第47回理研原子核コロキウム
仁科ホール
June. 28, 2010

不安定核と核力
Exotic nuclei and nuclear forces

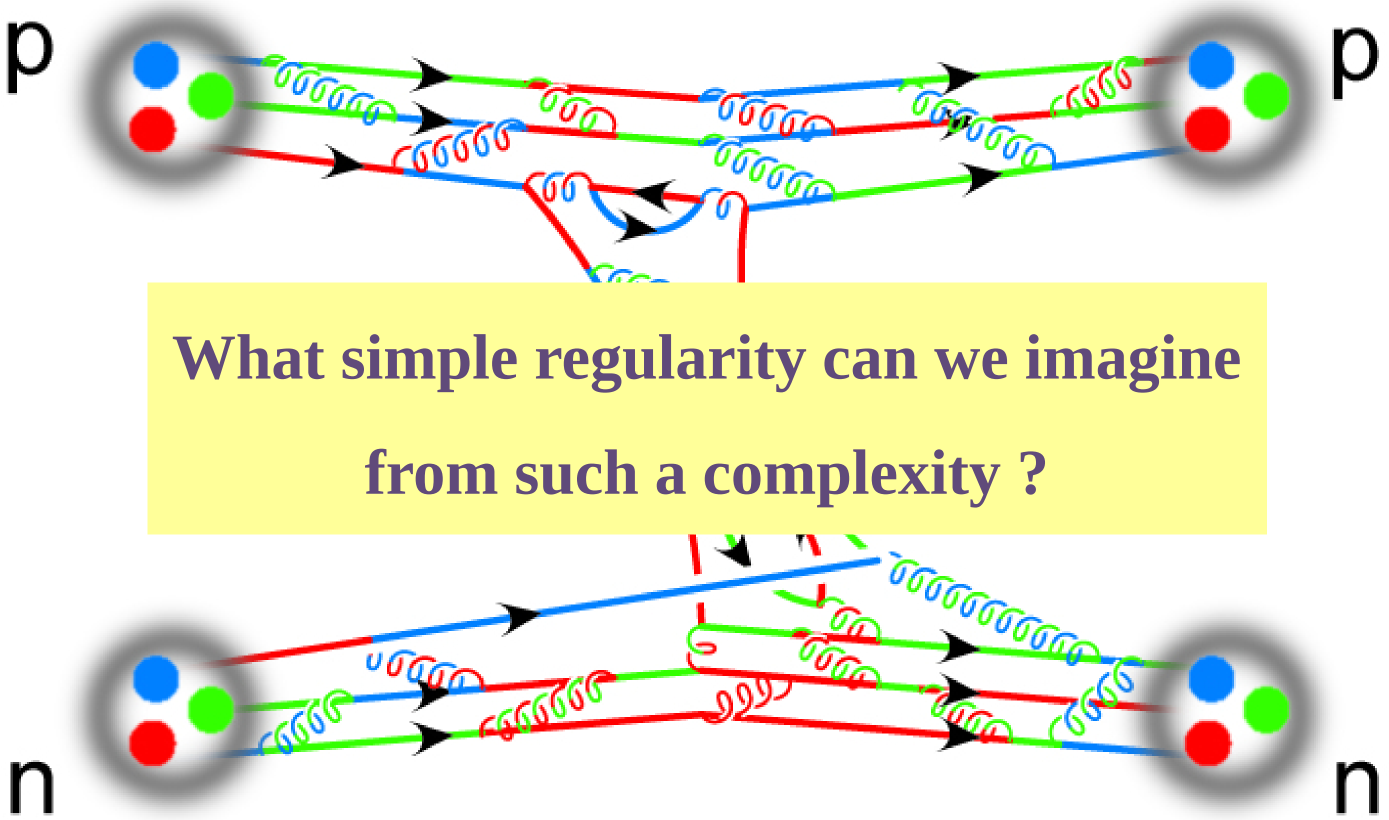
東京大学
THE UNIVERSITY OF TOKYO

Takaharu Otsuka
University of Tokyo / MSU

NSCL

3時40分

Graphical Image of NN force



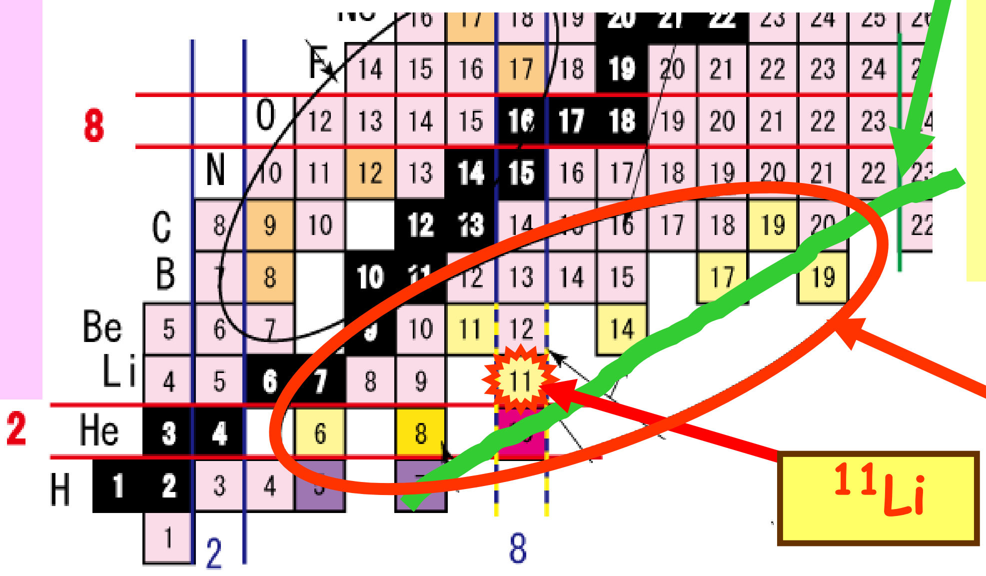
What simple regularity can we imagine from such a complexity ?

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

Studies on exotic nuclei in the 80~90’s

Left-lower part of the Nuclear Chart

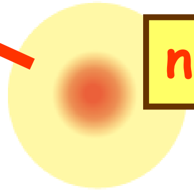
Proton number →



Stability line and drip lines are not so far from each other

→ Physics of loosely bound neutrons, e.g., halo

while other issues like ^{32}Mg



neutron halo

Neutron number →

A nuclei (mass number)

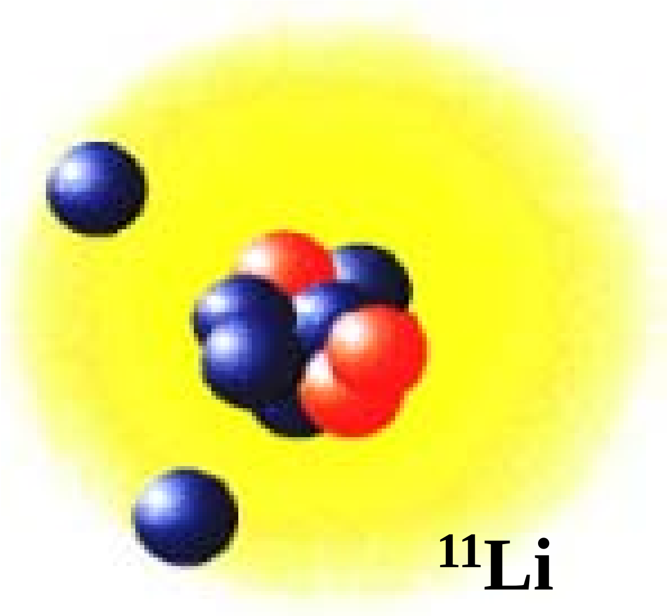
■ stable

□ exotic

🟨 -- with halo

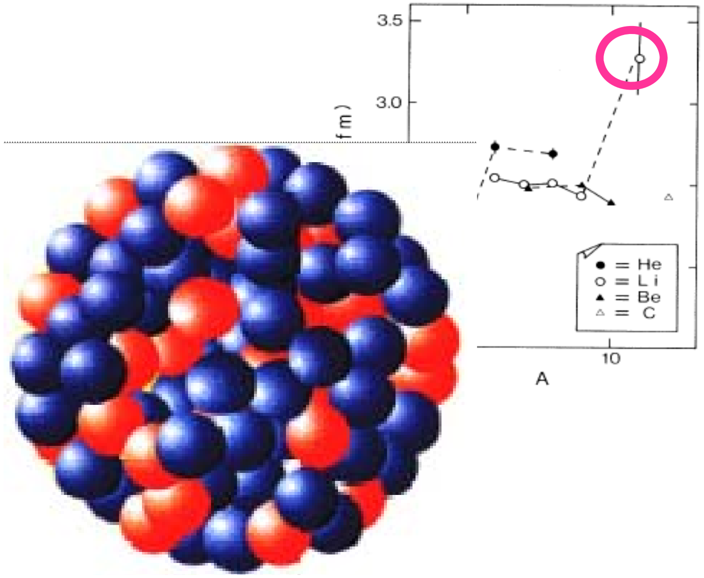
Neutron halo

Strong tunneling of loosely bound excess neutrons

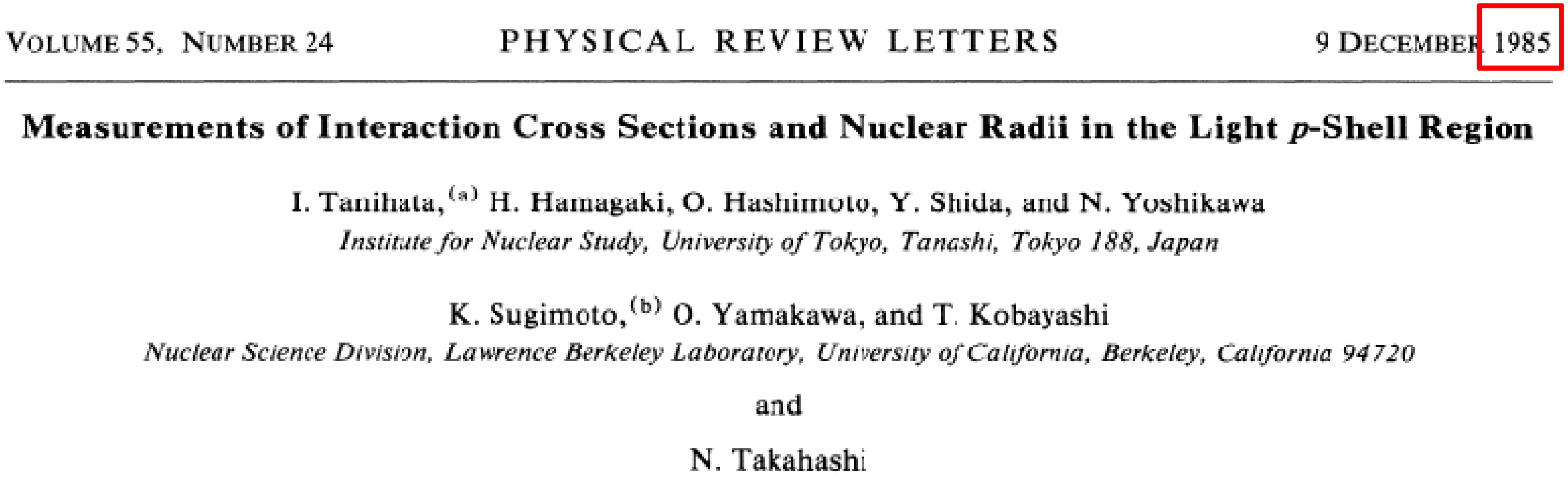


^{11}Li

About same radius



^{208}Pb



VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Measurements of Interaction Cross Sections and Nuclear Radii in the Light *p*-Shell Region

I. Tanihata,(a) H. Hamagaki, O. Hashimoto, Y. Shida, and N. Yoshikawa
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

