9thInt Symp on
High-Resolution Spectroscopy & Tensor Interaction
(HST15)
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Ten years of the shell evolution driven by the tensor forces

- from magic numbers to dual quantum liquid picture -

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HPCI project field 5
"The origin of matter and the universe"

Outline

1. Shell evolution and tensor force

2. Shell evolution and QCD

3. Dual quantum liquid picture

4. Summary and perspectives

Eigenvalues of HO potential

Magic numbers by Mayer and Jensen (1949)

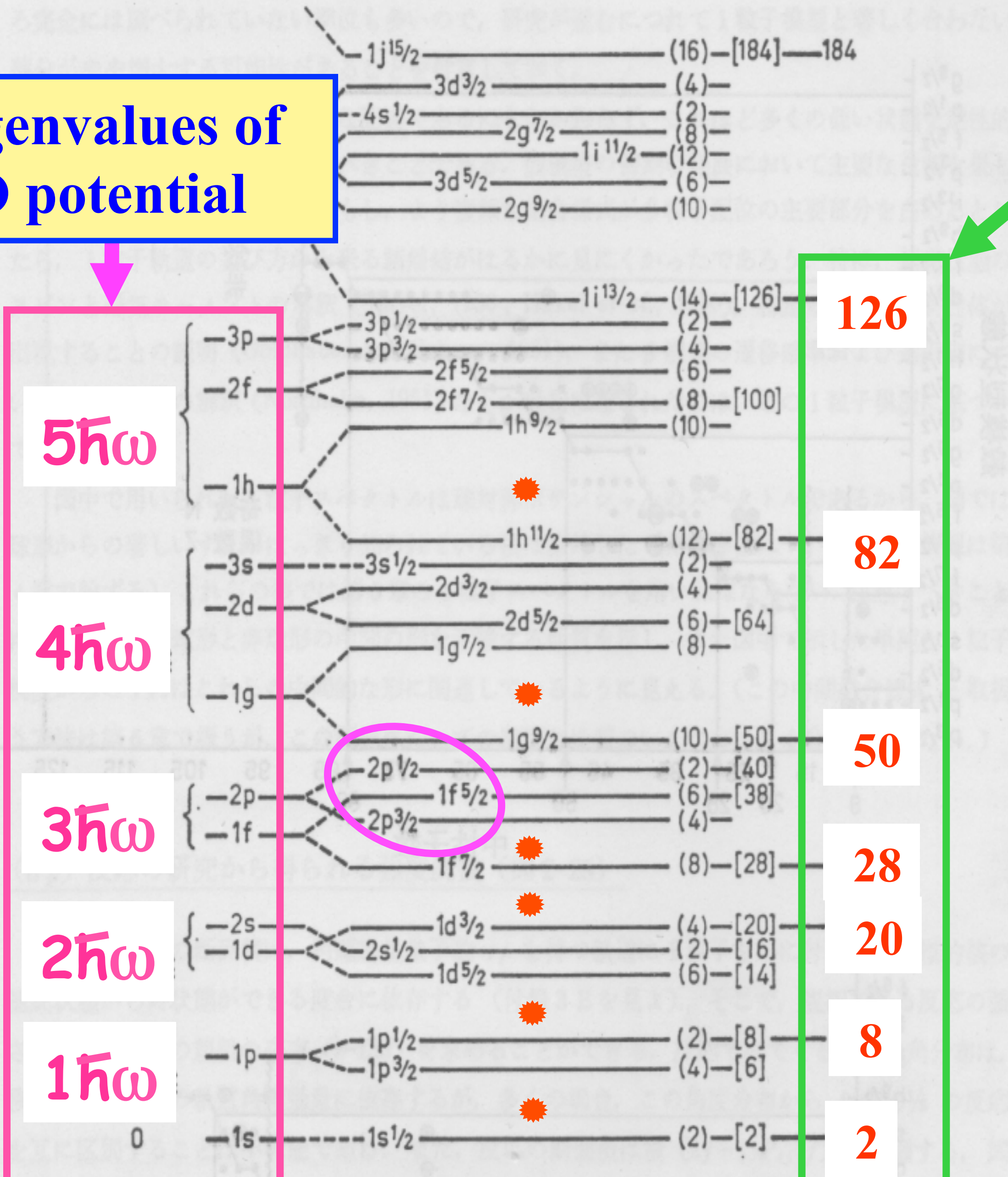
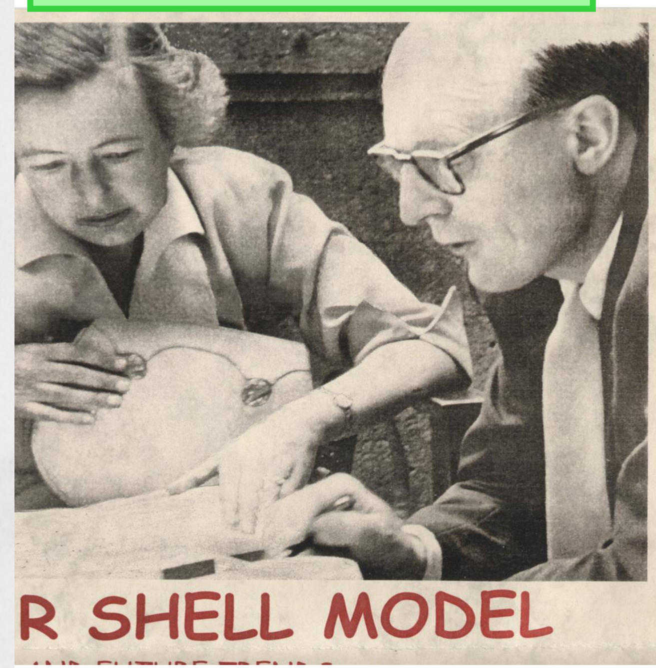


図2-23 1粒子軌道の順序. 図は M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1955 からとった.



As *N* or *Z* is changed in an open shell,
the shell structure is changed (evolved), and
the change can be described by

- **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'

This can be substantial change in exotic nuclei.
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))

