A presentation supported by the JSPS Core-to-Core Program International Research Network for **E**xotic **F**emto **S**ystems **(EFES)**

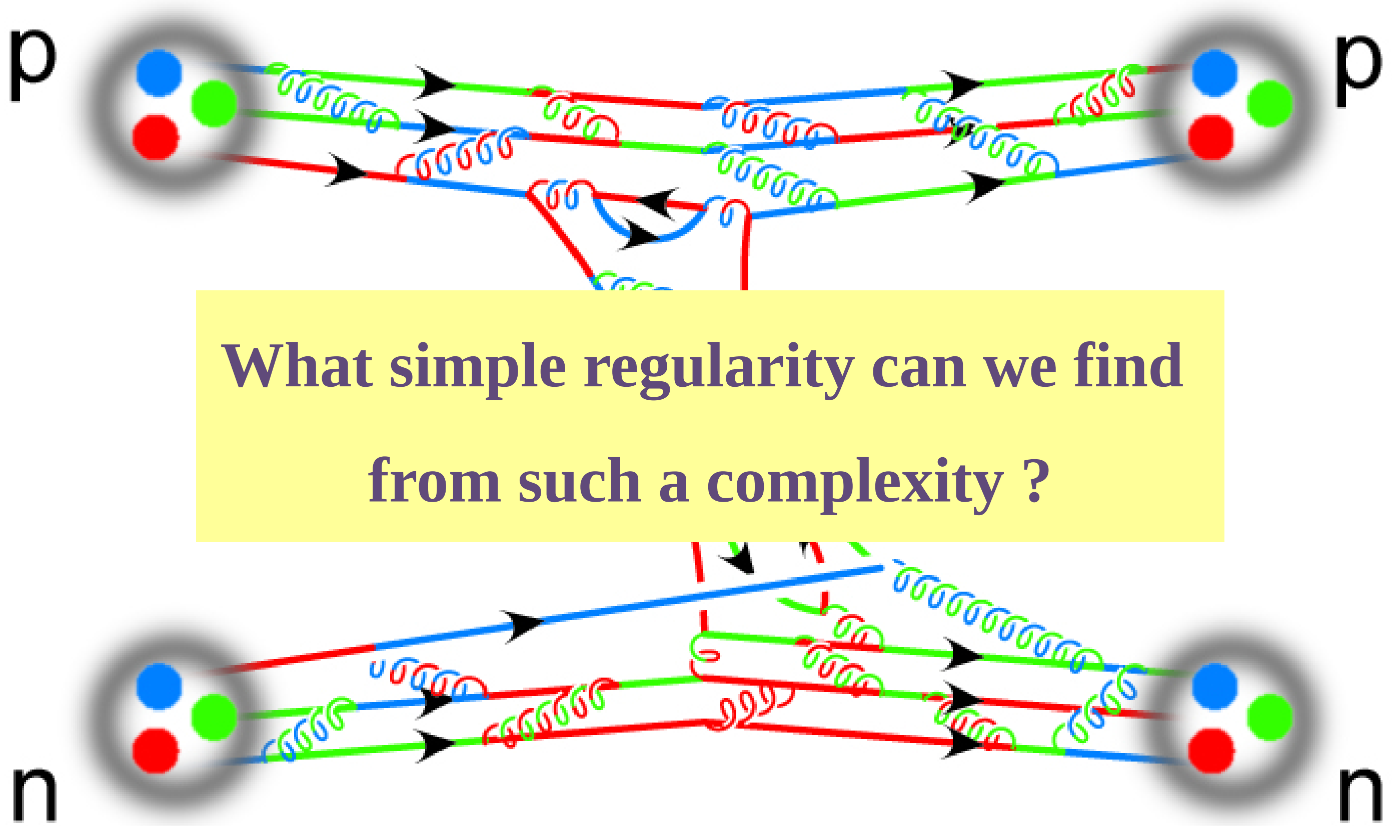
EMMI Physics Days
GSI, Darmstadt
November 3, 2010

Neutron-rich Exotic Nuclei and Nuclear Forces

Takaharu Otsuka
University of Tokyo / MSU

22時57分

Graphical Image of NN force



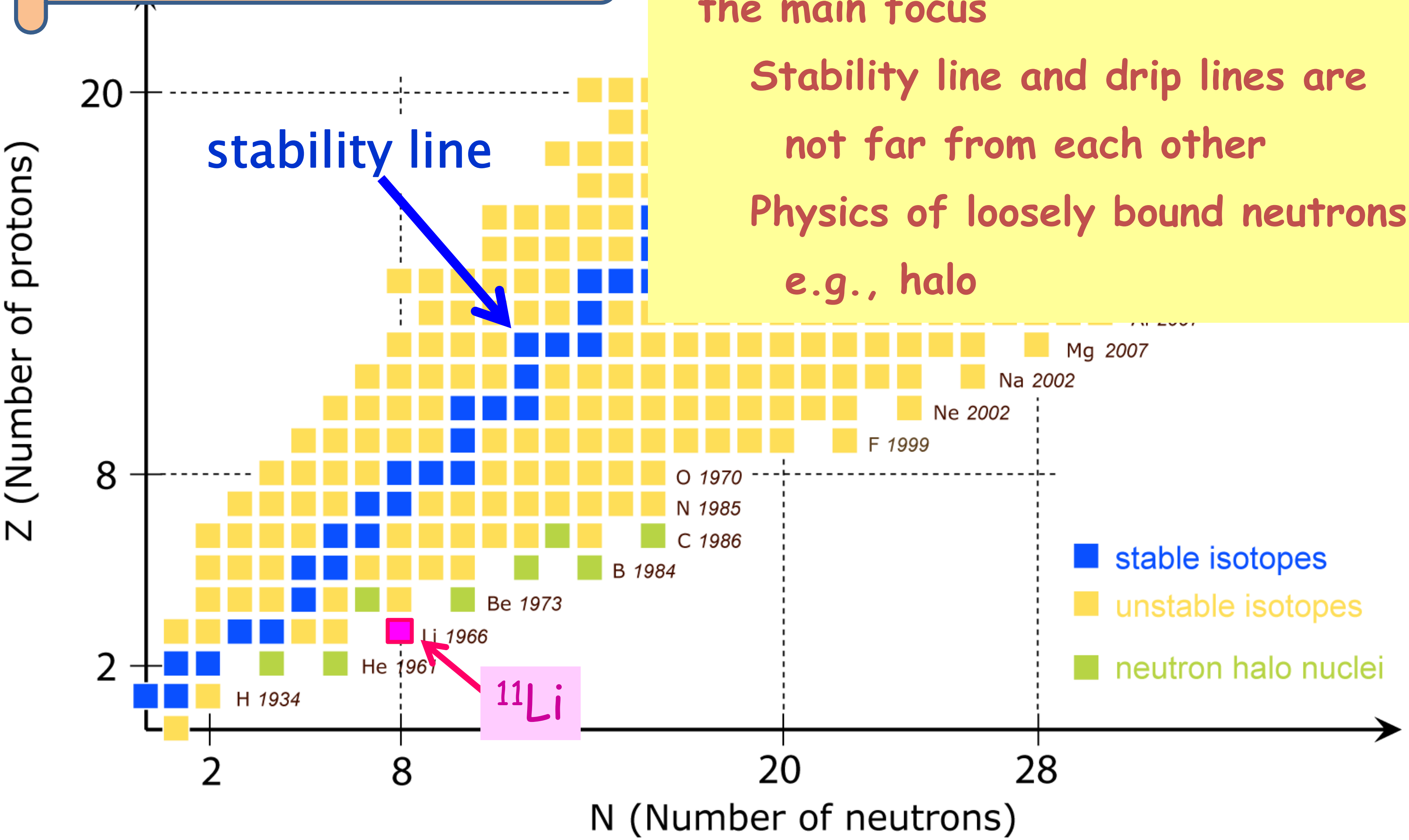
What simple regularity can we find from such a complexity ?

Image Bank (ph004), School of Science, University of Tokyo

Nuclear Chart
- Left Lower Part -

At early stage of physics on exotic nuclei, lighter (small Z) nuclei were the main focus

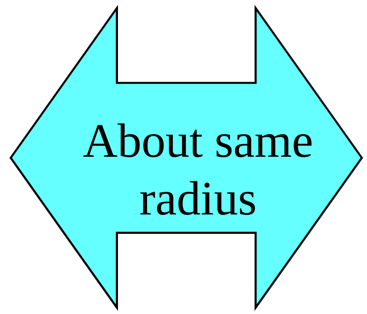
- Stability line and drip lines are not far from each other
- Physics of loosely bound neutrons, e.g., halo

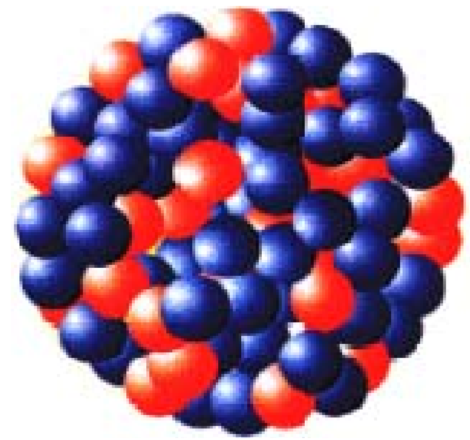


Neutron halo

Strong tunneling of loosely bound excess neutrons

^{11}Li





^{208}Pb

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS

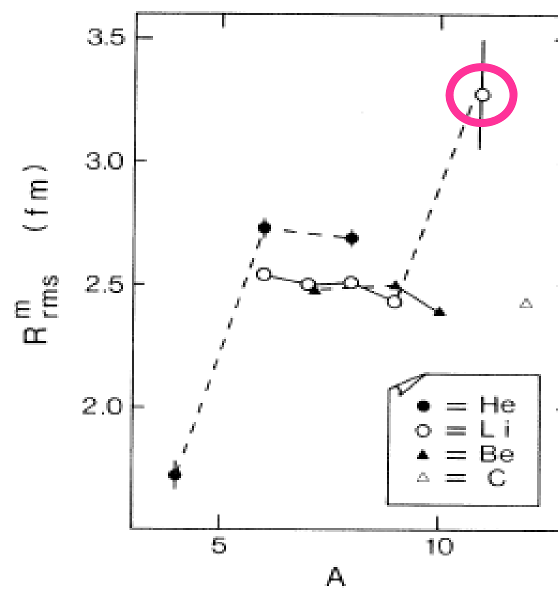
Measurements of Interaction Cross Sections and Nuclear Radii in the

I. Tanihata,[a] H. Hamagaki, O. Hashimoto, Y. Shida, and N. Yosh
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Jaj

K. Sugimoto,[b] O. Yamakawa, and T. Kobayashi
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkele

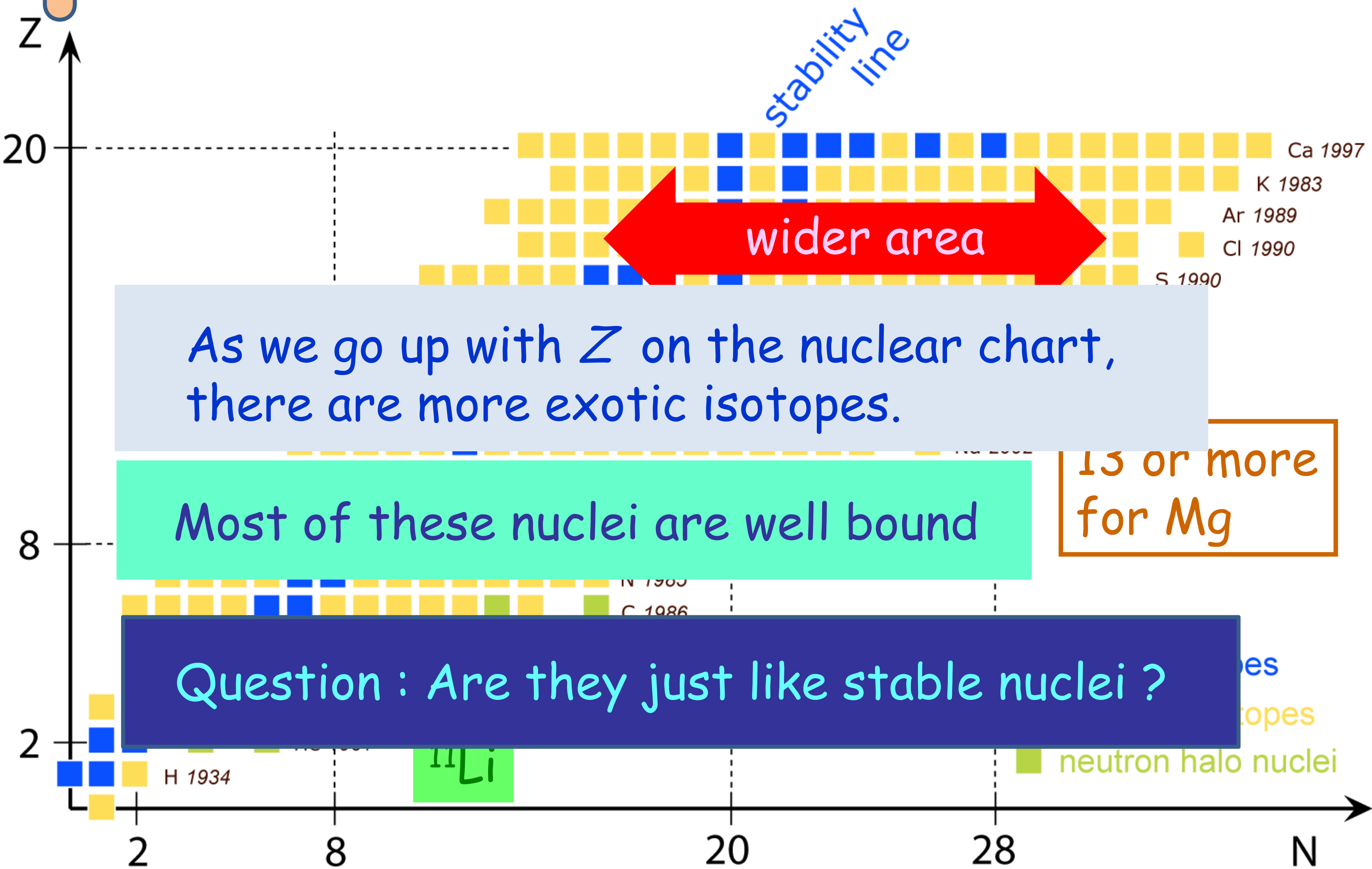
and

N. Takahashi



Nuclear Chart - Left Lower Part -

For Z larger, more exotic isotopes.



As we go up with Z on the nuclear chart, there are more exotic isotopes.

Most of these nuclei are well bound

Question : Are they just like stable nuclei ?

How does the nuclear force work in neutron-rich exotic nuclei ?

What can we learn about the nuclear force from exotic nuclei ?