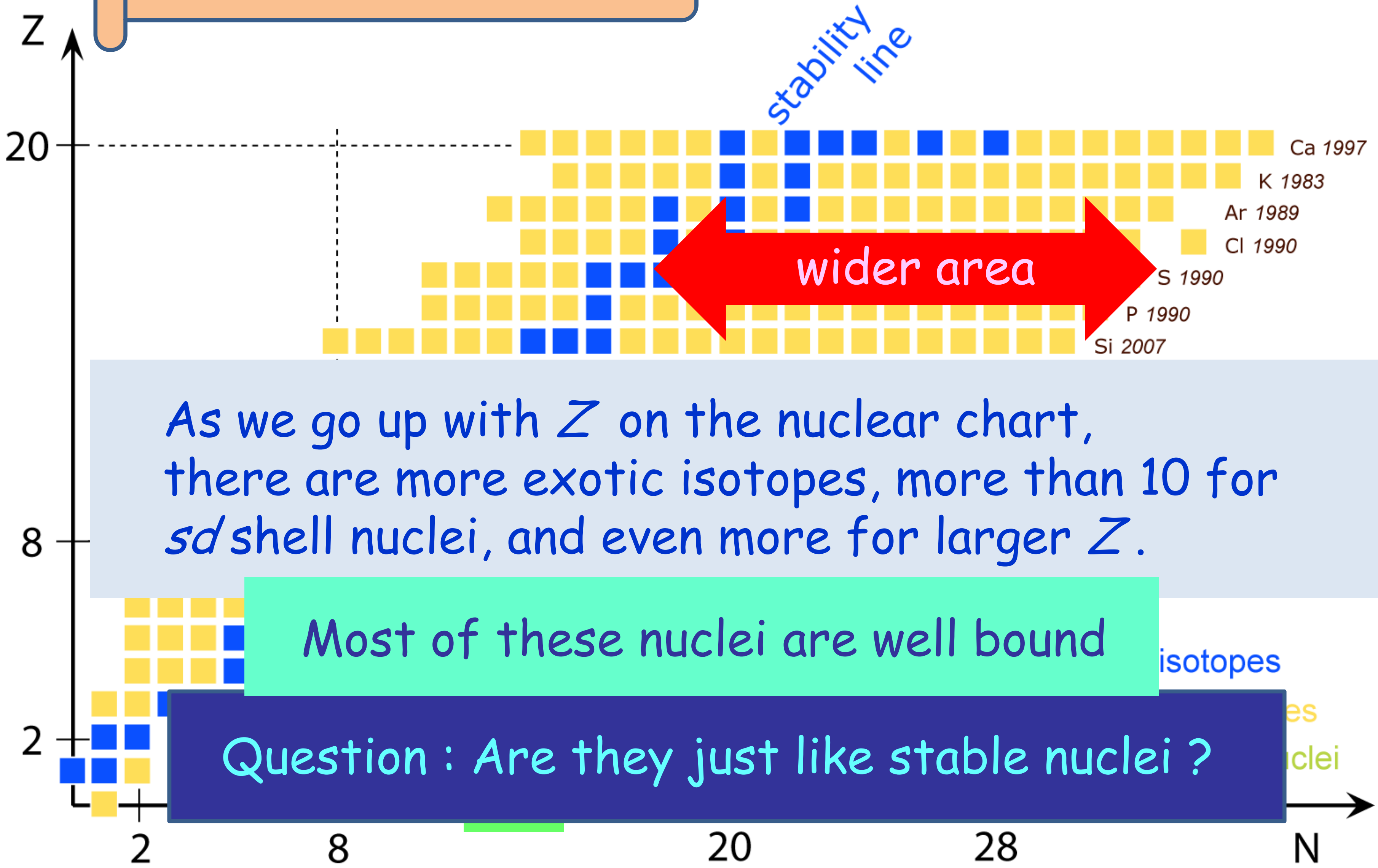
K. Sugimoto,(b) O. Yamakawa, and T. Kobayashi
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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, more than 10 for *sd* shell nuclei, and even more for larger *Z* .

Most of these nuclei are well bound

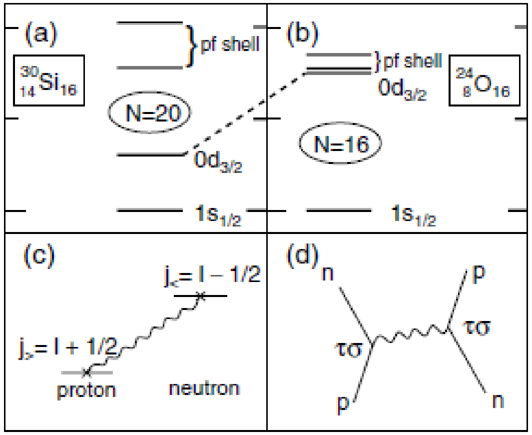
Question : Are they just like stable nuclei ?

3つの論文

VOLUME 87, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 2001

Magic Numbers in Exotic Nuclei and Spin-Isospin Properties of the NN Interaction

Takaharu Otsuka,[1,2] Rintaro Fujimoto,[1] Yutaka Utsuno,[3] B. Alex Brown,[4] Michio Honma,[5] and Takahiro Mizusaki[6]
[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*
[2]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*

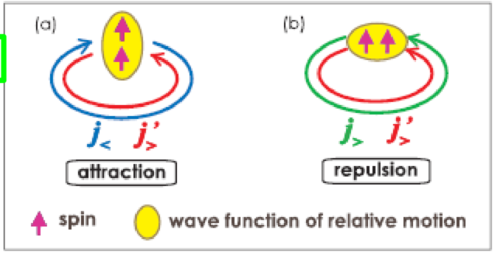


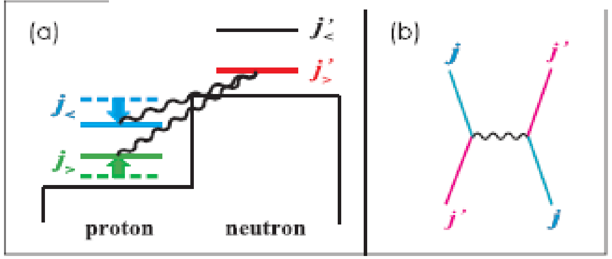
魔法数までもがスピンアイソスピン核力で変わる

PRL 95, 232502 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Evolution of Nuclear Shells due to the Tensor Force

Takaharu Otsuka,[1,2,3,*] Toshio Suzuki,[4] Rintaro Fujimoto,[1] Hubert Grawe,[5] and Yoshinori Akaishi[6]
[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*



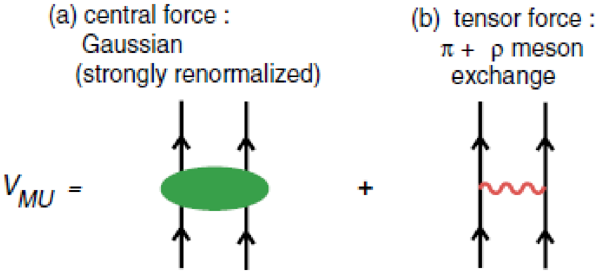


テンソル力の特異な効果

Selected for a Viewpoint in *Physics*
PRL 104, 012501 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

Takaharu Otsuka,[1,2] Toshio Suzuki,[3] Michio Honma,[4] Yutaka Utsuno,[5] Naofumi Tsunoda,[1] Koshiroh Tsukiyama,[1] and Morten Hjorth-Jensen[6]



テンソル力と中心力によるWeinberg 型モデル

Focus of this talk

Changes in the structure of exotic nuclei
as compared to stable ones

shell structure (incl. magic numbers)
binding energies, drip lines

experimentally, a lot of recent progress by
combining direct reactions and γ-ray spectroscopy

Nuclear and hadronic forces are responsible
for such changes

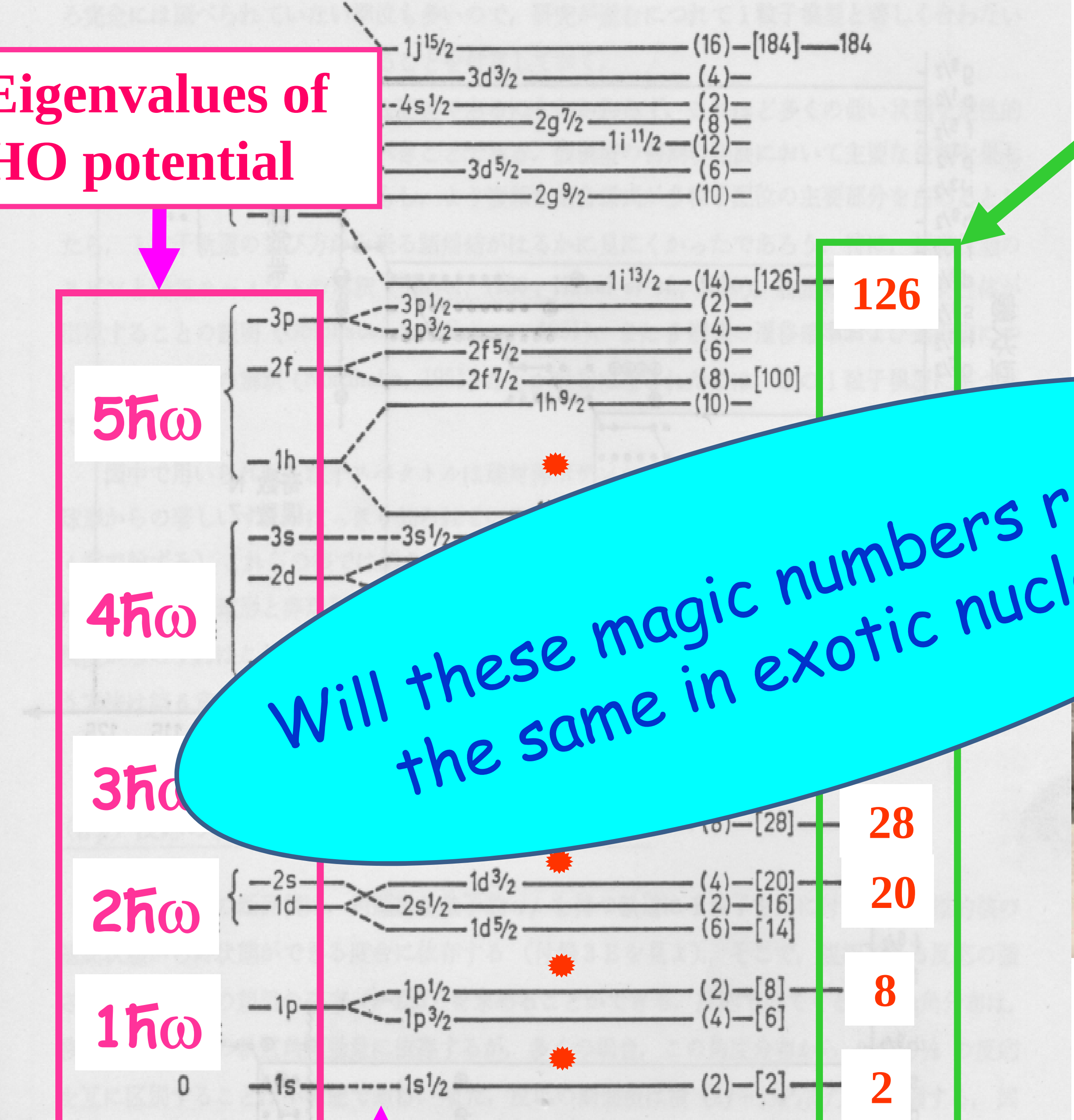
2-body and 3-body forces

Monopole-based universal force V_{MU}

→ similarity to Weinberg's chiral perturbation

Importance of Fujita-Miyazawa force

Eigenvalues of HO potential



5ħω

4ħω

3ħω

2ħω

1ħω

126

28

20

8

2

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．

**Magic numbers
Mayer and
Jensen (1949)**

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))

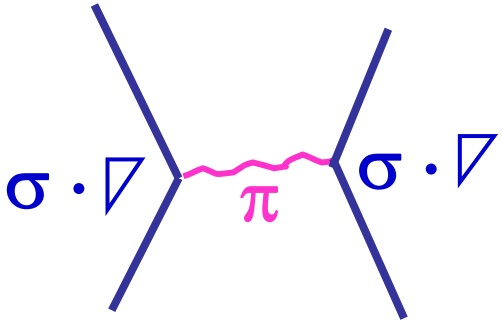
Tensor Interaction by pion exchange

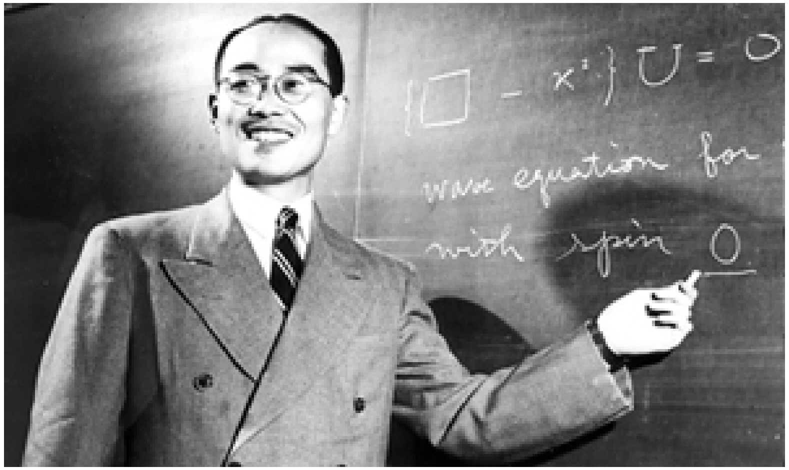
$$V_T = (\tau_1\tau_2)\,(\,[\sigma_1\sigma_2]^{(2)}\,Y^{(2)}(\Omega)\,)\,Z(r)$$

contributes
only to **S=1** states

relative motion

π meson : primary source





Yukawa

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

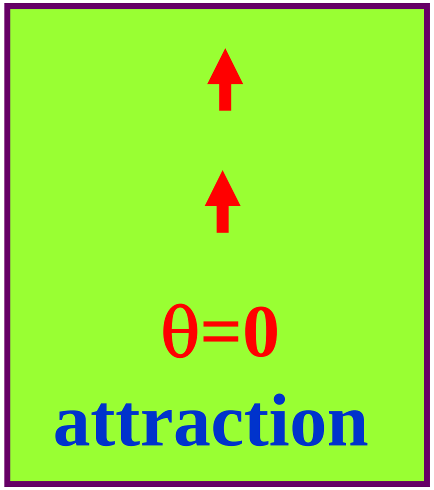
Ref: Osterfeld, Rev. Mod. Phys. 64, 491 (92)

How does the tensor force work ?