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

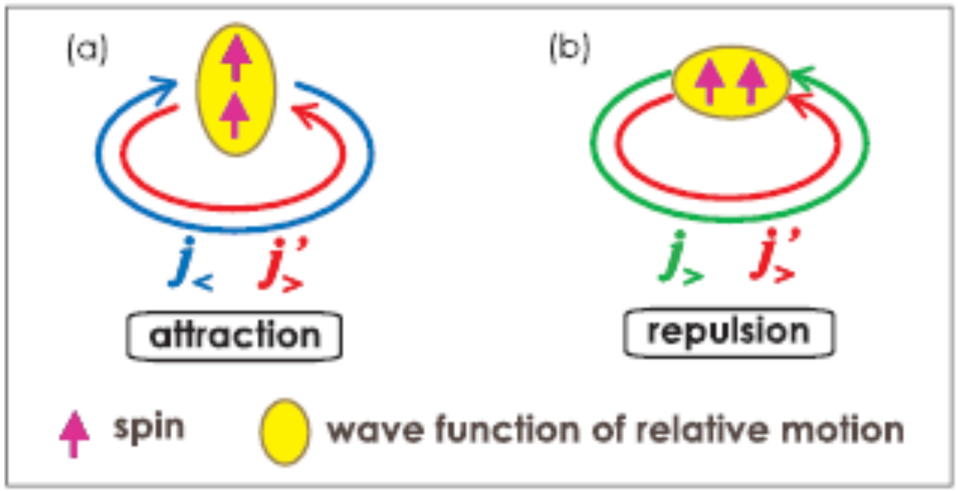
large relative momentum k

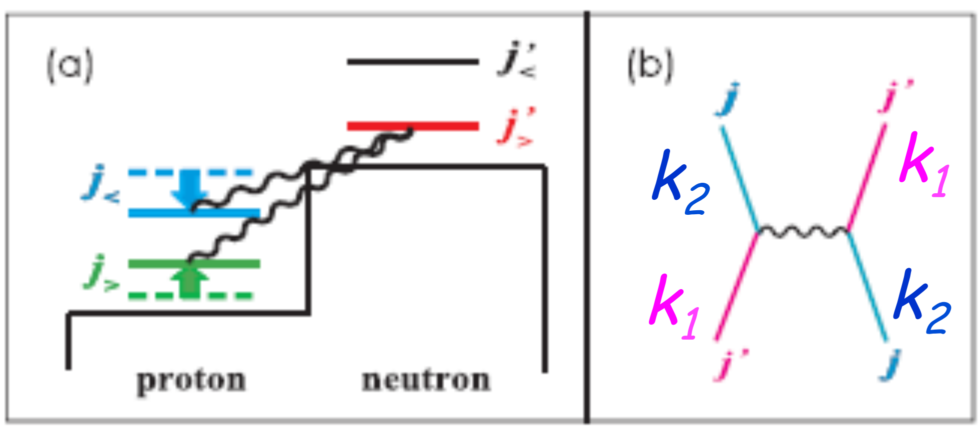
⇩

strong damping

⇩

wave function of relative coordinate





← k_2 ← k_1

small relative momentum k

⇩

loose damping

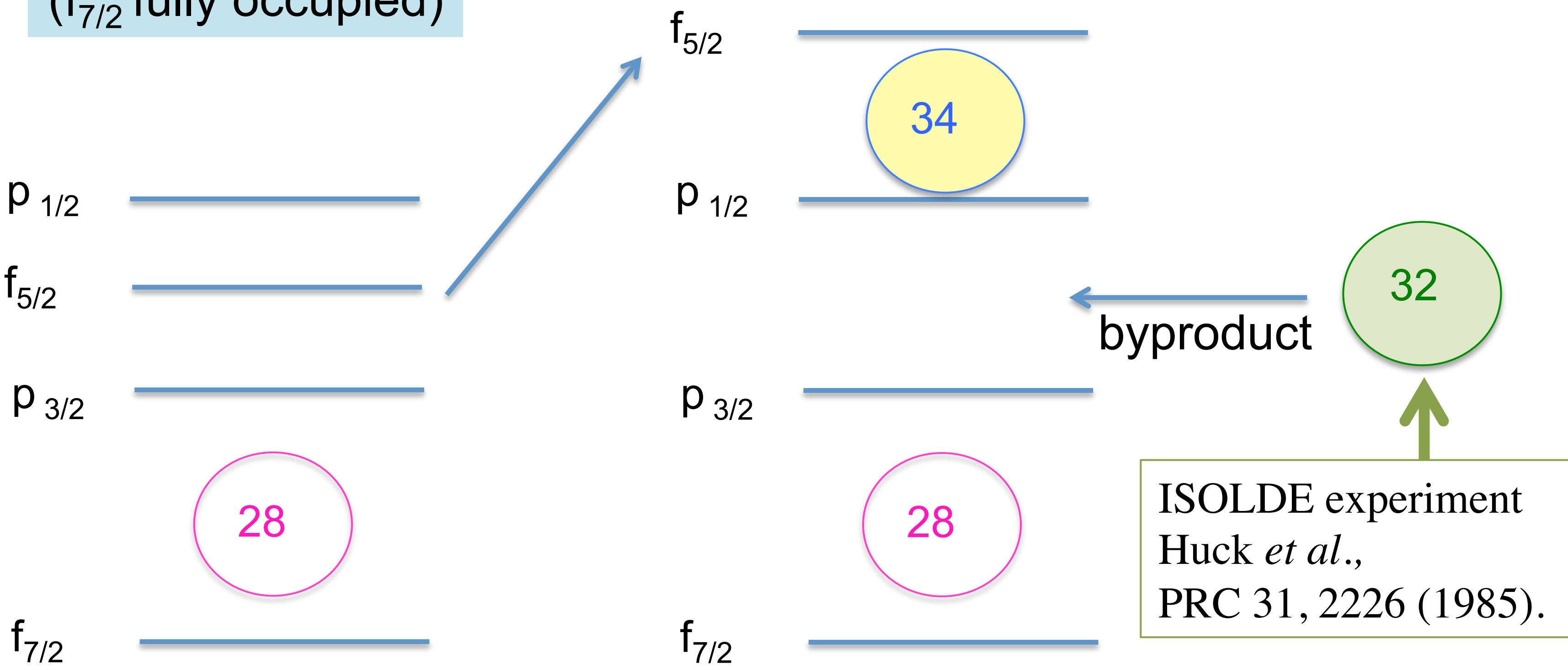
⇩

wave function of relative coordinate

Appearance of N= 32 and 34 magic structures

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

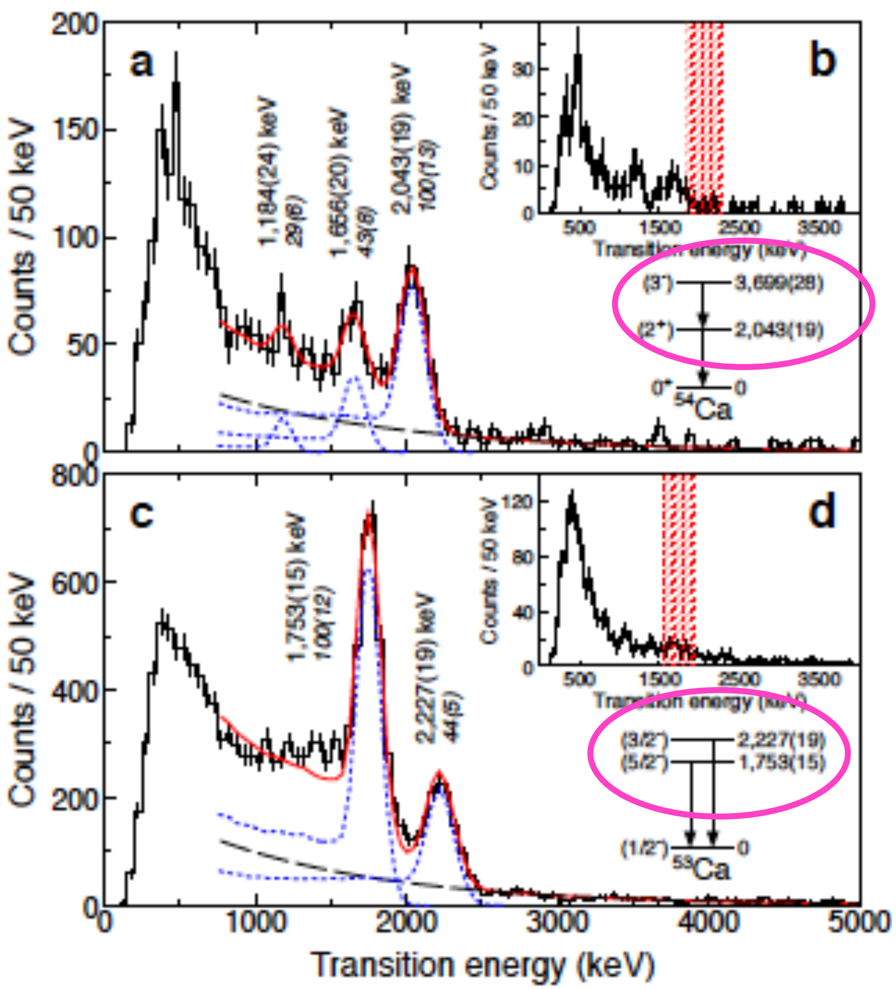
N=34 magic number may appear
if proton $f_{7/2}$ becomes vacant (Ca)
($f_{5/2}$ becomes less bound)



Mayer-Jensen

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

Experiment @ RIBF → Finally confirmed



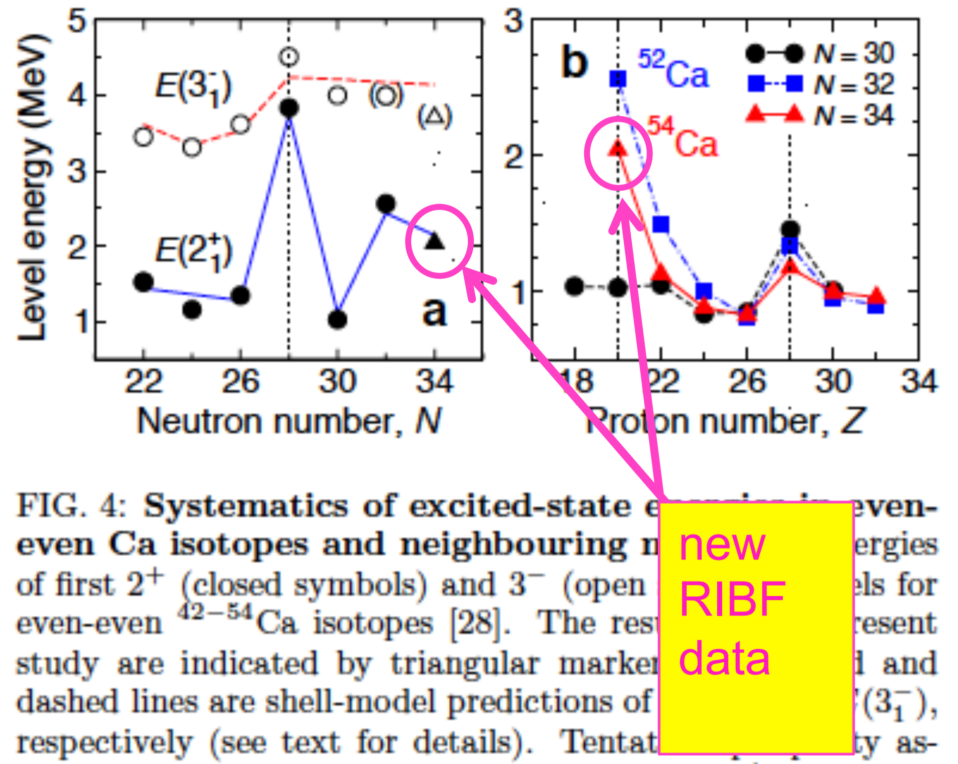


FIG. 4: **Systematics of excited-state e[...] in even-even Ca isotopes and neighbouring n[...]** [...]ergies of first 2^+ (closed symbols) and 3^- (open [...]ls for even-even $^{42-54}$Ca isotopes [28]. The res[...]resent study are indicated by triangular marke[...] and dashed lines are shell-model predictions of [...](3_1^-), respectively (see text for details). Tentat[...]ty assignments are enclosed by parentheses. **b,** $E(2_1^+)$ along the $N = 30$, 32 and 34 isotonic chains. The solid and dashed lines are intended to guide the eye. Vertical dotted lines represent the traditional magic numbers in both plots.

[...]er-corrected γ-ray energy spectra. De-excitation γ rays measured in coinci-

[...]^{54}Ca and **c,** ^{53}Ca reaction products. Peaks a[...]

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

[...]ve intensities are indicated by italic fonts. The short-blue and long-black dashed

Outline

1. Shell evolution and tensor force

2. Shell evolution and QCD

3. Dual quantum liquid picture

4. Summary and perspectives

Input from chiral Effective Field Theory (EFT) of QCD

N3LO *NN* interaction — D. R. Entem and R. Machleidt, Phys. Rev. C **68**, 041001 (2003).

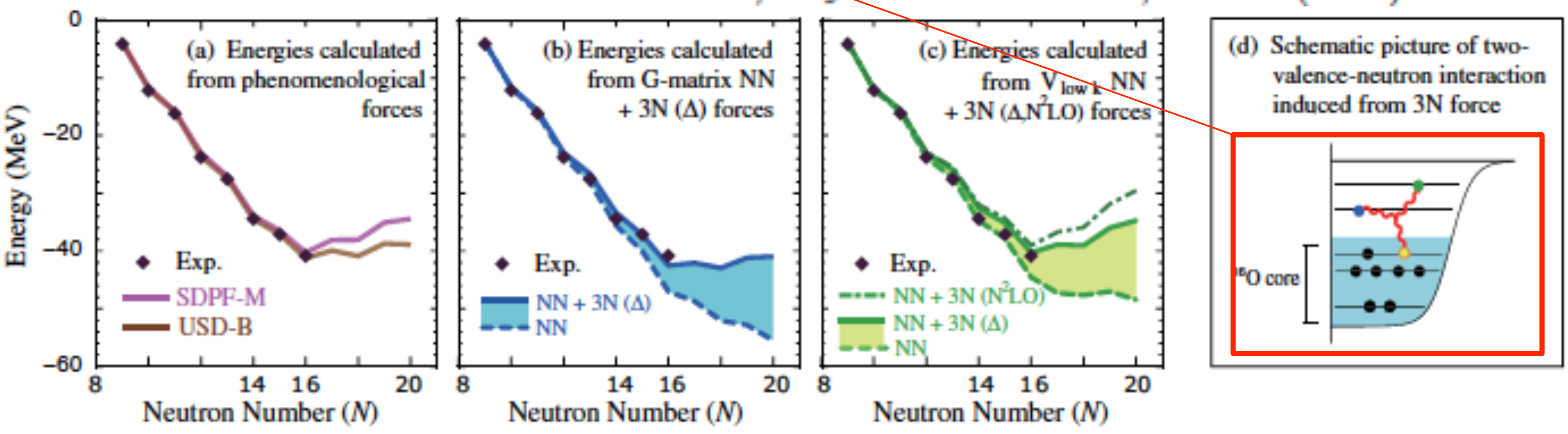
$V_{\text{low }k}$ treatment of high momentum part — S.K. Bogner, T.T.S. Kuo, and A. Schwenk, Phys. Rep. **386**, 1 (2003); S. K. Bogner *et al.*, Nucl. Phys. A **784**, 79 (2007).

Fujita-Miyazawa type 3*N* interaction — J. Fujita and H. Miyazawa, Prog. Theor. Phys.. **17**, 360 (1957).

↓

Effective *NN* int.

T. Otsuka, T. Suzuki, J. D. Holt, A. Schwenk, and Y. Akaishi, Phys. Rev. Lett. **105**, 032501 (2010).



Novel method for in-medium correction

Kuo-Krenciglowa method *

KK method

Divergence problem in multi-shell

$$H = H_0 + V = \begin{pmatrix} PH_0P & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} PVP & PVQ \\ QVP & QVQ \end{pmatrix}$$

$$\hat{Q}(E) = PVP + PVQ\frac{1}{E - QHQ}QVP$$

$$V_{\mathrm{eff}}^{(n)} = \hat{Q}(\epsilon_0) + \sum_{k=1}^{\infty} \hat{Q}_k(\epsilon_0)\{V_{\mathrm{eff}}^{(n-1)}\}^k.$$

Extended KK method **

EKK method

New parameter E (arbitrary parameter)

$$H = H_0' + V' = \begin{pmatrix} E & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} P\tilde{H}P & PVQ \\ QVP & QVQ \end{pmatrix},$$

$$H_{\mathrm{BH}}(E) = PHP + PVQ\frac{1}{E - QHQ}QVP.$$

$$\tilde{H}_{\mathrm{eff}}^{(n)} = \tilde{H}_{\mathrm{BH}}(E) + \sum_{k=1}^{\infty} \hat{Q}_k(E)\{\tilde{H}_{\mathrm{eff}}^{(n-1)}\}^k$$

* E. M. Krenciglowa and T. T. S. Kuo, Nucl. Phys. A 235, 171 (1974).

** N. Tsunoda, K. Takayanagi, M. Hjorth-Jensen, and T. Otsuka, Phys. Rev. C 89, 024313 (2014).

EFT *NN* int. + Fujita-Miyazawa 3*N* int. with averaging

(to be replaced by EFT N2LO 3*N* int.)

↓

$V_{\text{low k}}$: treatment of high-momentum components

EKK : in-medium correction (core polarization)

