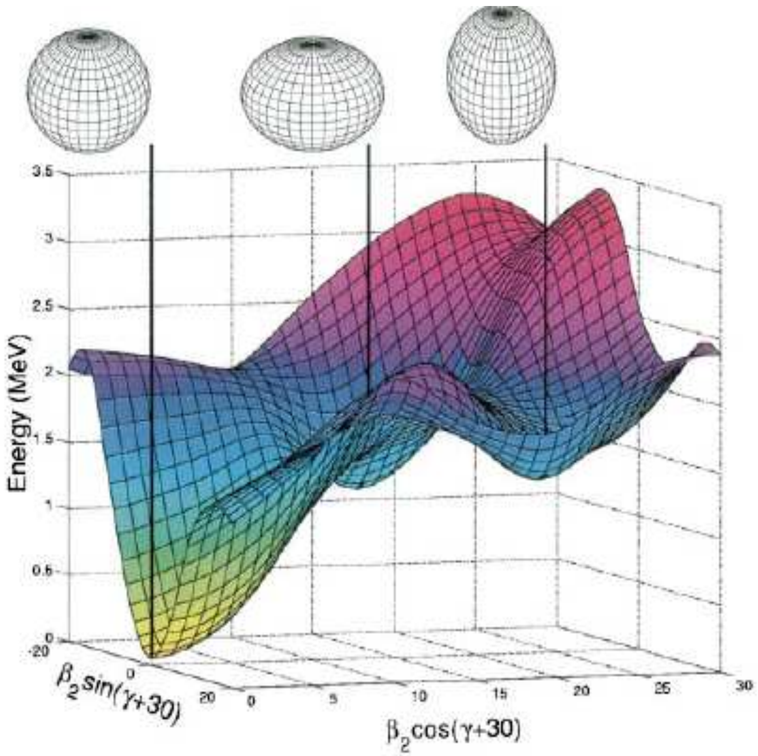


From Nuclear Structure from a Simple Perspective, R.F. Casten (2001)

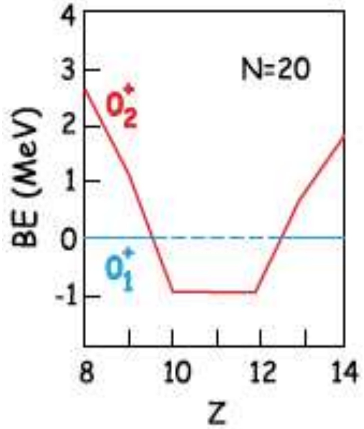
shape coexistence



^{16}O
H. Morinaga
(1956)



^{186}Pb
A.N. Andreyev *et al.*,
Nature **405**, 430 (2000)



Island of Inversion
(Z=10~12, N=20)

REVIEWS OF MODERN PHYSICS, VOLUME 83,
Shape coexistence in atomic nuclei
Kris Heyde* John L. Wood†

“Canonical” shell structure

Eigenvalues of HO potential

Magic numbers by Mayer and Jensen (1949)

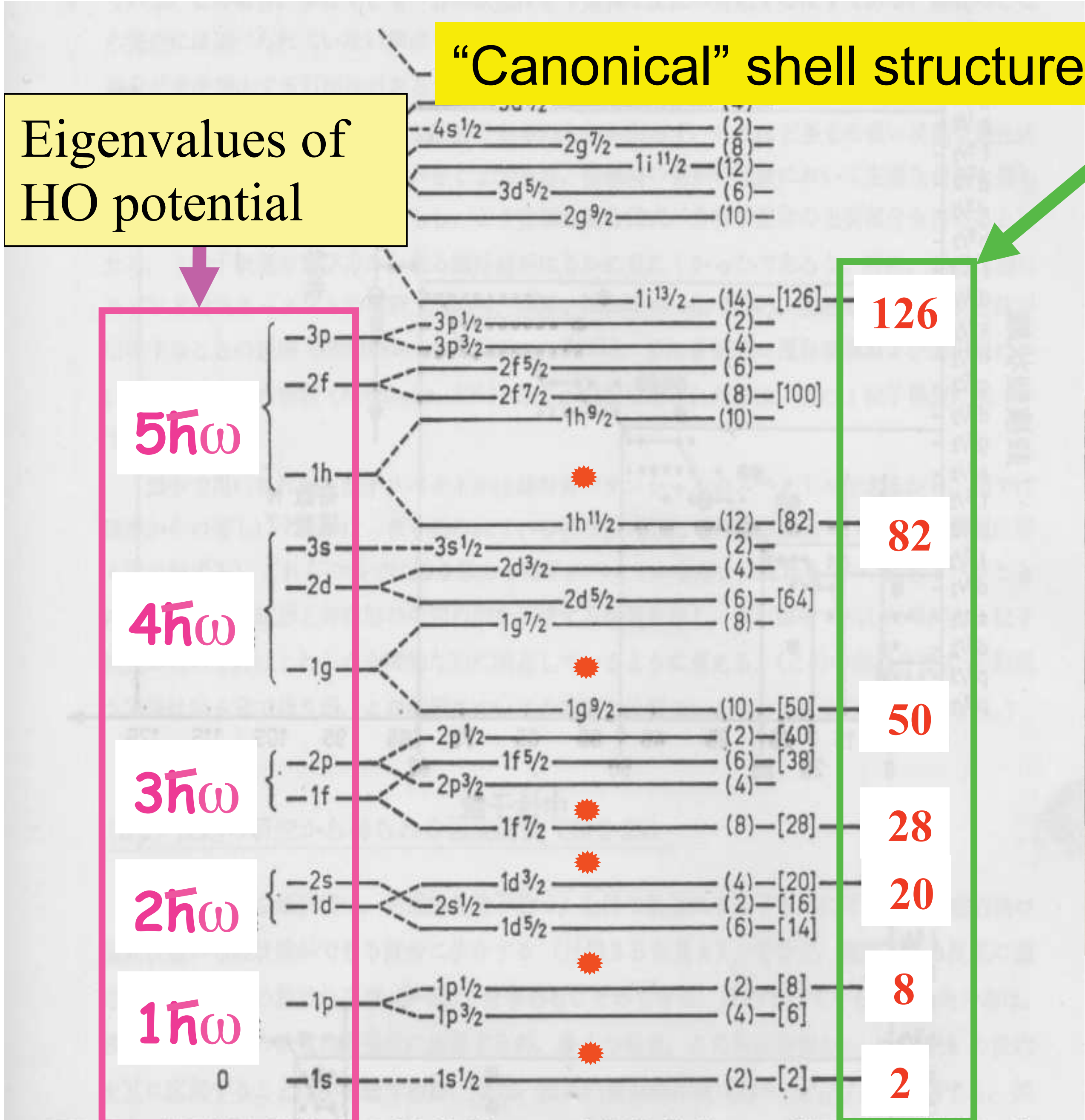


図2-23 1粒子軌道の順序. 図は M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1955 からとった.

As N or Z is changed to a large extent in exotic nuclei, the shell structure may be changed (evolved) .

- **Monopole component of the *NN* interaction**

$$v_{m;j,j'} = \sum_{k,k'} \langle jkj'k'|V|jkj'k'\rangle \Big/ \sum_{k,k'} 1,$$

→ Averaged over possible orientations

Linearity: Shift

$$\Delta\epsilon_j = v_{m;j,j'} n_{j'}$$

$n_{j'}$: # of particles in j'

For j' = 9/2, the multiplication by a factor of 10 !

Poves and Zuker made a major contribution in initiating systematic use of the monopole interaction. (Poves and Zuker, Phys. Rep. 70, 235 (1981))

What parts of nuclear forces are relevant ?

$$v_{m;j\,j'} = \Sigma_J\ (2J+1) \langle j_1, j_2, J \mid V \mid j_1, j_2, J \rangle / \Sigma_J\ (2J+1)$$

This becomes larger generally, if the overlap of radial wave functions of orbits j_1 and j_2 becomes larger.

The monopole interaction $v_{m;j\,j'}$ becomes stronger for central force with a short range.

e.g., Federman-Pittel (1977)

The overlap of the radial wave functions are larger, if

- j_1 and j_2 are spin-orbit partner, *e.g.*, $d_{3/2}$ and $d_{5/2}$
- j_1 and j_2 are both high j orbits, *e.g.*, $f_{7/2}$ and $g_{9/2}$

What else ?

Monopole effect of tensor force

TO, Suzuki *et al*. PRL 95, 232502 (2005)
TO, Phys. Scr. T152, 014007 (2013)

One-dimensional collision model

At collision point: $\Psi \propto e^{ik_1x_1}e^{ik_2x_2} + e^{ik_2x_1}e^{ik_1x_2} = 2\,e^{iKX}\cos(kx)$