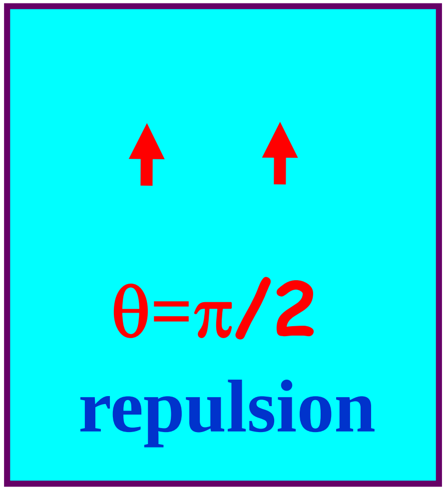
Spin of each nucleon ↑ is parallel, because the total spin must be S=1

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

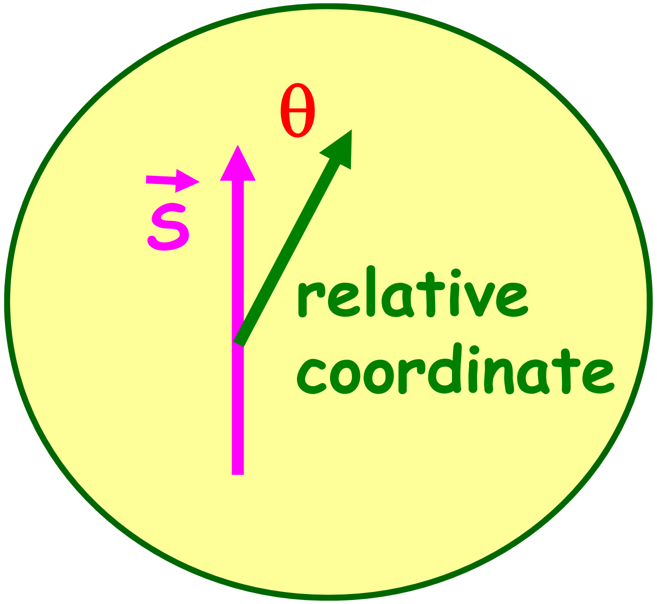
$$V \sim Y_{2,0} \sim 1 - 3\cos^2\theta$$


$\theta=0$

attraction


$\theta=\pi/2$

repulsion

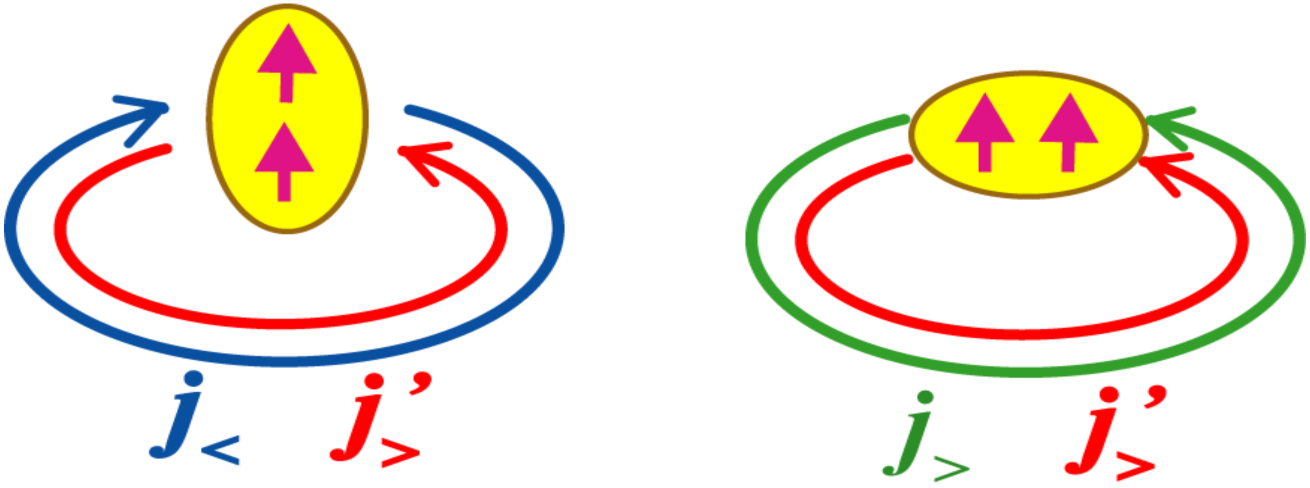


Monopole effects due to the tensor force
- An intuitive picture -

⬭ wave function of relative motion

↑↑ spin of nucleon

large relative momentum | small relative momentum



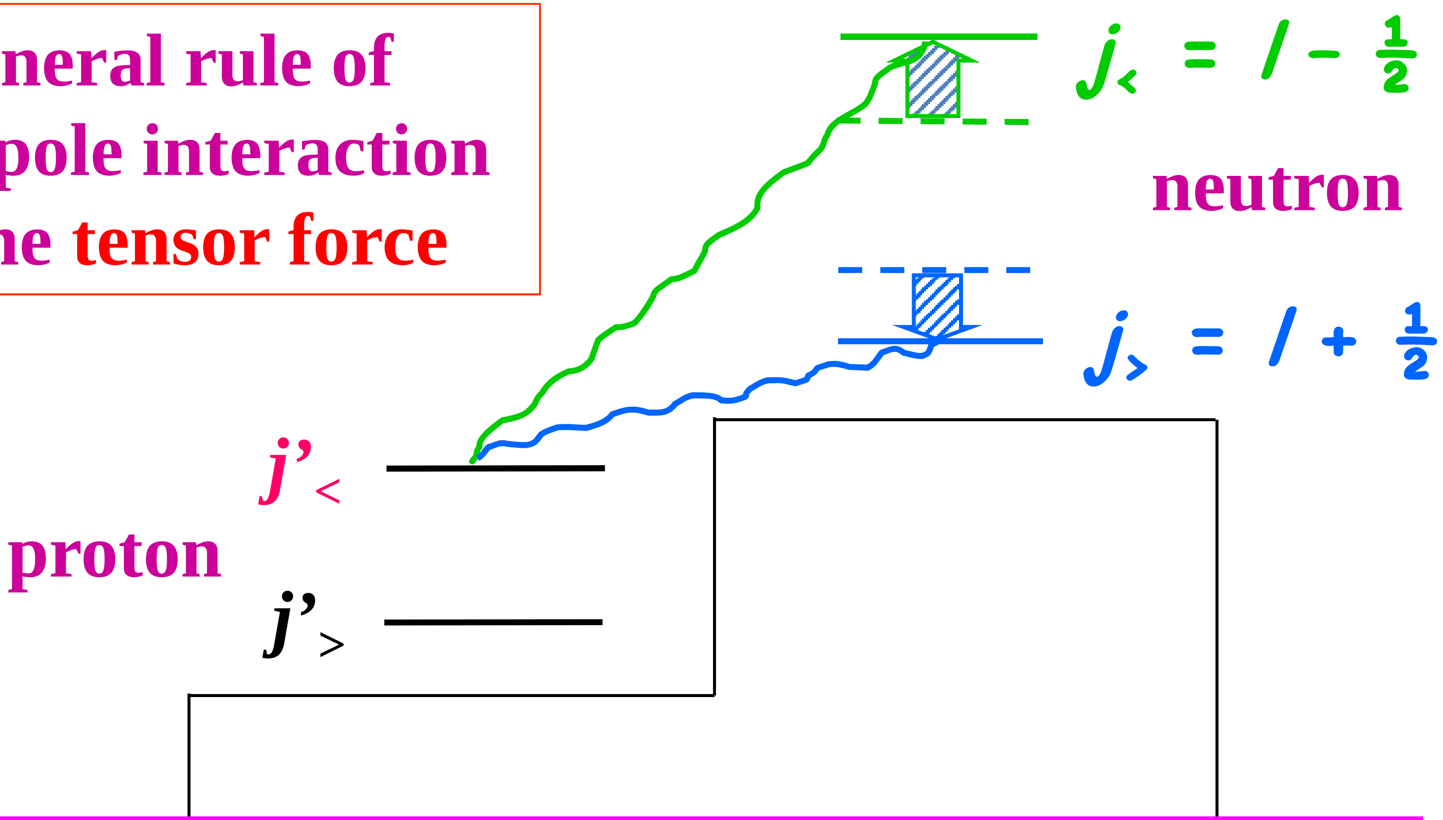
attractive | **repulsive**

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

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

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

General rule of monopole interaction of the tensor force

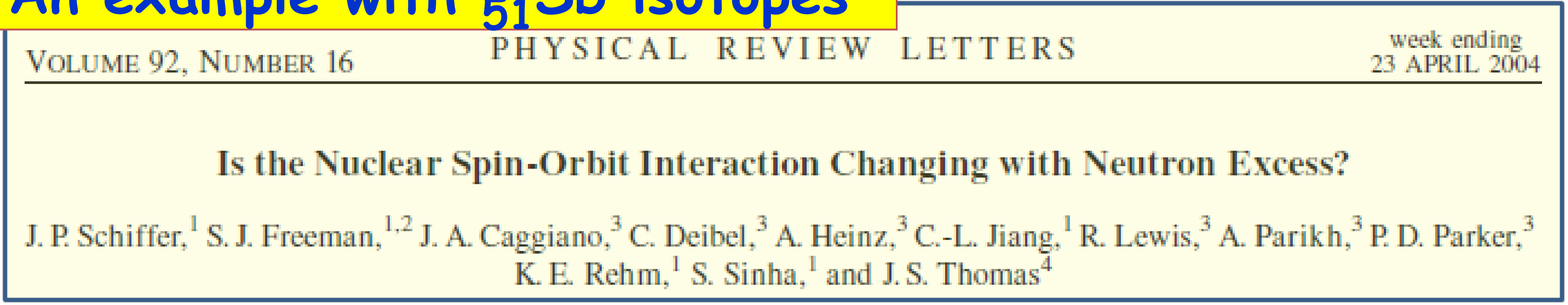


Identity for tensor monopole interaction

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

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

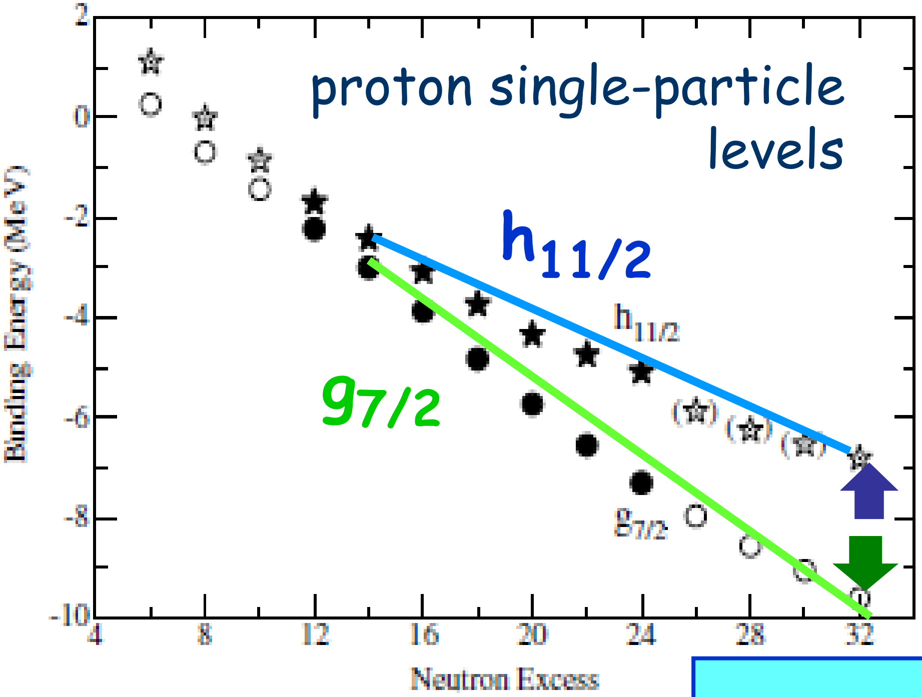
An example with $_{51}$Sb isotopes



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 isotopes

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

$h_{11/2}$ - $h_{11/2}$ repulsive ⬆

$h_{11/2}$ - $g_{7/2}$ attractive ⬇

$\pi + \rho$ meson exchange tensor force

(splitting increased by ~ 2 MeV)

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

What are the major monopole components

in the shell-model effective interaction

which are successful in systematic

description over many nuclei ?