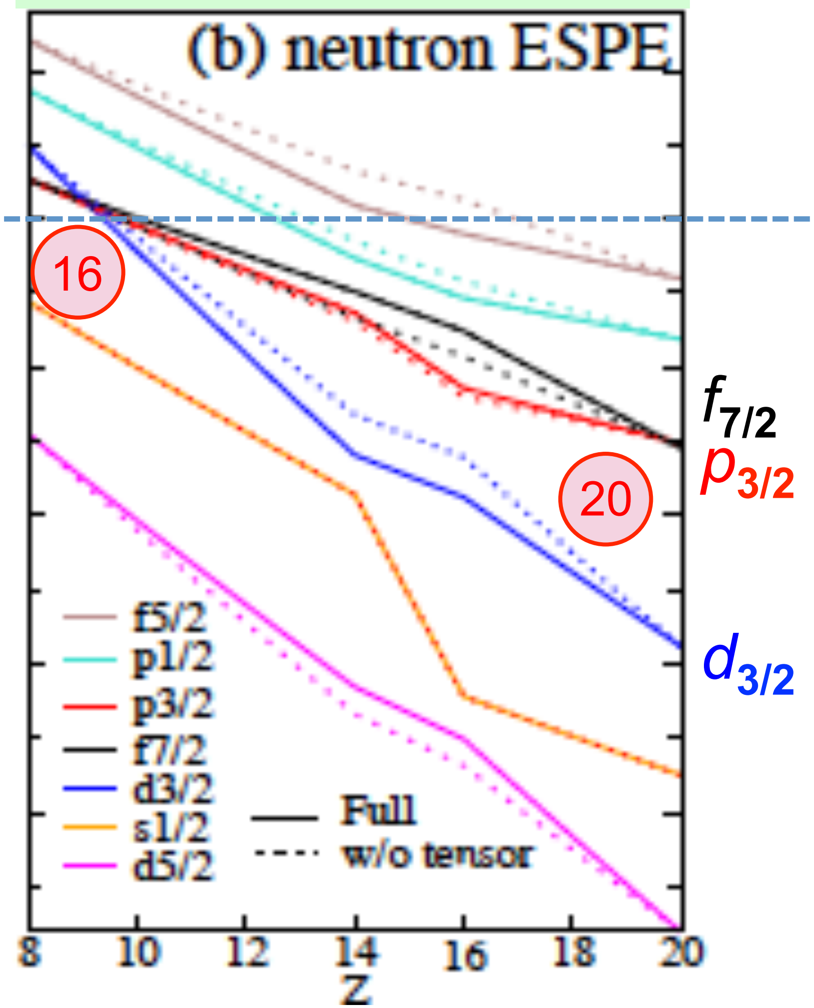
Shell model Hamiltonian

↳

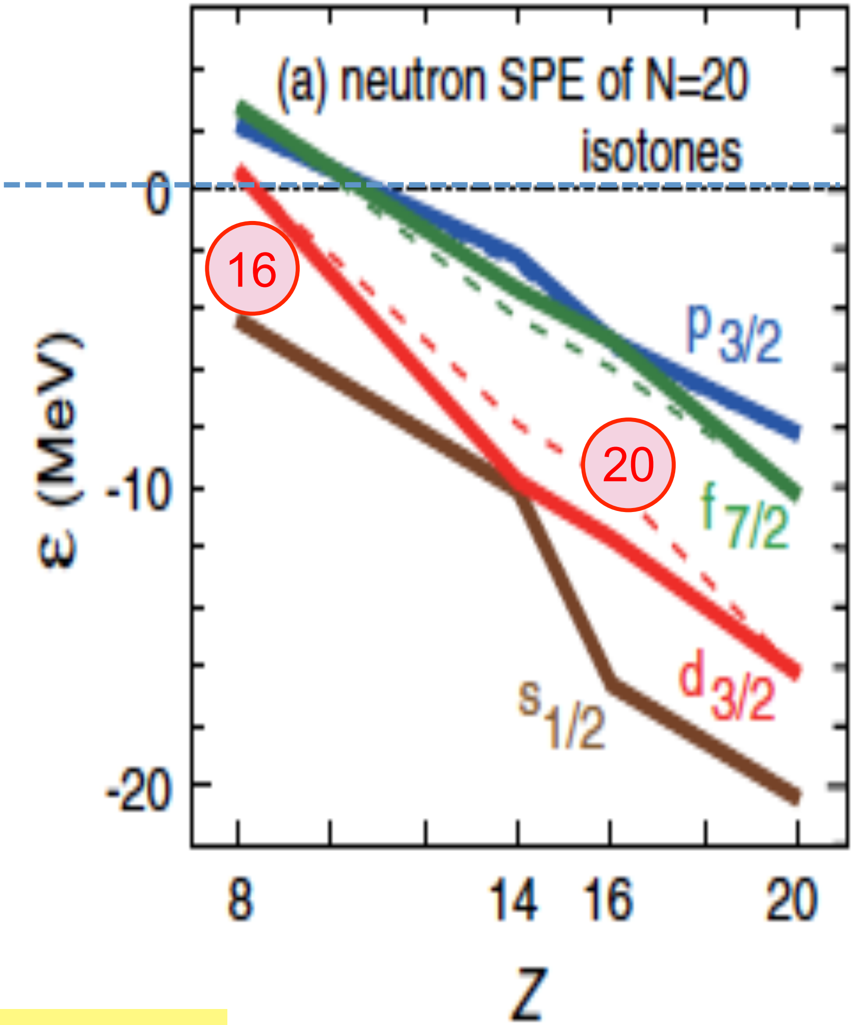
- Effective single-particle energy
  (*N* or *Z* dependence of effects of monopole int.)
- Energy levels, electromagnetic matrix elements
  (diagonalization of Hamiltonian matrix)

Island of Inversion : neutron effective single-particle energies

Present work (EFT + EKK)



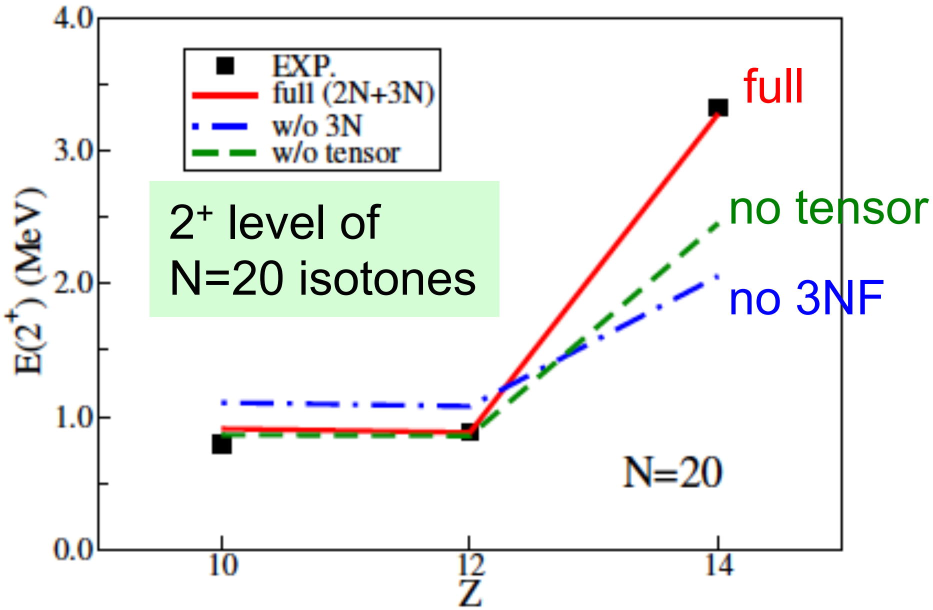
Meson exchange potential

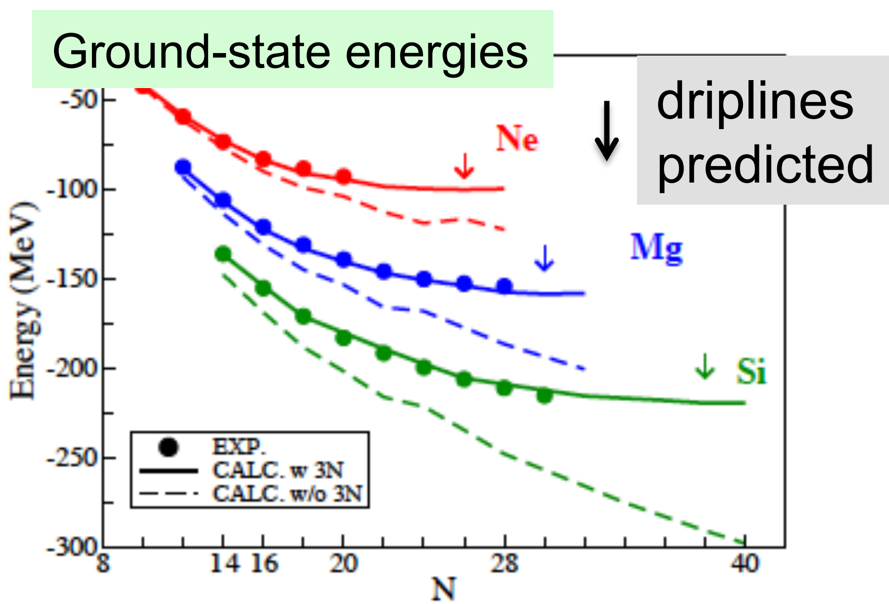


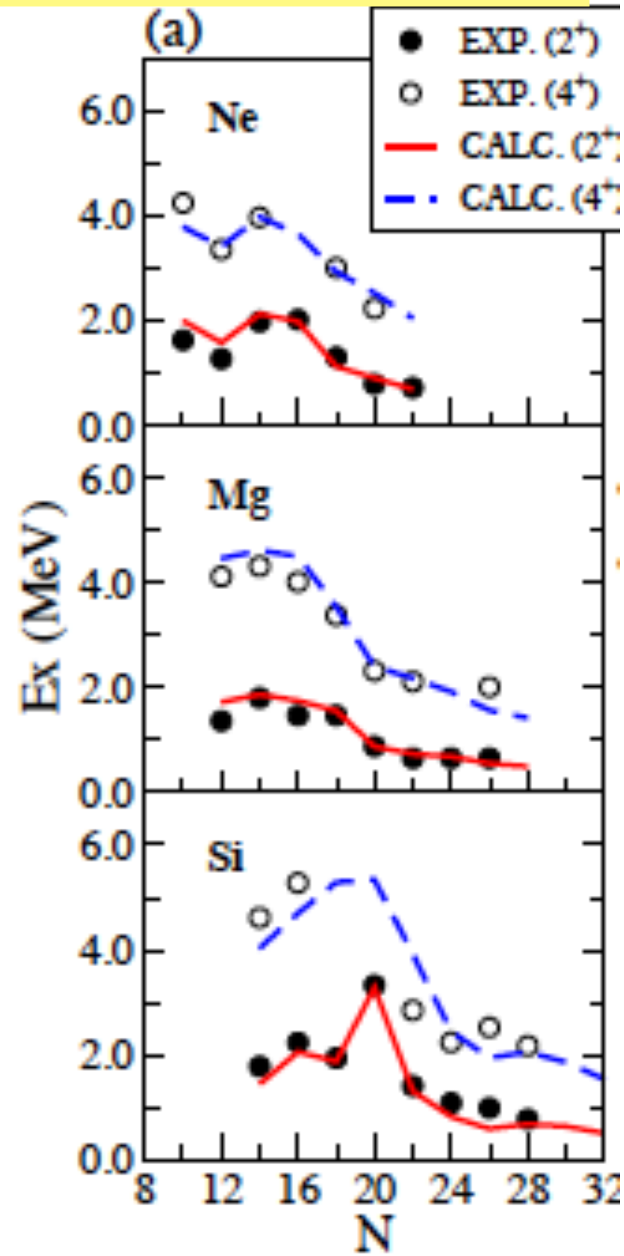
Shell evolution arises also from QCD

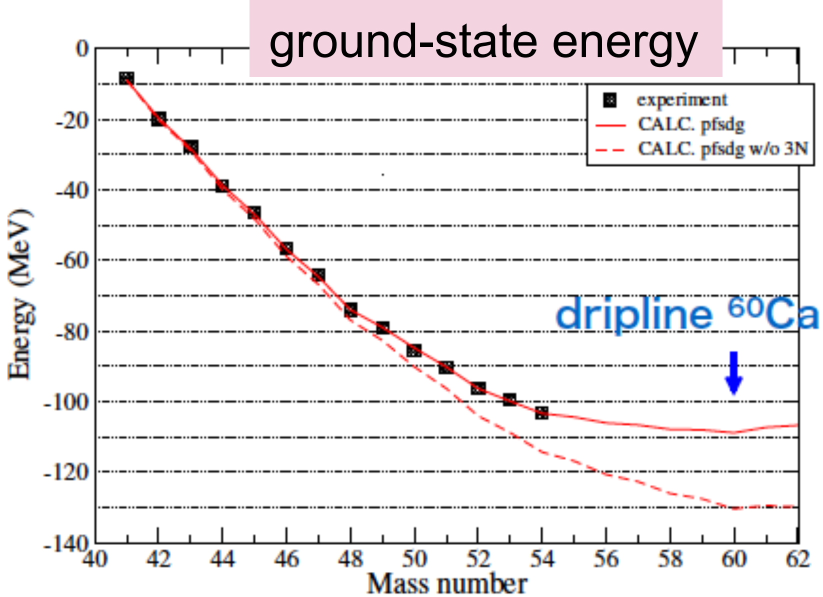
TO *et al*. Phys. Rev. Lett. 104, 012501 (2010)

… and other properties obtained by the shell-model diagonalization in the sd + pf shell