$k = k_1 - k_2\,,\quad K = k_1 + k_2$

k_2 → ← k_1

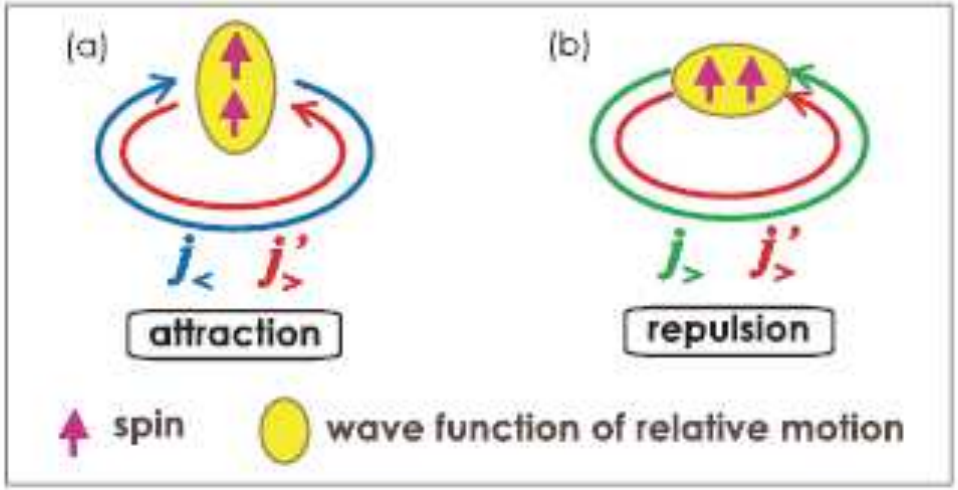
large relative momentum k

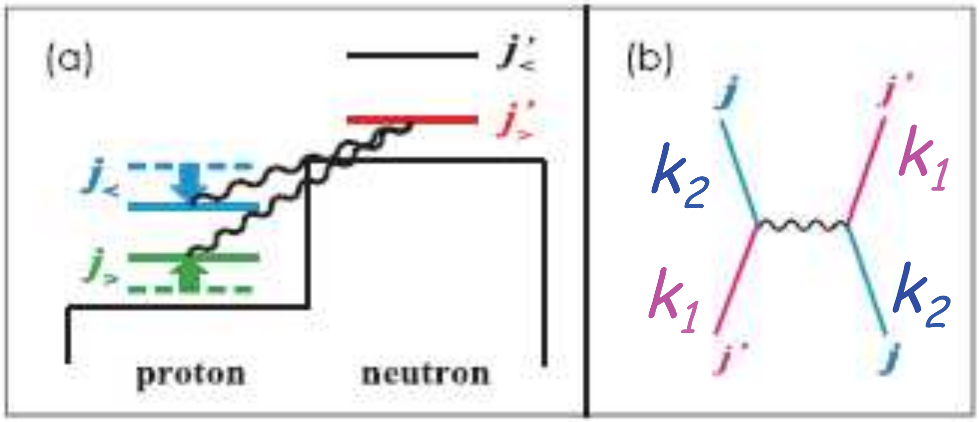
⇩

strong damping

⇩

wave function of relative coordinate





k_2 ← ← k_1

small relative momentum k

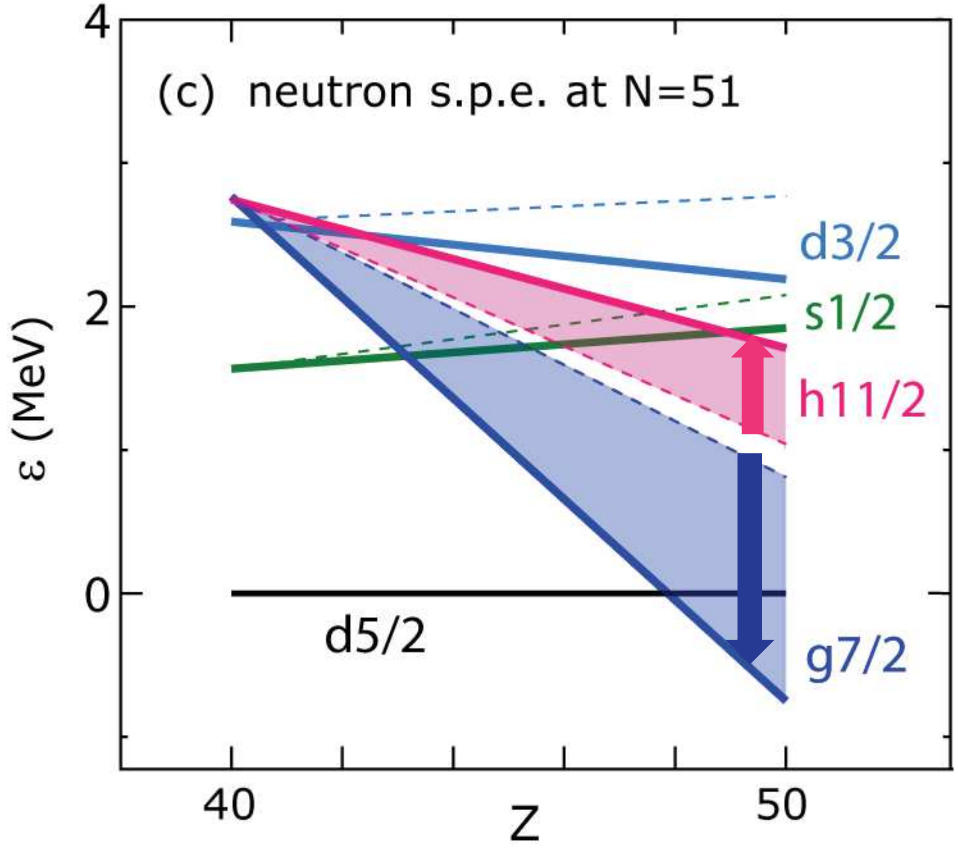
⇩

loose damping

⇩

wave function of relative coordinate

Shell evolution from ^{90}Zr to ^{100}Sn



solid line : full
(central + tensor)

dashed line : central only

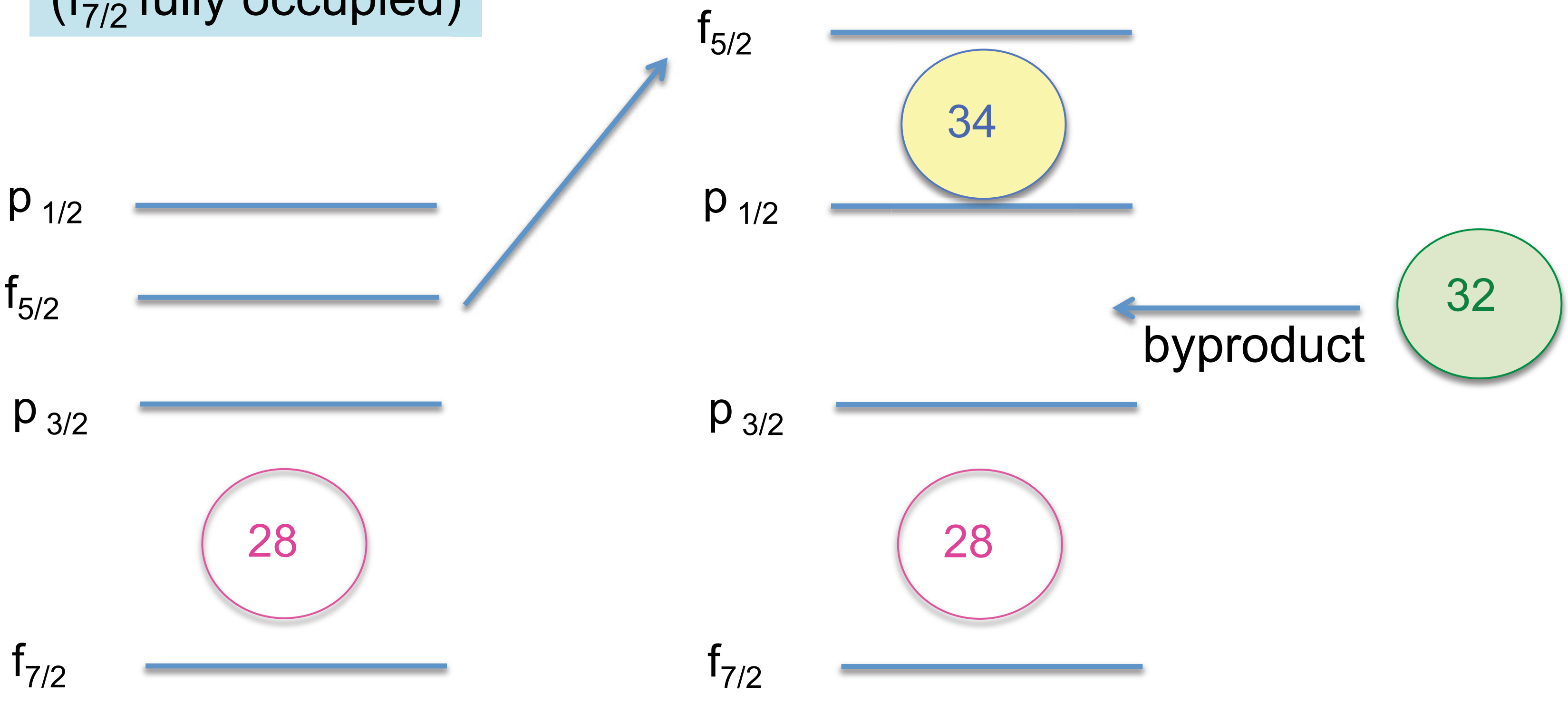
shaded area :
effect of tensor force

Exp. d5/2 and g7/2 should be close
Seweryniak et al.
Phys. Rev. Lett. 99, 022504 (2007)
Gryzywacz et al.

Appearance of N= 32 and 34 magic structures

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

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



Predicted by TO *et al*, PRL 87, 082502 (2001)

N=34 magic number
and the shell evolution due to proton-neutron interaction

neutron $f_{5/2}$ – $p_{1/2}$ spacing increases by ~0.5 MeV per one-proton removal from $f_{7/2}$, where tensor and central forces works coherently and almost equally.