Example taken from pf-shell

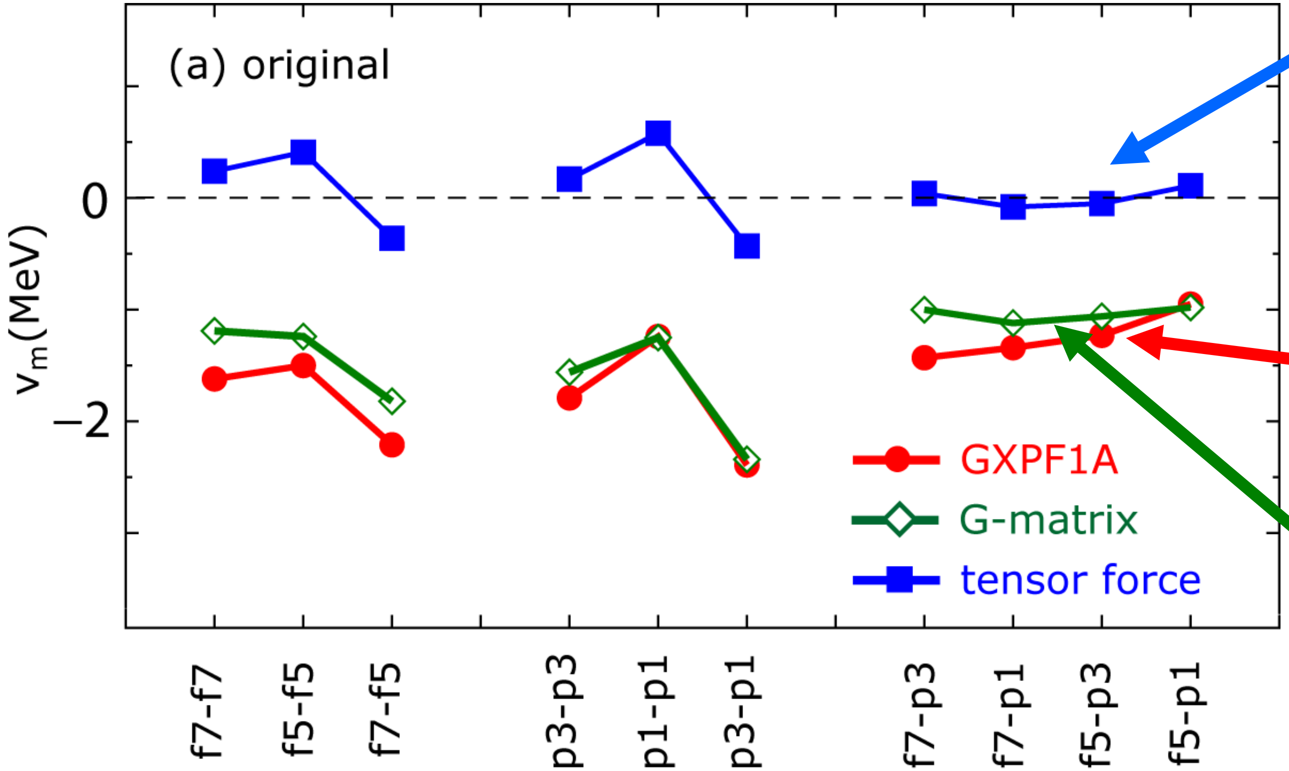
GXPF1A interaction *

G-matrix obtained from Bonn-C potential + 3rd order Q_{box}

+ empirical refinement by χ^2-fit to experimental data

*) M. Honma et al., PRC65 (2002) 061301(R)

T=0 monopole interactions in the pf shell



Tensor force
(π+ρ exchange)

GXPF1A

G-matrix
(H.-Jensen)

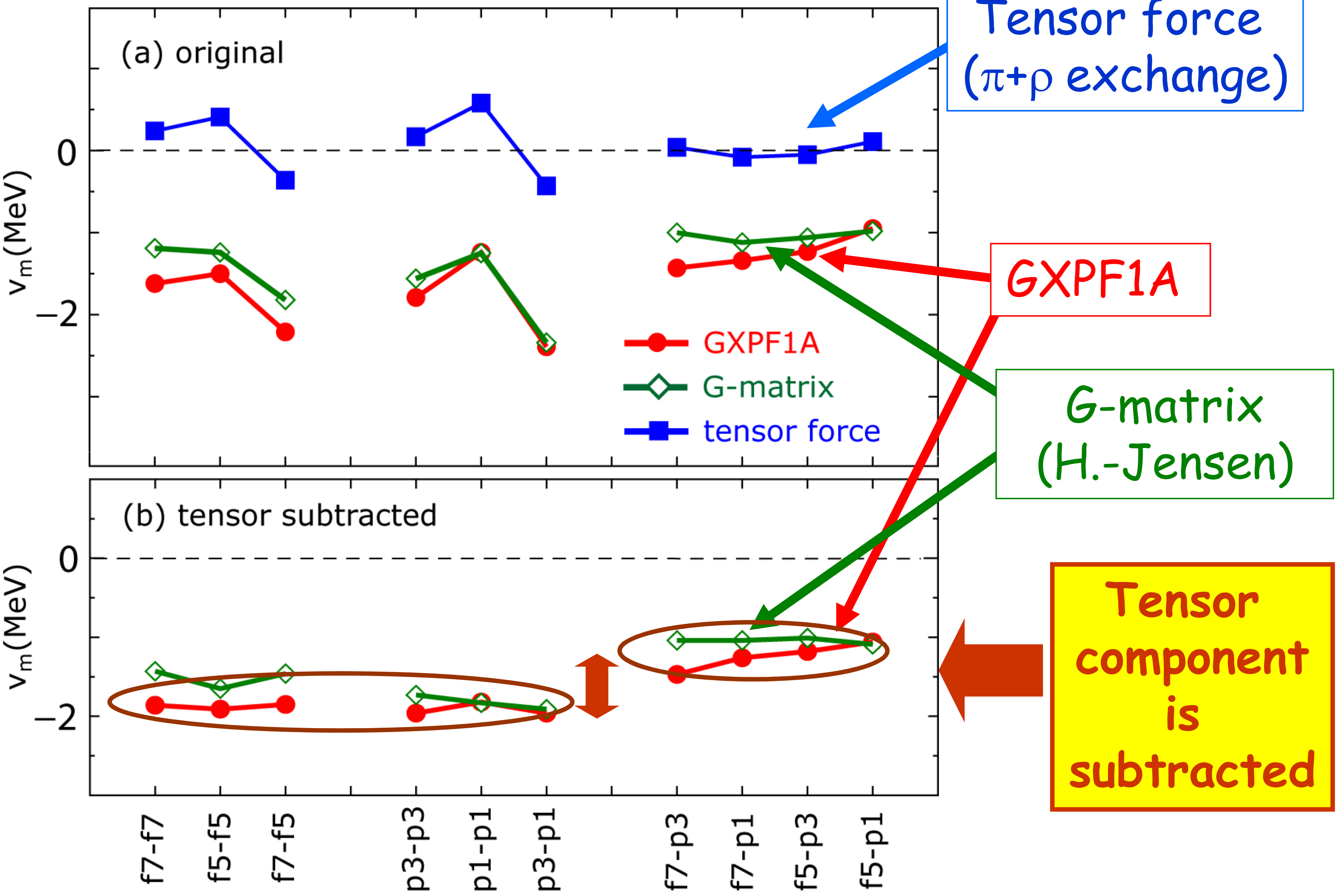
f-f

p-p

f-p

"Local pattern" ← tensor force

T=0 monopole interactions in the pf shell



Tensor force (π+ρ exchange)

GXPF1A

G-matrix (H.-Jensen)

Tensor component is subtracted

The central force is modeled by a Gaussian function

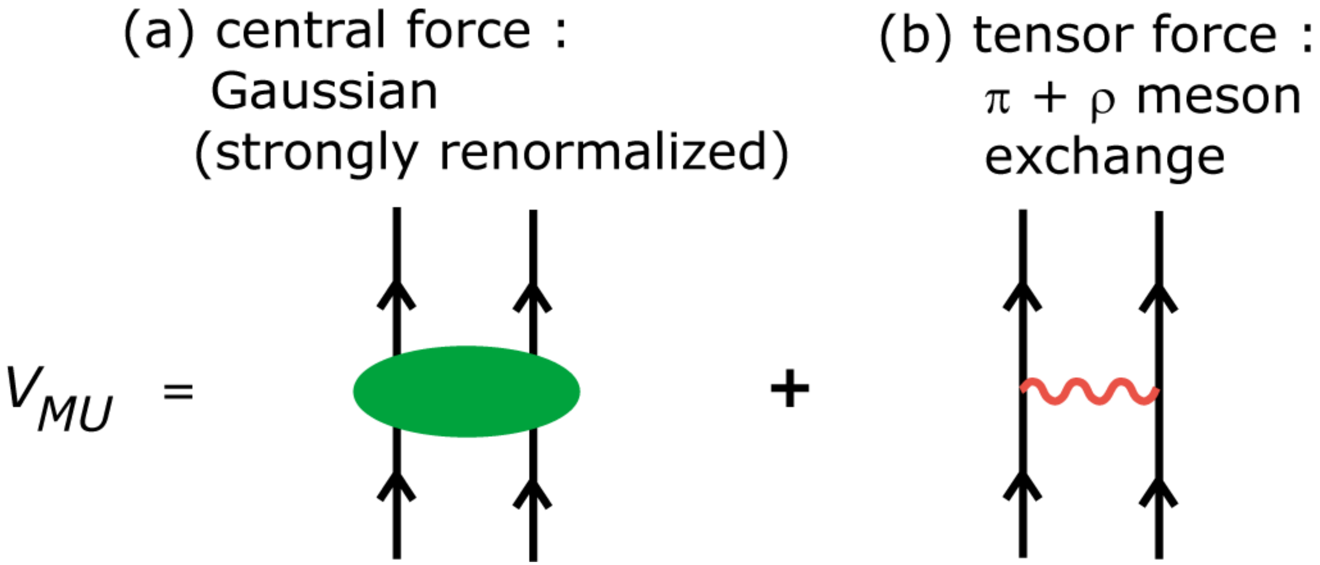
$$V = V_0 \ \exp(-(r/\mu)^2) \quad \text{(S,T dependences)}$$

with V_0 = -166 MeV, μ=1.0 fm,

(S,T) factor	(0,0)	(1,0)	(0,1)	(1,1)
relative strength	1	1	0.6	-0.8

Can we explain the difference between f-f/p-p and f-p ?

Systematic description of monopole properties of exotic nuclei can be obtained by an extremely simple interaction as



(a) central force :
Gaussian
(strongly renormalized)

(b) tensor force :
π + ρ meson
exchange

V_{MU} = +

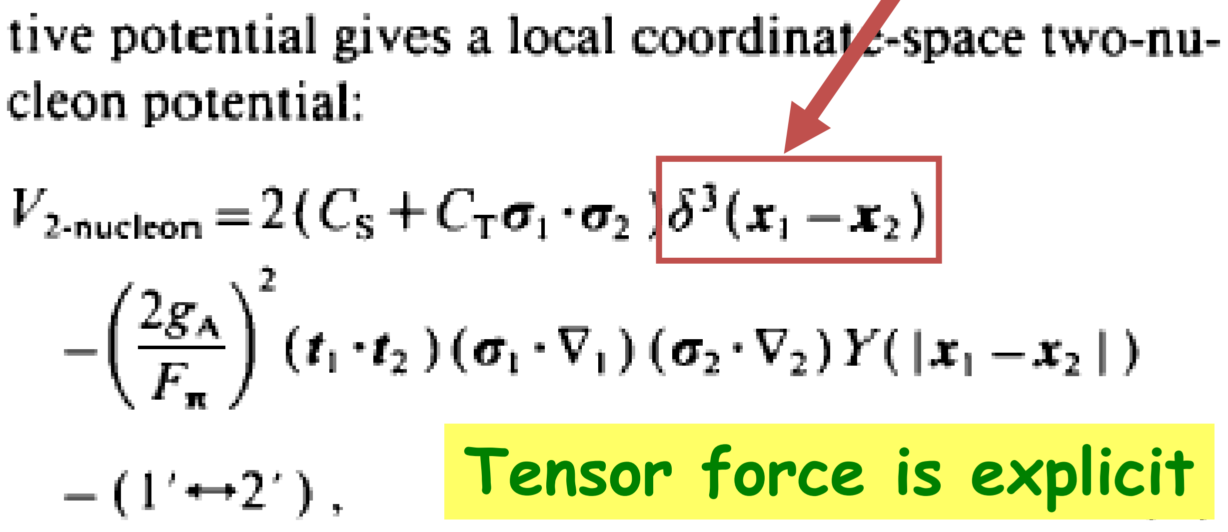
Parameters are fixed for all nuclei

The tensor part of the effective *NN* interaction for valence nucleons is similar to the bare tensor force.