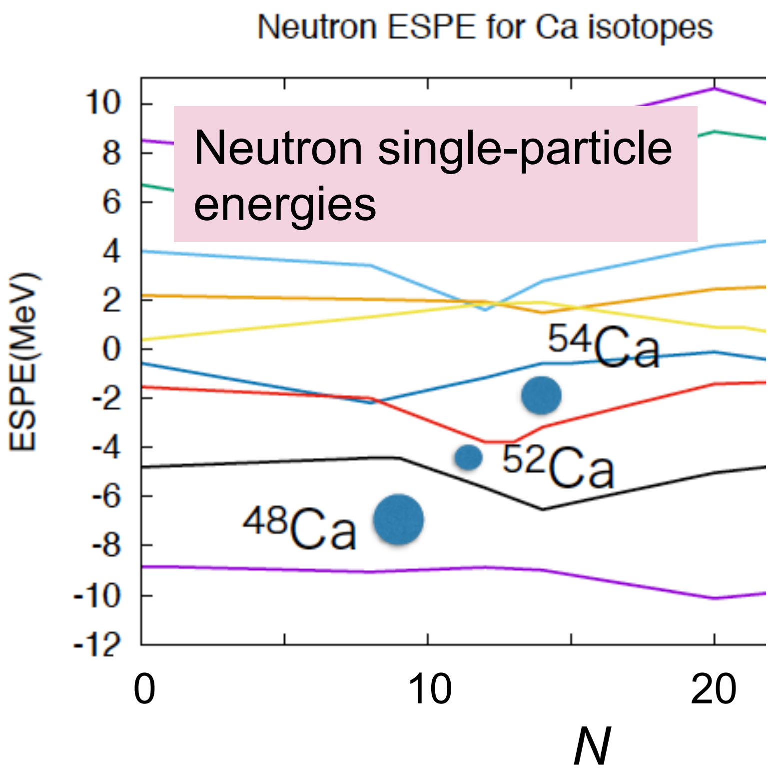


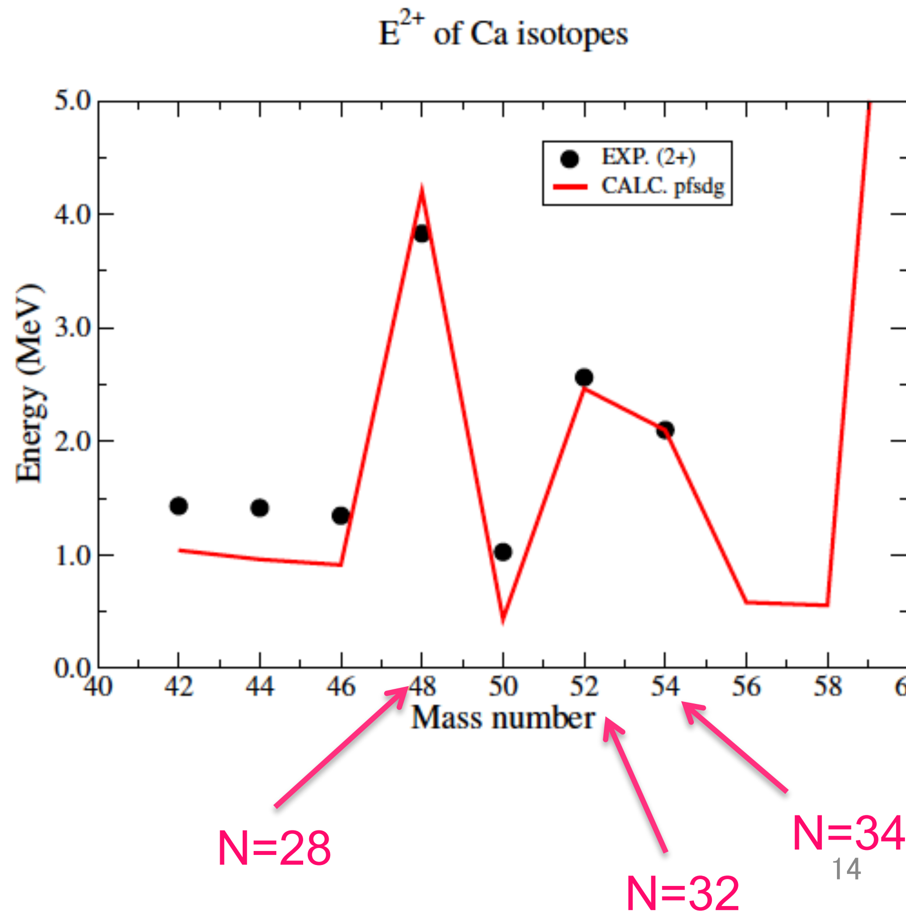


Ca isotopes in the pf + sdg shell

The prediction of N=34 magic number (2001) Is consistent with EFT (QCD) + EKK theoretical calculation.

TO et al, PRL 87, 082502 (2001)





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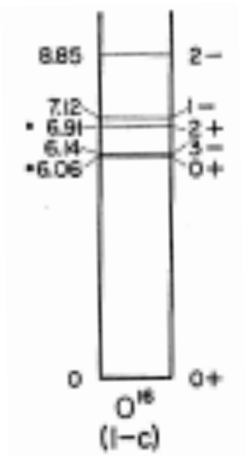
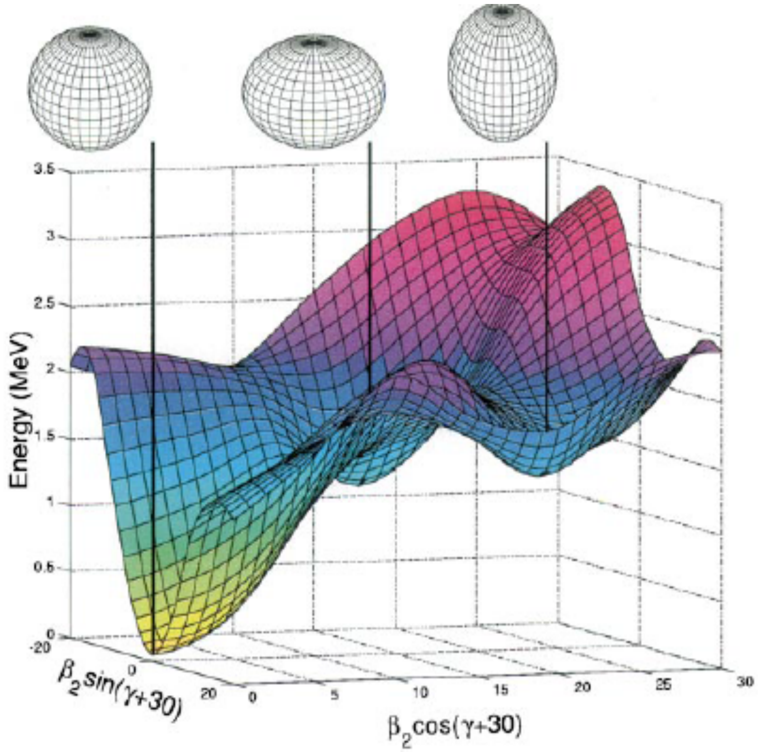
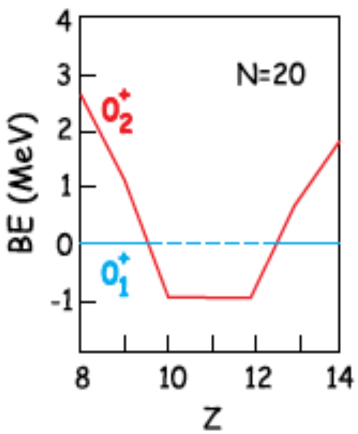
shape coexistence



^{16}O
H. Morinaga
(1956)



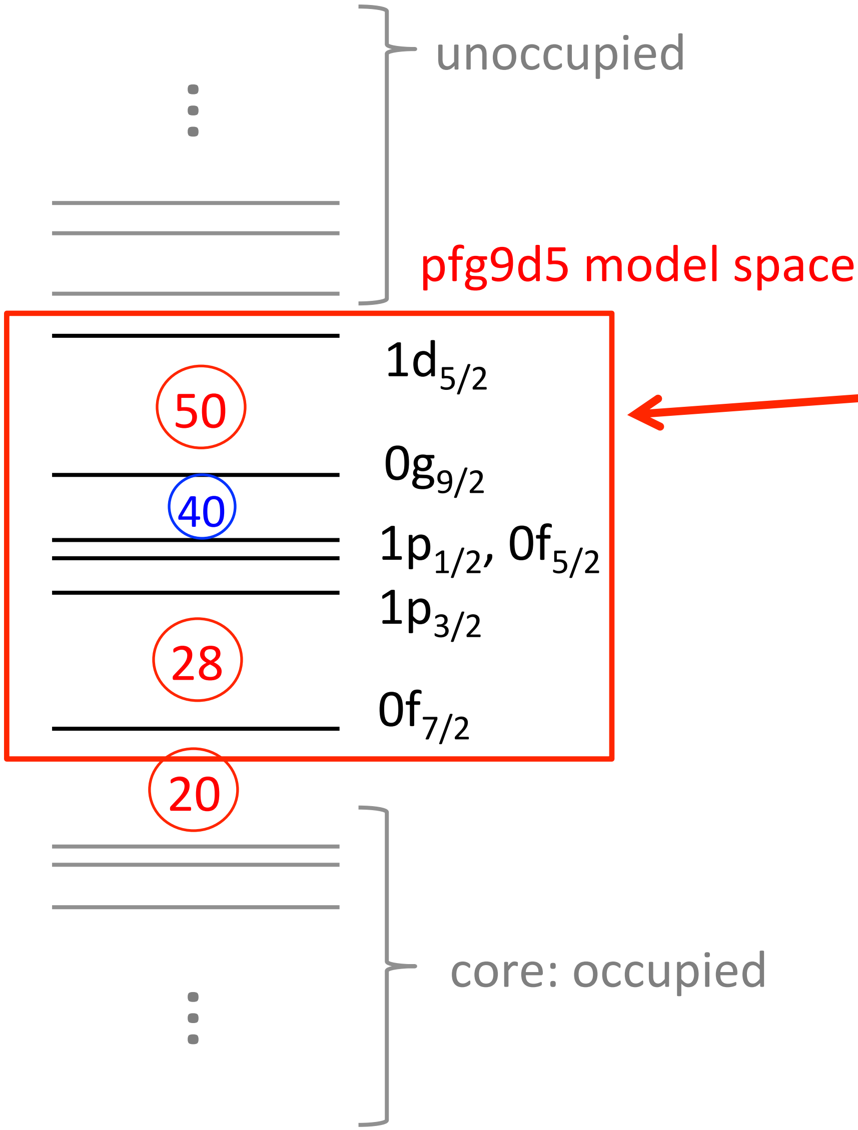
^{186}Pb
A.N. Andreyev *et al.*,
Nature **405**, 430 (2000)

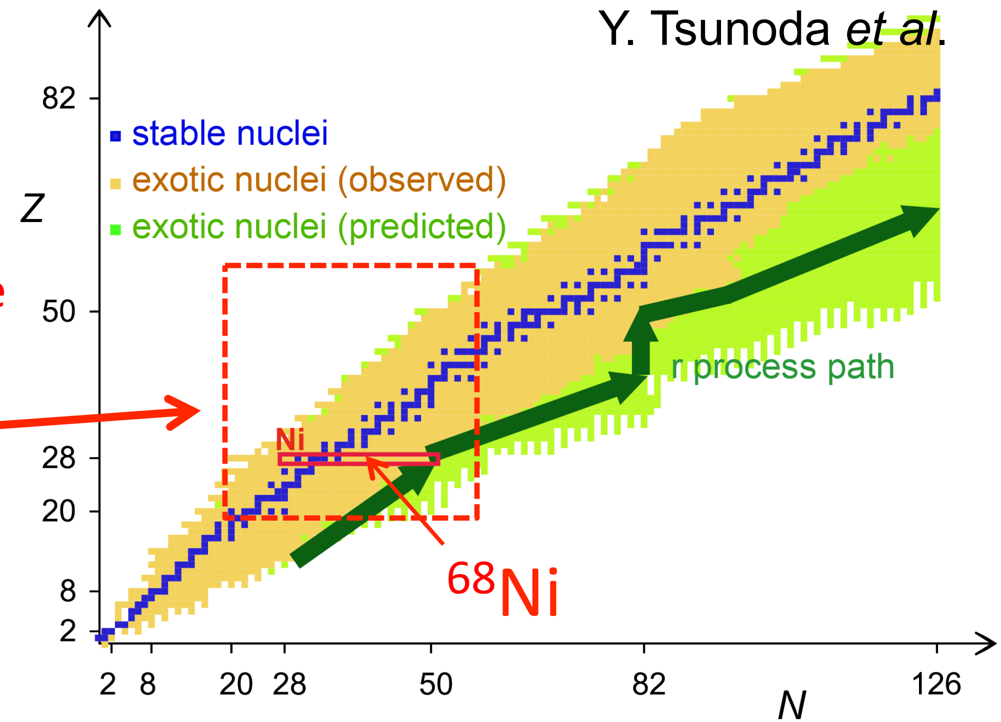


Island of Inversion
(Z=10~12, N=20)

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

Monte Carlo Shell Model (MCSM) calculation on Ni isotopes





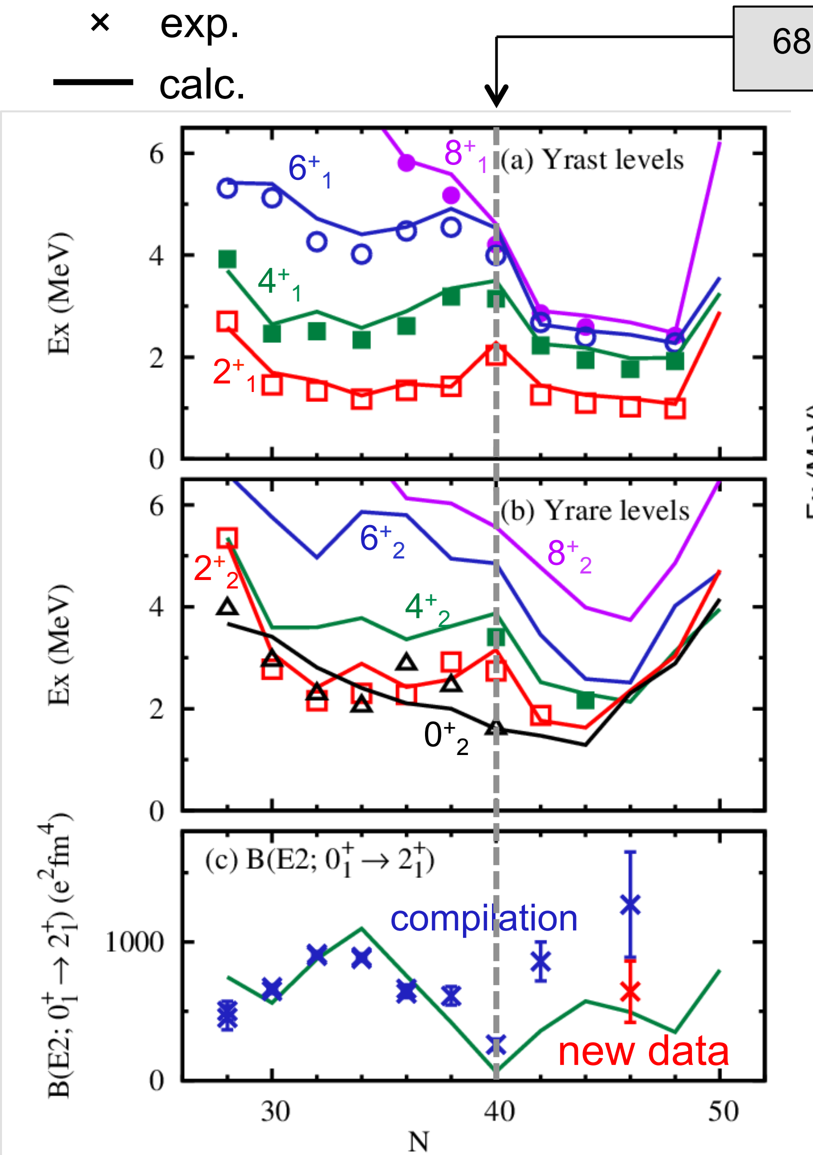
This model space is wide enough to discuss how magic numbers 28, 50 and semi-magic number 40 are visible or smeared out.