note : $f_{5/2} = j_<$ $f_{7/2} = j_>$

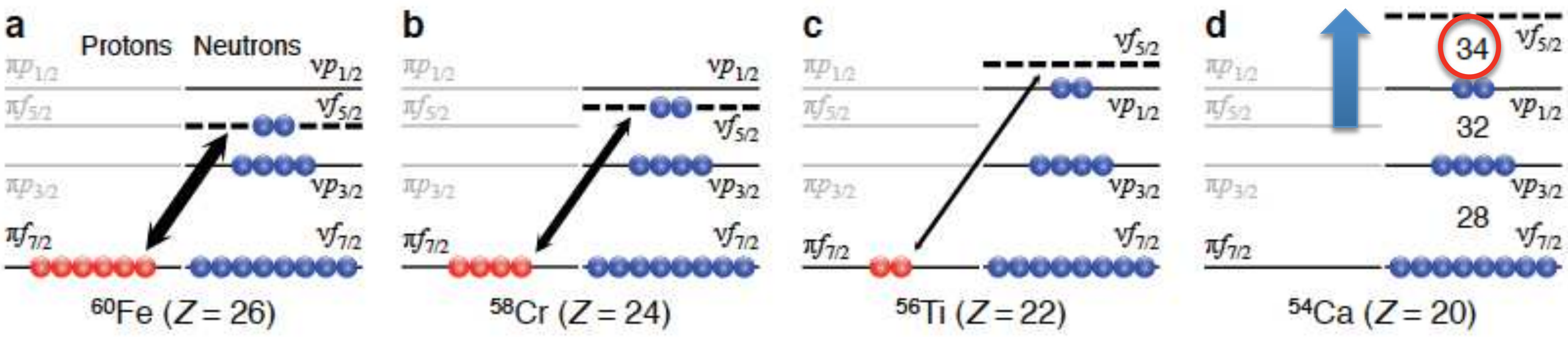
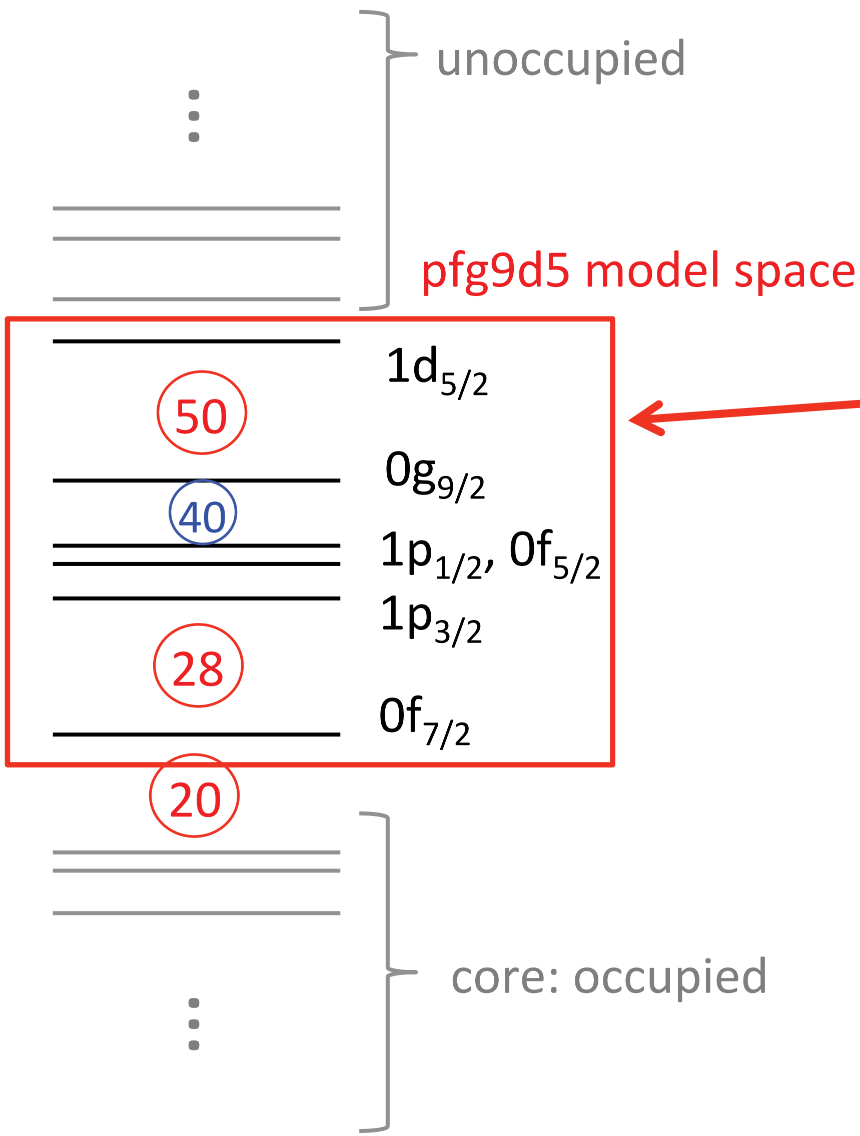
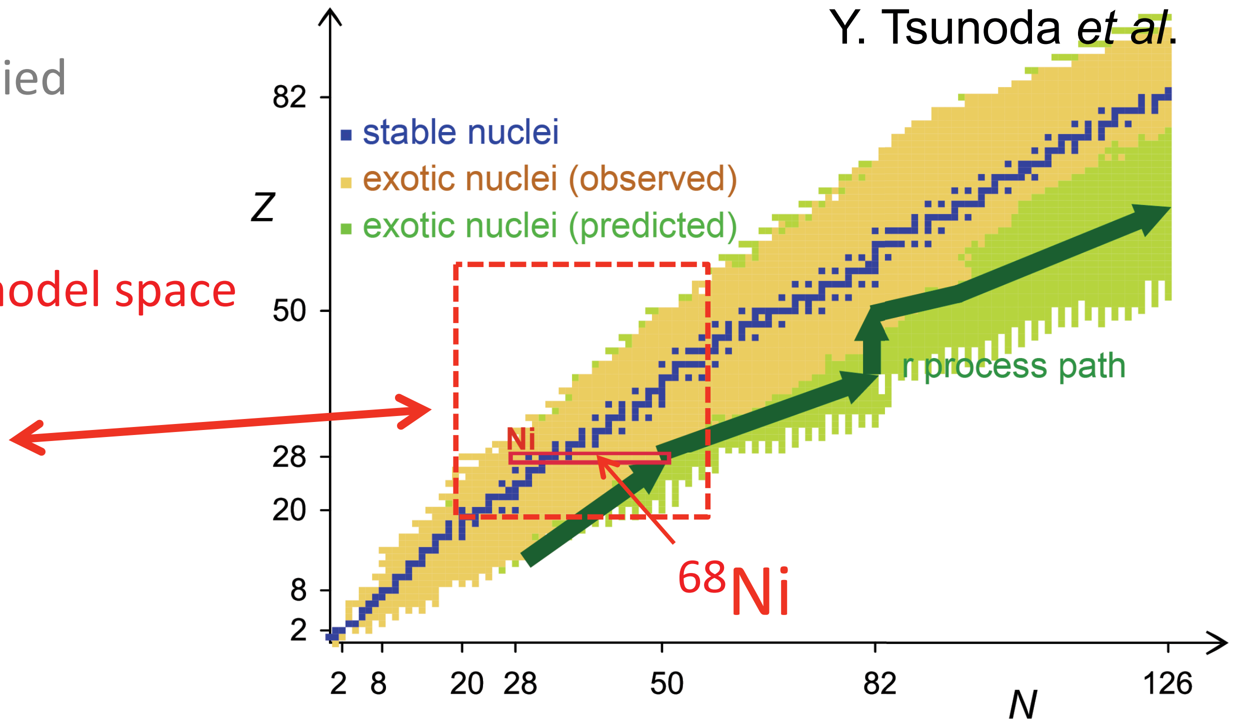


FIG. 1: **Schematic illustration highlighting the attractive interaction between the proton $\pi f_{7/2}$ and neutron $\nu f_{5/2}$ single particle orbitals for $N = 34$ isotones. a–c,** As protons are removed from the $\pi f_{7/2}$ orbital (from **a**, ^{60}Fe, through **b**, ^{58}Cr to **c**, ^{56}Ti), the strength of the π-ν interaction reduces, as represented by the decreasing width of the diagonal arrows, causing the $\nu f_{5/2}$ orbital to shift up in energy relative to the $\nu p_{3/2}$-$\nu p_{1/2}$ spin-orbit partners. Consequently, a significant shell closure presents itself at $N = 32$ in isotopes far from stability. **d,** The possibility of an additional shell closure at $N = 34$ for ^{54}Ca is presented. The $\nu f_{5/2}$ SPO is indicated as a bold-dashed line to help guide the eye.

Steppenbeck *et al.* Nature, 502, 207 (2013)

Monte Carlo Shell Model (MCSM) calculation on Ni isotopes



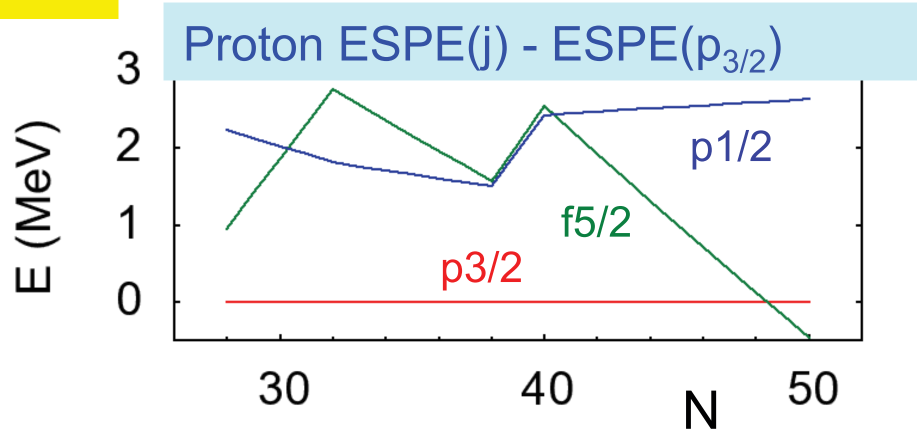


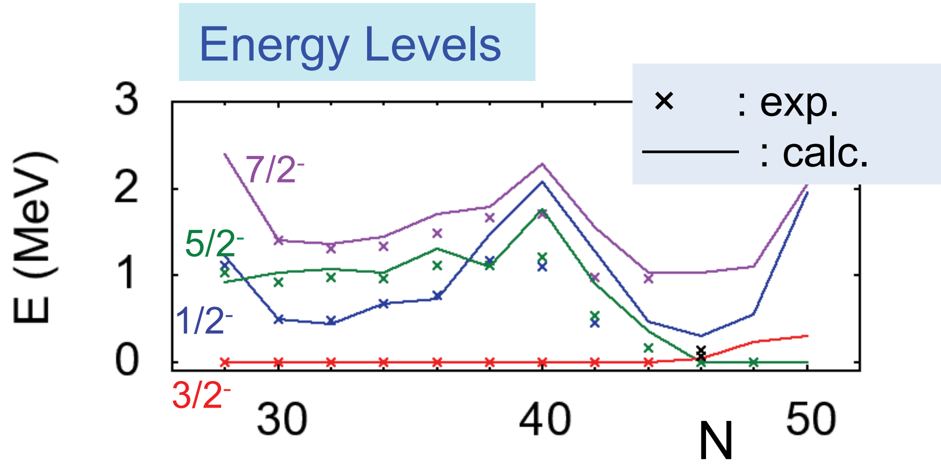
This model space is wide enough to discuss how magic numbers 28, 50 and semi-magic number 40 are visible or smeared out.

Interaction:
A3DA interaction is used with minor corrections

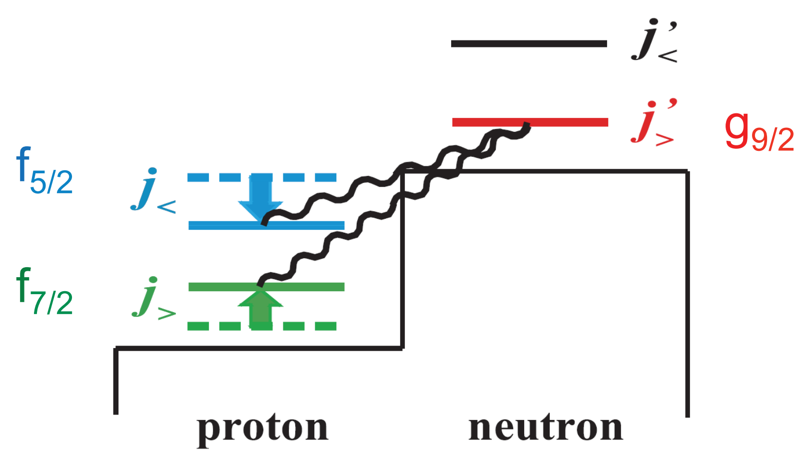
Cu isotopes

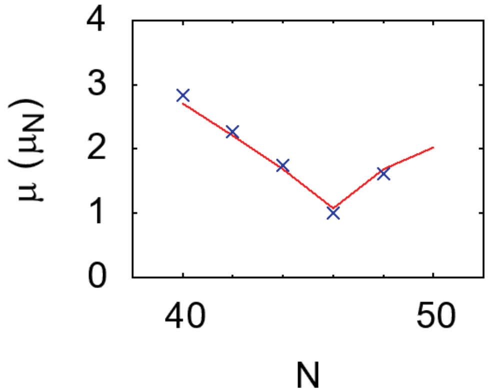
- proton $p_{3/2}$-$f_{5/2}$ level crossing from N = 40 to N = 50 (type I shell evolution)