- Tensor force
- 3-body force -> Achim Schwenk's talk

Eigenvalues of HO potential

Magic numbers Mayer and Jensen (1949)

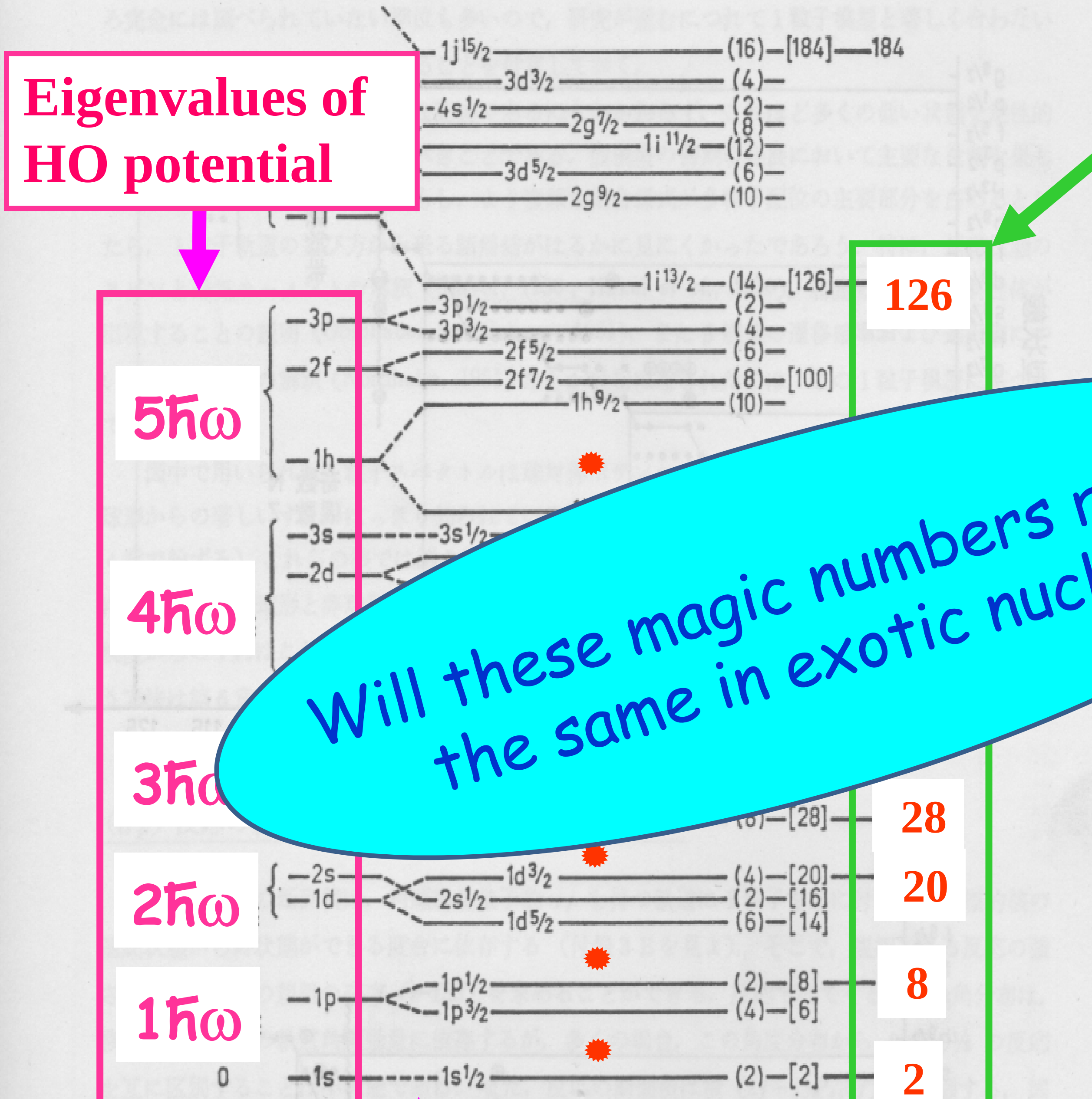
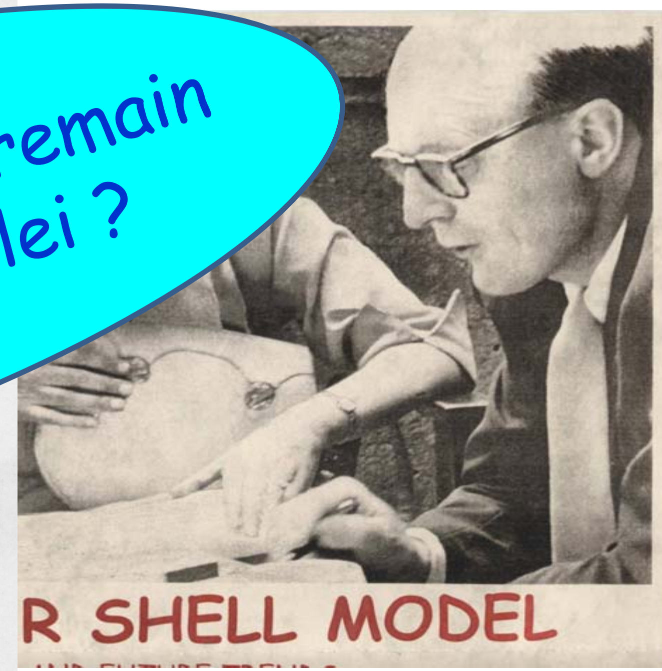


図2-23 1粒子軌道の順序. 図は M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1955 からとった.



Will these magic numbers remain the same in exotic nuclei ?

From undergraduate nuclear-physics course,

density saturation
+ short-range *NN* interaction
+ spin-orbit splitting

→ **Mayer-Jensen's magic number with rather constant gaps**
(except for gradual A dependence)

robust feature -> no way out

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

$\langle n_{j'}\rangle$ can be ~ 10 in exotic nuclei
-> effect quite relevant to neutron-rich exotic nuclei

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

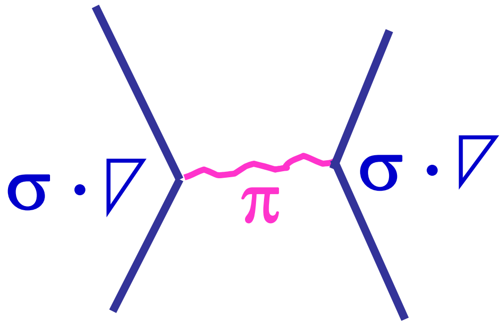
Tensor Interaction by pion exchange

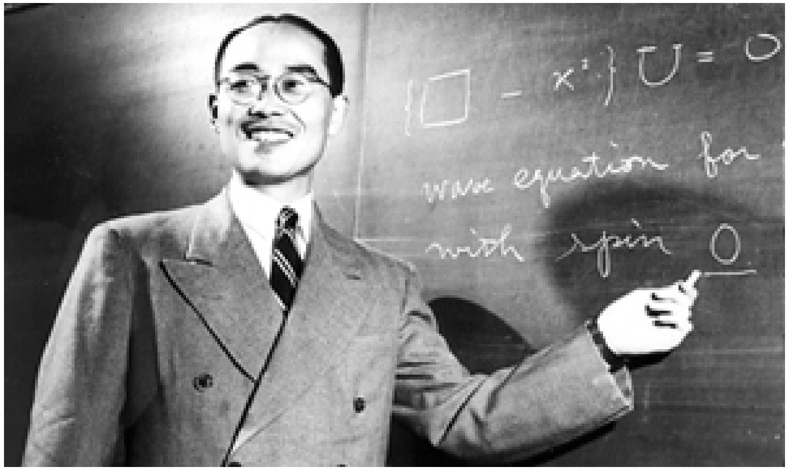
$$V_T = (\tau_1\tau_2)\,(\,[\sigma_1\sigma_2]^{(2)}\,Y^{(2)}(\Omega)\,)\,Z(r)$$

contributes only to **S=1** states

relative motion

π meson : primary source





Yukawa

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

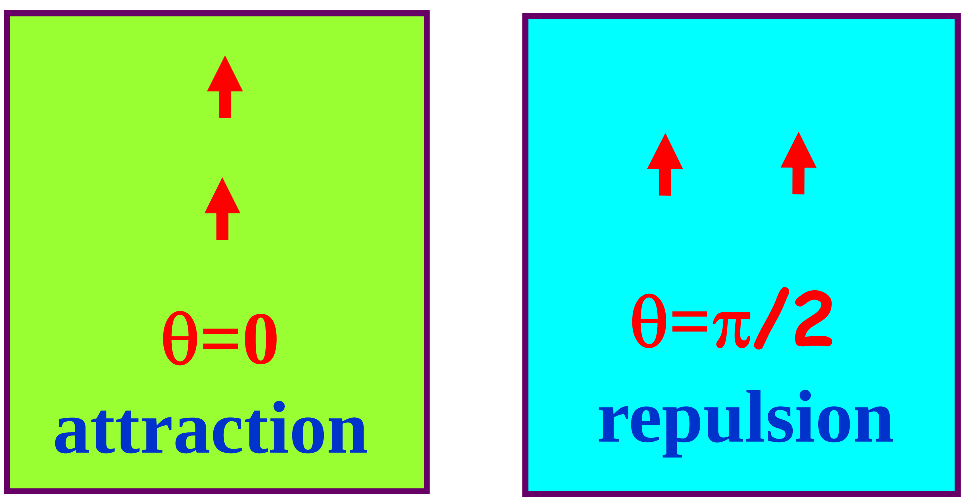
Ref: Osterfeld, Rev. Mod. Phys. 64, 491 (92)

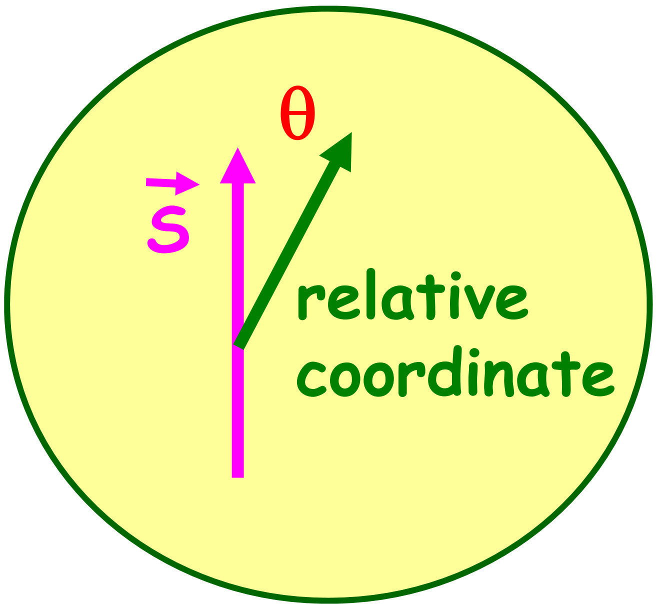
How does the tensor force work ?

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

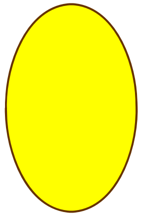
The potential has the following dependence on the angle θ with respect to the total spin $\vec{S}$.

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

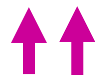




Monopole effects due to the tensor force
- An intuitive picture -

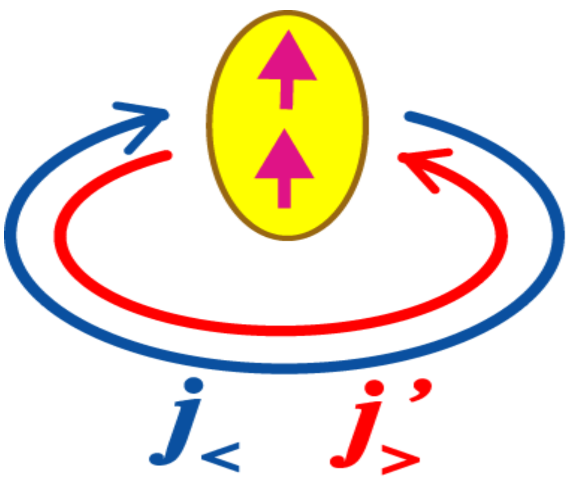


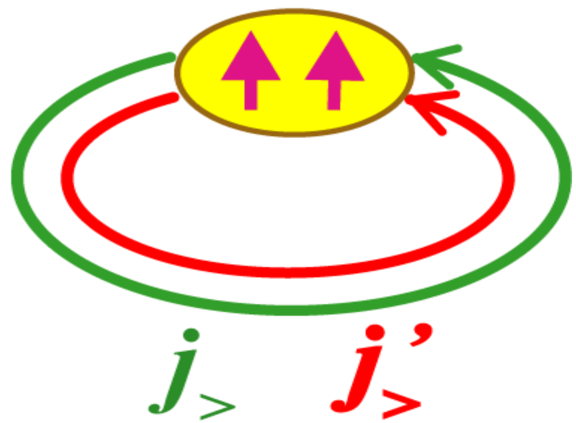
wave function of relative motion



spin of nucleon

large relative momentum **small relative momentum**





attractive **repulsive**

$$j_> = l + \frac{1}{2}, \quad j_< = l - \frac{1}{2}$$

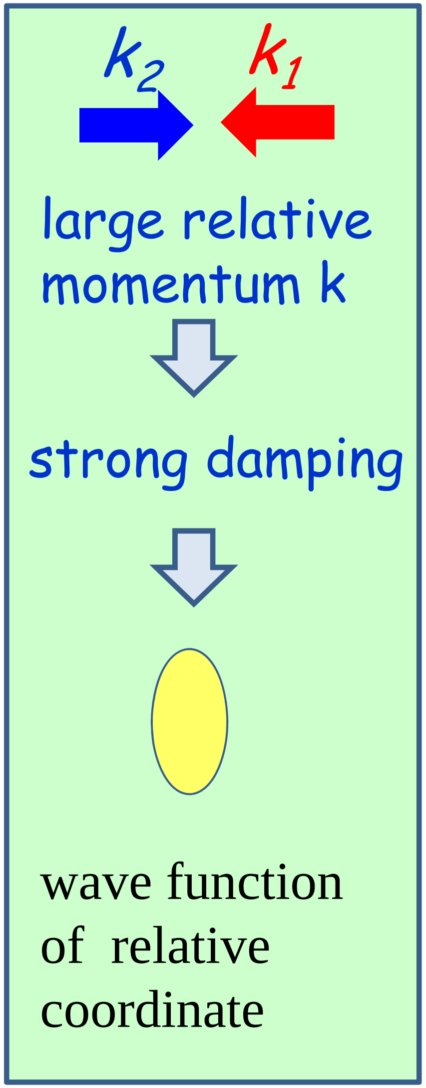
TO *et al.*, Phys. Rev. Lett. 95, 232502 (2005)

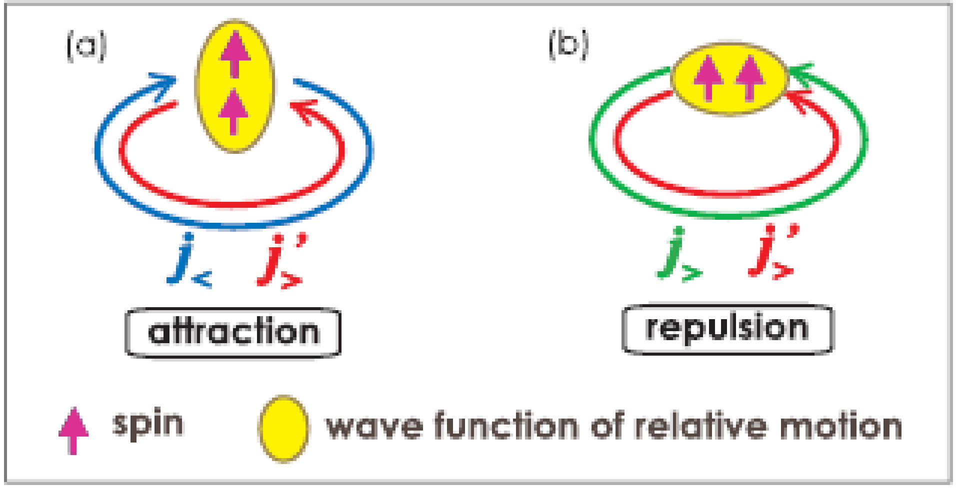
wave function when two nucleons interact