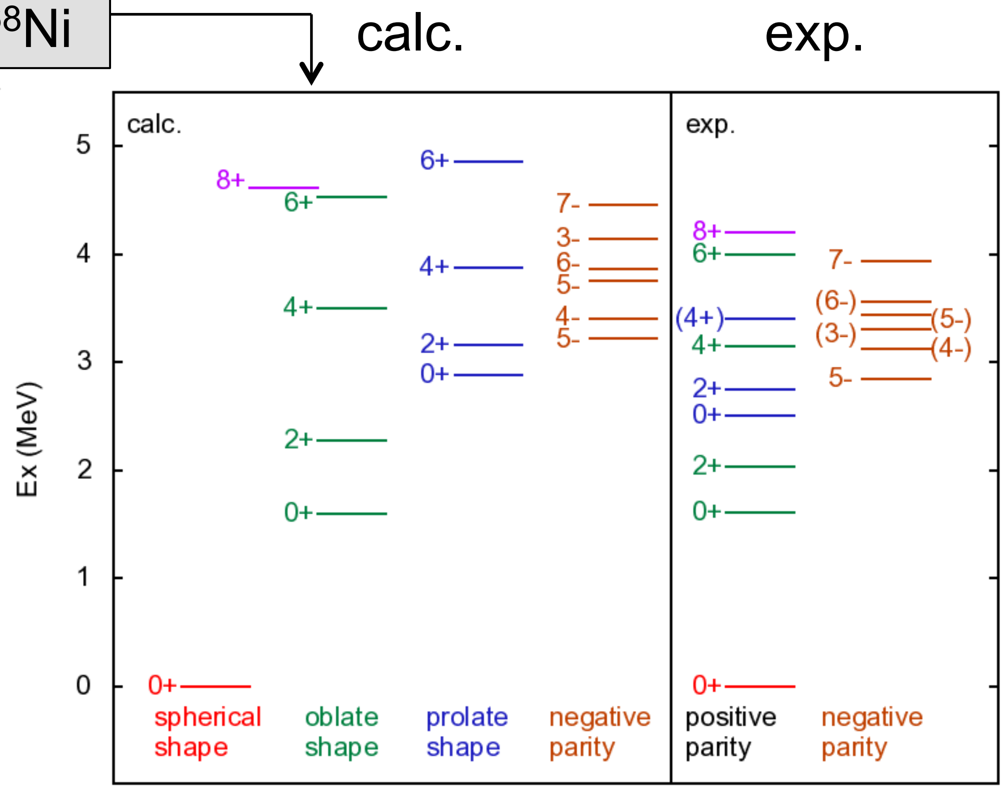
Interaction:
A3DA interaction is used with minor corrections

Energy levels and B(E2) values of Ni isotopes

Description by the same Hamiltonian

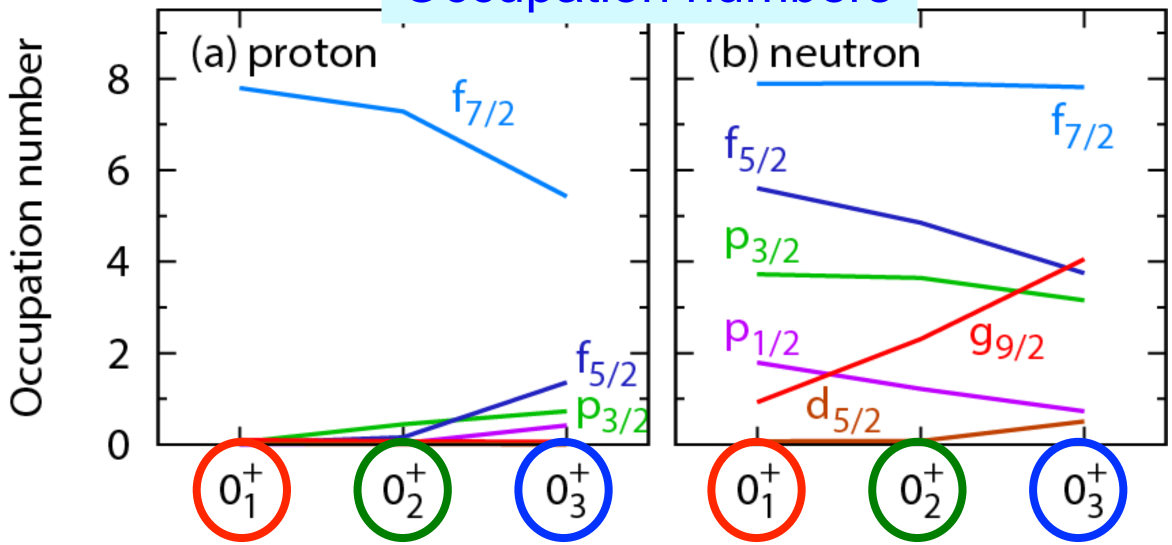
Shape coexistence in ^{68}Ni

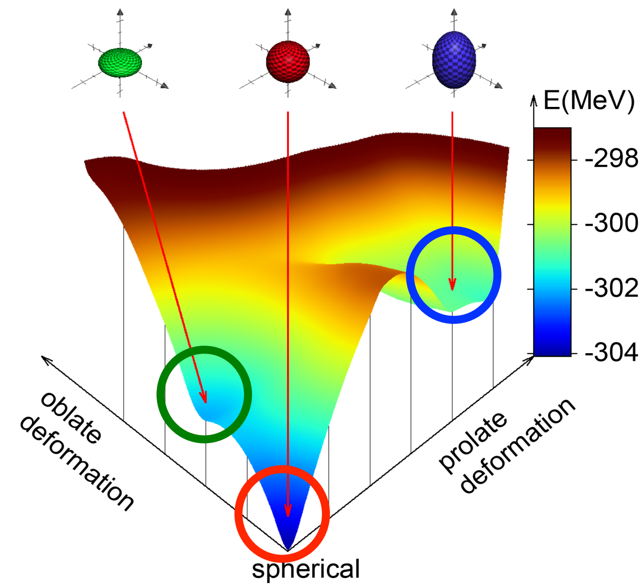




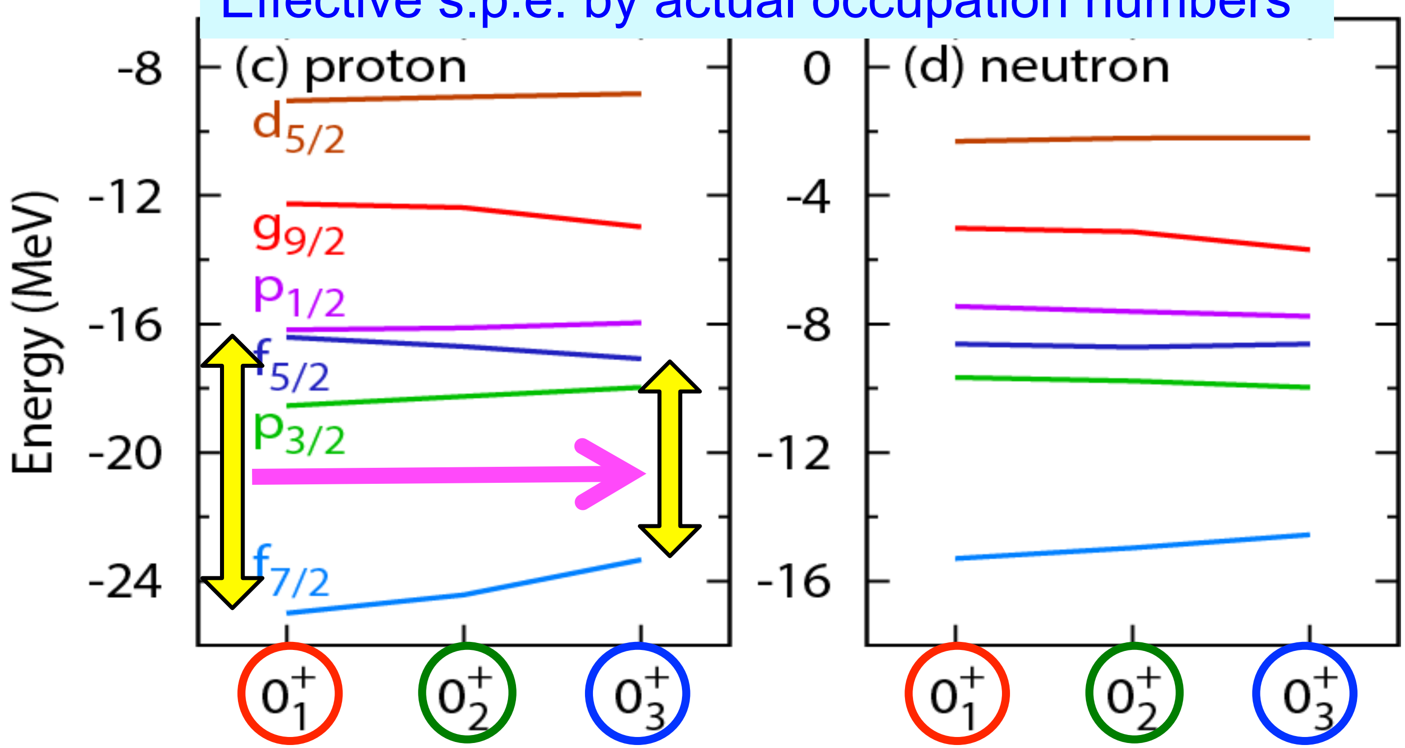
Y. Tsunoda, TO, Shimizu, Honma and Utsuno, PRC 89, 031301 (R) (2014)

Occupation numbers





Effective s.p.e. by actual occupation numbers

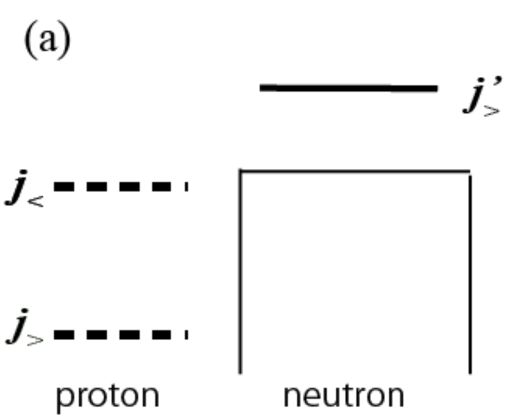


0^+ state

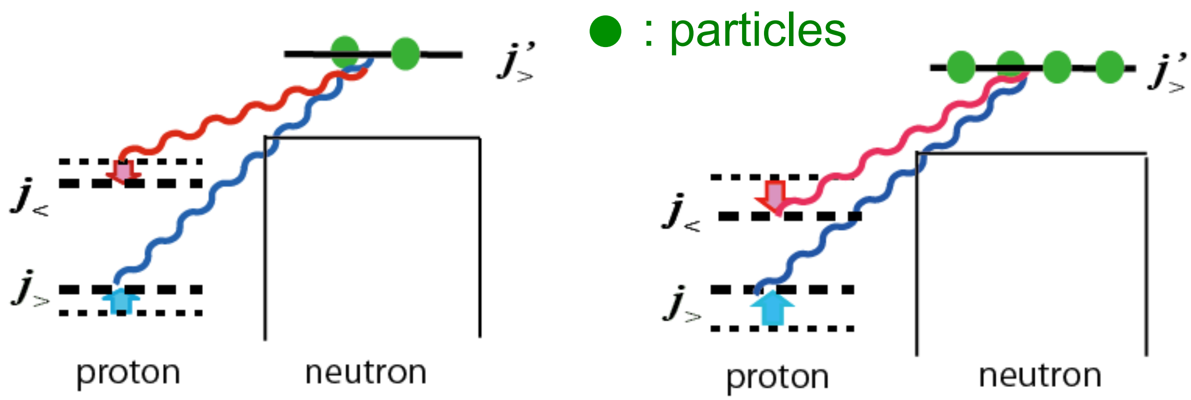
1st	modest correlations	
2nd	2p-2h	
3rd		6p-6h