Monopole effect of tensor force



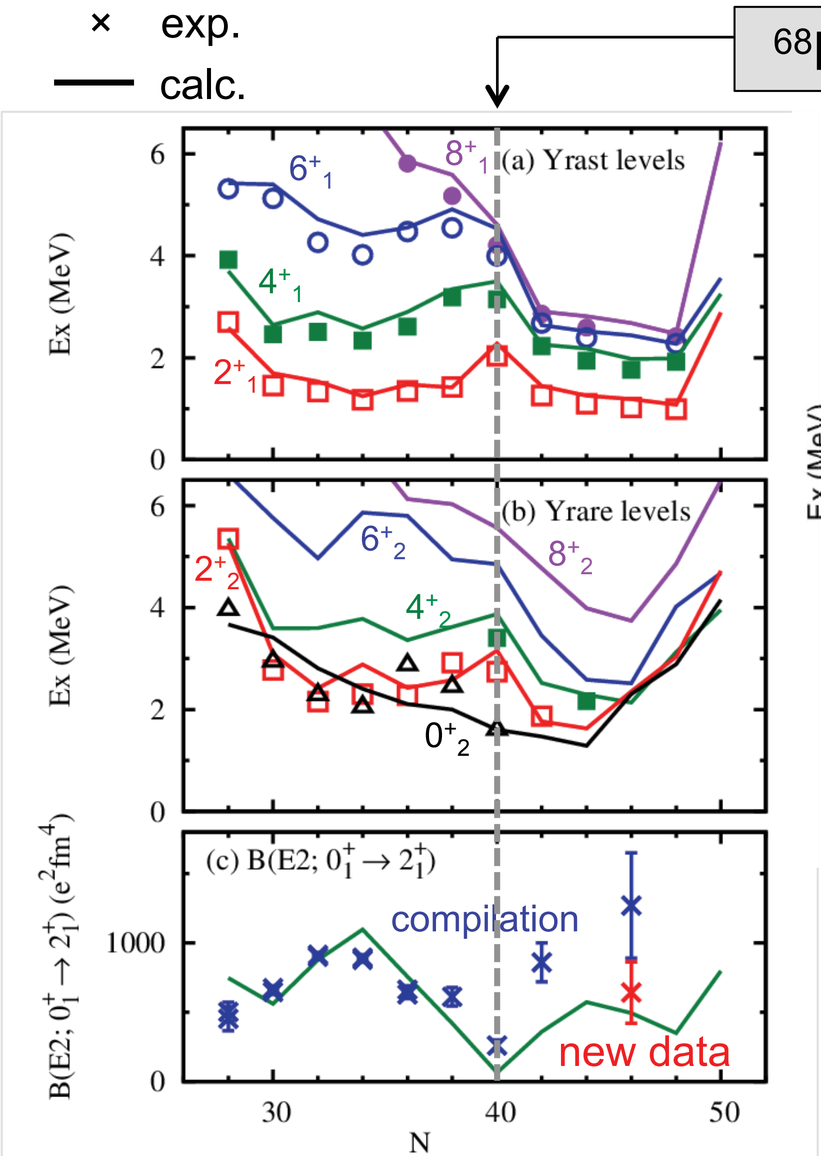


Magnetic moment of ground state

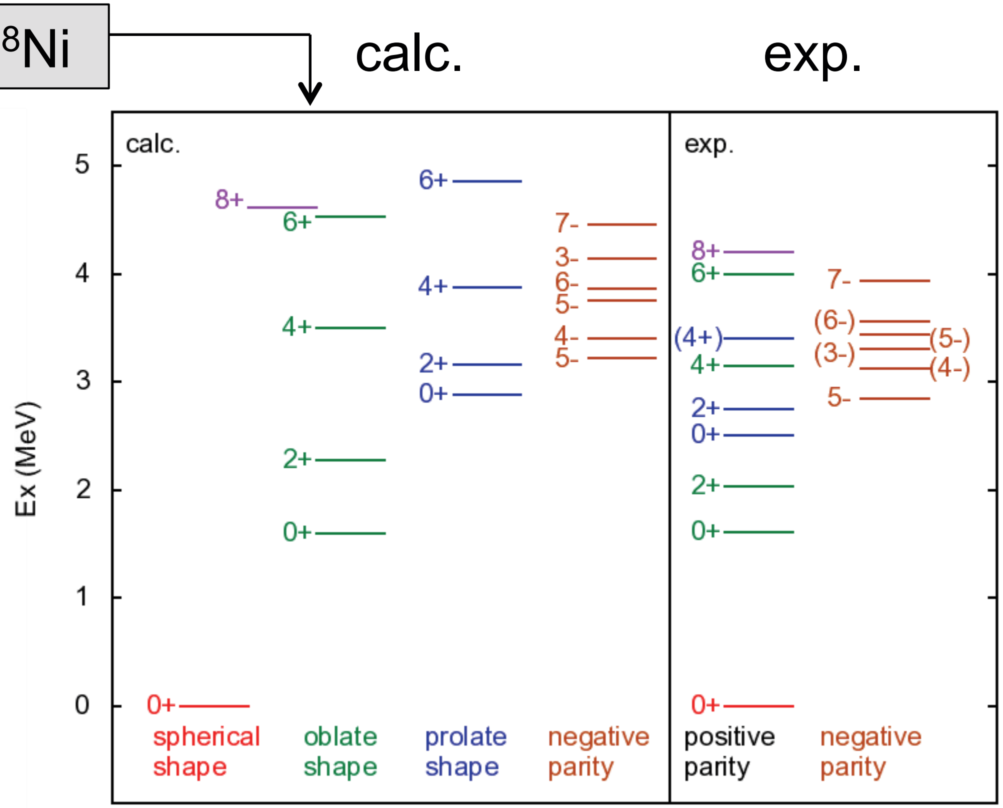
exp. :Flanagan et al. (2009)

Energy levels and B(E2) values of Ni isotopes

Description by the same Hamiltonian



Shape coexistence in ^{68}Ni



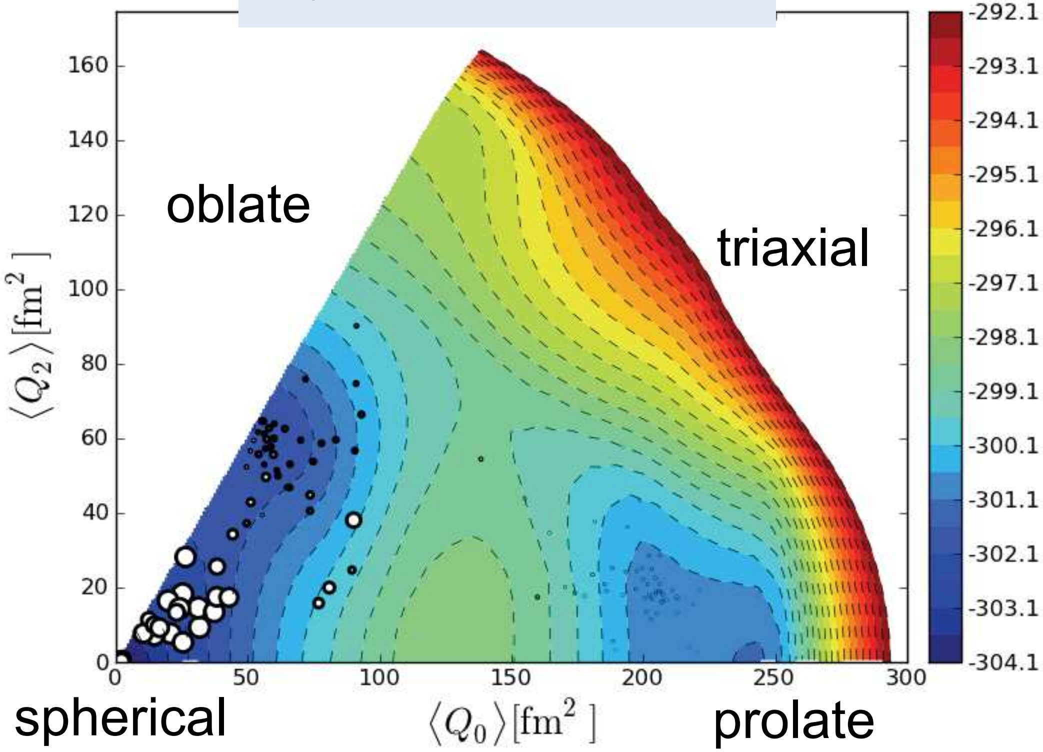
Y. Tsunoda, TO, Shimizu, Honma and Utsuno, PRC 89, 031301 (R) (2014)

MCSM basis vectors on Potential Energy Surface

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

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



Called ***T-plot*** in reference to

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

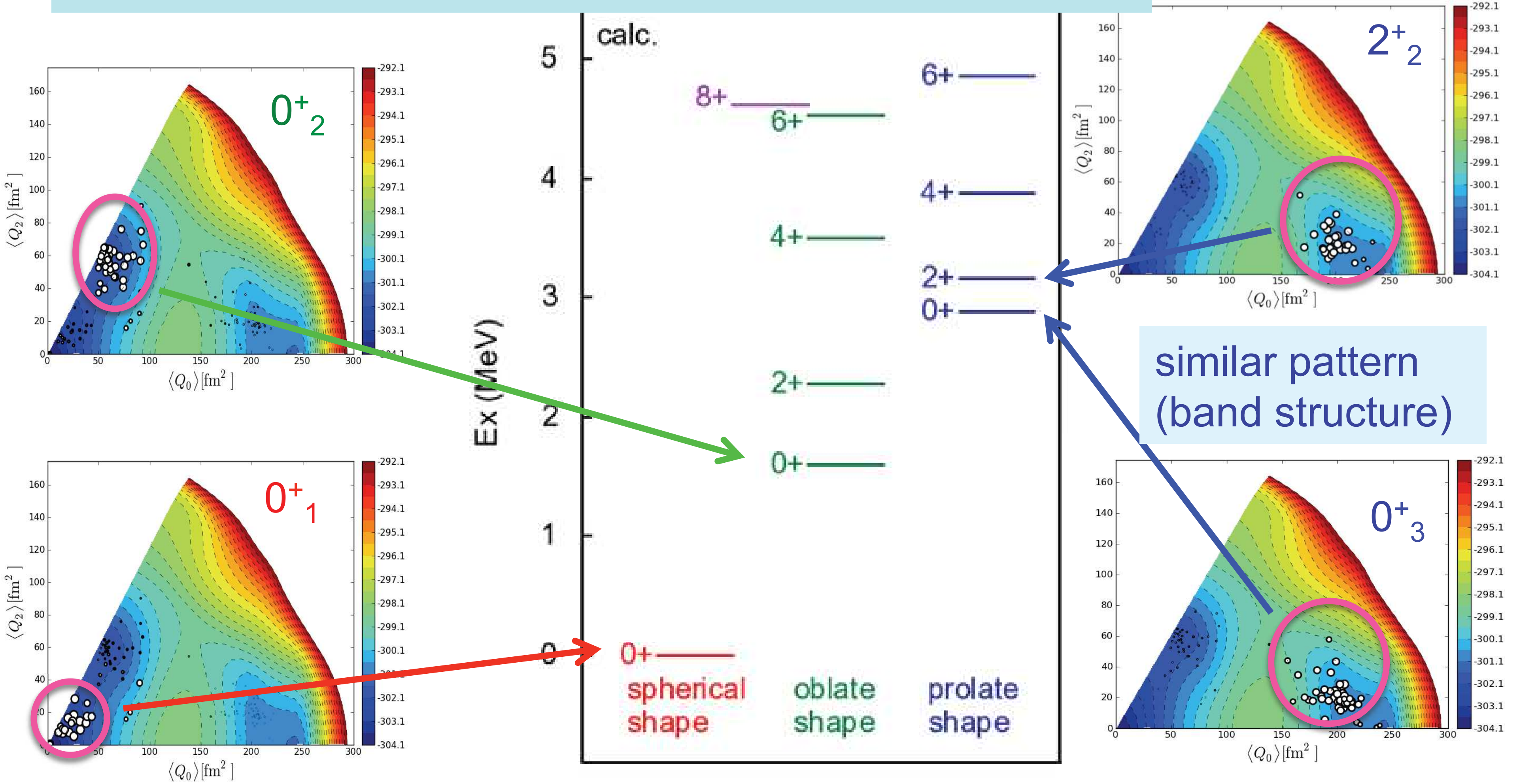
General properties of T-plot :