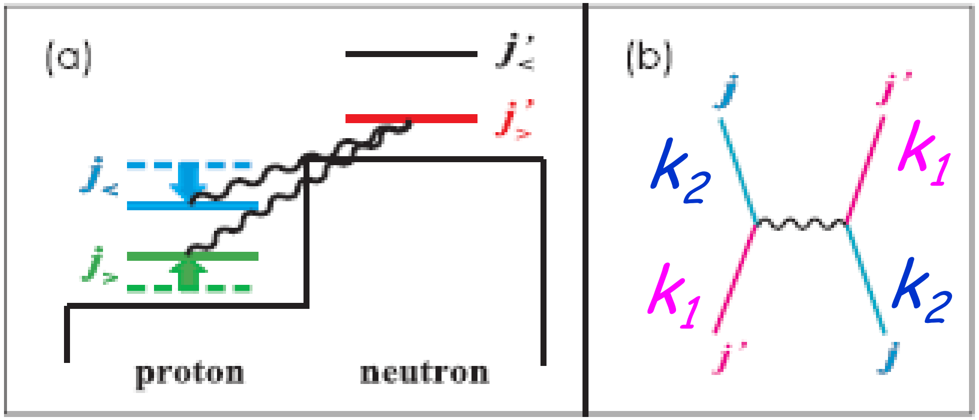
- approx. by linear motion -

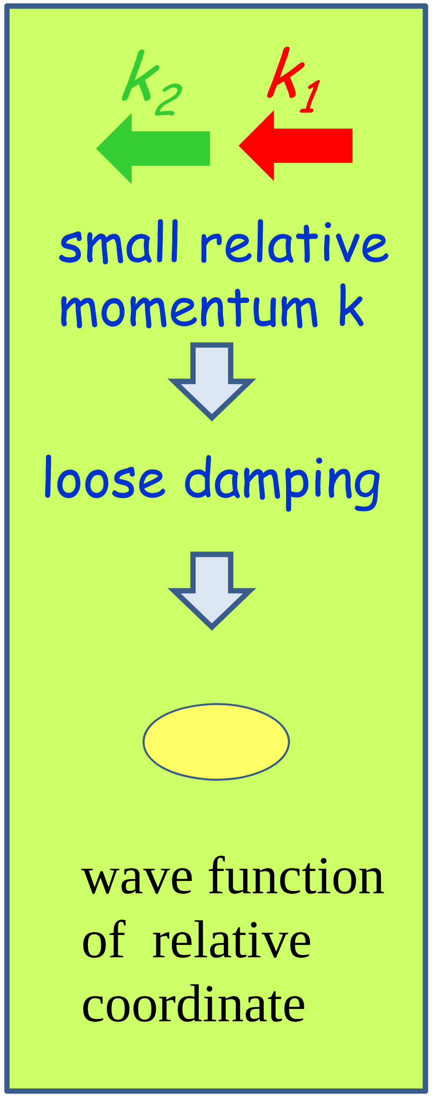
$$\Psi \propto e^{ik_1x_1}e^{ik_2x_2} + e^{ik_2x_1}e^{ik_1x_2} = 2\,e^{iKX}\cos(kx)$$

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



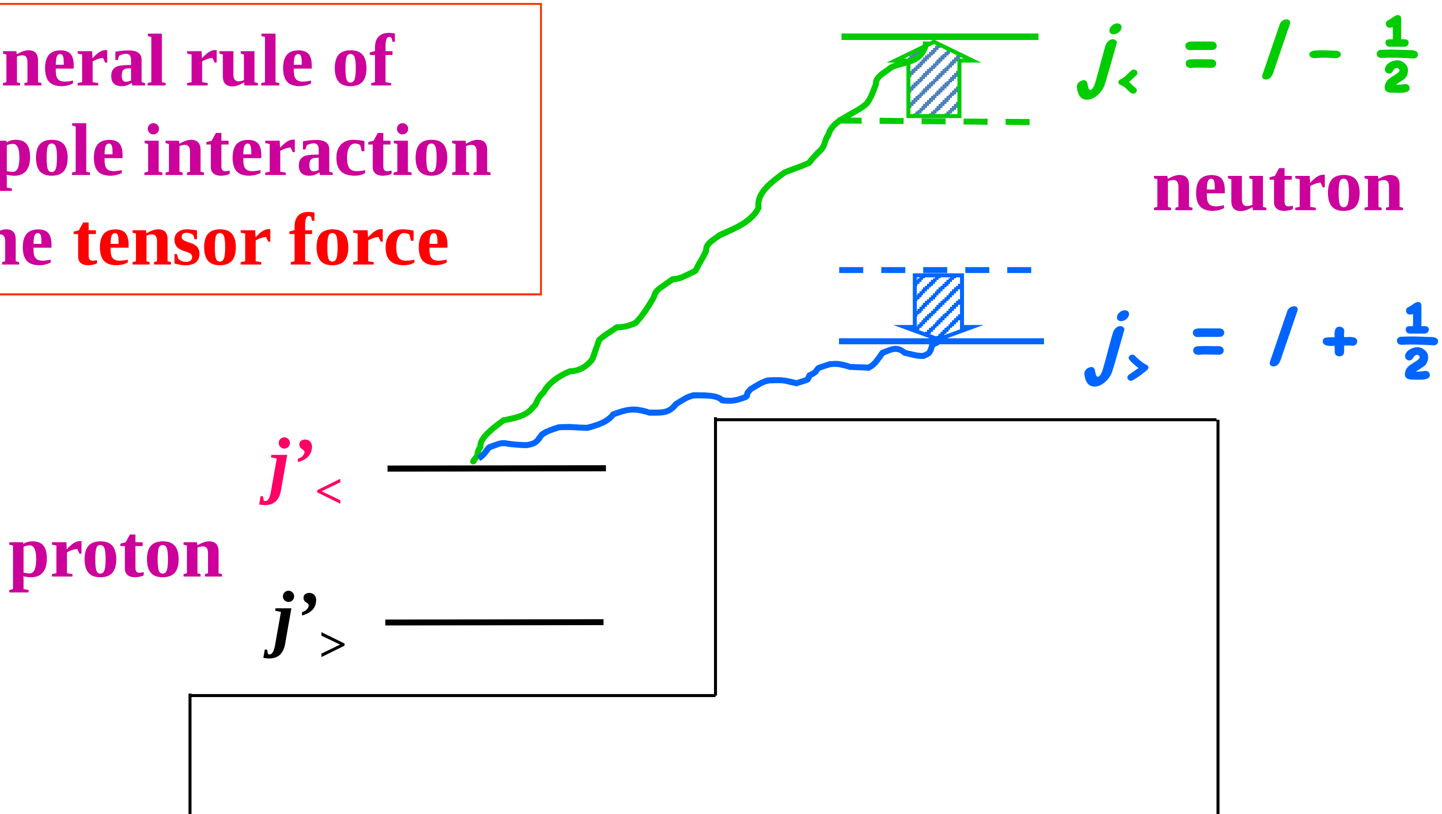






TO. *et al.*, Phys. Rev. Lett. 95, 232502 (2005)

General rule of monopole interaction of the tensor force

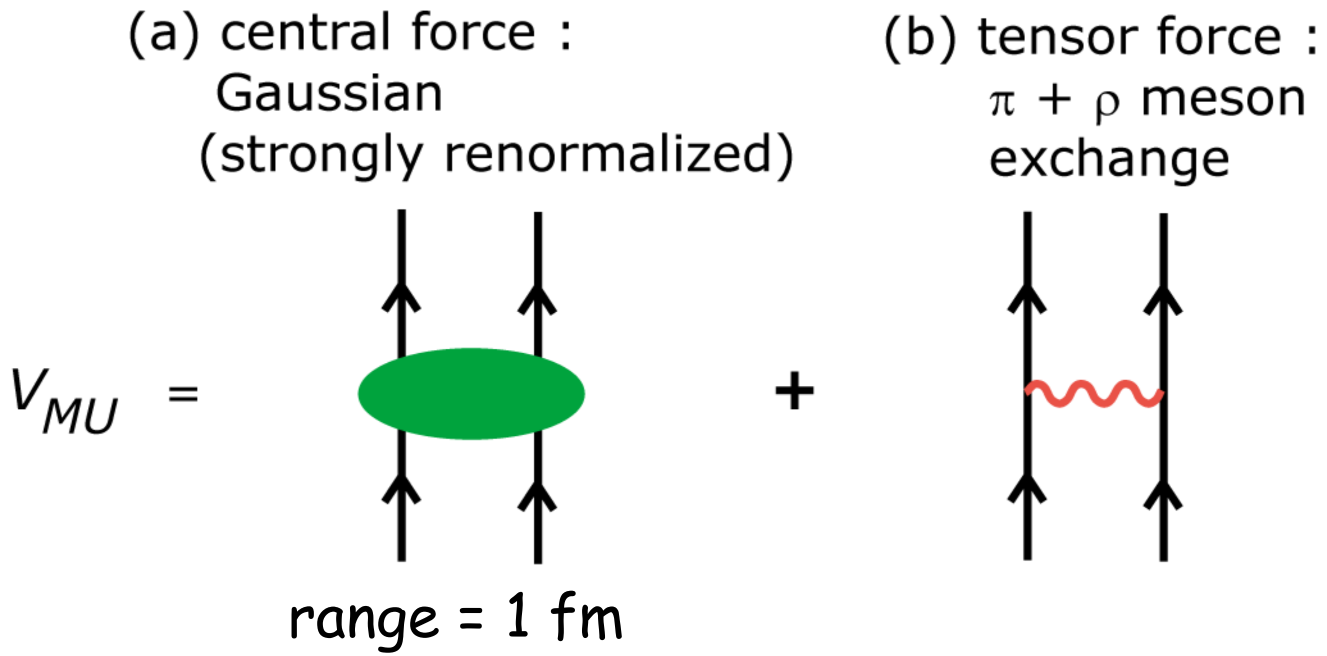


Identity for tensor monopole interaction

$$(2j_> +1)\; v_{m,T}^{(j' j_>)} + (2j_< +1)\; v_{m,T}^{(j' j_<)} = 0$$

$v_{m,T}$: monopole strength for isospin T

From a comparison to shell model interactions which can reproduce many experimental data in *sd* and *pf* shells, an extremely simple interaction "Monopole-based Universal Interaction V_{MU} has been introduced.



The same interaction for all nuclei

Similarity to Chiral Perturbation of QCD

S. Weinberg, PLB 251, 288 (1990)

Central force: strongly renormalized

tive potential gives a local coordinate-space two-nucleon potential:

$$V_{2\text{-nucleon}} = 2(C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\delta^3(\boldsymbol{x}_1 - \boldsymbol{x}_2)$$

$$-\left(\frac{2g_A}{F_\pi}\right)^2 (\boldsymbol{t}_1 \cdot \boldsymbol{t}_2)(\boldsymbol{\sigma}_1 \cdot \nabla_1)(\boldsymbol{\sigma}_2 \cdot \nabla_2) Y(|\boldsymbol{x}_1 - \boldsymbol{x}_2|)$$

$$-(1' \leftrightarrow 2'),$$

Tensor force is explicit

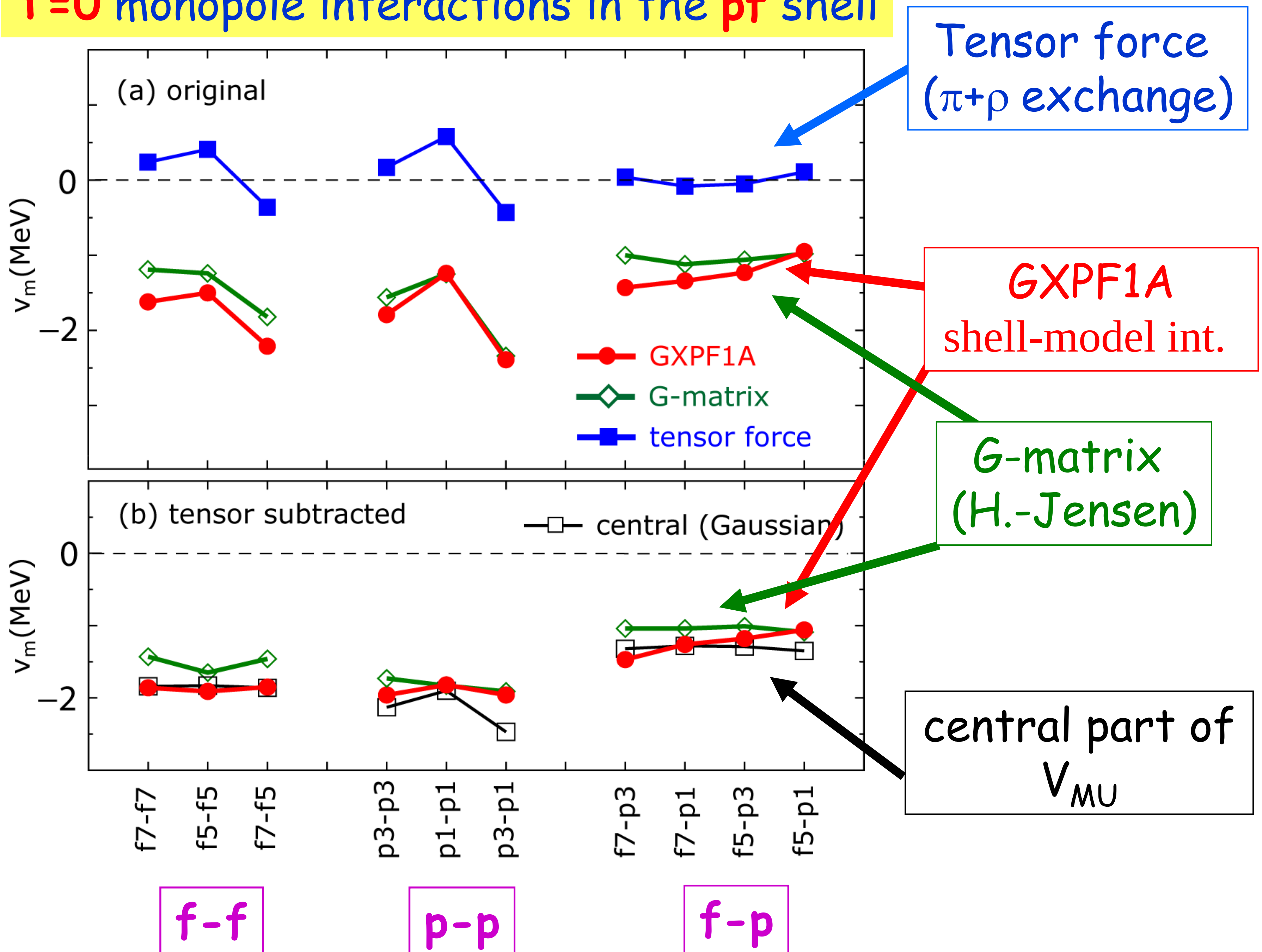
where $Y(r) \equiv \exp(-m_\pi r)/4\pi r$ is the usual Yukawa potential. [Throughout it should be understood that these are local potentials, containing a delta function factor like $\delta^3(\boldsymbol{x}'_1 - \boldsymbol{x}_1)$ for each nucleon.]