bare tensor force : π + ρ meson exchange

S. Weinberg,
PLB 251, 288 (1990)

Central force:
strongly renormalized



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

$$V_{\text{2-nucleon}} = 2\left(C_S + C_T\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right)\boxed{\delta^3(\boldsymbol{x}_1-\boldsymbol{x}_2)} - \left(\frac{2g_A}{F_\pi}\right)^2 (\boldsymbol{t}_1\cdot\boldsymbol{t}_2)(\boldsymbol{\sigma}_1\cdot\nabla_1)(\boldsymbol{\sigma}_2\cdot\nabla_2)Y(|\boldsymbol{x}_1-\boldsymbol{x}_2|) - (1'\leftrightarrow 2')\,,$$

Tensor force is explicit

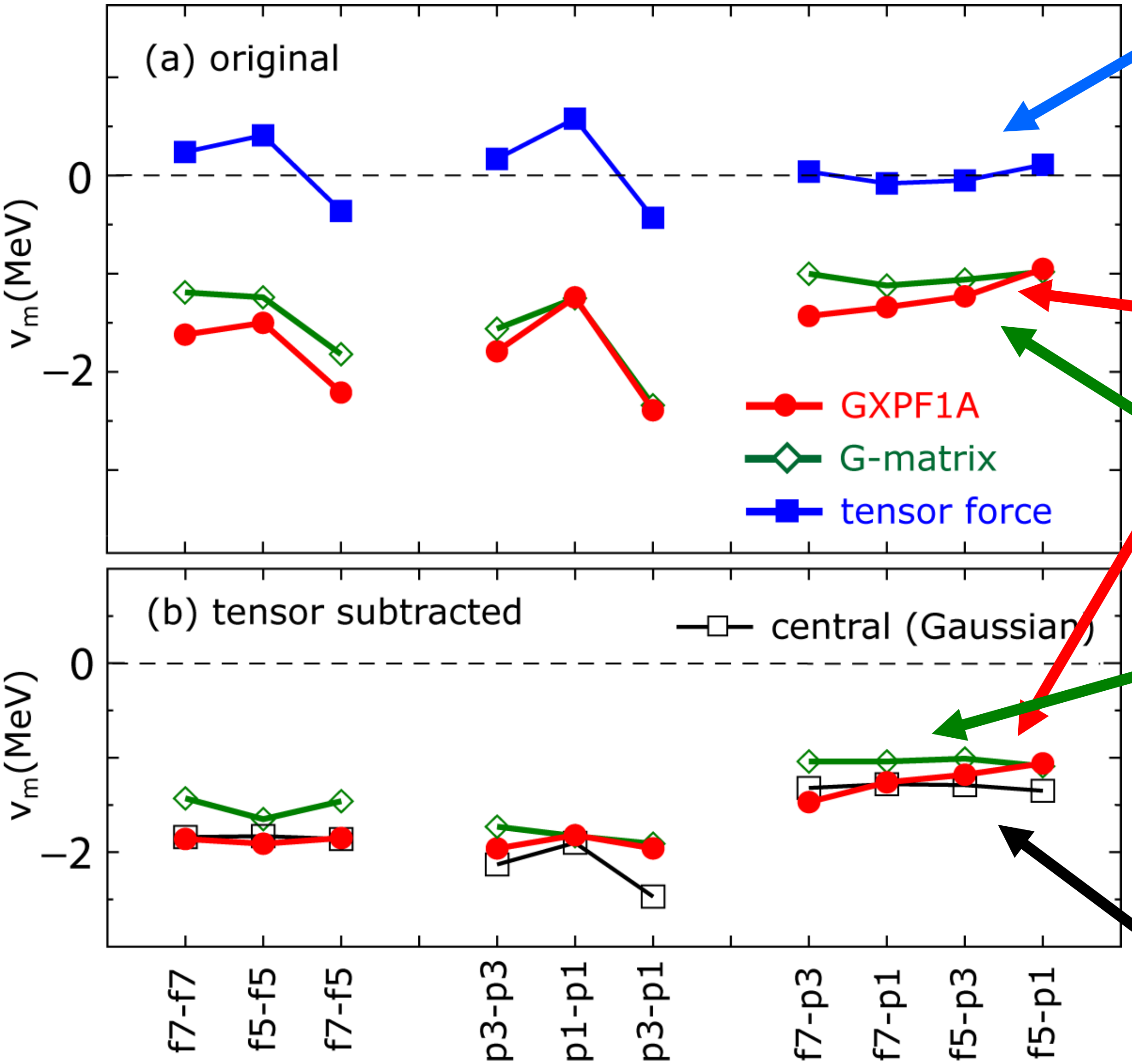
In nuclei

finite
range

π + ρ
exchange

→ Chiral Perturbation of QCD

T=0 monopole interactions in the pf shell



f-f

p-p

f-p

Tensor force
($\pi+\rho$ exchange)

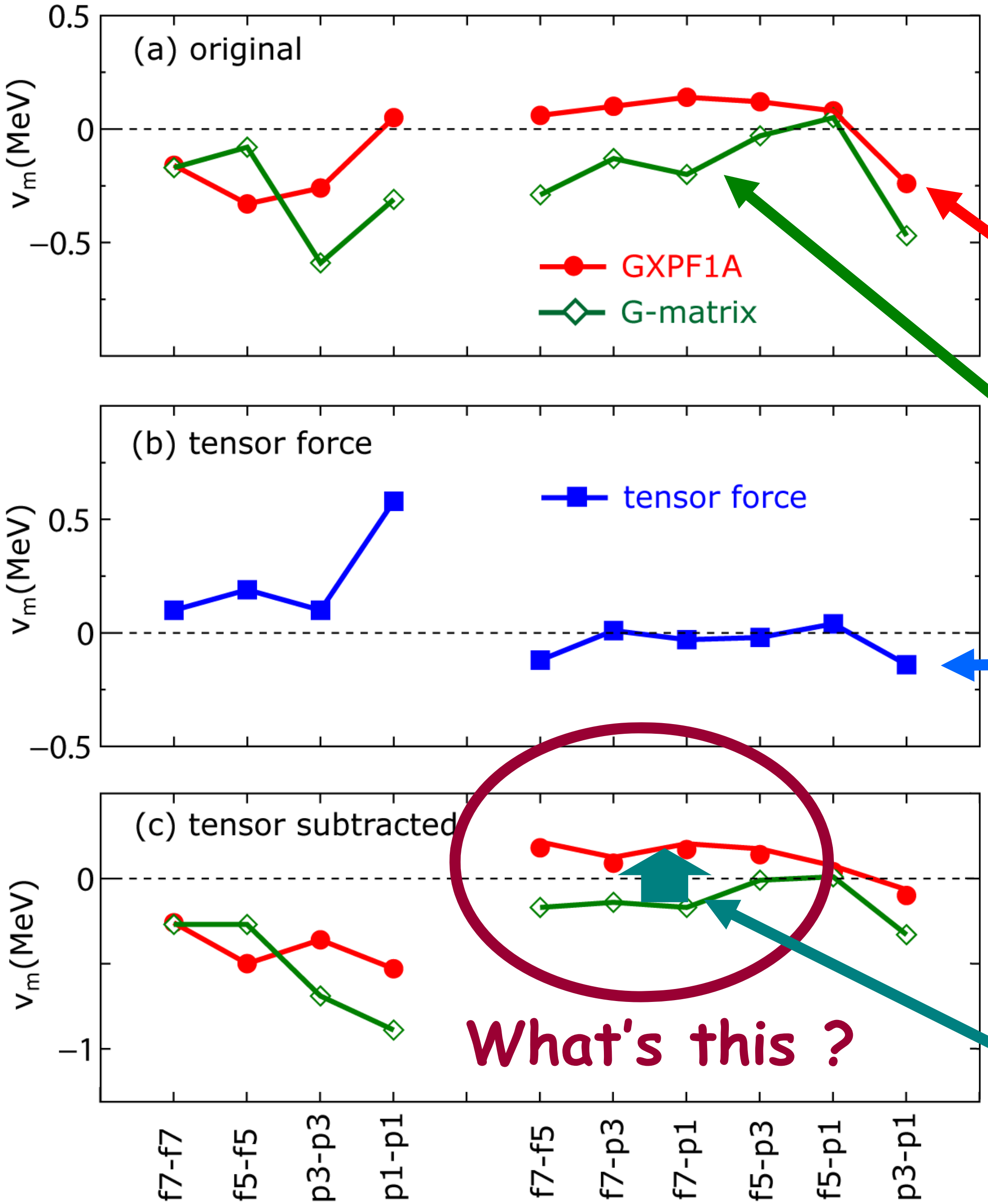
GXPF1

G-matrix
(H.-Jensen)

Central (Gaussian)
- Reflecting
radial overlap -

T=1 monopole interaction

T=1 monopole interactions in the pf shell



What's this ?

GXPF1A

G-matrix (H.-Jensen)

Tensor force (π+ρ exchange)

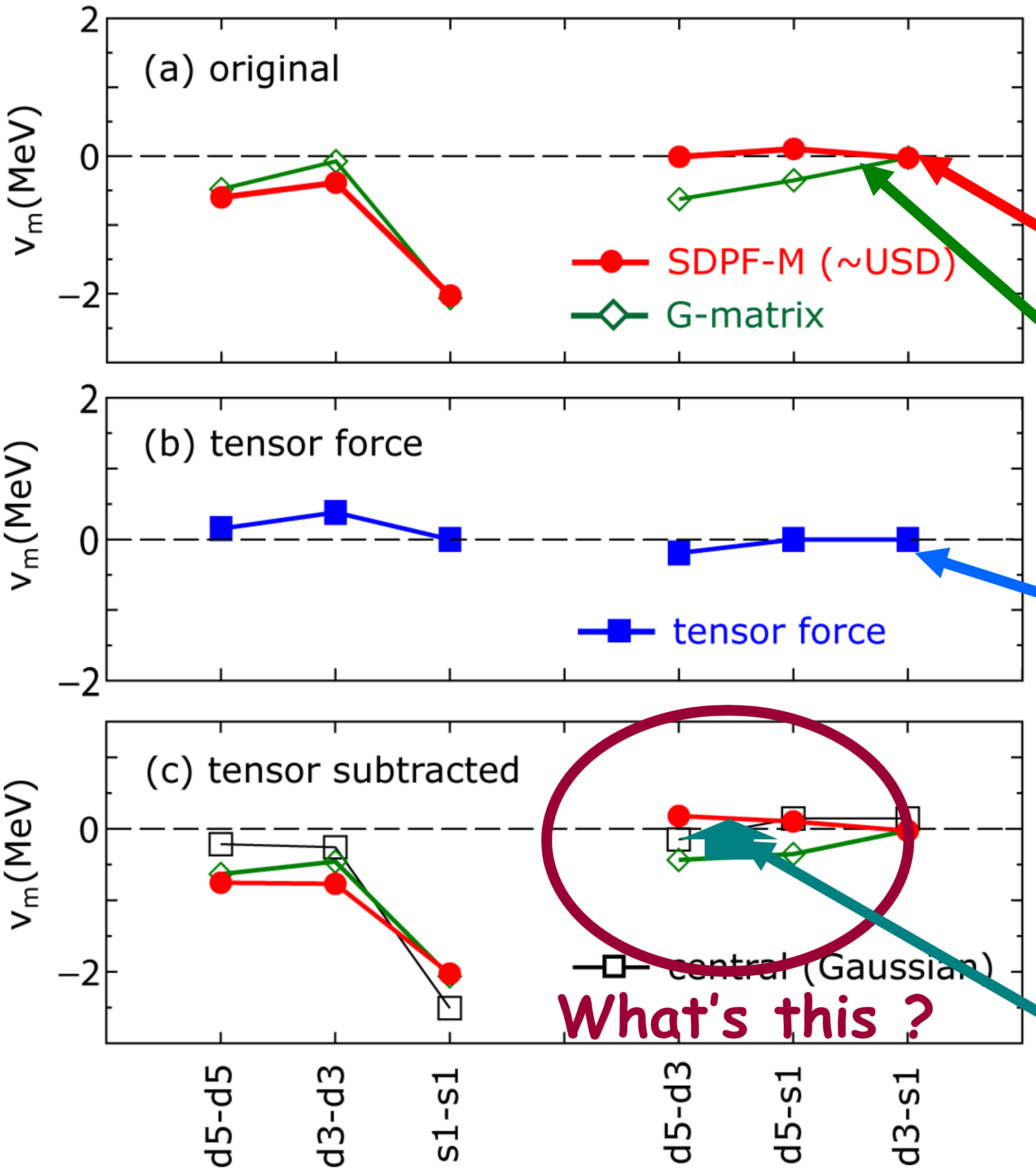
Basic scale ~ 1/10 of T=0

Repulsive corrections to G-matrix

j = j'

j ≠ j'

T=1 monopole interactions in the sd shell



SDPF-M (~USD)

G-matrix
(H.-Jensen)

Tensor force
(π+ρ exchange)

What's this ?