Certain number of large circles in a small region of PES

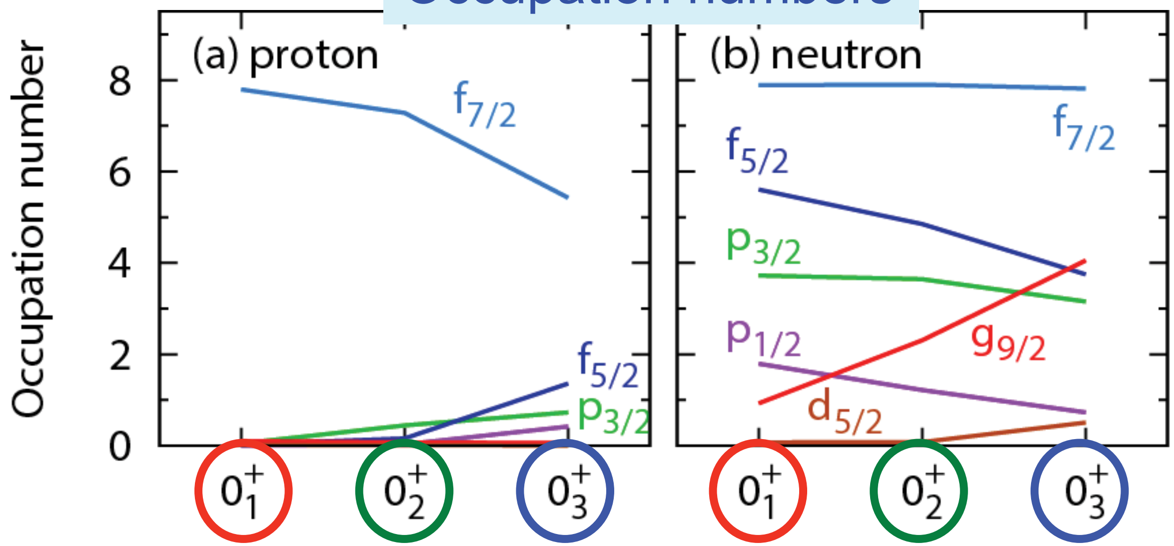
⇔ pairing correlations

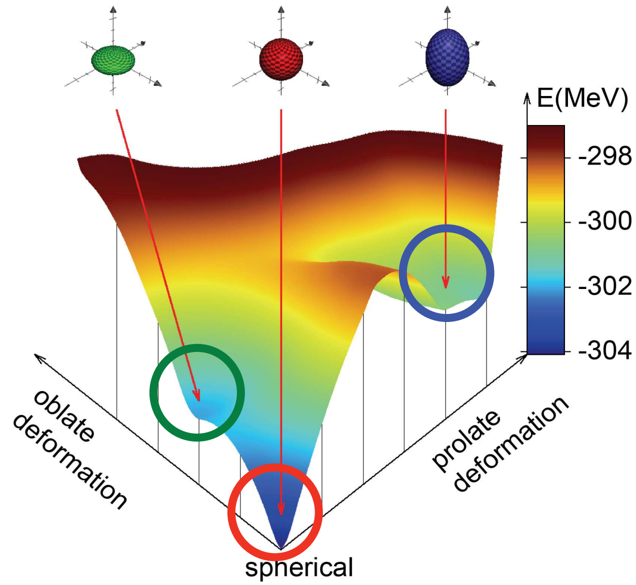
Spreading beyond this can be due to shape fluctuation

Example : shape assignment to various 0^+ states of ^{68}Ni

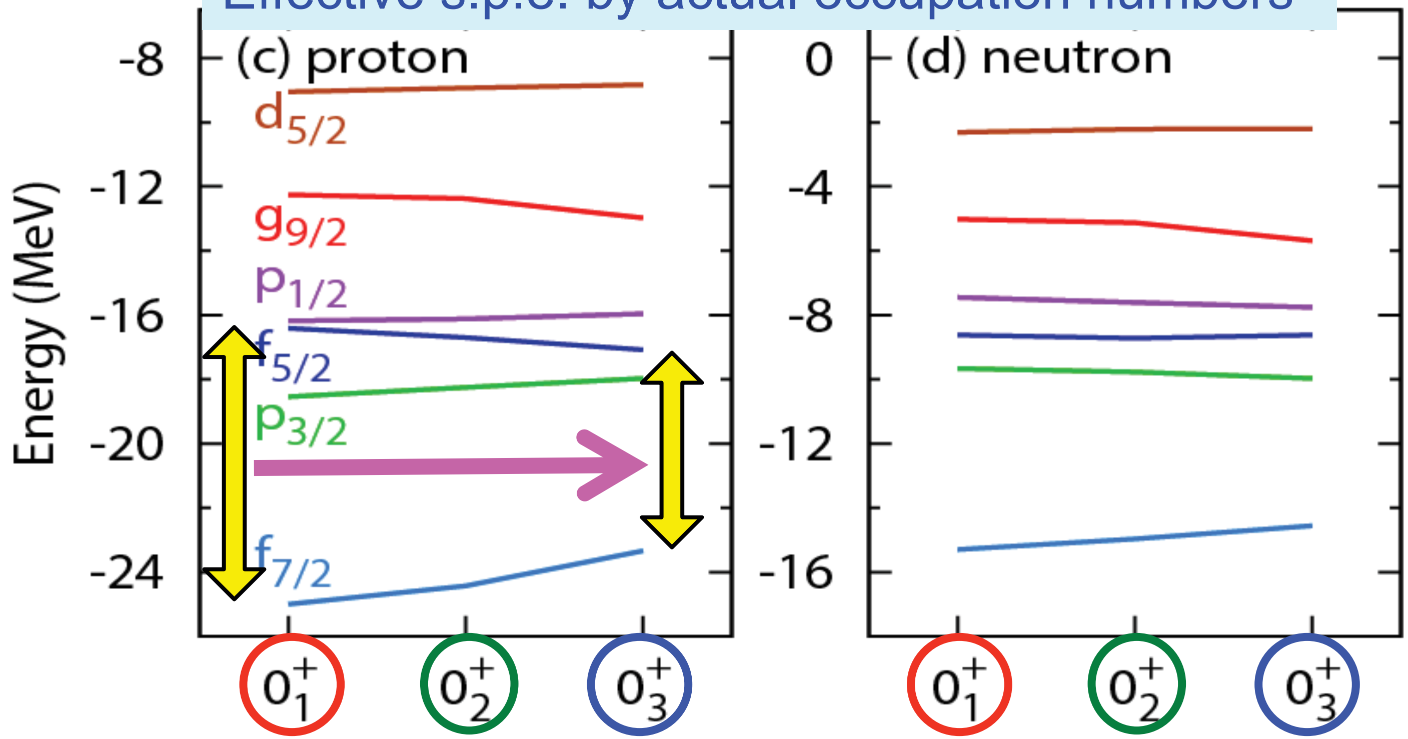


Occupation numbers





Effective s.p.e. by actual occupation numbers

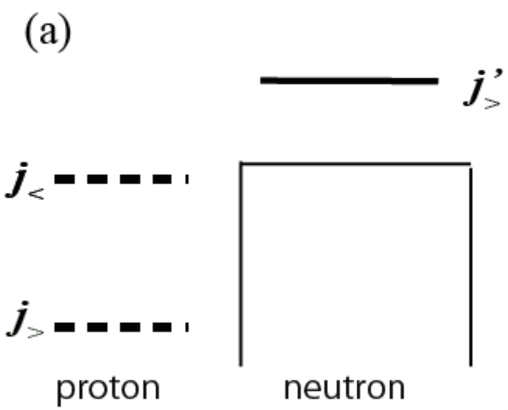


0^+ state

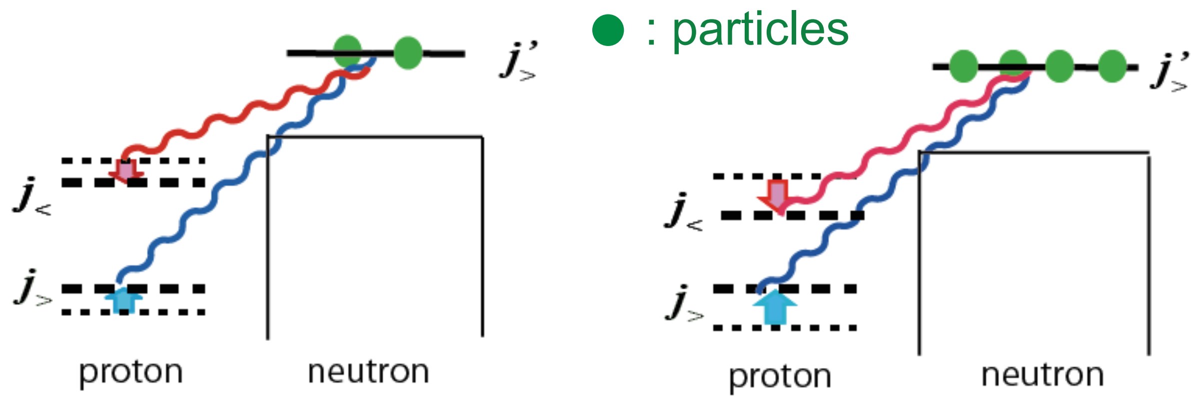
1st	modest correlations	
2nd	2p-2h	
3rd		6p-6h

Underlying mechanism of the appearance of low-lying deformed states : Type II Shell Evolution