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

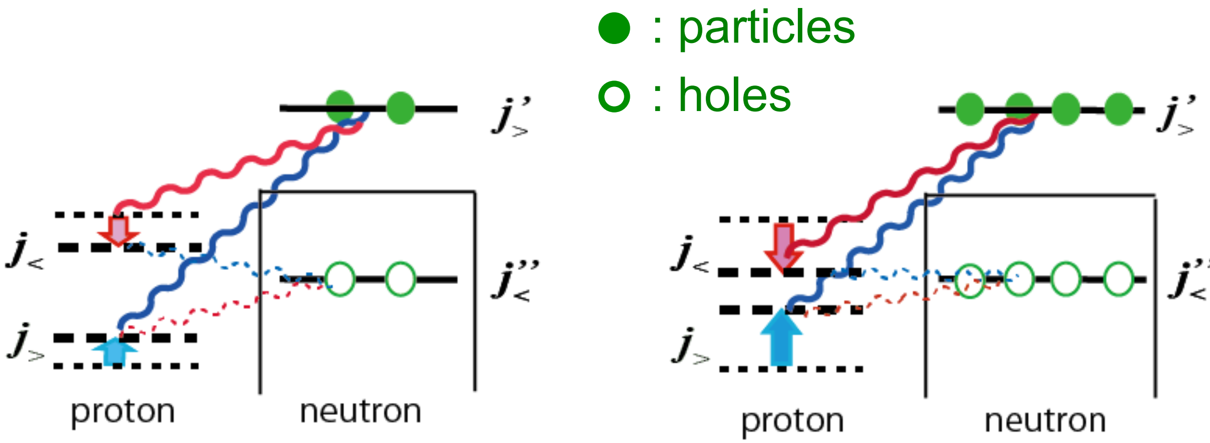
Monopole effects on the shell structure from the tensor interaction



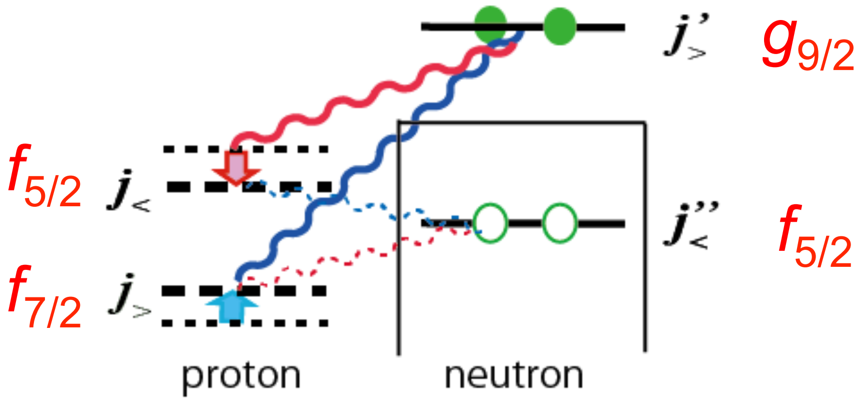
Type I Shell Evolution : different isotopes



Type II Shell Evolution : within the same nucleus



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



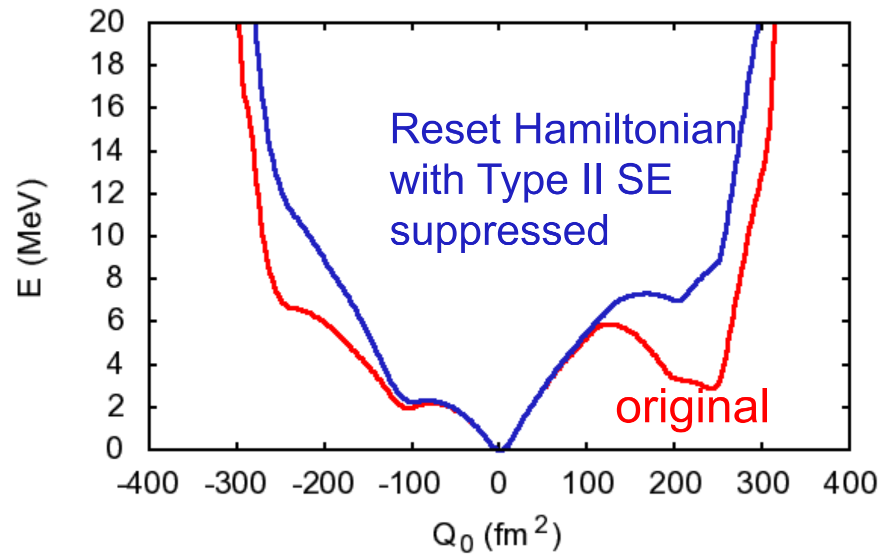
Spin-orbit splitting works against quadrupole deformation (*cf. Elliott's SU(3)*).

weakening of spin-orbit splitting

Type II shell evolution

stronger deformation of protons
→ more neutron p-h excitation

PES along axially symmetric shape



Type II shell evolution is suppressed by resetting monopole interactions as

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

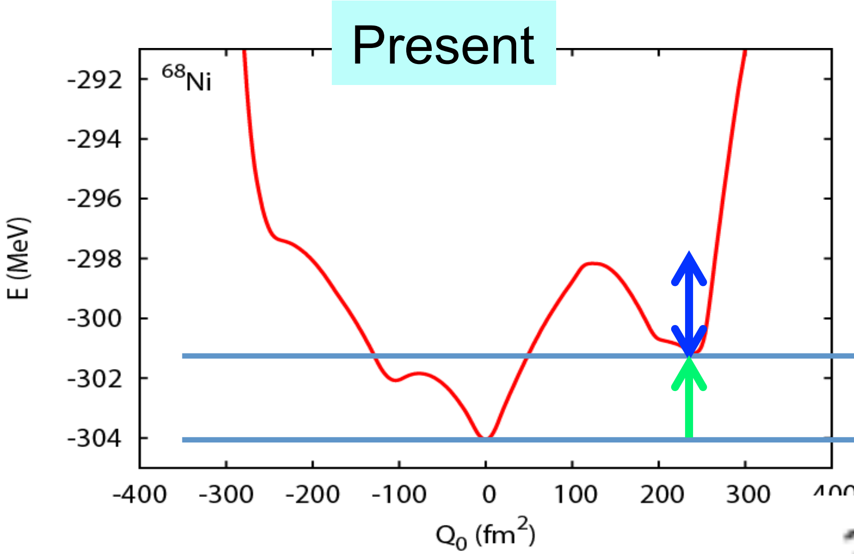
$\pi f_{7/2} - \nu f_{5/2} = \pi f_{5/2} - \nu f_{5/2}$

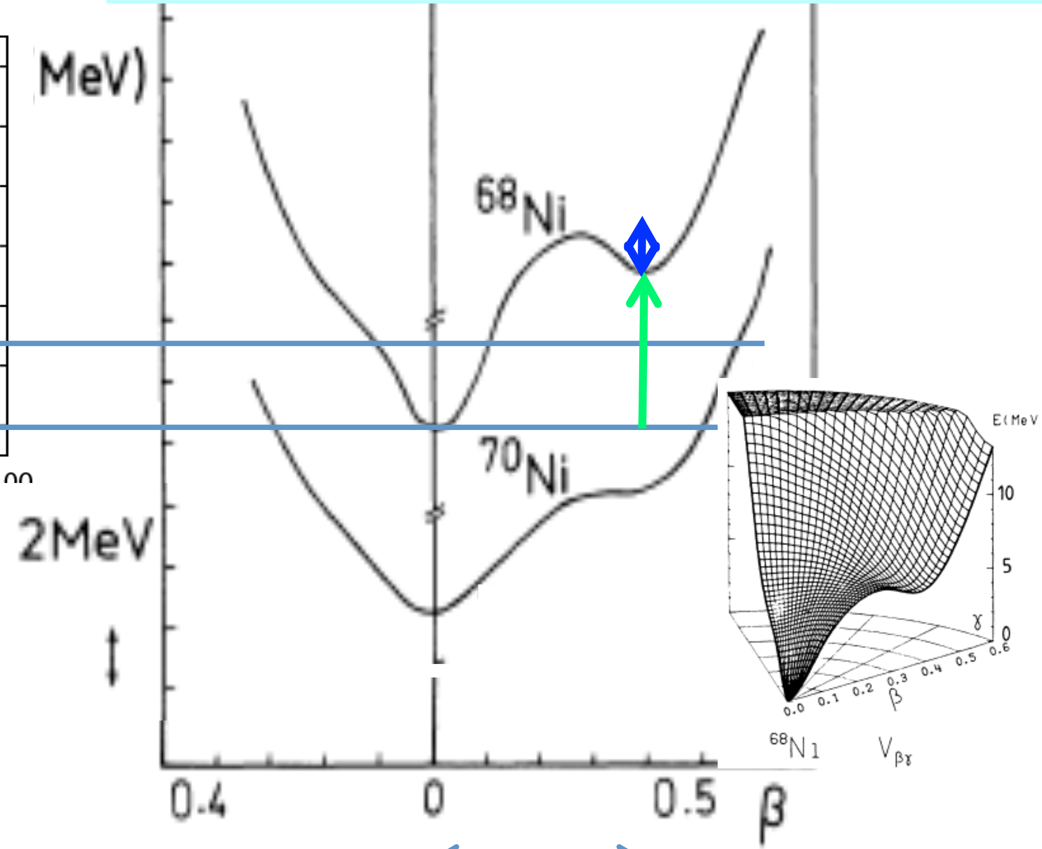
The local minima become much less pronounced.

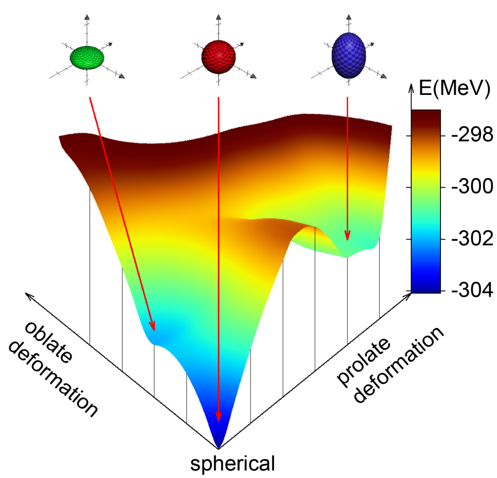
Shape coexistence is enhanced by type II shell evolution as the same quadrupole interaction works more efficiently.

Effect of the tensor force

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

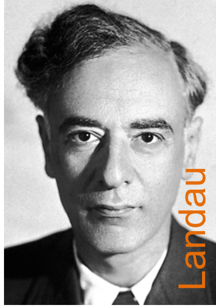






no (expicit) tensor force

This picture may be expanded …



Dual quantum liquids in the same nucleus

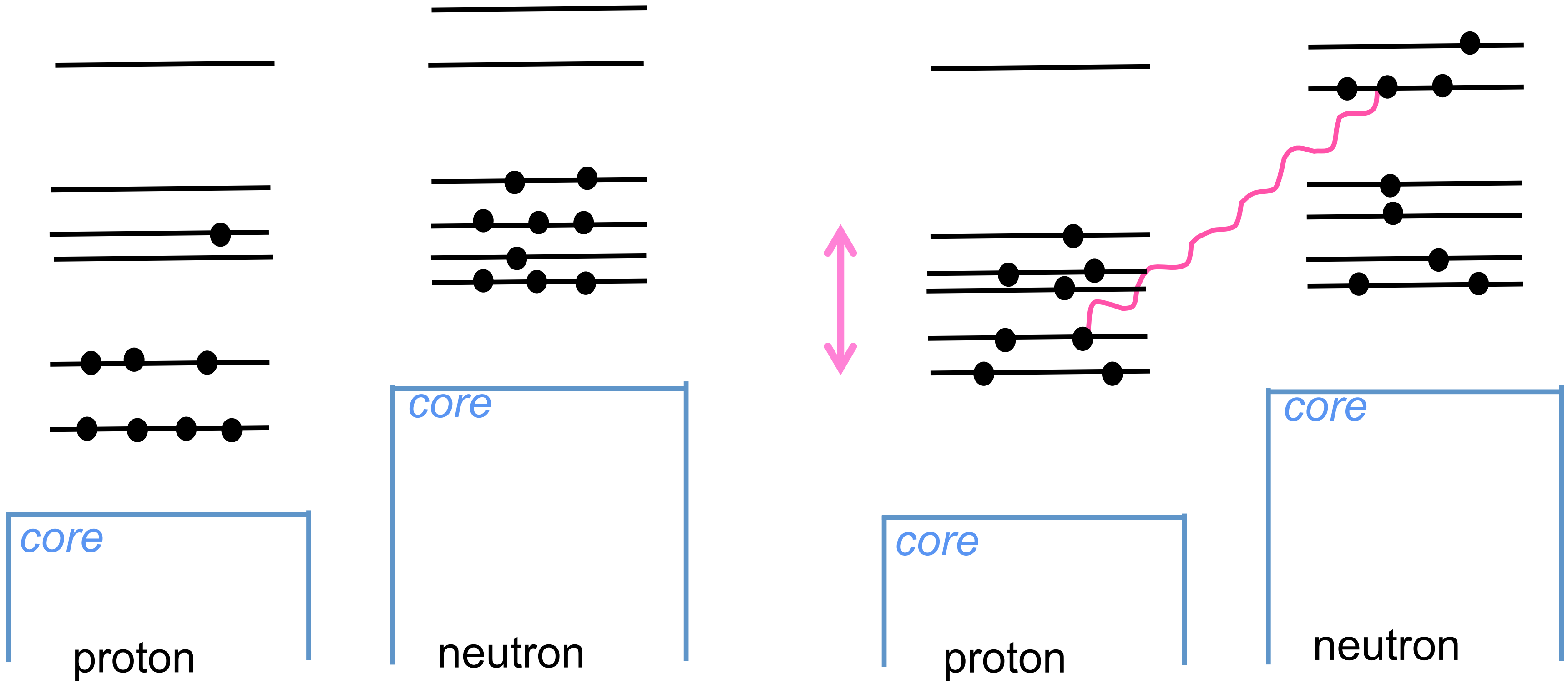
Certain configurations produce different shell structures owing to (i) tensor force and (ii) proton-neutron compositions