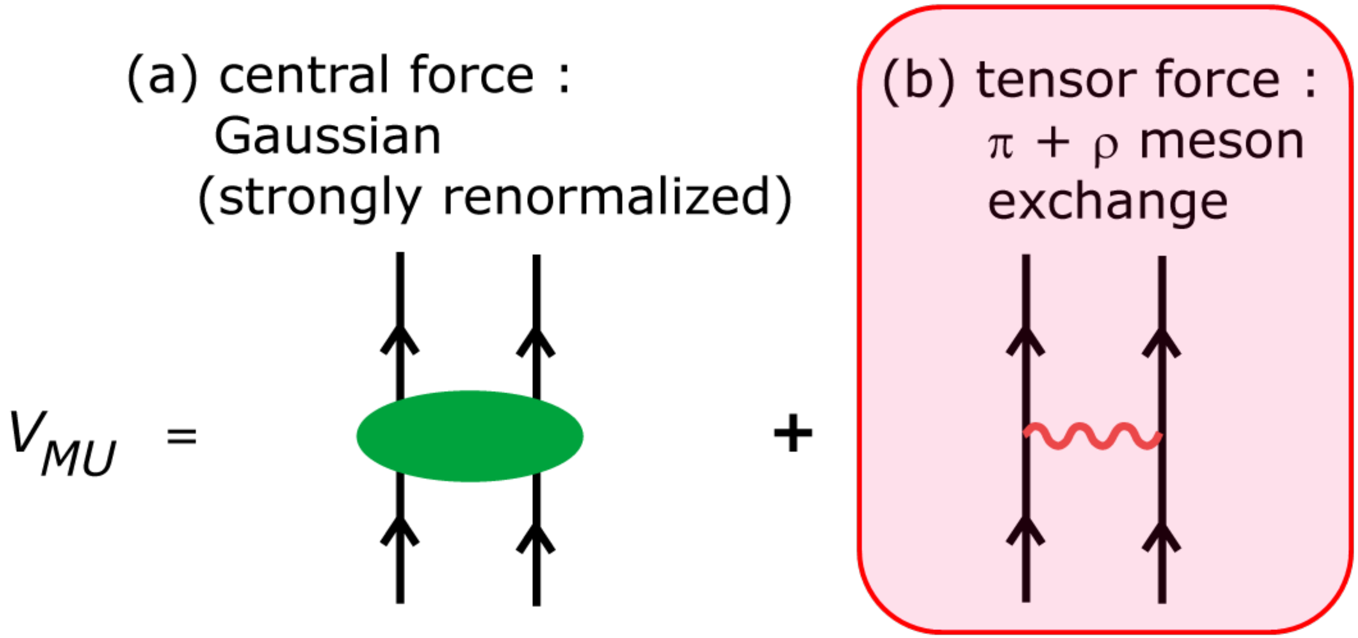
In nuclei

finite range (Gaussian)

$\pi + \rho$ exchange

T=0 monopole interactions in the pf shell



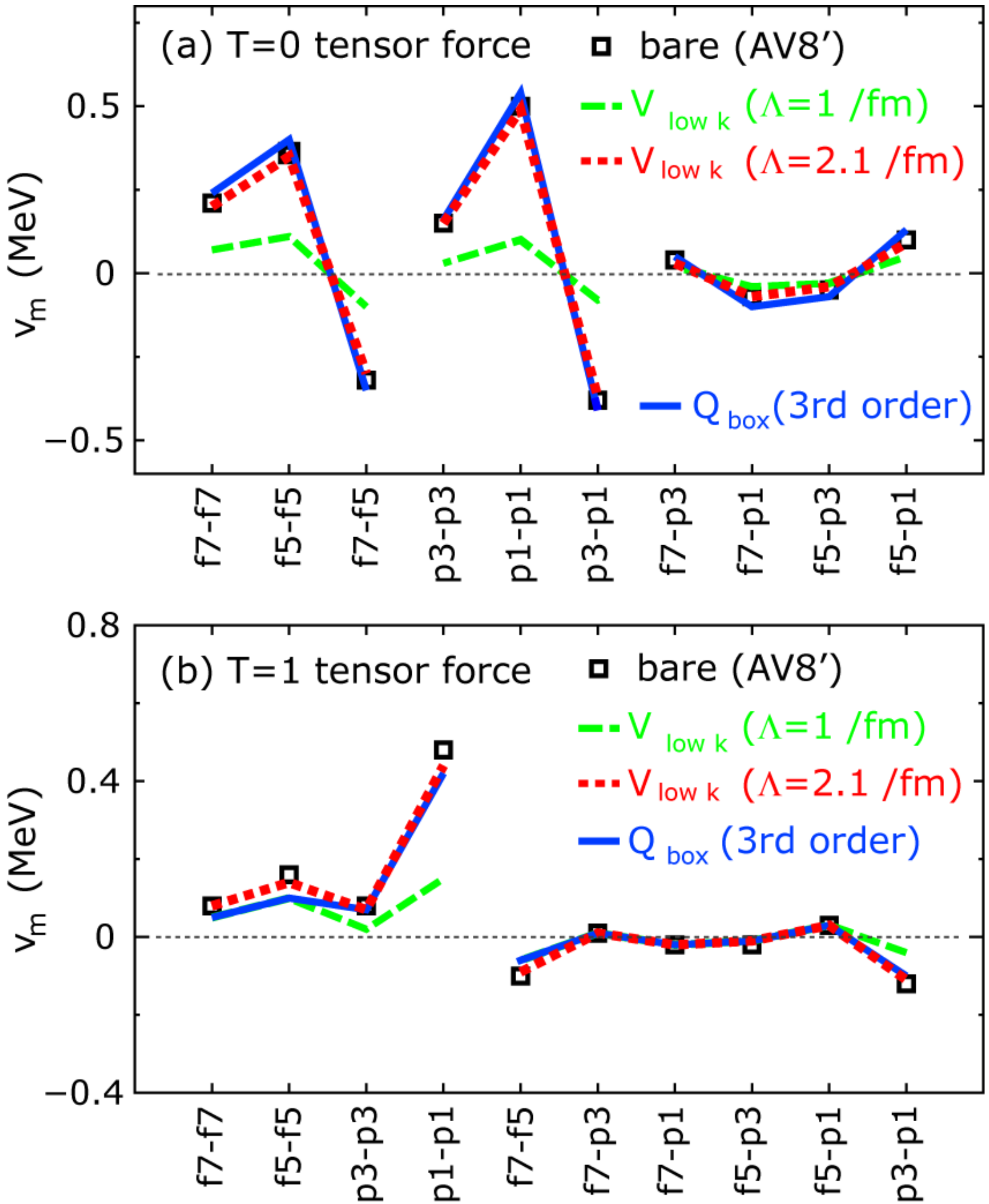


monopole component of tensor force **in nuclear medium**

almost equal ?

monopole component of tensor force **in free space**

Treatment of tensor force by $V_{low\ k}$ and Q box (3rd order)



Monopole component of tensor interactions in *pf* shell

□ Bare (AV8′)

⇩ short-range correlation by $V_{low\ k}$

- - -

⇩ in-medium correction with intermediate states (> 10 hw, 3rd order)

—

- - - only for comparison

$V_{low\ k}$: Bogner, Kuo, Schwenk

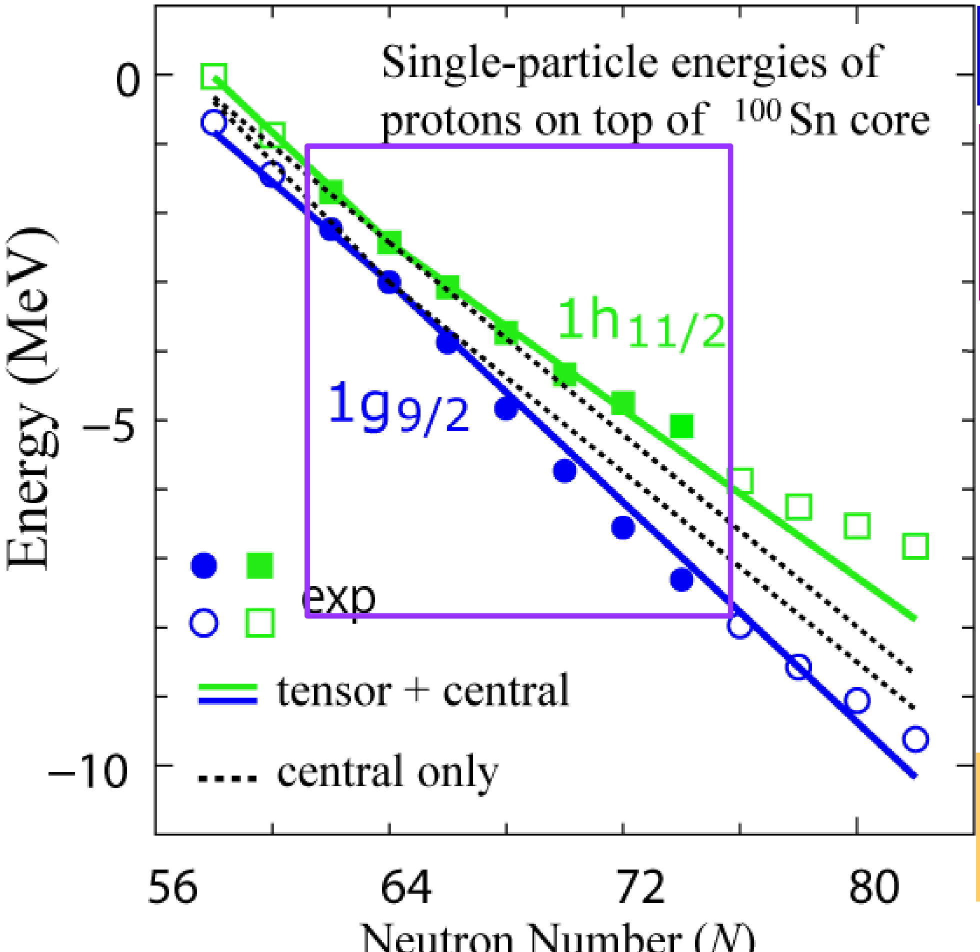
Test by experiments

An example with $_{51}$Sb isotopes

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]



Z=51 (= 50 + 1) isotopes

change driven by neutrons in $1h_{11/2}$

tensor force
(splitting increased by ~ 2 MeV)

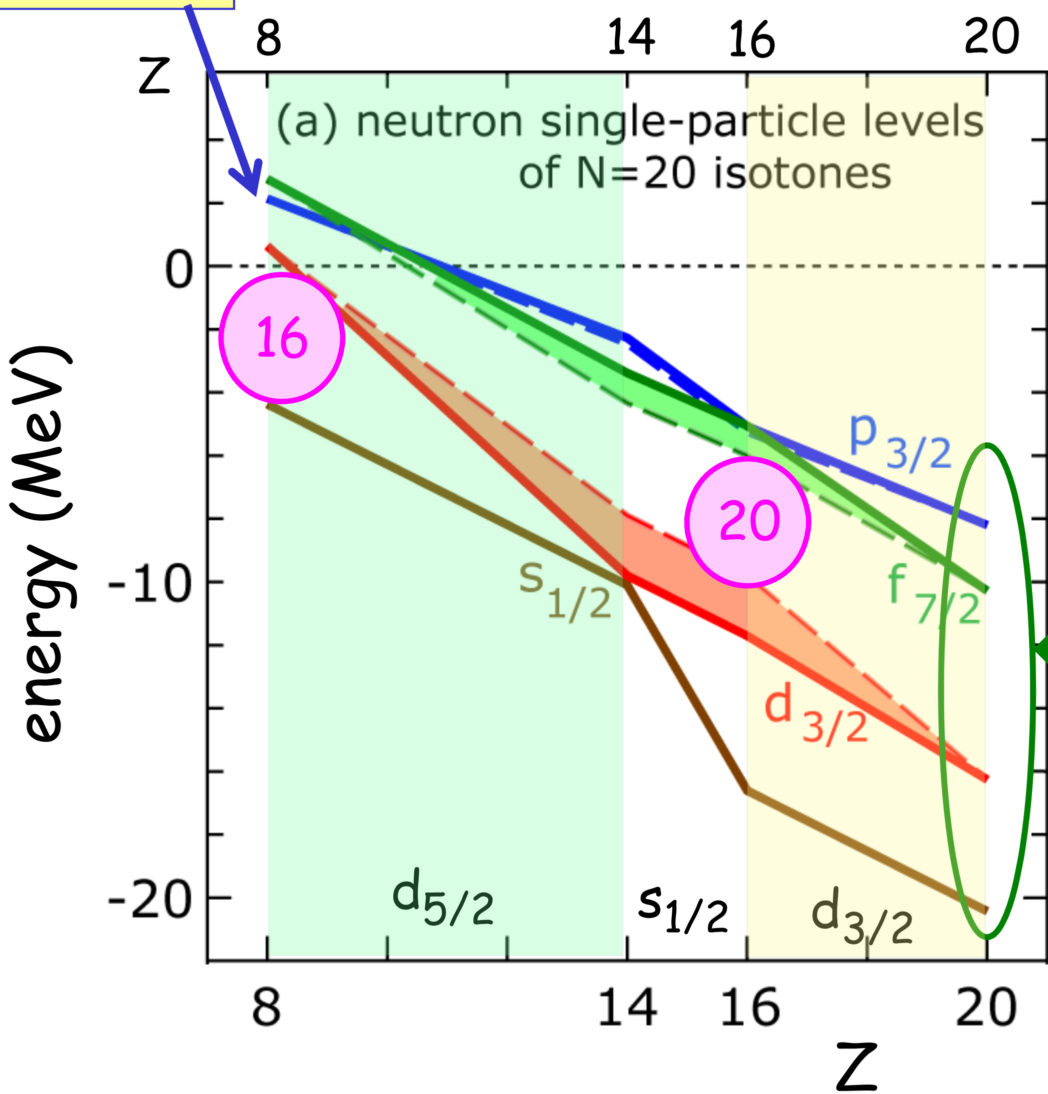
$h_{11/2}$ - $h_{11/2}$ repulsive

$h_{11/2}$ - $g_{7/2}$ attractive

No mean field theory, (Skyrme, Gogny, RMF) explained this before.

Neutron single-particle energies at N=20 for Z=8~20

$p_{3/2}$ low



solid line : full
(central + tensor)

dashed line : central only

Tensor force makes changes more dramatic.