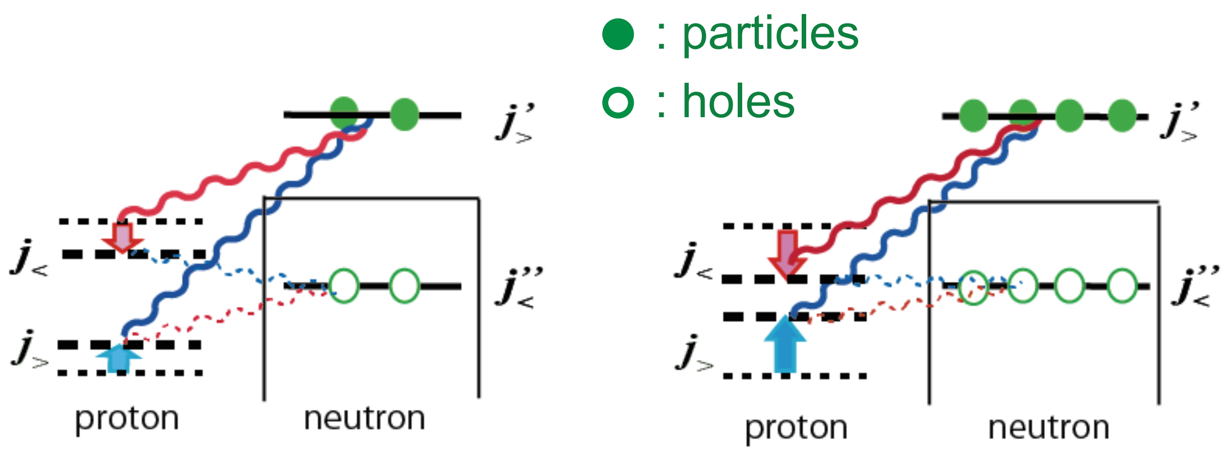
Monopole effects on the shell structure from the tensor interaction



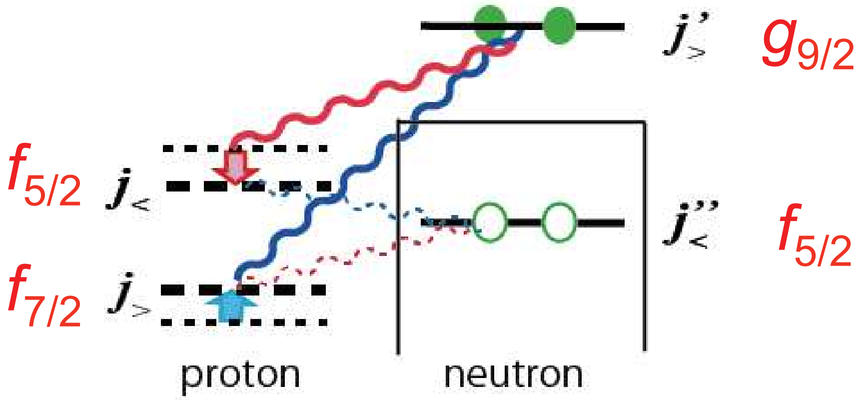
Type I Shell Evolution : different isotopes



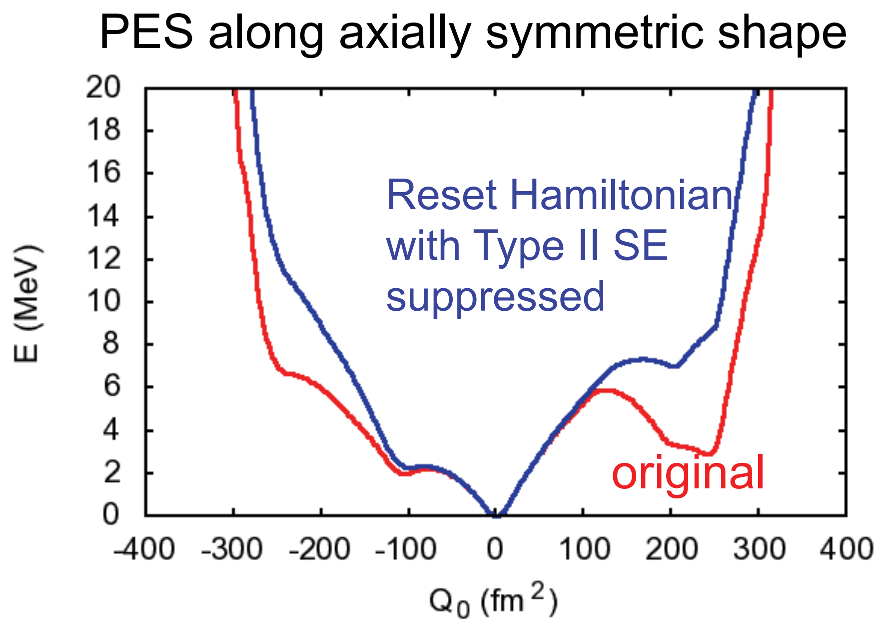
Type II Shell Evolution : within the same nucleus



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



Spin-orbit splitting works against quadrupole deformation (*cf. Elliott's SU(3)*).



weakening of spin-orbit splitting

Type II shell evolution

stronger deformation of protons
→ more neutron p-h excitation

Type II shell evolution is suppressed by resetting monopole interactions as

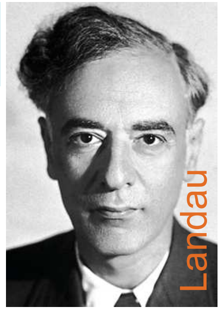
$\pi f_{7/2} - \nu g_{9/2} = \pi f_{5/2} - \nu g_{9/2}$

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

The local minima become much less pronounced.

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

Nucleus is a quantum liquid



Dual quantum liquids in the same nucleus

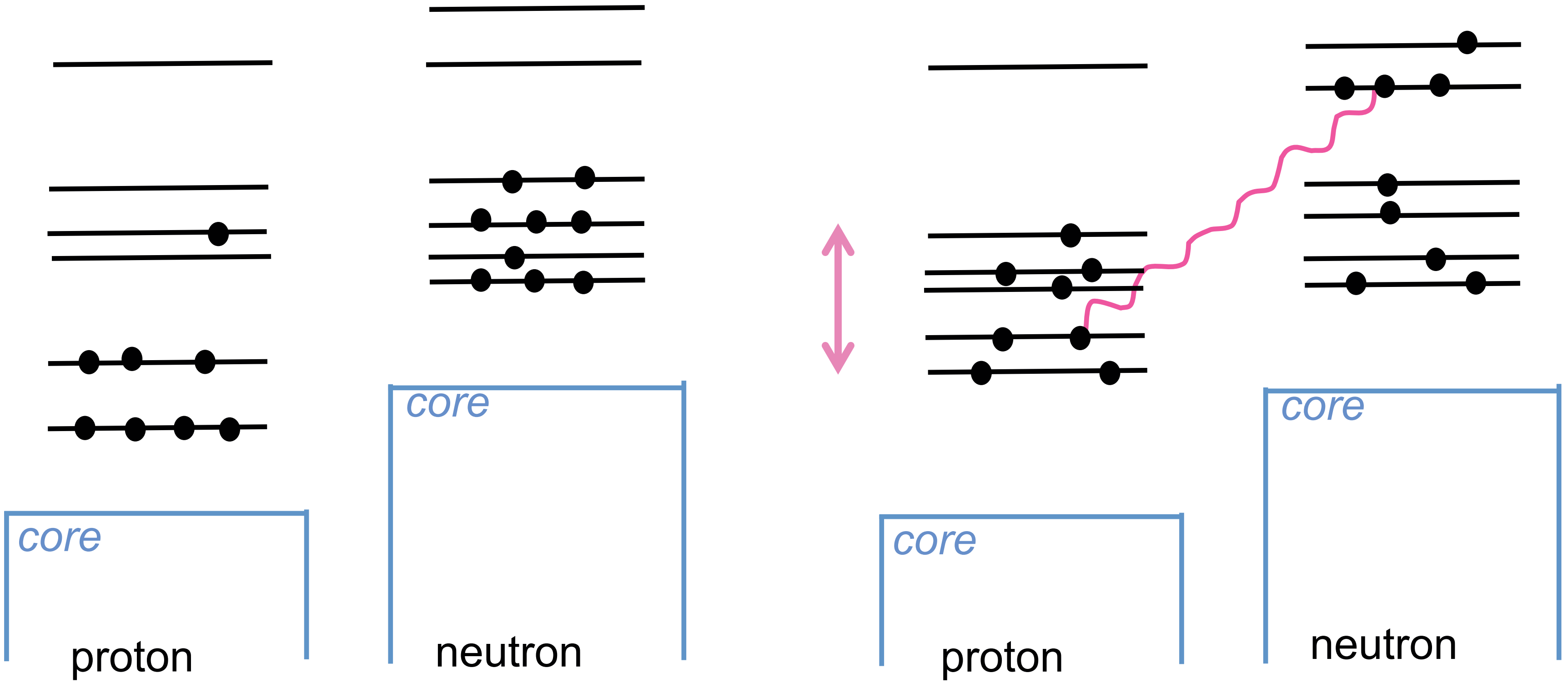
Certain configurations produce different shell structures owing to (i) tensor force and (ii) proton-neutron compositions

Liquid 1 (~constant spherical SPE)

relevant to normal states in general

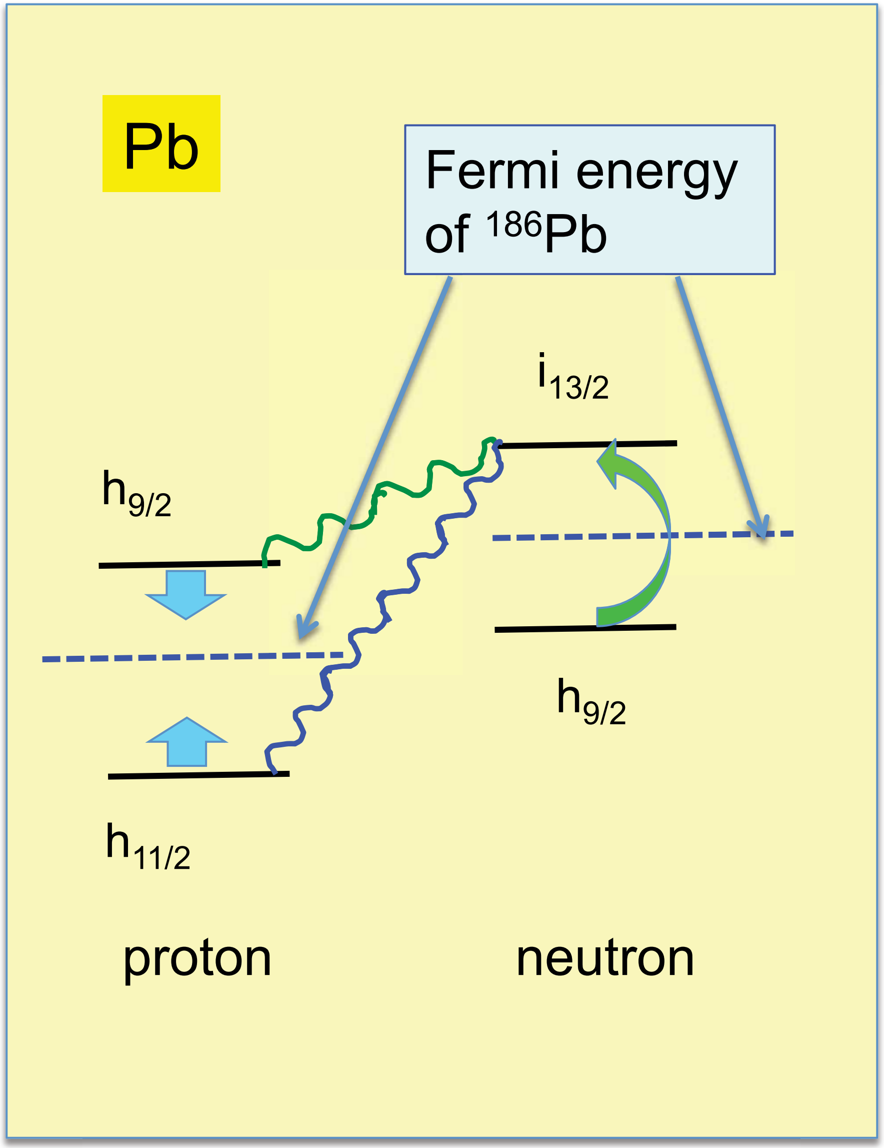
Liquid 2 (varying spherical SPE)