Liquid 1 (~constant spherical SPE)

relevant to normal states in general

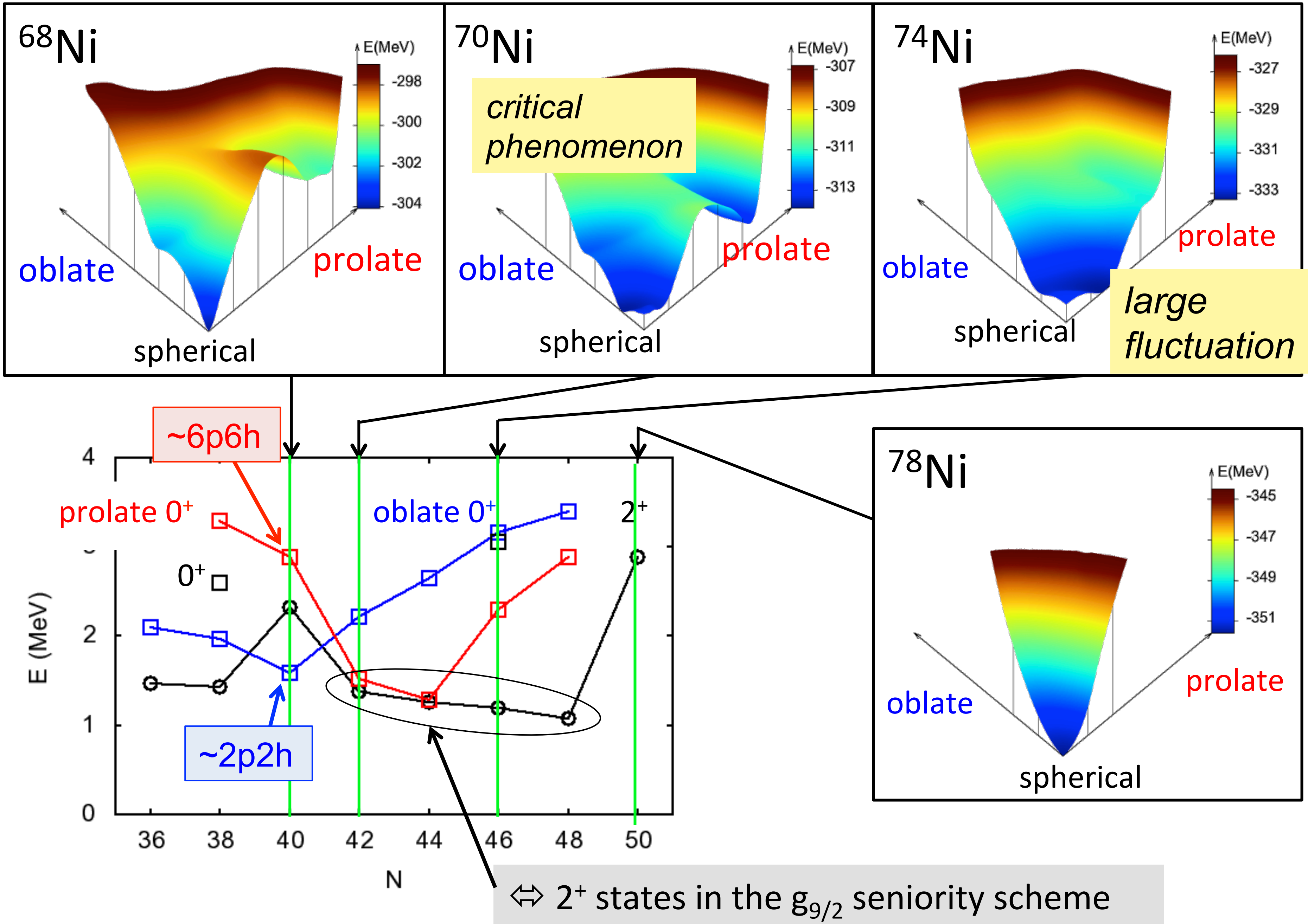
Liquid 2 (varying spherical SPE)

relevant to specific intruder states

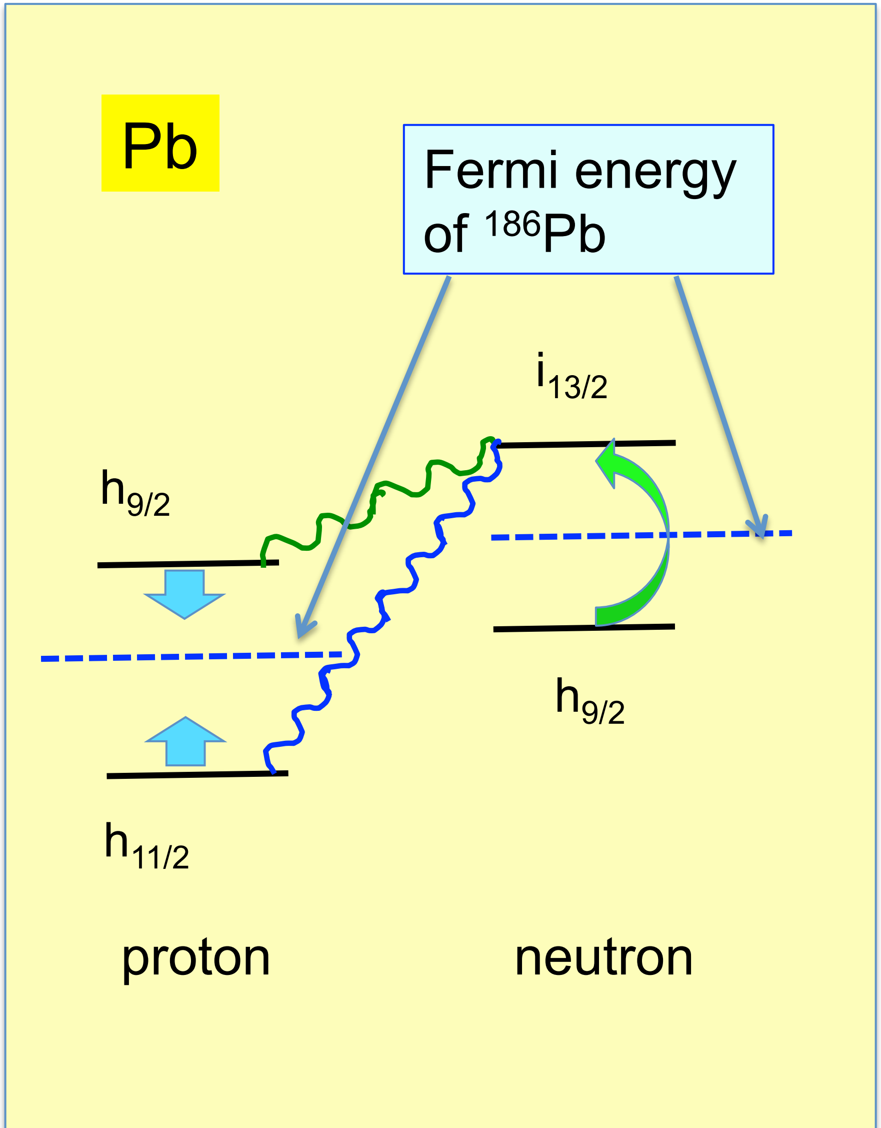


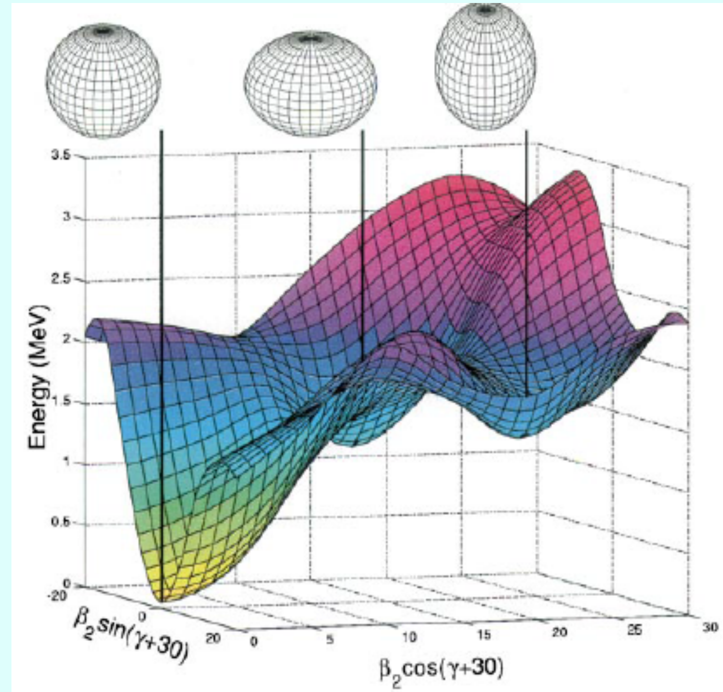
Note : density -> single-particle energies in other many-body systems

Shape evolution and phase transitions



Other cases ….. just an example

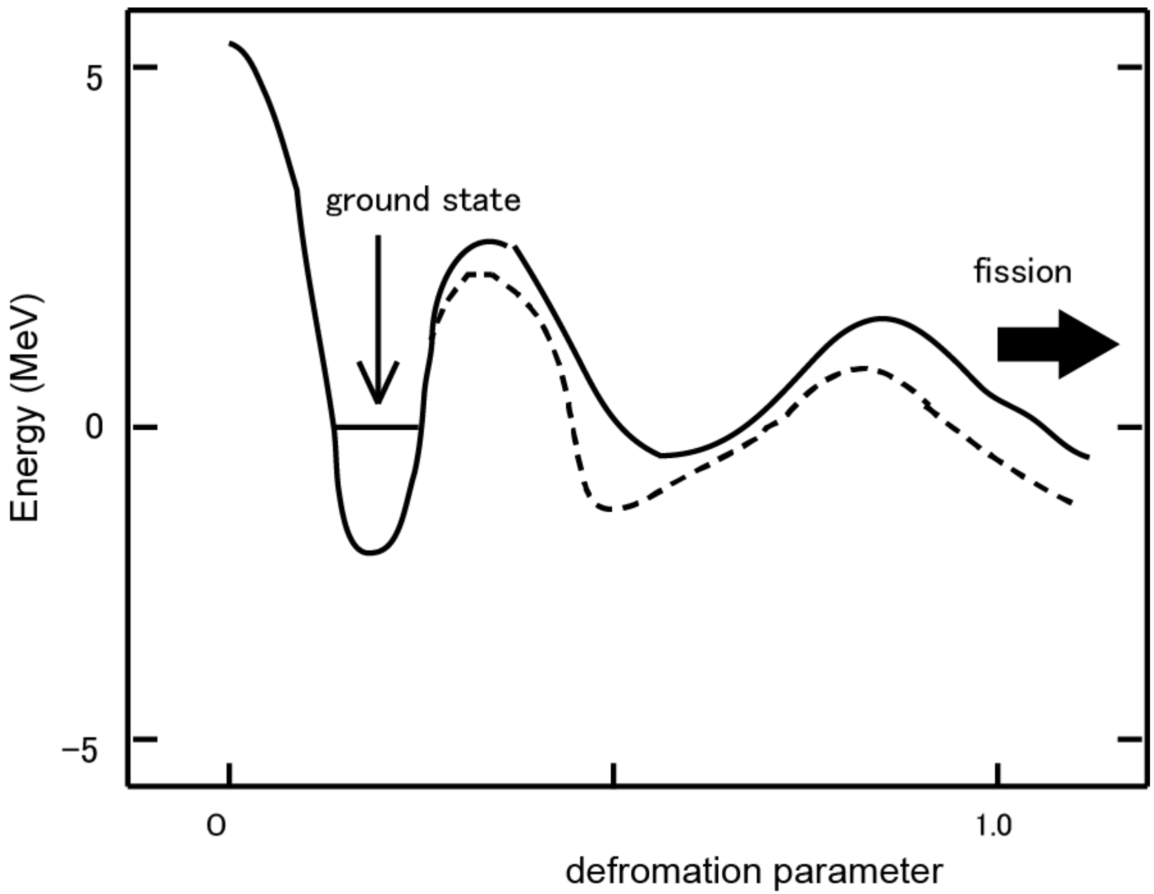




^{186}**Pb** Andreyev *et al.*, Nature **405**, 430 (2000)

Fission and Type II shell evolution

Type II shell evolution reduces the barrier and make the local minimum more profound
 -> passage to fission … (long-term open question)



Summary and perspectives

Quantum Liquid picture (of Landau) with stable shell structure (*a la* Mayer-Jensen) has been a good conceptual guidance for most of states of many nuclei near the stability line on the Segre chart.