These single-particle energies are "normal"

$f_{7/2}$-$p_{3/2}$ 2~3 MeV
N=20 gap ~ 6 MeV

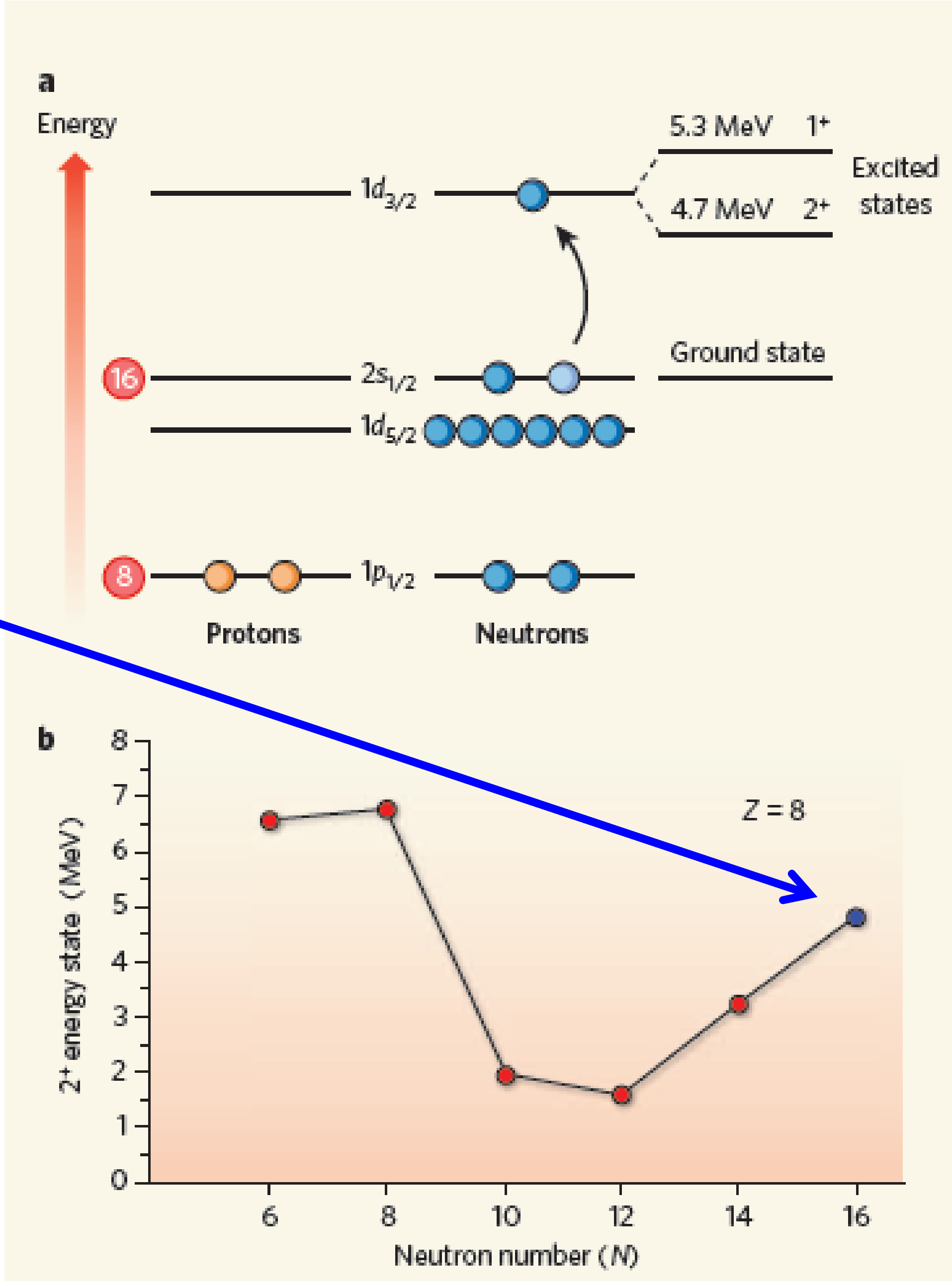
NATURE|Vol 459|25 June 2009

NUCLEAR PHYSICS

Unexpected doubly magic nucleus

Robert V. F. Janssens

Nuclei with a 'magic' number of both protons and neutrons, dubbed doubly magic, are particularly stable. The oxygen isotope ^{24}O has been found to be one such nucleus — yet it lies just at the limit of stability.



Increase of 2+ excitation energy

1. Kanungo, R. *et al.* *Phys. Rev. Lett.* **102**, 152501 (2009).
2. Hoffman, C. R. *et al.* *Phys. Lett. B* **672**, 17–21 (2009).
3. Warner, D. *Nature* **430**, 517–519 (2004).
4. Janssens, R. V. F. *Nature* **435**, 897–898 (2005).
5. Warner, D. *Nature* **425**, 570–571 (2003).
6. Baumann, T. *et al.* *Nucl. Instrum. Meth. A* **543**, 517–527 (2005).
7. Sakurai, H. *et al.* *Phys. Lett. B* **448**, 180–184 (1999).
8. Otsuka, T. *et al.* *Phys. Rev. Lett.* **87**, 082502 (2001).

Consistent with recent experiment

- Position of $p_{3/2}$

One of the Day 1 experiments at **RIBF** by Nakamura et al.

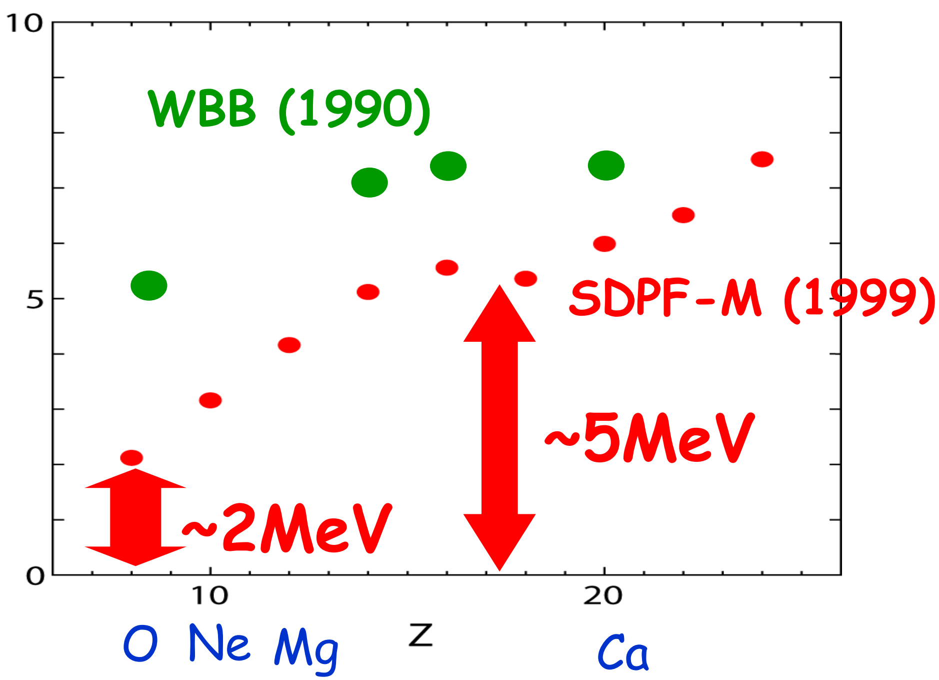
PRL **103,** 262501 (2009) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2009

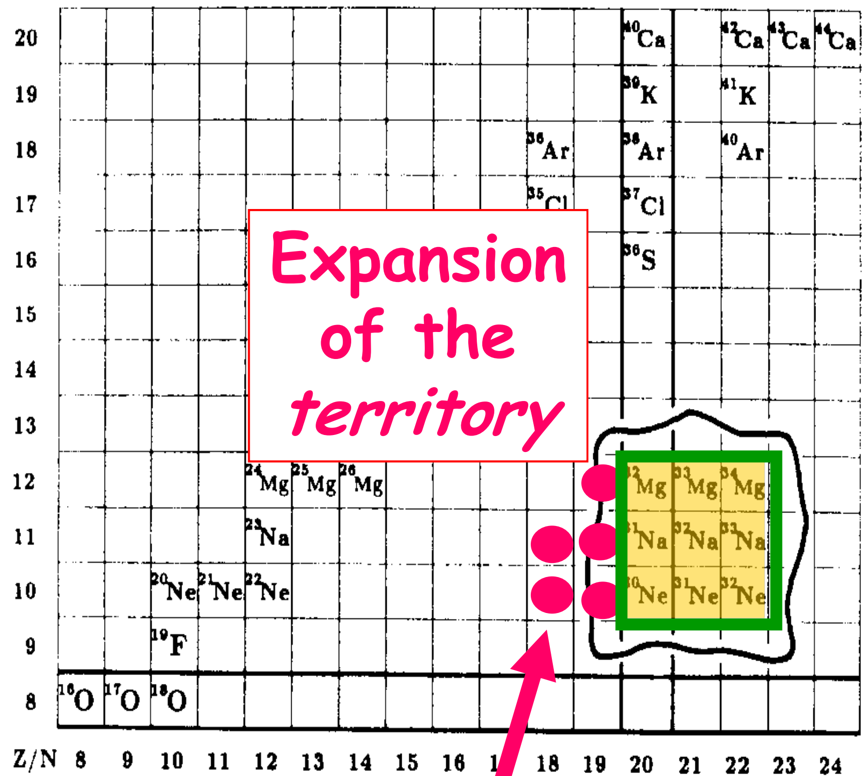
Halo Structure of the Island of Inversion Nucleus ^{31}Ne

T. Nakamura,[1] N. Kobayashi,[1] Y. Kondo,[1] Y. Satou,[1] N. Aoi,[2] H. Baba,[2] S. Deguchi,[1] N. Fukuda,[2] J. Gibelin,[3] N. Inabe,[2] M. Ishihara,[2] D. Kameda,[2] Y. Kawada,[1] T. Kubo,[2] K. Kusaka,[2] A. Mengoni,[4] T. Motobayashi,[2] T. Ohnishi,[2] M. Ohtake,[2] N. A. Orr,[3] H. Otsu,[2] T. Otsuka,[5] A. Saito,[5] H. Sakurai,[2] S. Shimoura,[5] T. Sumikama,[6] H. Takeda,[2] E. Takeshita,[2] M. Takechi,[2] S. Takeuchi,[2] K. Tanaka,[2] K. N. Tanaka,[1] N. Tanaka,[1] Y. Togano,[2] Y. Utsuno,[7] K. Yoneda,[2] A. Yoshida,[2] and K. Yoshida[2]

Monte Carlo Shell Model (MCSM) results have been obtained by the SDPF-M interaction for the full-*sd* + *f7/2* + *p3/2* space.

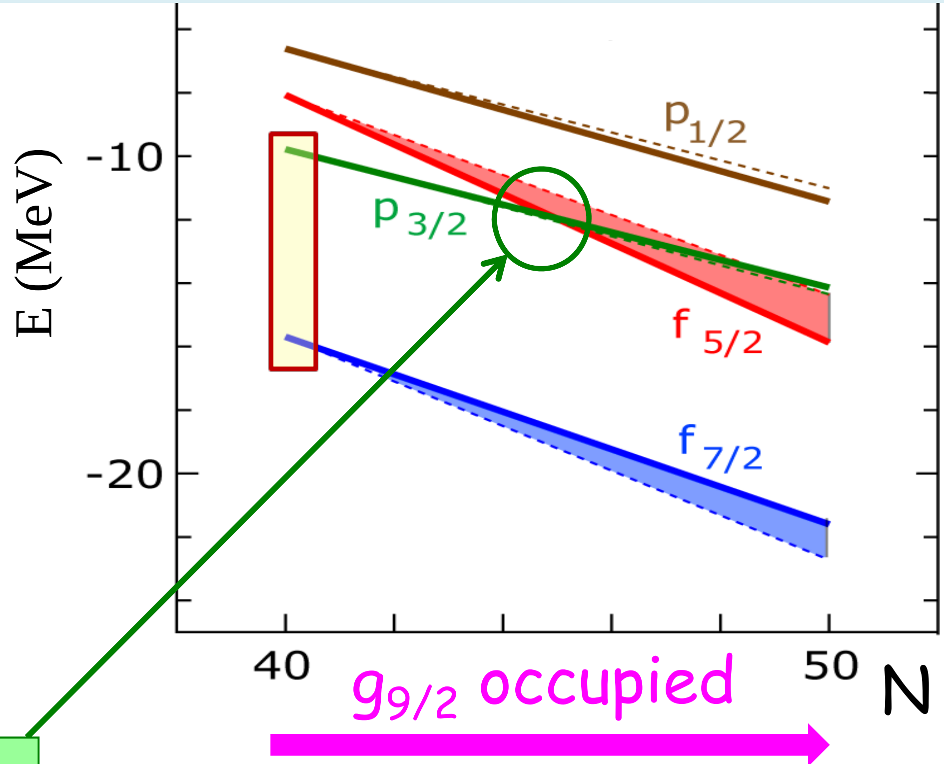
Effective N=20 gap between sd and pf shells





Neyens *et al.* 2005 **Mg**
Tripathi *et al.* 2005 **Na**
Dombradi *et al.* 2006 **Ne**
Terry *et al.* 2007 **Ne**

Proton single-particles levels of Ni isotopes



Central Gaussian + Tensor

solid line: full effect

dotted line: central only

shaded area : effect of tensor force

From Grawe, EPJA25, 357

Crossing here is consistent with exp. on Cu isotopes

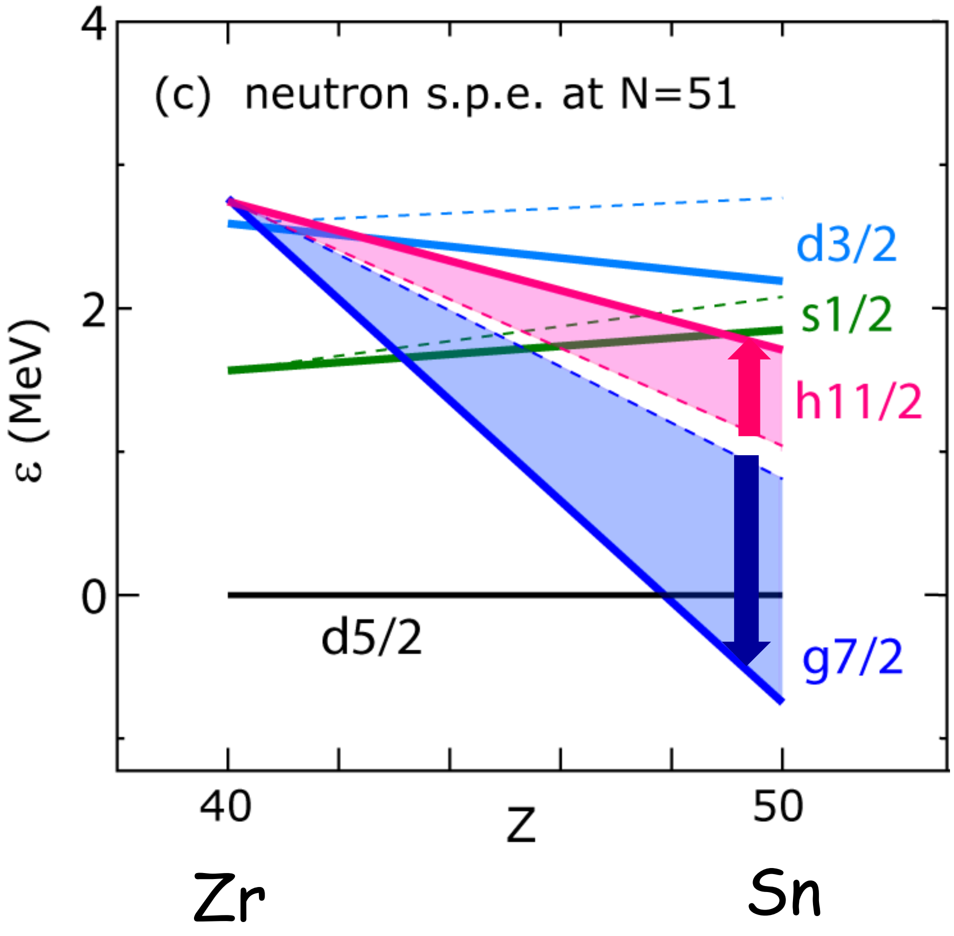
PRL 103, 142501 (2009) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2009