Basic scale
~ 1/10 of T=0

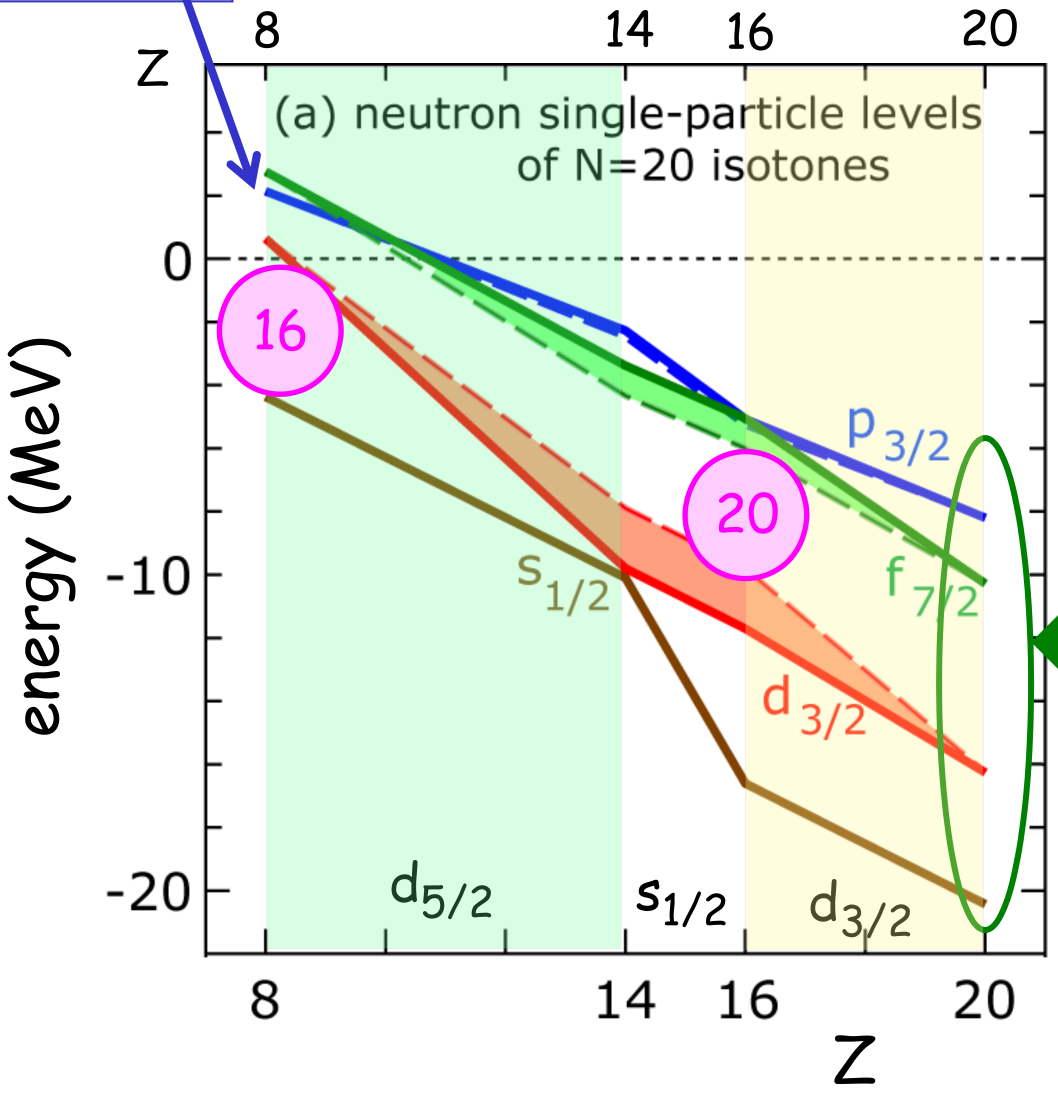
Repulsive
corrections
to G-matrix

j = j'

j ≠ j'

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

$p_{3/2}$ low



solid line : full
(central + tensor)

dashed line : central only

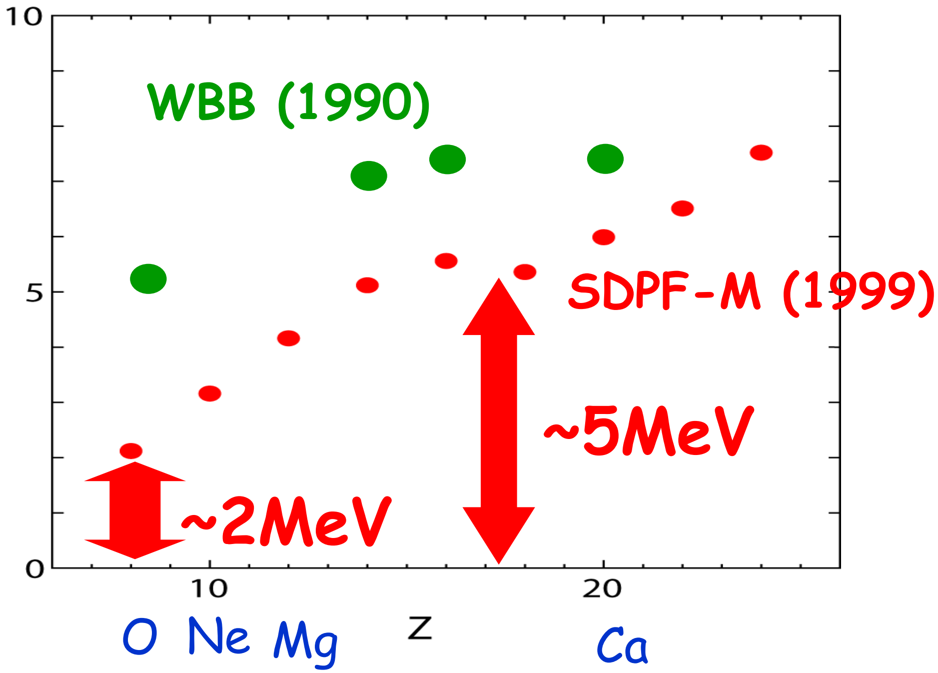
Tensor force makes changes more dramatic.

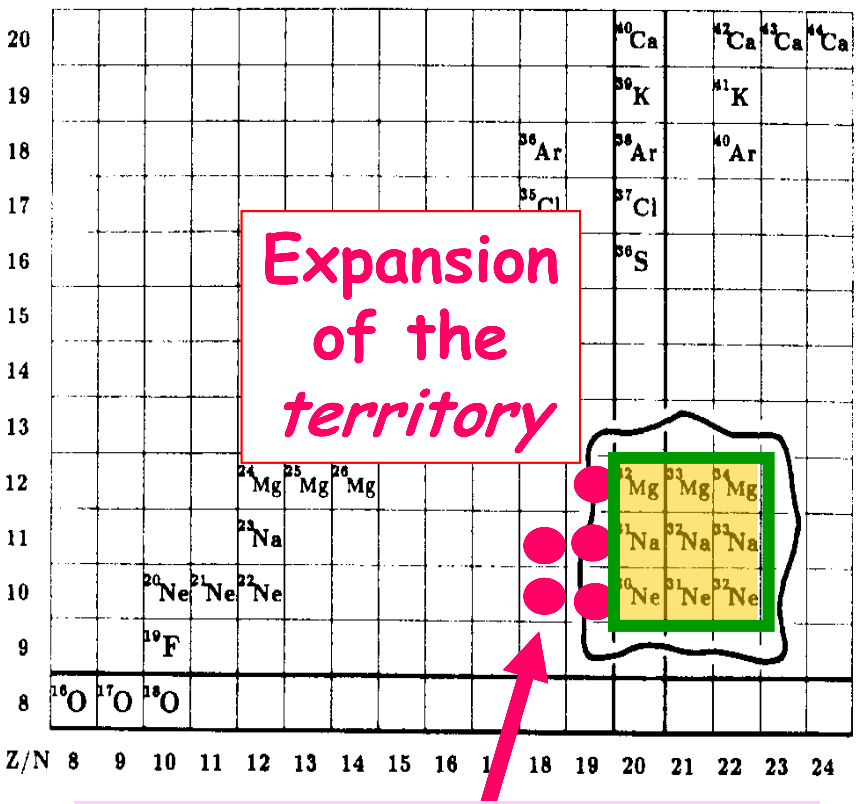
These single-particle energies are "normal"