The central and tensor parts of nuclear force produce Type I Shell Evolution in many domains on the nuclear chart particularly away from the stability line, presenting a paradigm shift. Type I Shell Evolution is shown to occur in *ab initio*-type approaches with EFT (QCD) + EKK.

There is another new aspect, Type II Shell Evolution, resulting in Dual Quantum Liquid picture. This produces dynamical (softer) shell structure in a non-linear way, where the two essential ingredients may be

- force that can change ***ls***-splitting, like the tensor force
- proton-neutron contents of quantum liquids

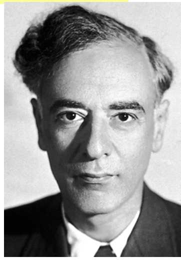
Could we solve the problem of (spontaneous) fission ?
Could it be a way to Island of Stability ?

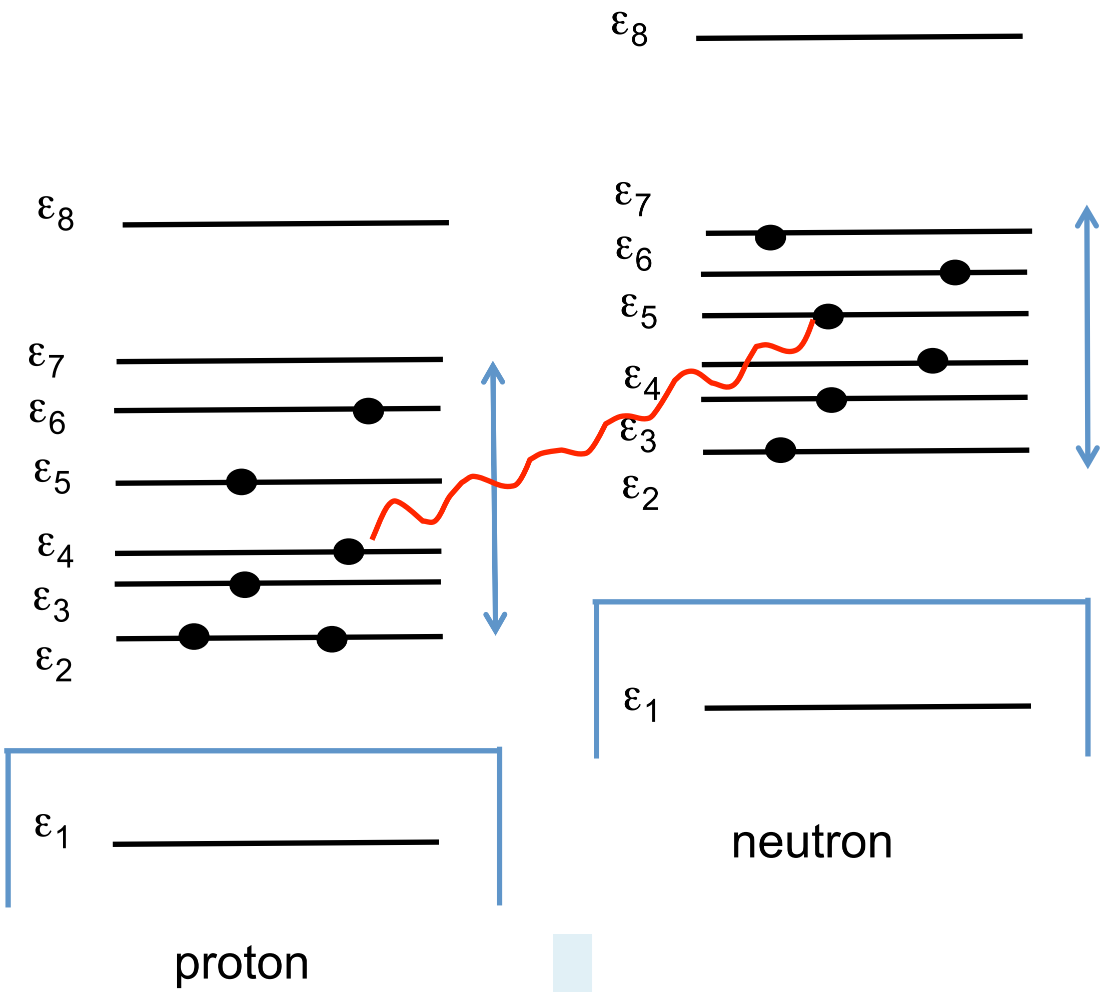
Collaborators

- Naofumi Tsunoda (CNS-HPCI, Tokyo)
- K. Takayanagi (Sophia)
- Morten Hjorth-Jensen (Oslo/MSU)
- Yusuke Tsunoda (CNS, Tokyo)
- Noritaka Shimuzu (CNS-HPCI, Tokyo)
- Yutaka Utsuno (JAEA)
- Michio Honma (Aizu)

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.

Evolution of shell structure due to the tensor force

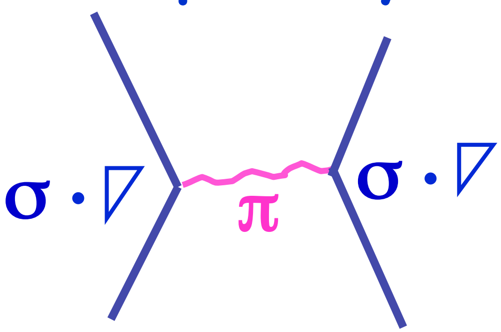
Tensor Interaction by pion exchange

$$V_T = (\tau_1\tau_2)\,(\,[\sigma_1\sigma_2]^{(2)}\,Y^{(2)}(\Omega)\,)\,Z(r)$$

contributes only to **S=1** states ($[\sigma_1\sigma_2]^{(2)}$)

relative motion (Ω, r)

π meson : primary source



Proc. Phys. Math. Soc. Japan 17, 48 (1935)

ρ meson (~ π+π) : minor (~1/4) cancellation

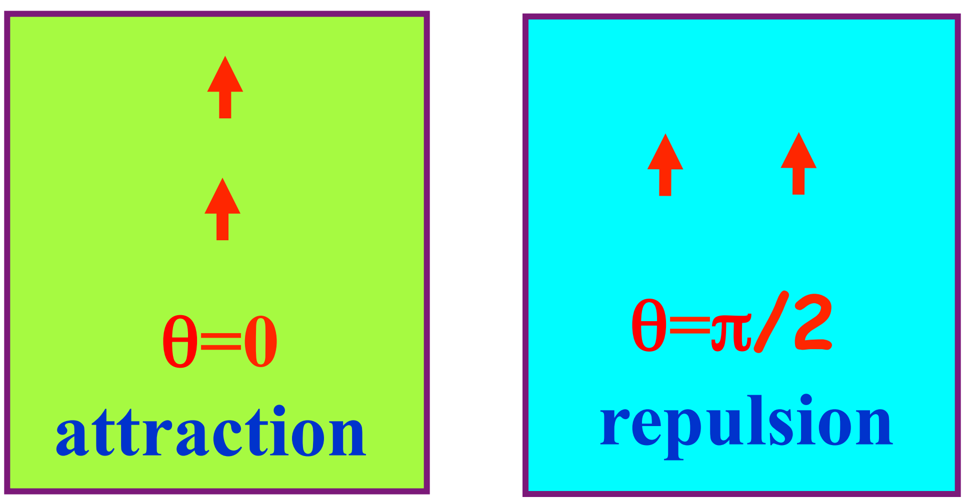
Ref: Osterfeld, Rev. Mod. Phys. 64, 491 (92)

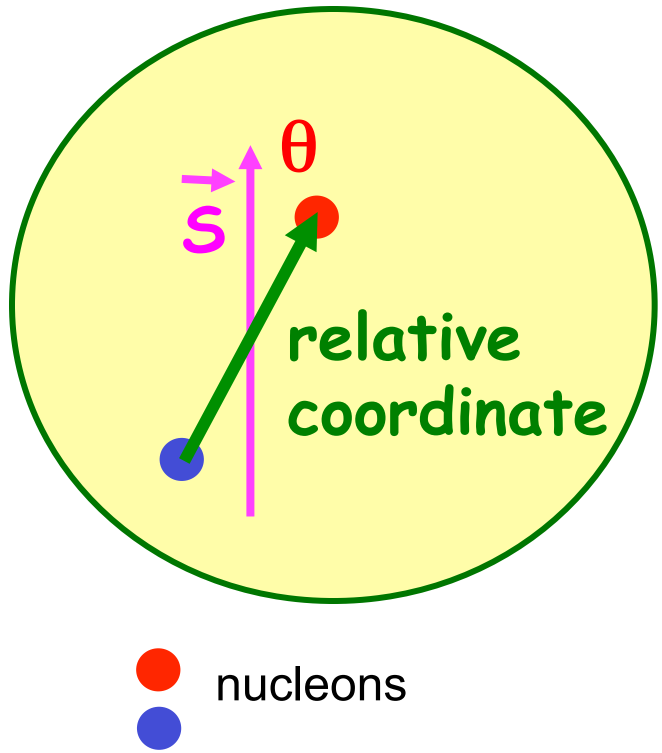
How does the tensor force work ?

Spin of each nucleon ↑ is parallel, because the total spin must be S=1

The potential has the following dependence on the angle θ with respect to the total spin $\vec{S}$.

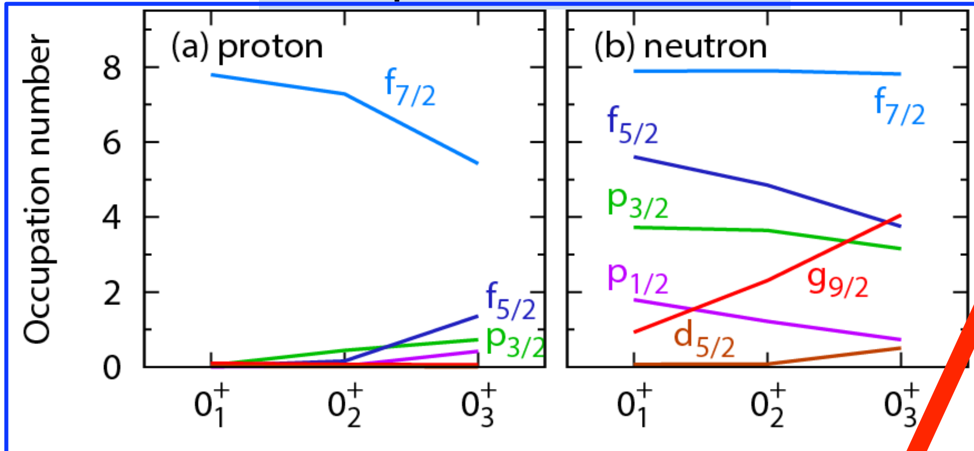
$$V \sim Y_{2,0} \sim 1 - 3\cos^2\theta$$





^{68}Ni 0^+ states

occupation numbers



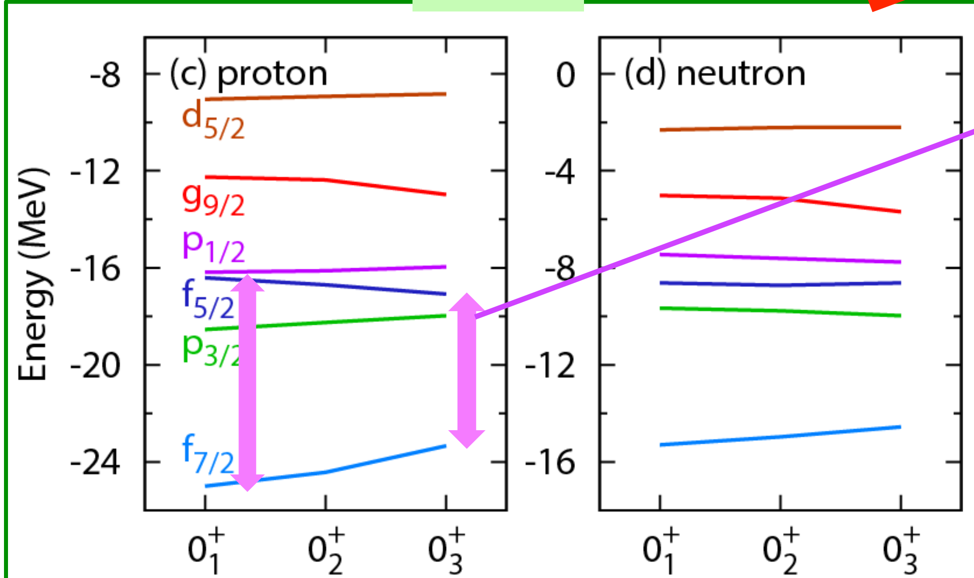
effective single-particle energies (ESPE) for correlated eigenstate

$$\epsilon_j = < \frac{\partial H_m}{\partial n_j} >$$

H_m monopole part of H

< > : by actual occup. numbers

ESPE



Gaps