Nuclear Spins and Magnetic Moments of ^{71,73,75}Cu: Inversion of $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ Levels in ^{75}Cu

K. T. Flanagan,[1,2] P. Vingerhoets,[1] M. Avgoulea,[1] J. Billowes,[3] M. L. Bissell,[1] K. Blaum,[4] B. Cheal,[3] M. De Rydt,[1] V. N. Fedosseev,[5] D. H. Forest,[6] Ch. Geppert,[7,8] U. Köster,[10] M. Kowalska,[11] J. Krämer,[9] K. L. Kratz,[9] A. Krieger,[9] E. Mané,[3] B. A. Marsh,[5] T. Materna,[10] L. Mathieu,[12] P. L. Molkanov,[13] R. Neugart,[9] G. Neyens,[1] W. Nörtershäuser,[9,7] M. D. Seliverstov,[13,16] O. Serot,[12] M. Schug,[4] M. A. Sjoedin,[17] J. R. Stone,[14,15] N. J. Stone,[14,15] H. H. Stroke,[18] G. Tungate,[6] D. T. Yordanov,[4] and Yu. M. Volkov[13]

[1]*Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium*

Shell structure of a key nucleus ^{100}Sn

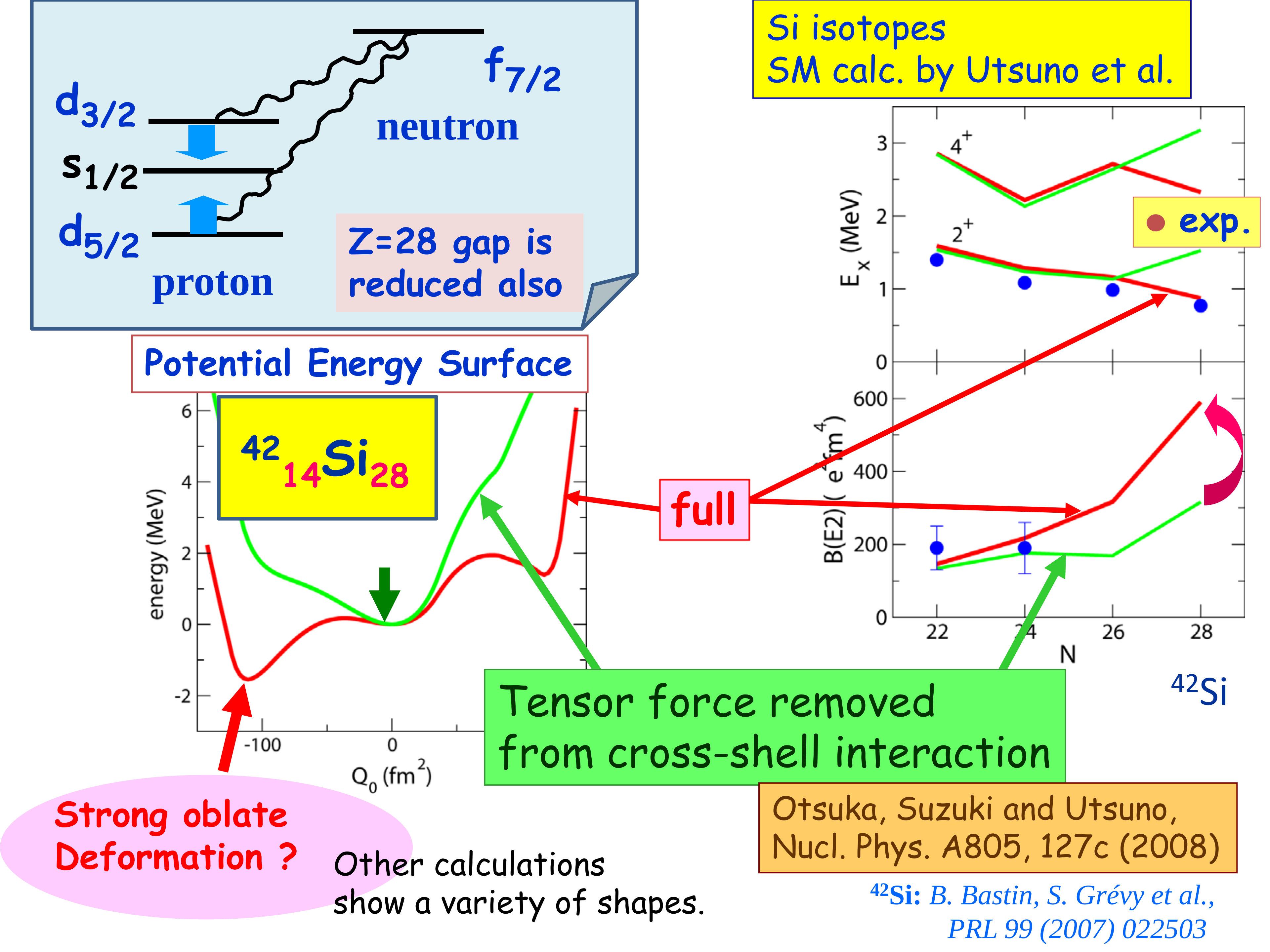


solid line : full (central + tensor)

dashed line : central only

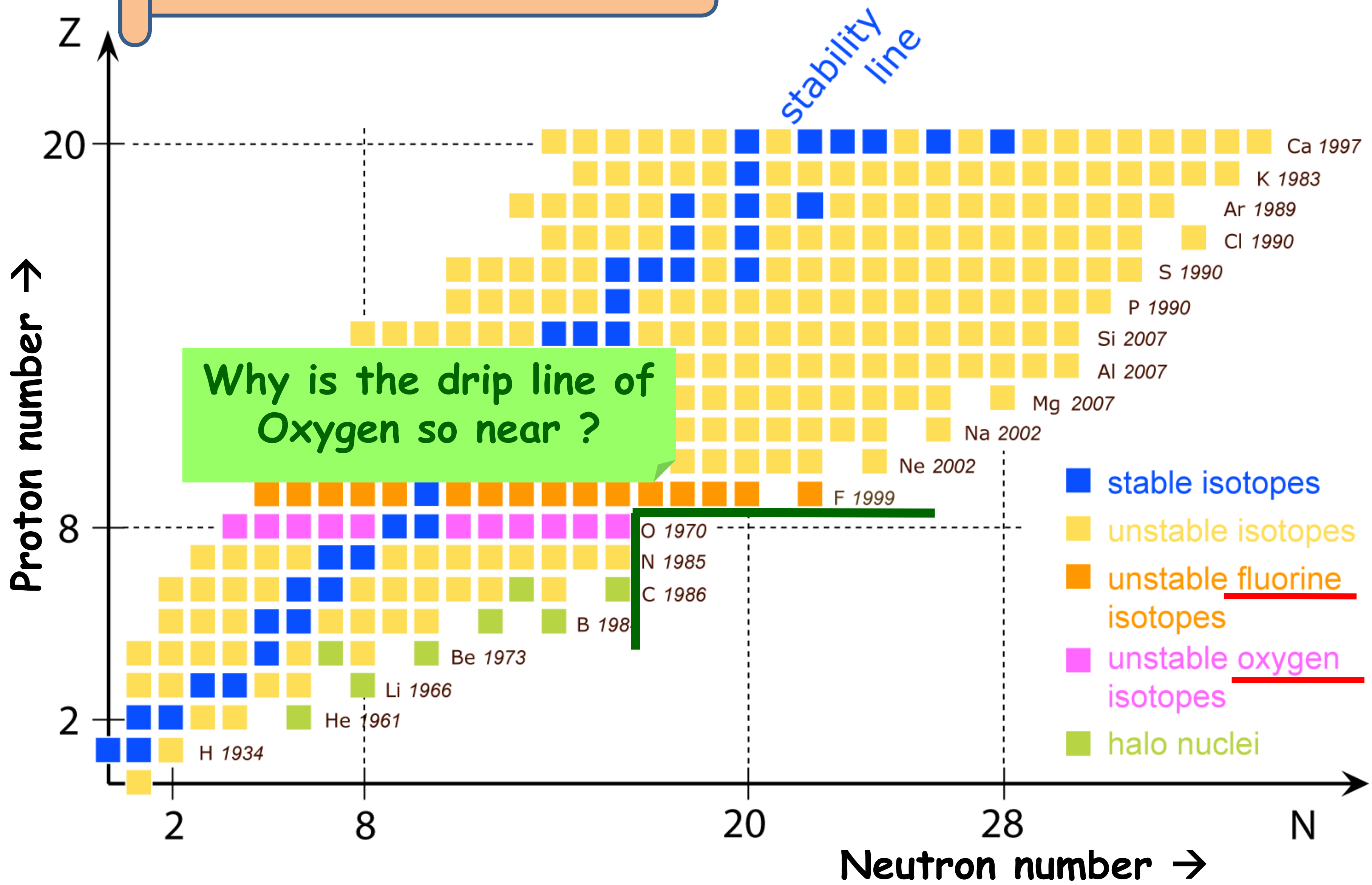
shaded area : effect of tensor force

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


d3/2
s1/2
d5/2
f7/2
neutron
proton
Z=28 gap is reduced also
Si isotopes
SM calc. by Utsuno et al.
4+
2+
exp.
Ex (MeV)
B(E2) (e2fm4)
N
22
24
26
28
0
1
2
3
200
400
600
Potential Energy Surface
42 14 Si 28
energy (MeV)
Q0 (fm2)
-100
0
6
4
2
0
-2
full
Tensor force removed
from cross-shell interaction
42Si
Strong oblate
Deformation ?
Other calculations
show a variety of shapes.
Otsuka, Suzuki and Utsuno,
Nucl. Phys. A805, 127c (2008)
42Si: B. Bastin, S. Grévy et al.,
PRL 99 (2007) 022503

Three-body force
and
exotic nuclei

Nuclear Chart
- Left Lower Part -



Why is the drip line of Oxygen so near ?

Single-Particle Energy for Oxygen isotopes

by microscopic eff. int.

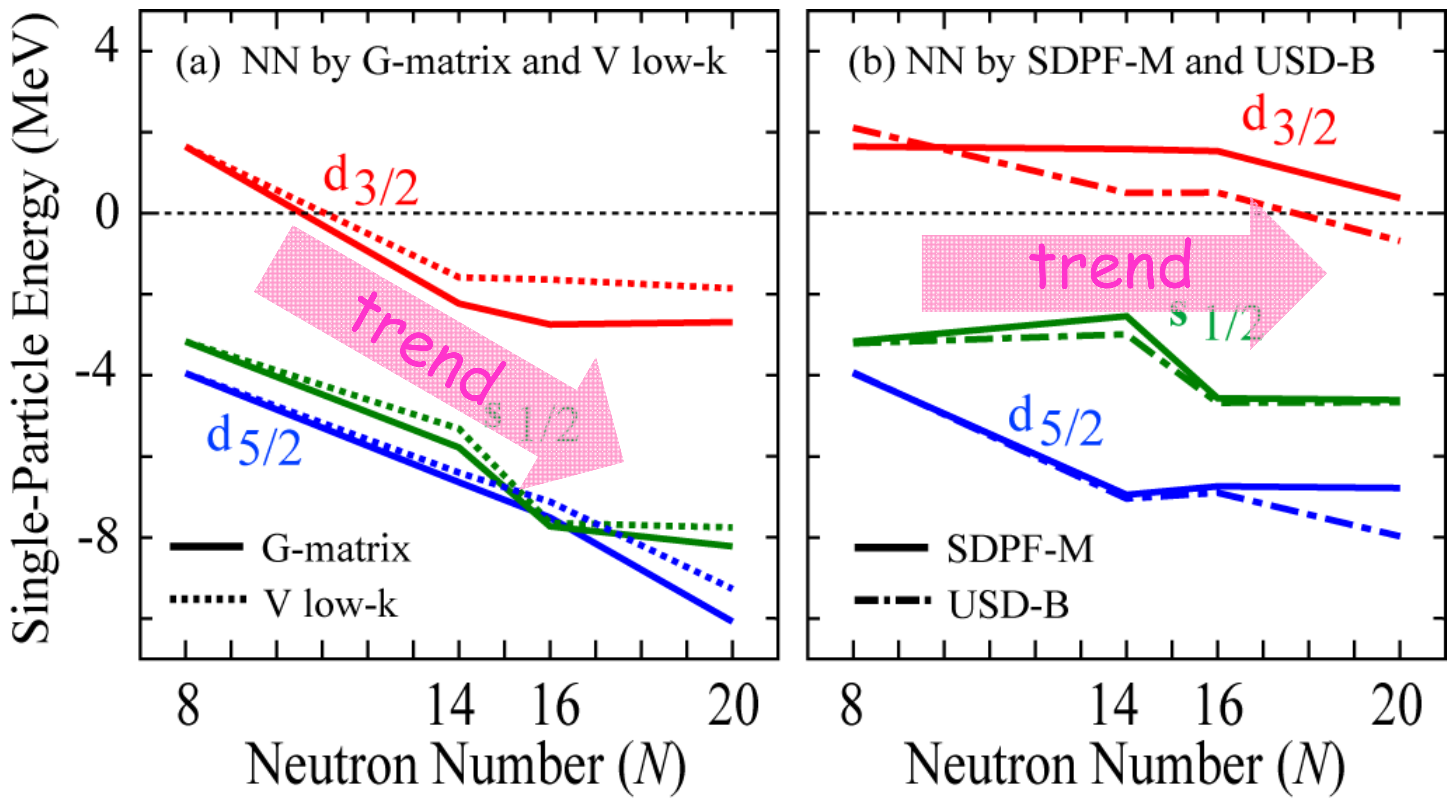
G-matrix+ core-pol. : Kuo, Brown

V_{low-k} : Bogner, Schwenk, Kuo

by phenomenological eff. int.
- G-matrix + fit -

SDPF-M — Utsuno, O., Mizusaki, Honma, Phys. Rev. C **60**, 054315 (1999)

USD-B — Brown and Richter, Phys. Rev. C **74**, 034315 (2006)



What is the origin of

the ***repulsive modification*** of

T=1 monopole matrix elements ?