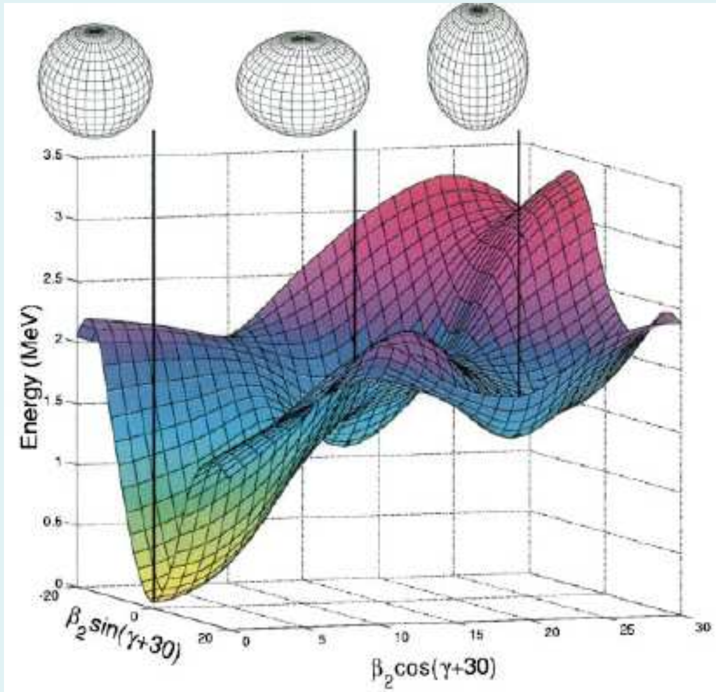
relevant to specific intruder states



Note : Despite almost the same density, different single-particle energies appear

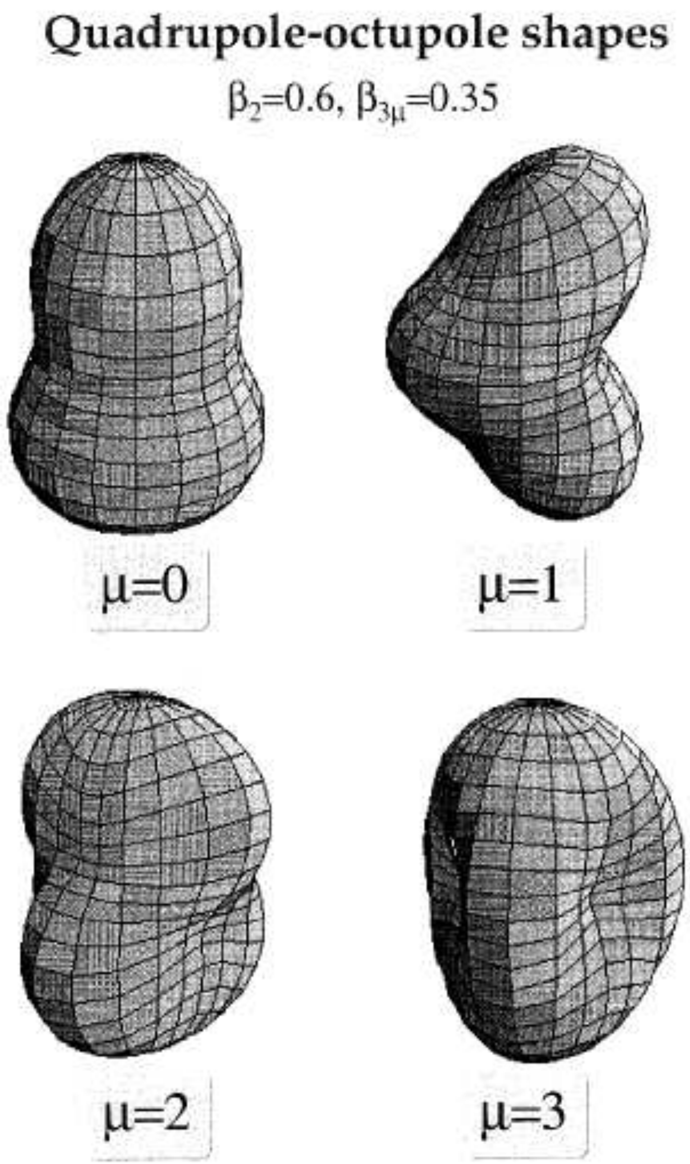
Other cases ….. just an example





^{186}**Pb** Andreyev *et al.*, Nature **405**, 430 (2000)

Reflection asymmetric shapes



Intrinsic reflection asymmetry in atomic nuclei

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Liverpool L69 3BX, United Kingdom