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

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

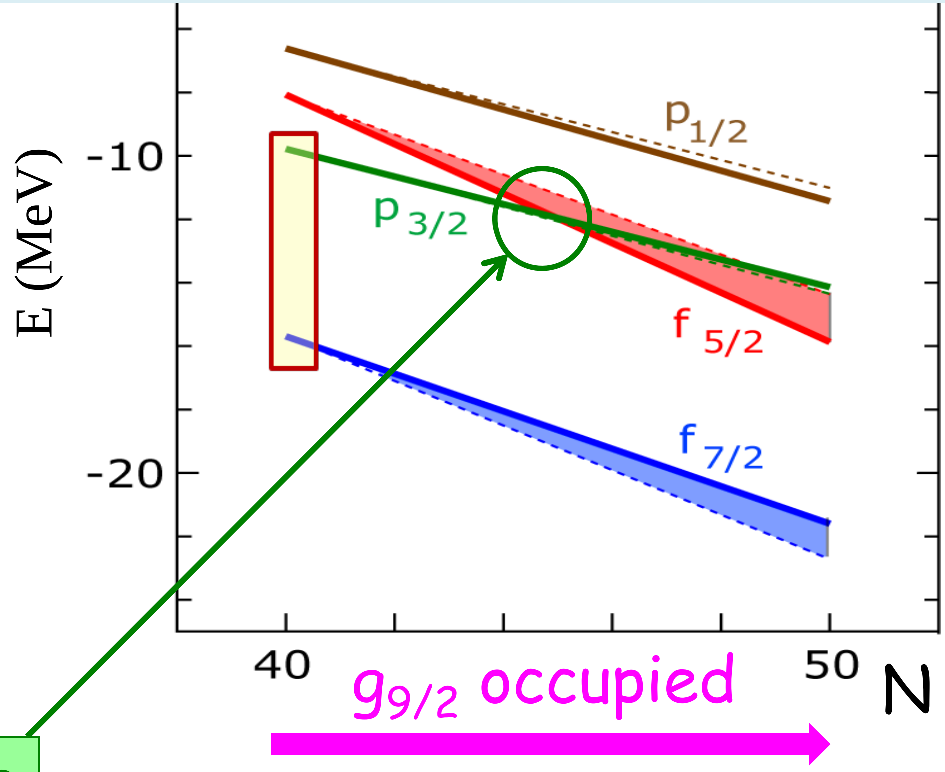




Expansion of the *territory*

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



$g_{9/2}$ occupied

Central Gaussian + Tensor

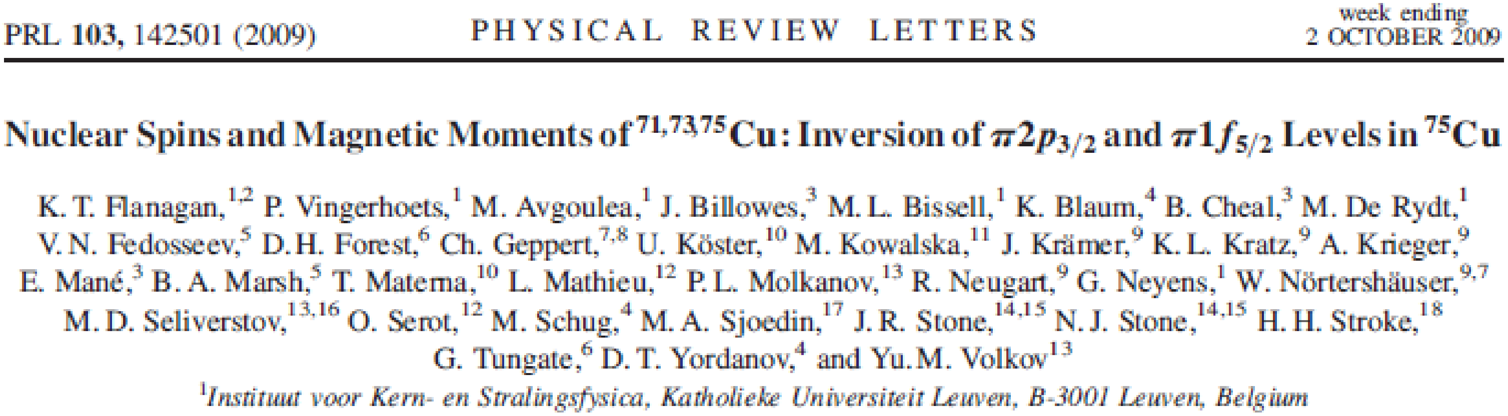
solid line:
full effect

dotted line:
central only

shaded area :
effect of
tensor force

From Grawe, EPJA25, 357

Crossing here is consistent with exp. on Cu isotopes



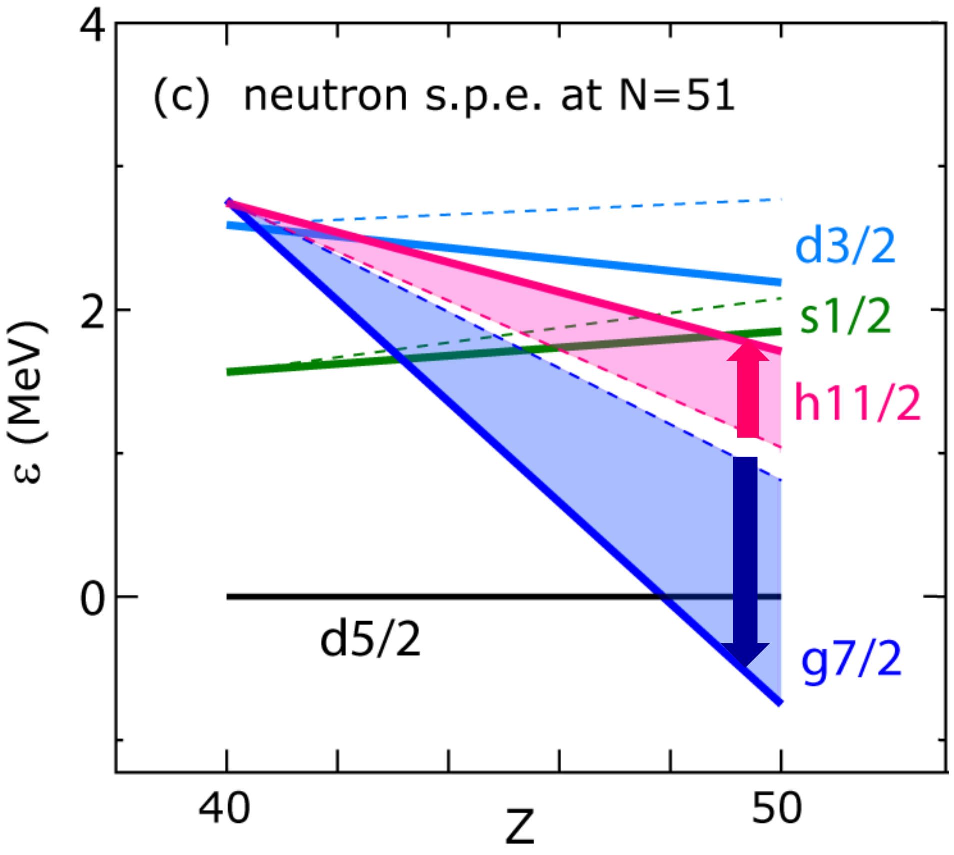
PRL 103, 142501 (2009) PHYSICAL REVIEW LETTERS week ending 2 OCTOBER 2009

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

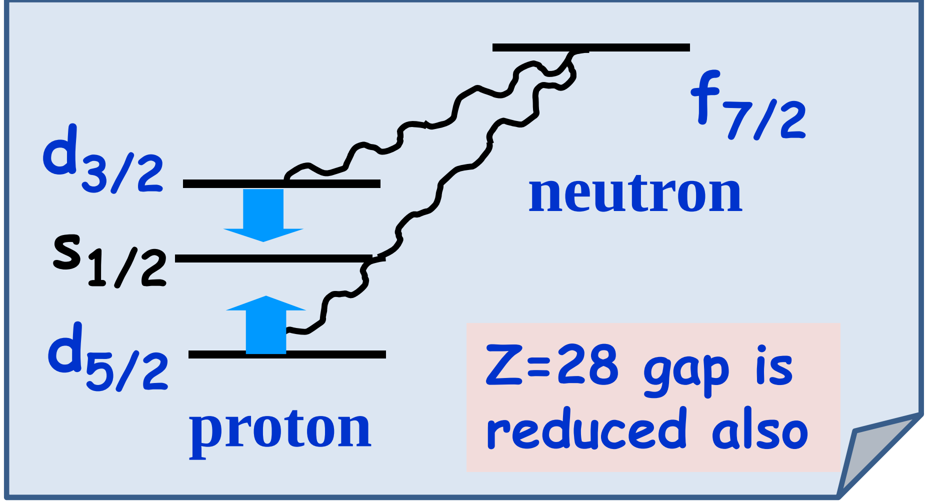


solid line : full
(central + tensor)

dashed line : central only

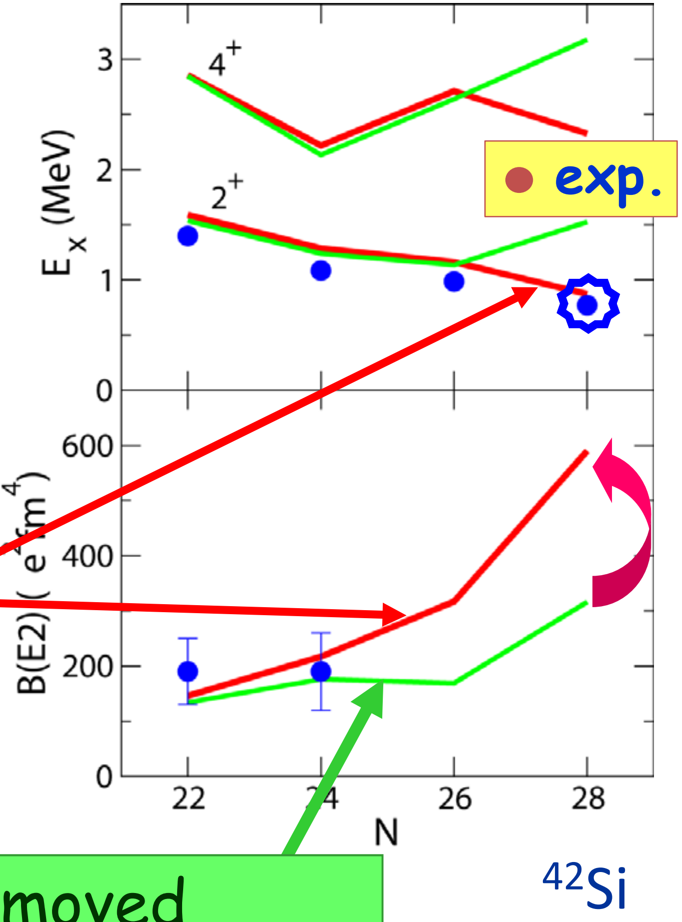
shaded area :
effect of tensor force

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

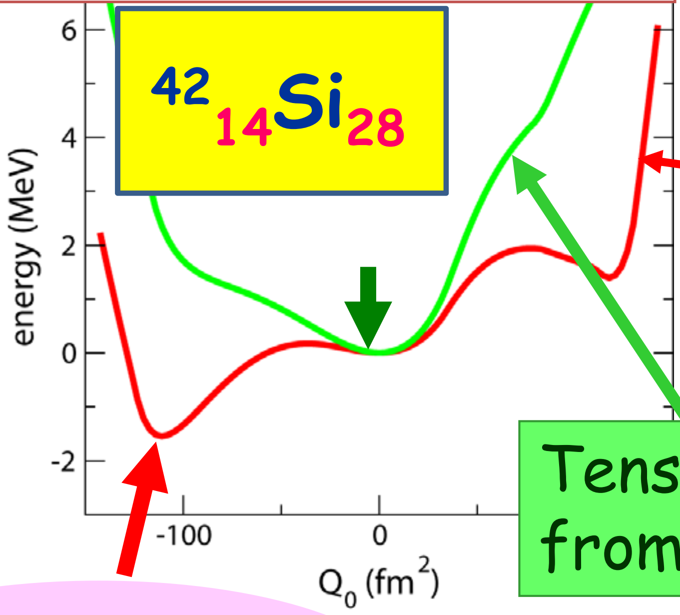


Z=28 gap is reduced also

Si isotopes
SM calc. by Utsuno et al.



Potential Energy Surface



full

Tensor force removed
from cross-shell interaction

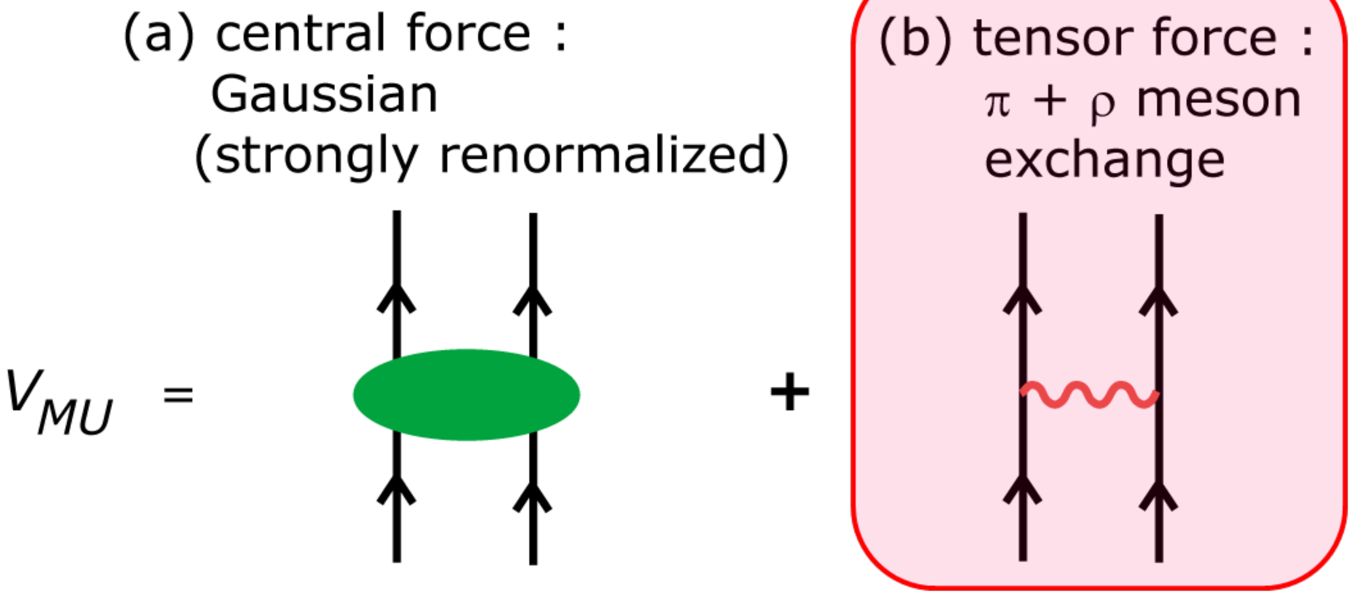
Strong oblate
Deformation ?

Other calculations
show a variety of shapes.

Otsuka, Suzuki and Utsuno,
Nucl. Phys. A805, 127c (2008)

^{42}**Si:** *B. Bastin, S. Grévy et al.,*
PRL 99 (2007) 022503

Systematic description of monopole properties of exotic nuclei can be obtained by an extremely simple interaction as



V_{MU} =

(a) central force :
Gaussian
(strongly renormalized)

\+

(b) tensor force :
π + ρ meson
exchange

Can this be really the same as the bare tensor interaction ?

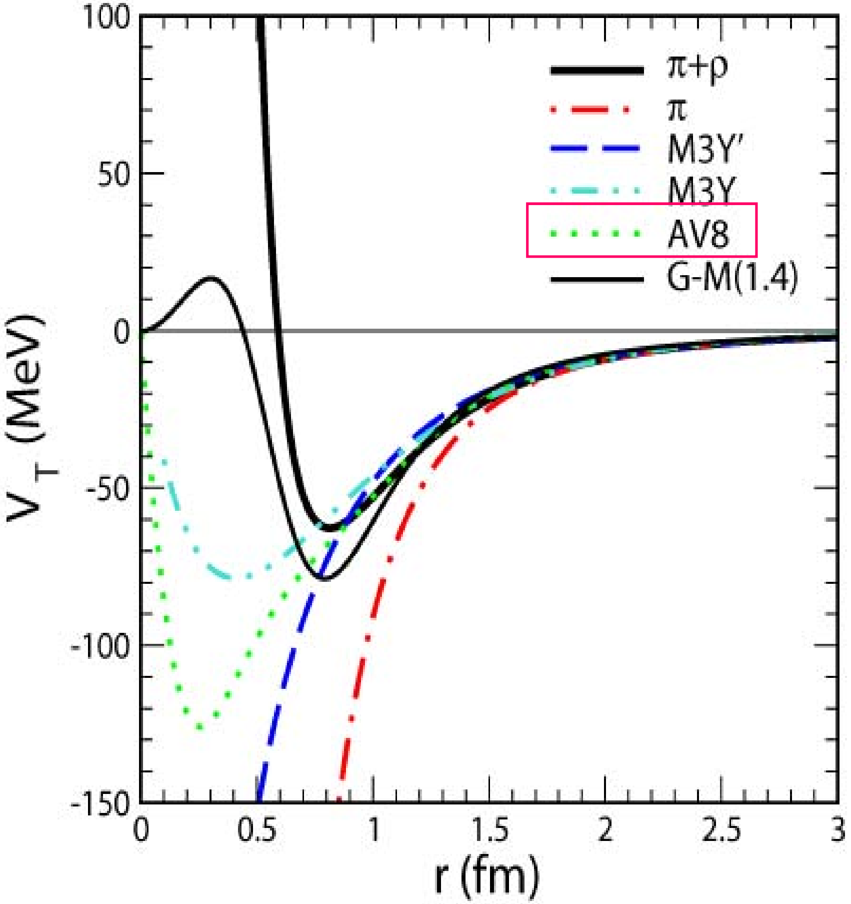
Question :