The same puzzle as in the pf shell

A solution within *bare* 2-body interaction
is very unlikely
(considering efforts made so far)
Zuker, Phys. Rev. Lett. 90, 042502 (2003)

→ 3-body interaction

The clue : Fujita-Miyazawa 3N mechanism (Δ-hole excitation)

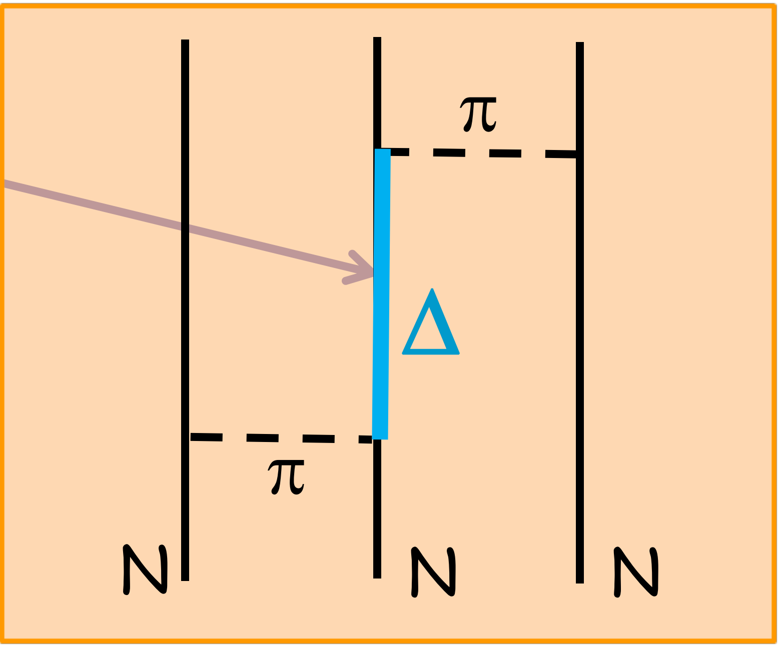
Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

Pion Theory of Three-Body Forces

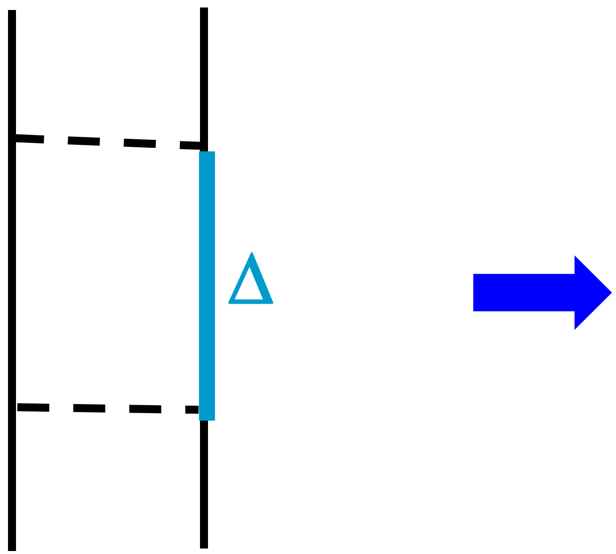
Jun-ichi FUJITA and Hironari MIYAZAWA

Miyazawa, 2007

Δ particle
m=1232 MeV
S=3/2, I=3/2



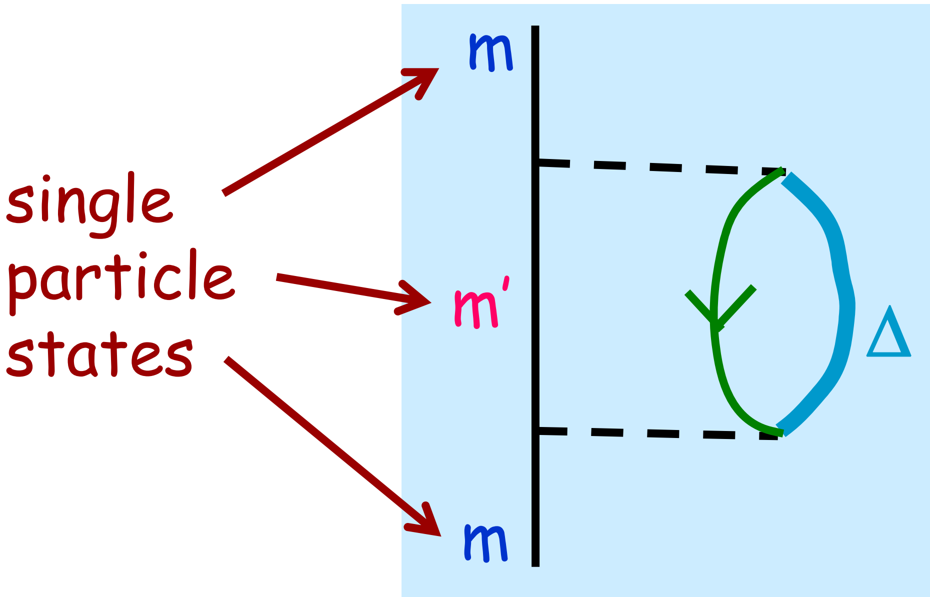
Renormalization of *NN* interaction due to Δ **excitation** in the intermediate state



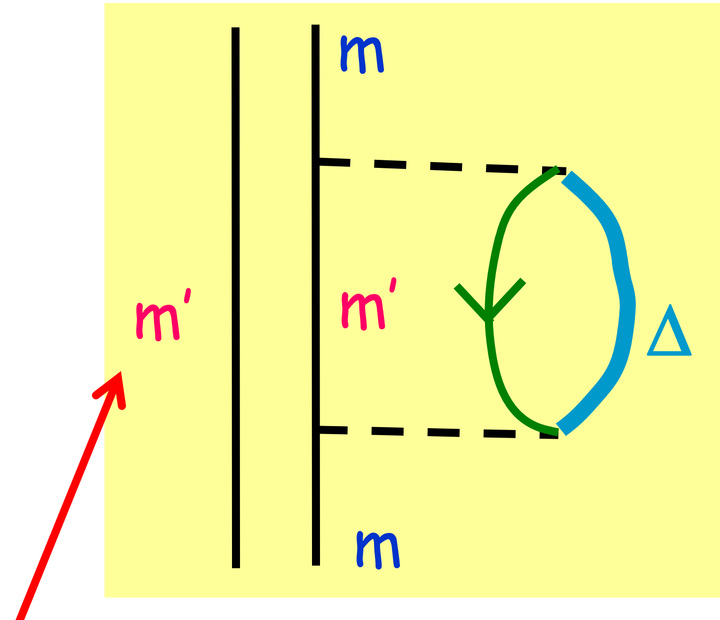
Modification to bare *NN* interaction (for *NN* scattering)

T=1 attraction between *NN* effectively

Pauli blocking effect on the renormalization of single-particle energy



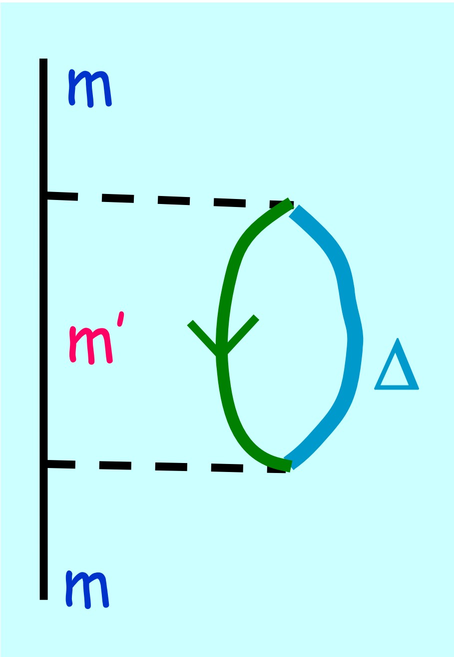
Renormalization of
single particle energy
due to
Δ-hole excitation
→ more binding (attractive)



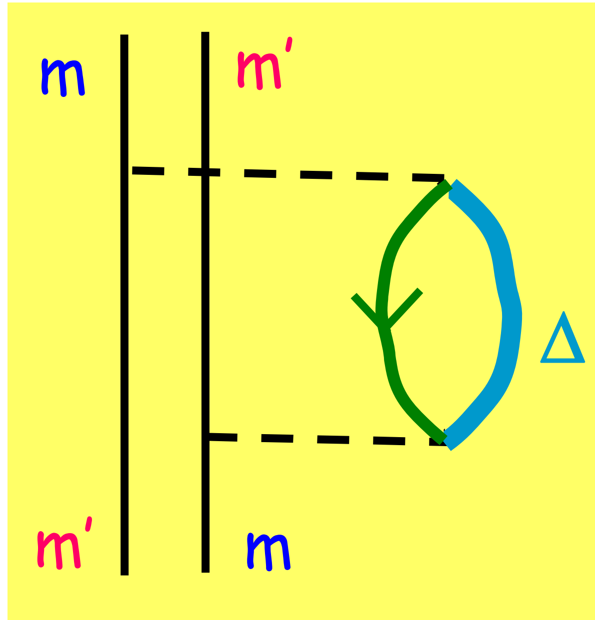
Another valence particle in state m′

Pauli Forbidden
→ *The effect is suppressed*

Most important message with Fujita-Miyazawa 3NF



+



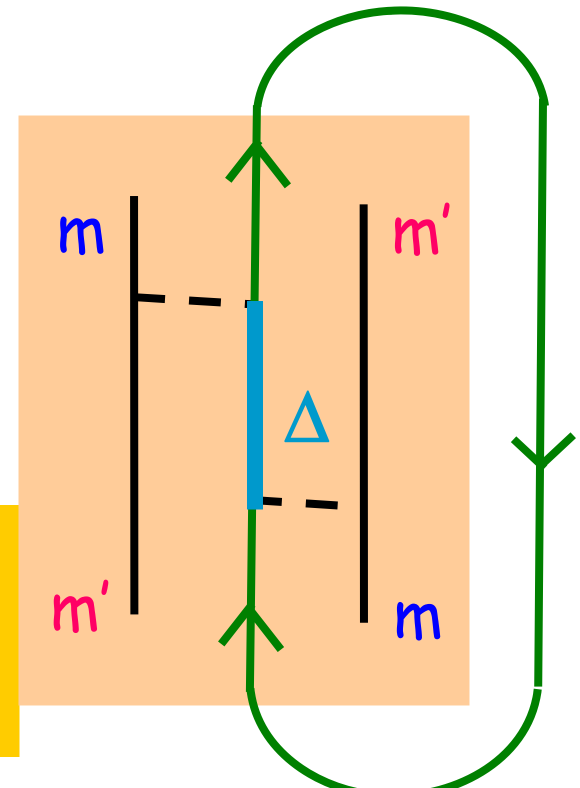
Effective monopole repulsive interaction

Renormalization of single particle energy

Pauli blocking

same

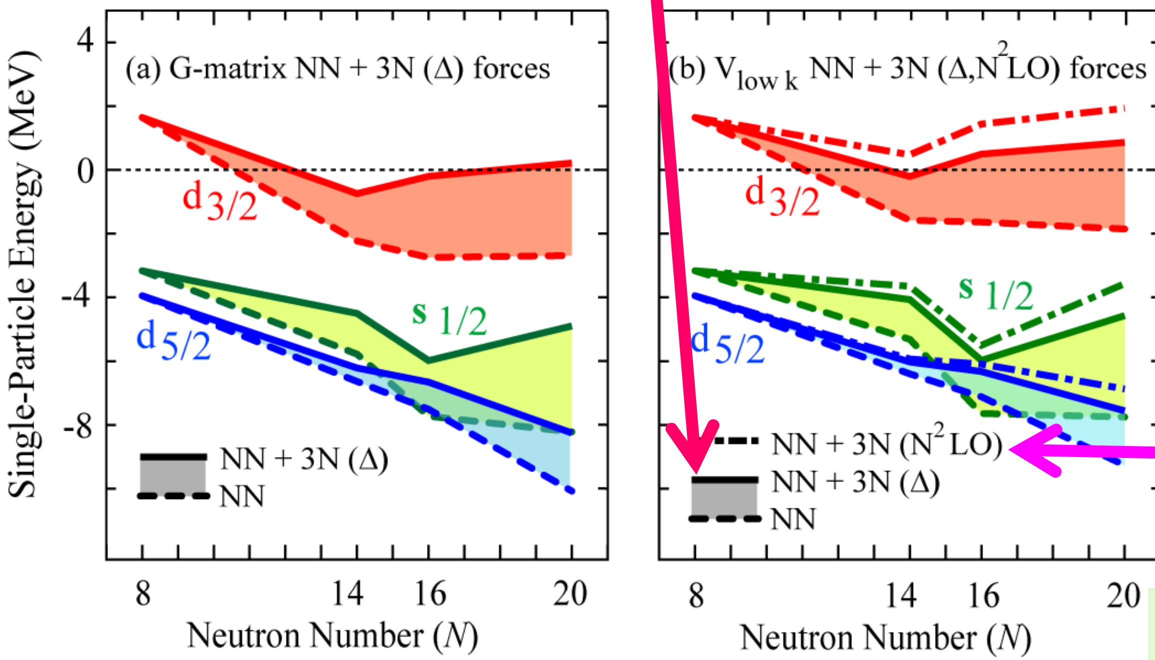
Monopole part of Fujita-Miyazawa 3-body force



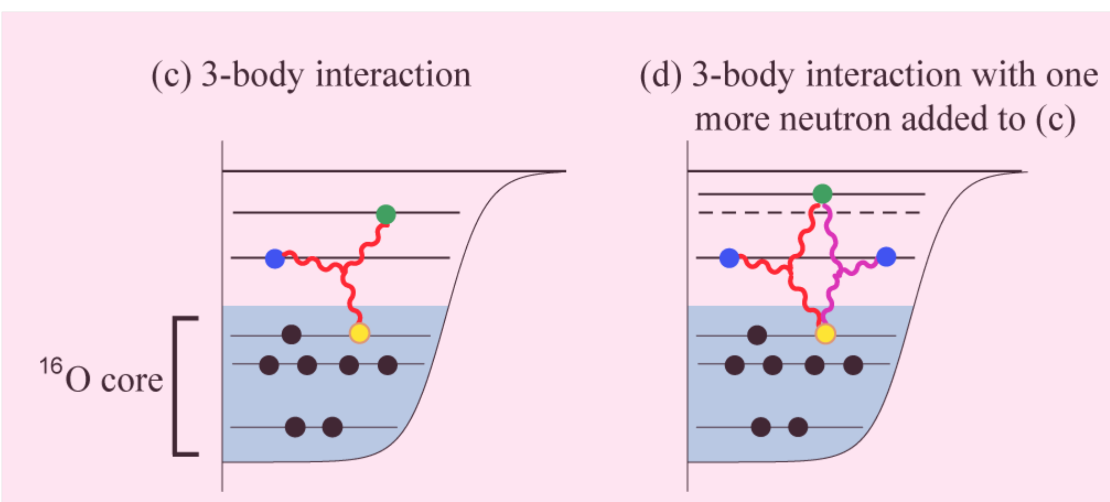
(i) Δ-hole excitation in a conventional way

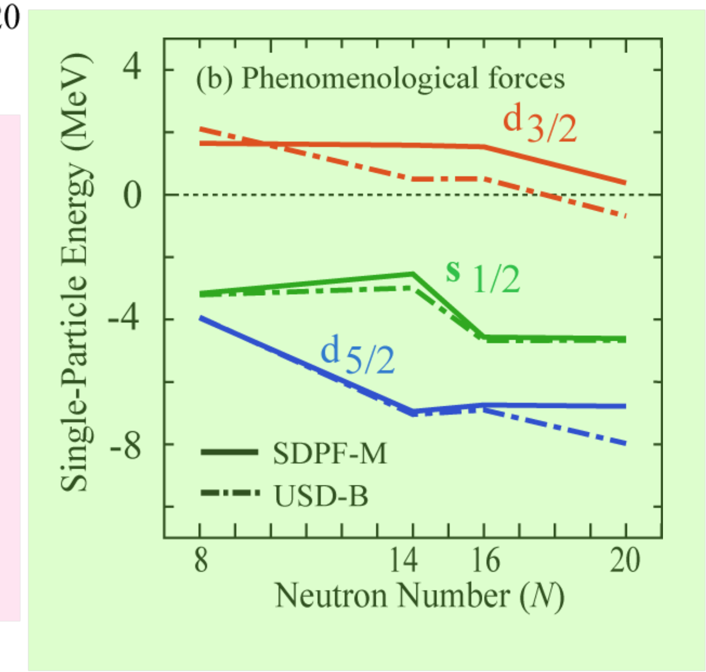
(ii) EFT with Δ

Δ-hole dominant role in determining oxygen drip line

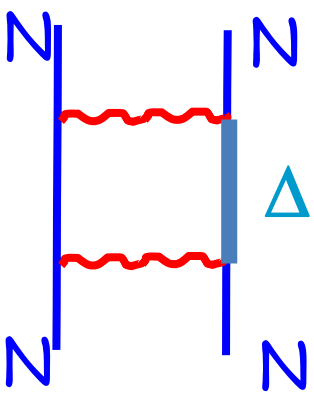


(iii) EFT incl. contact terms (N^2LO)