W. Nazarewicz

Reviews of Modern Physics, Vol. 68, No. 2, April 1996

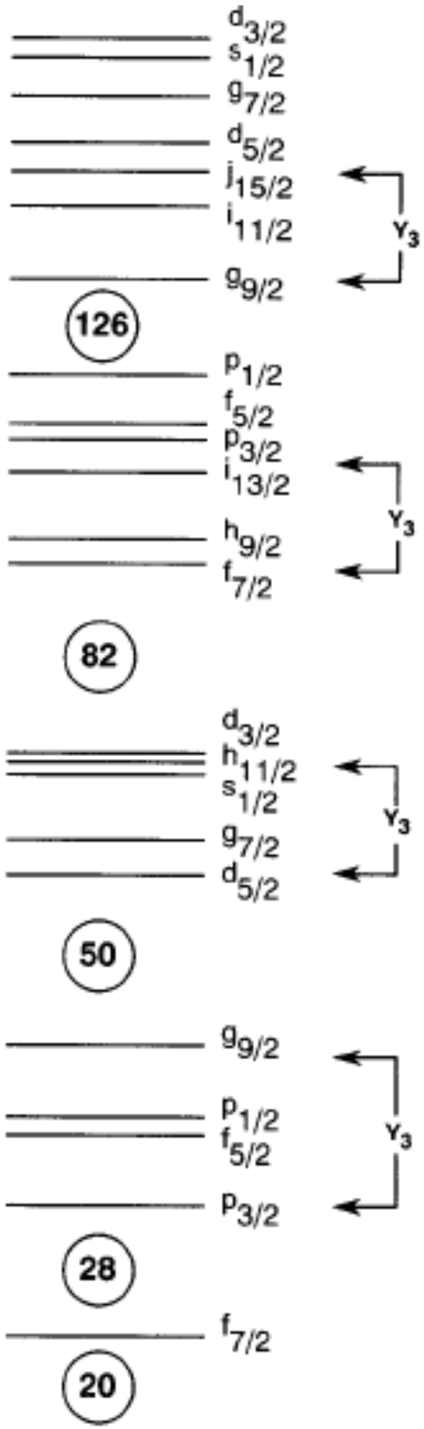
Zr isotopes

Core : ^{68}Ni

Proton orbits : $f_{5/2}$, p, gds

Neutron orbits : gds, $h_{11/2}$, $f_{7/2}$, $p_{3/2}$

Effective interaction :
JUN45 + jSNBG3 + VMU

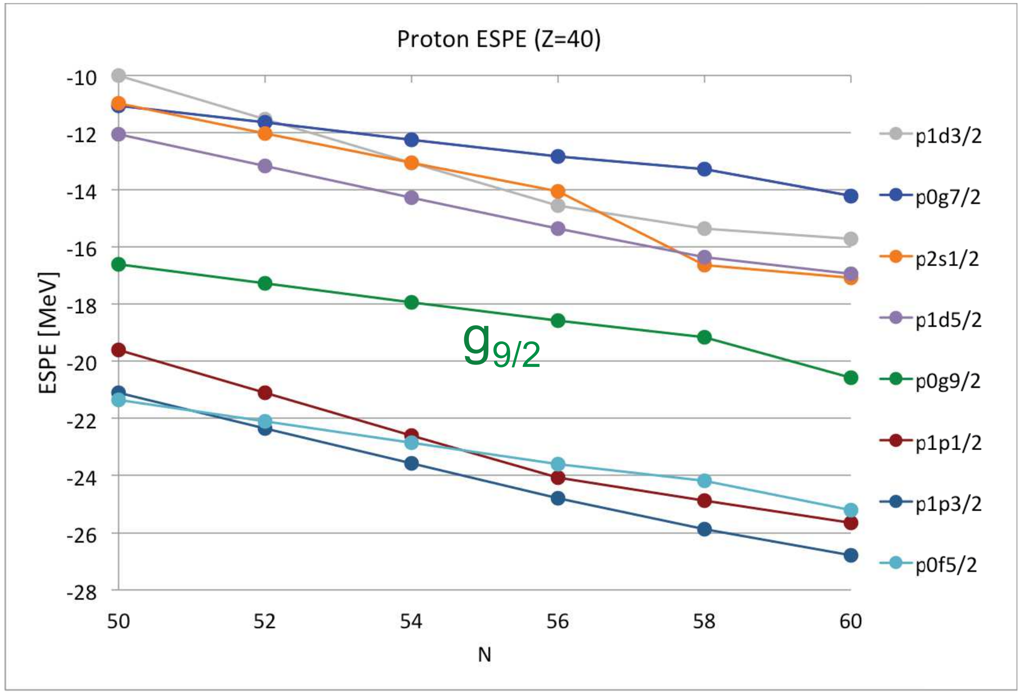


neutrons

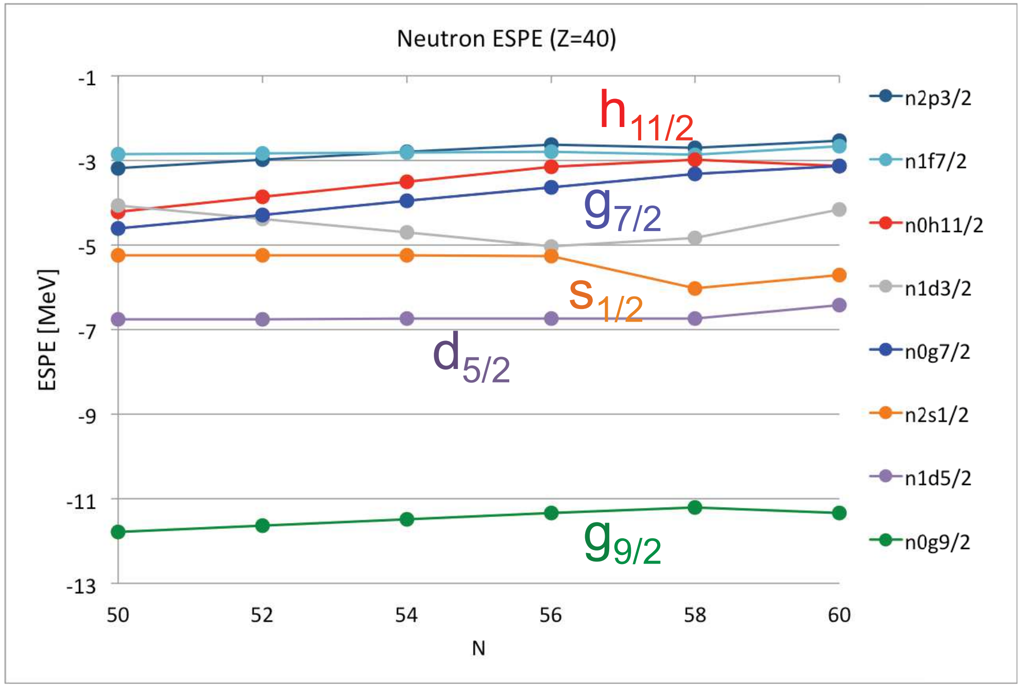
protons

FIG. 4. Nuclear spherical single-particle levels. The most important octupole couplings are indicated.

Effective single-particle energies
in filling scheme

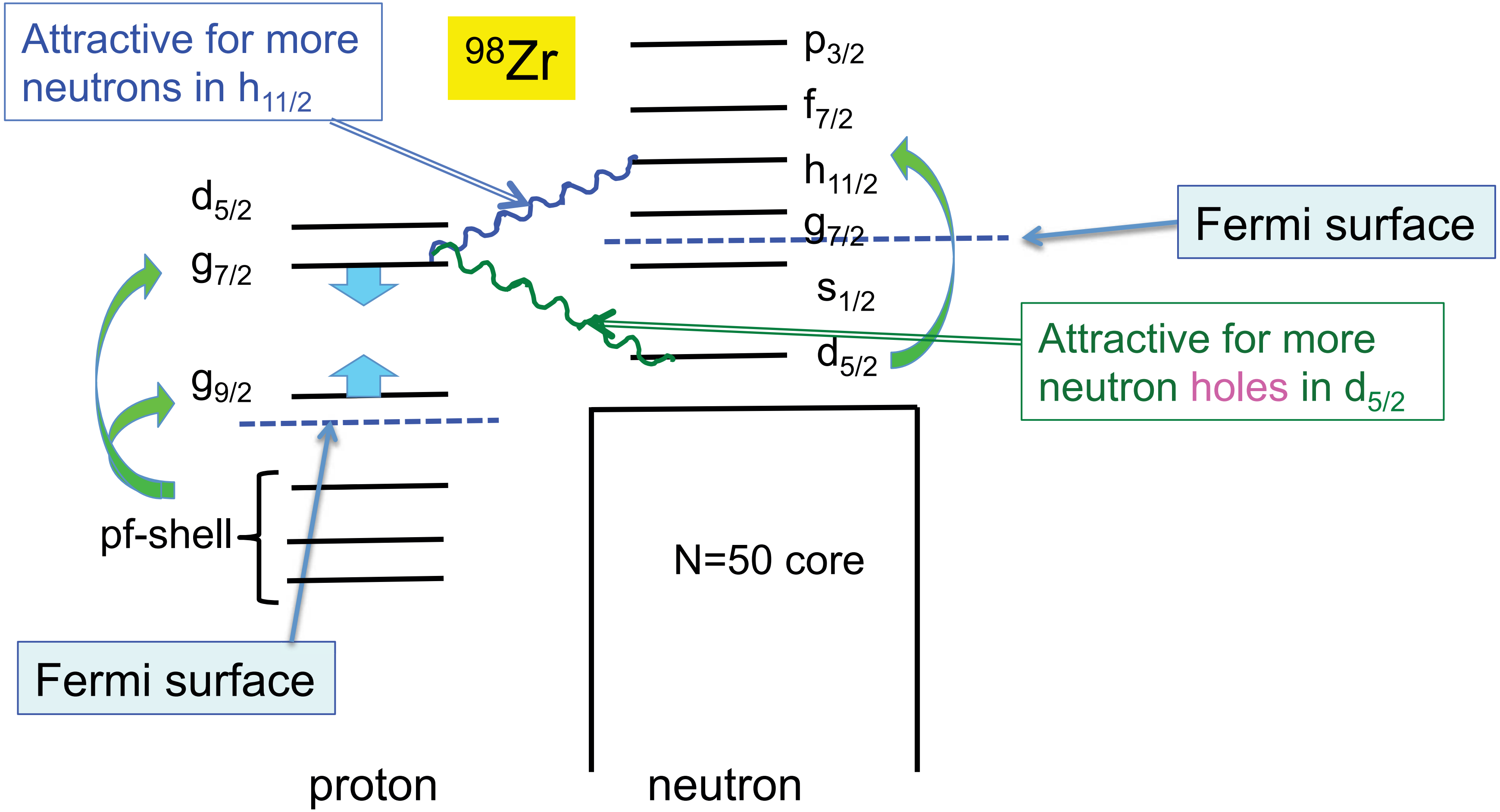


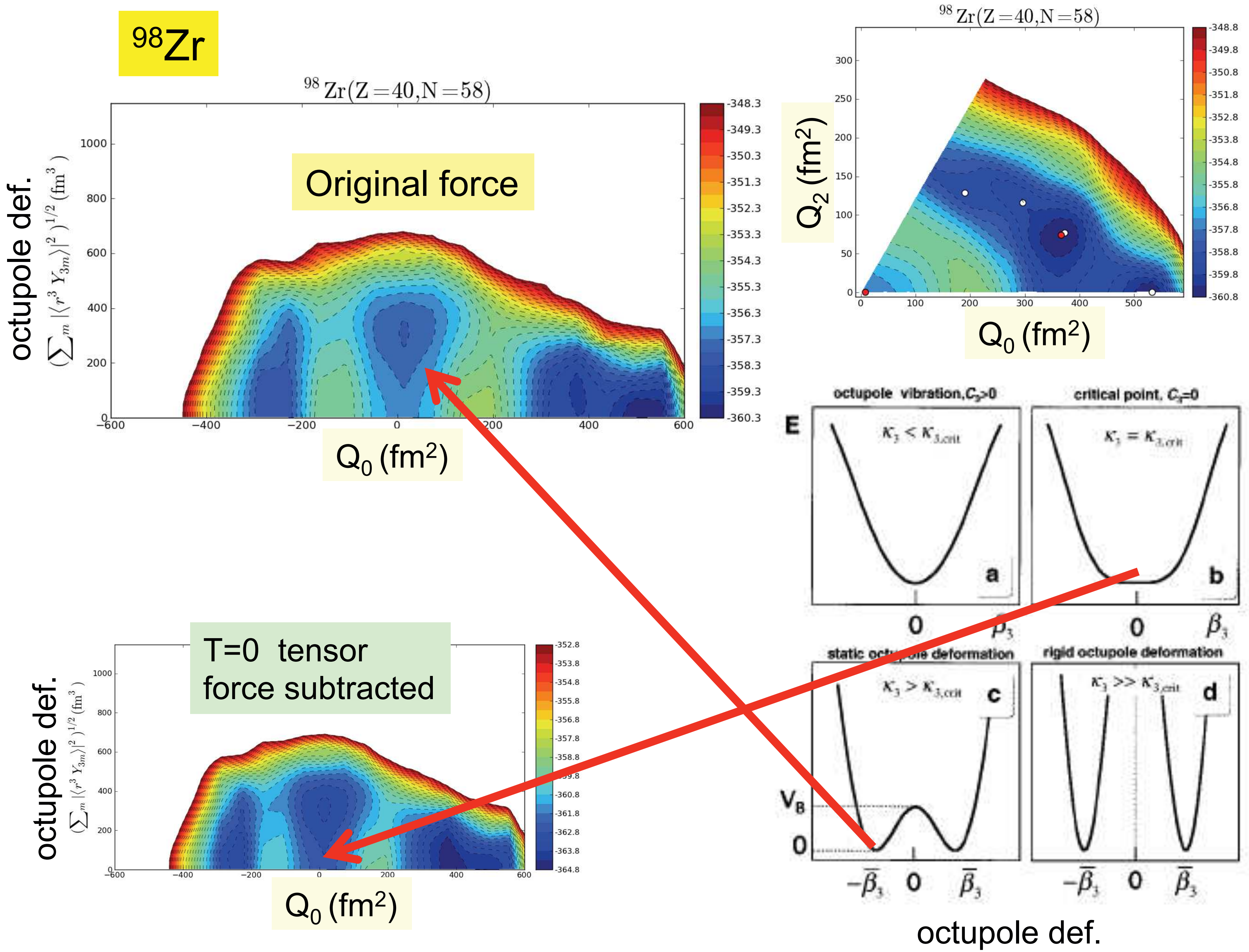
protons



neutrons

Type II shell evolution produces substantial effects with massive particle-hole excitations between two shells of both parities.
In certain cases, this enhances and/or is enhanced by octupole deformation, soft or static.





98Zr
98 Zr(Z=40,N=58)
Original force
octupole def.
Q0 (fm2)
T=0 tensor
force subtracted
Q2 (fm2)
octupole vibration, C3>0
critical point, C3=0
static octupole deformation
rigid octupole deformation
E
VB
a
b
c
d
octupole def.

Summary

Type I Shell Evolution, driven by central and tensor forces, can be found in many parts of the nuclear chart.

The shell evolution can be extended to Type II, resulting in
Dual Quantum Liquid : shell structure can be (i) stable or (ii) dynamical

- spin-orbit splitting reduction due to the nuclear force
- proton-neutron contents of quantum liquid

This effect produces (low local minimum) and stabilize (high barrier) shape coexistence in various cases through a non-linear mechanism.

Correlations towards reflection asymmetric shapes appear in certain cases, enhancing and being enhanced by Type II shell evolution.

Collaborators

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- Michio Honma (Aizu)