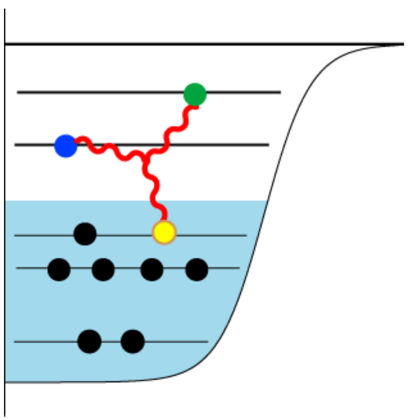


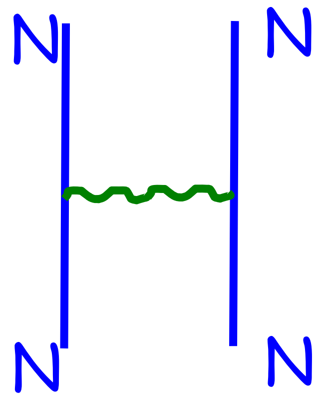


What was wrong with "microscopic theories" ?



present picture



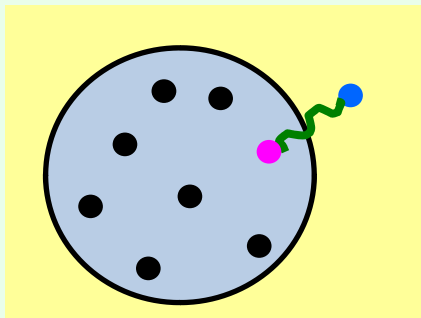


Observed in NN scattering

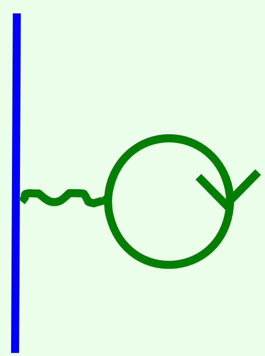
(Effective) two-body interaction

If the origin is "forgotten",

constant change of single-particle energy



or



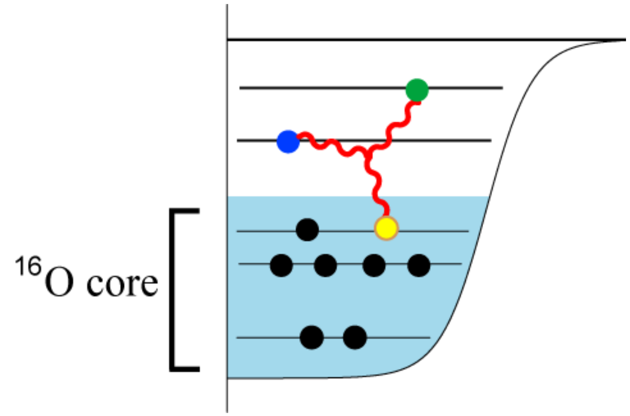
This is what happened in "microscopic theories", leading to wrong drip line.

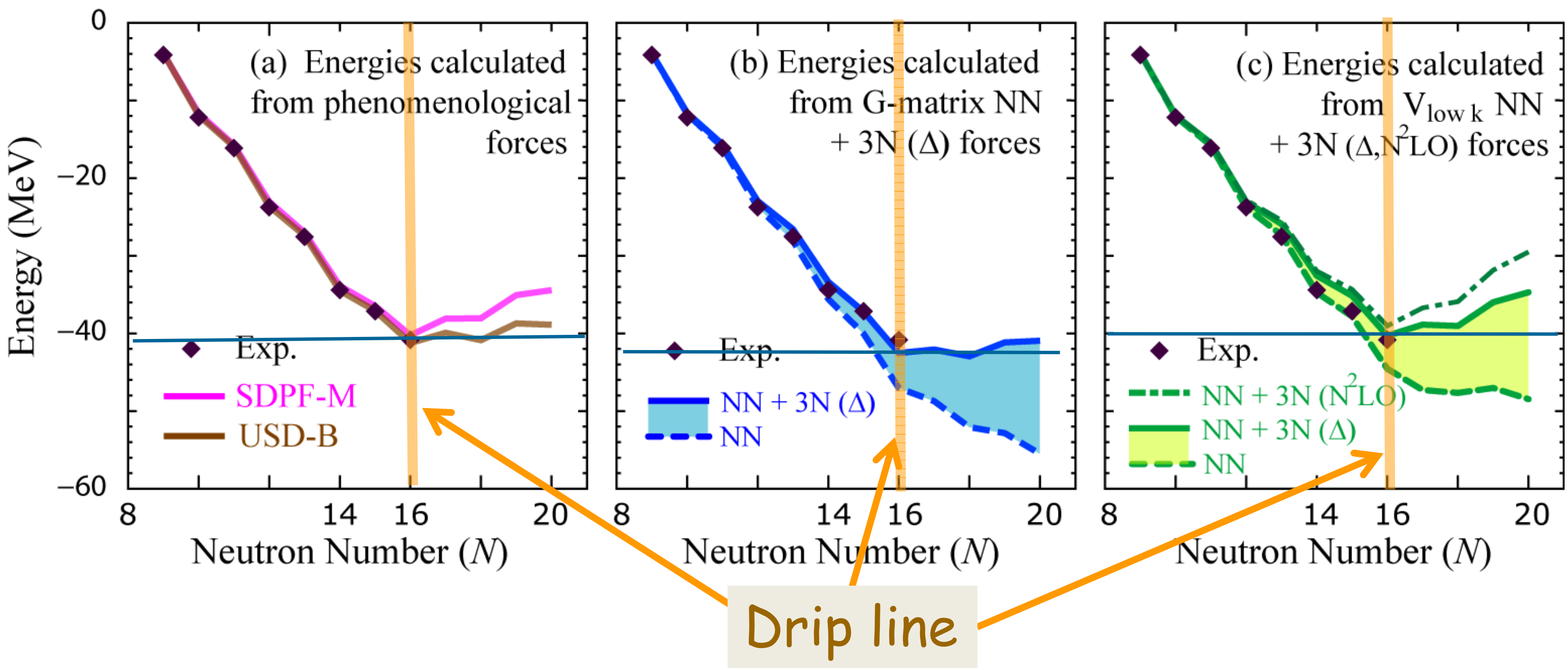
O, Suzuki, Holt, O, Schwenk, Akaishi, PRL 105 (2010)

Ground-state energies of oxygen isotopes

NN force + *3N*-induced *NN* force

(Fujita-Miyazawa force)





A future direction associated with EMMI Neutron-Matter

Inclusion of more correlations from realistic nuclear forces.

CPU: Fujitsu SPARC64 VIIIfx CPU
(8cores, 128GFLops)
total > 80k CPUs (>640k core)
memory: 16GB/1CPU total >1PB
Peak speed: 10 PFlops or more

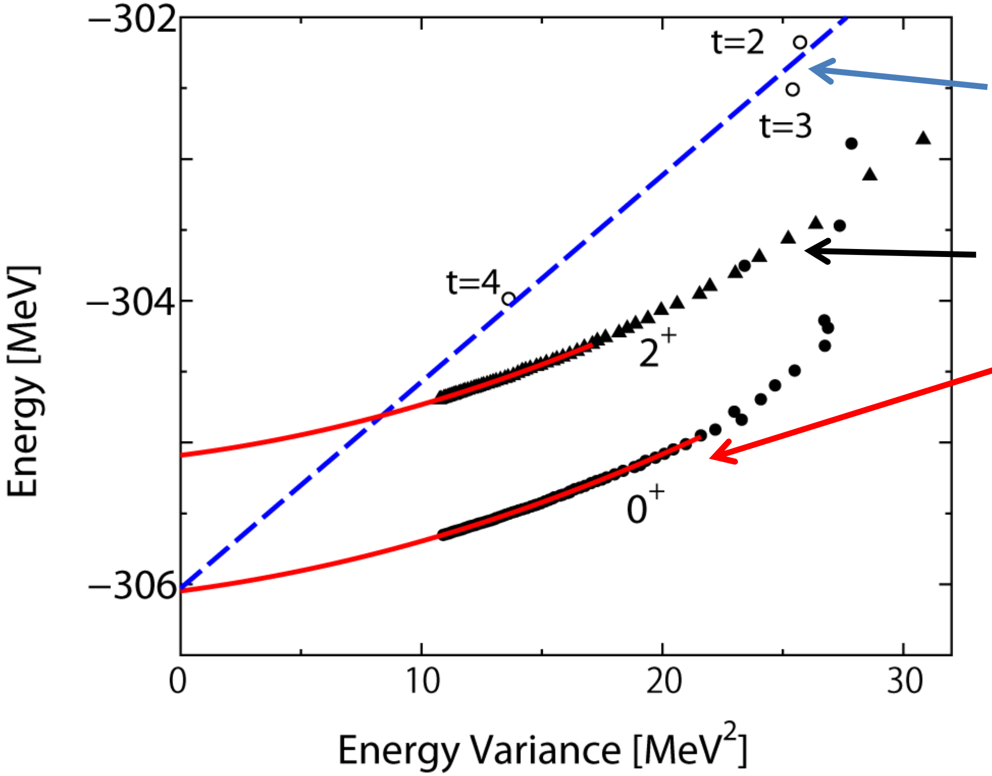
Test operation starts in April, 2011

Large-scale nuclear structure calculation is one of the major projects at the initial phase (~5 years) with certain emphasis on applications to nuclear-energy related data.

Monte Carlo Shell Model + extrapolation

Example : ^{64}Ge with ^{40}Ca core (24 active fermions)

dimension in conventional diagonalization : 1.7×10^{14}



conventional with truncation

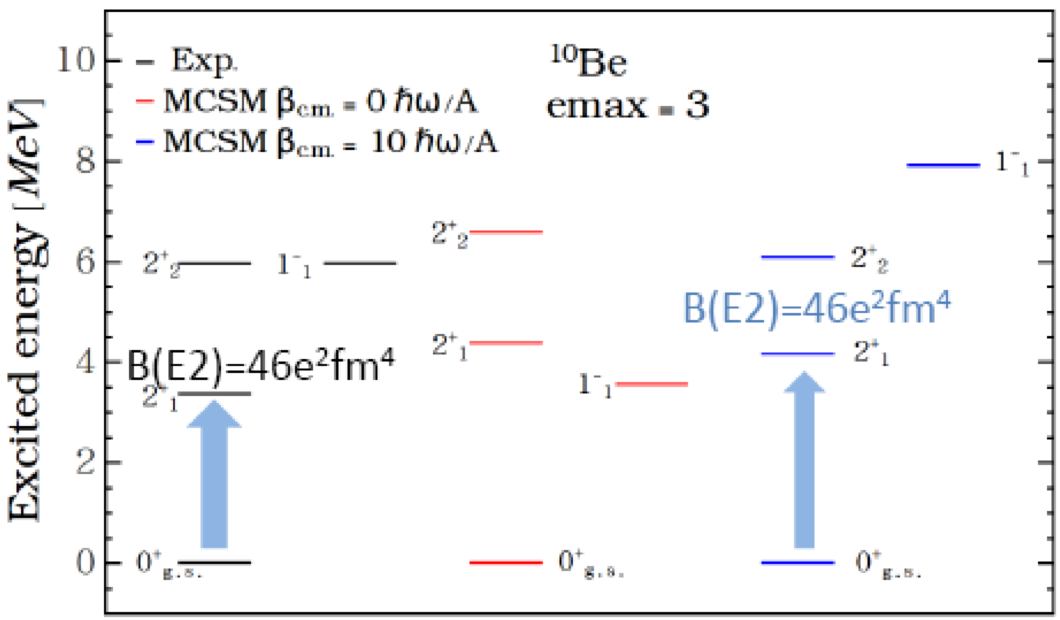
MCSM + extrapolation

Shimizu, Utsuno, Mizusaki, Otsuka and Honma, submitted (2010) ; soon in arXiv nucl-th

Based on Mizusaki and Imada, PR C67, 041301 (2003)

An EMMI outcome
in collaboration with Roth

MCSM ab-initio calculation with UCOM interaction
in spsdpf shell



^{10}C :

Exp. B(E2)=44e^{2}fm^4

MCSM:B(E2)=46.5e^{2}fm^4

Liang Liu, Ph.D thesis (U. Tokyo, 2010)

Summary

1. Monopole interactions : effects magnified in neutron-rich nuclei

2. Tensor force combined with central force : a unified description particularly for proton-neutron monopole correlation.
   -> N=20 Island of inversion, ^{42}Si, ^{78}Ni, ^{100}Sn, Sb, ^{132}Sn, Z=64,…
   Tensor force in nuclear medium is very similar to the bare one.
   This central force may be a challenge for microscopic theories.

3. Fujita-Miyazawa 3-body force produces repulsive effective interaction between valence neutrons in general.

   The spacings between neutron single-particle levels can become wider as N increases, and new magic numbers may arise.
   Examples are shown for O and Ca isotopes with visible effects.
   <--> shell quenching

4. Structure change on top of the shell evolution
   -> diagonalization with super computer

Collaborators

T. Suzuki	Nihon U.
M. Honma	Aizu
Y. Utsuno	JAEA
N. Tsunoda	Tokyo
K. Tsukiyama	Tokyo
M. H.-Jensen	Oslo
A. Schwenk	Darmstadt
J. Holt	ORNL
K. Akaishi	RIKEN

Quick Summary

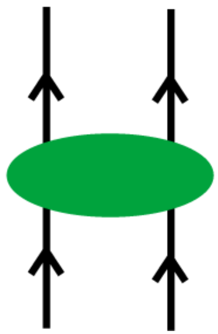
Dominant monopole forces are due to

(a) central force :
Gaussian
(strongly renormalized)

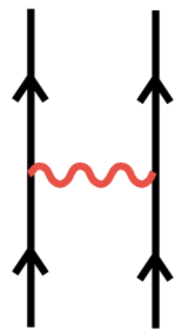
(b) tensor force :
$\pi + \rho$ meson
exchange

FM 3NF

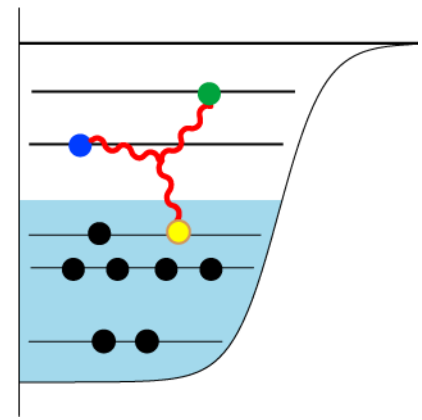
V =



+



+



+

μ=1 fm

basic binding

variation of shell structure

limit of existence

END