Can the tensor force
survive after

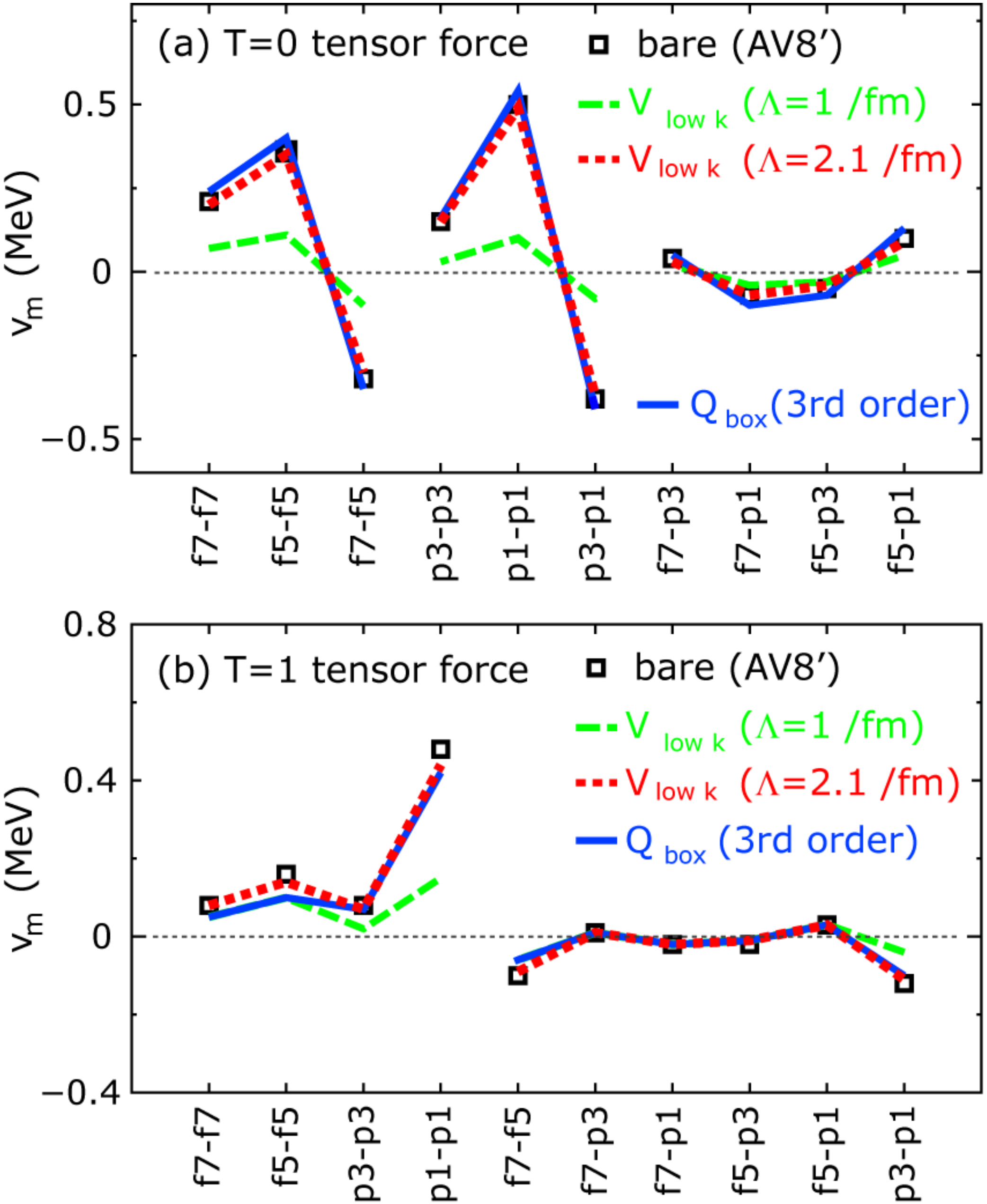
-treatment of
short-range correlations
(hard-core)

-treatment of
core polarization

Tensor potential



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



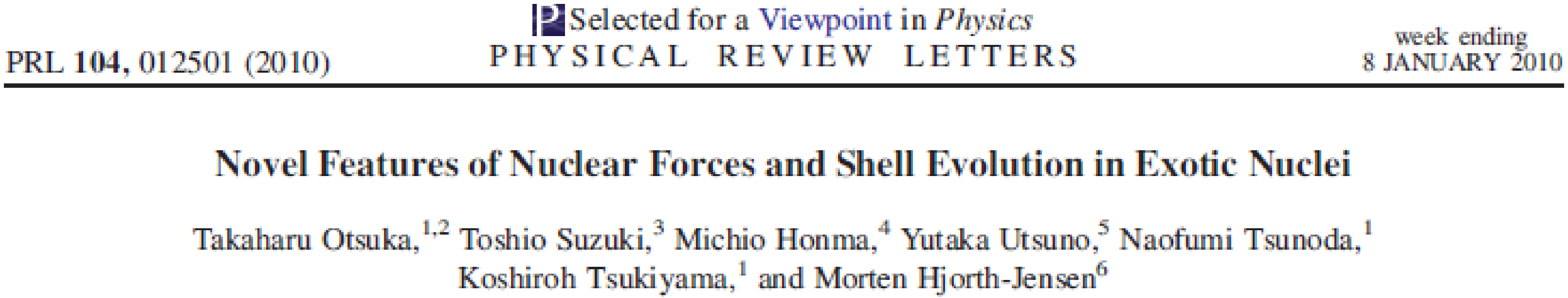
Monopole component of tensor interactions in *pf* shell

Input: AV8′

Almost no cut-off (Λ) dependence, except for extremely low Λ

$V_{\text{low k}}$: Kuo, Bogner, et al.

Shell evolution in exotic nuclei due to tensor + central forces



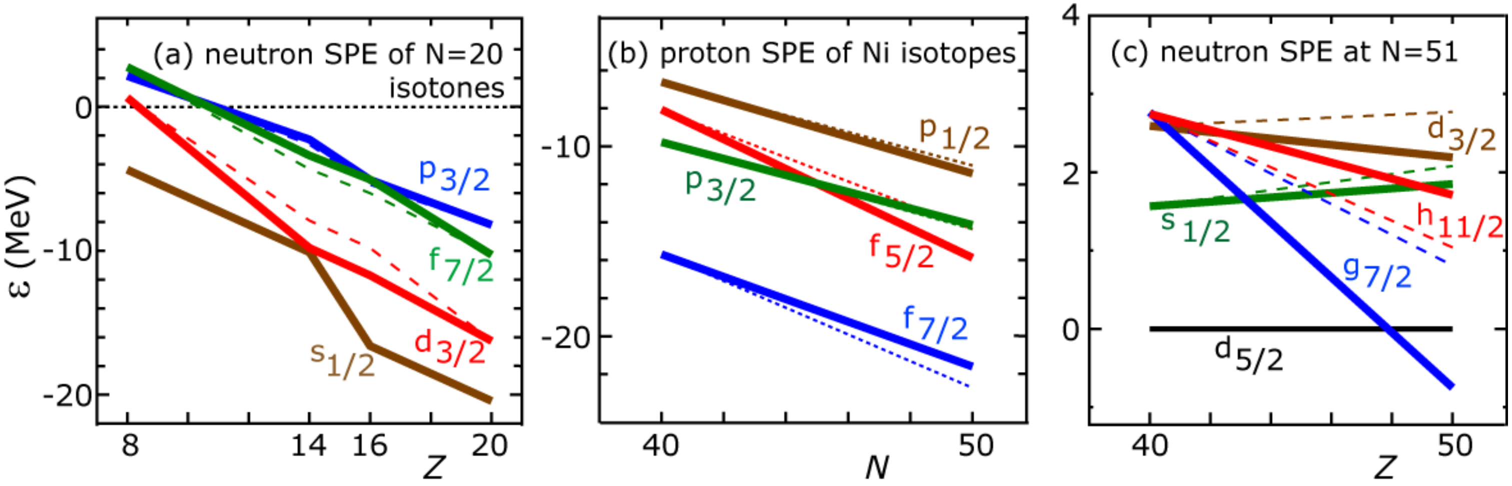
Selected for a Viewpoint in *Physics*

PRL **104,** 012501 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

Novel Features of Nuclear Forces and Shell Evolution in Exotic Nuclei

Takaharu Otsuka,[1,2] Toshio Suzuki,[3] Michio Honma,[4] Yutaka Utsuno,[5] Naofumi Tsunoda,[1]
Koshiroh Tsukiyama,[1] and Morten Hjorth-Jensen[6]

Changes of single-particle properties due to these nuclear forces

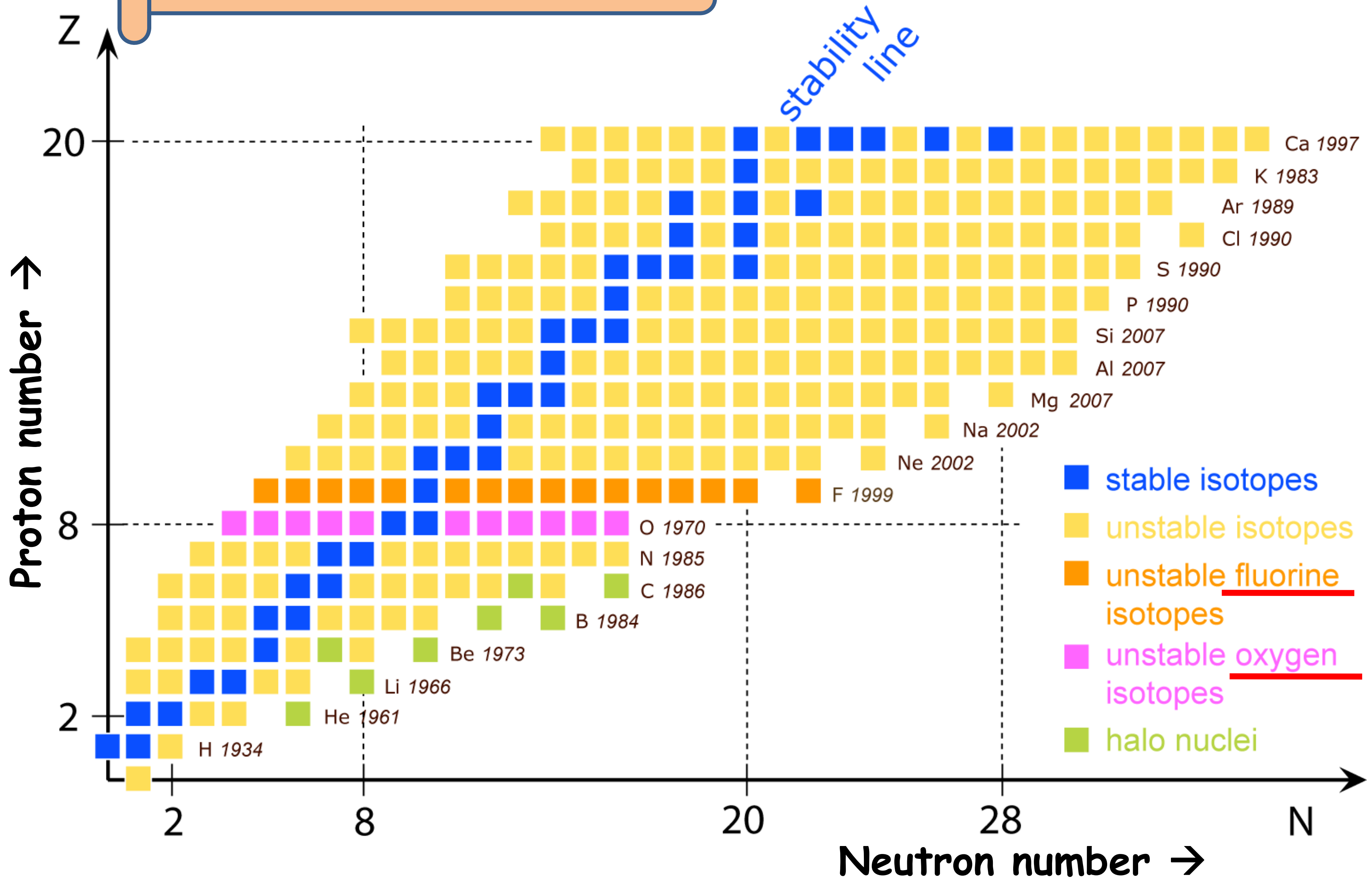


What is the next ?

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.

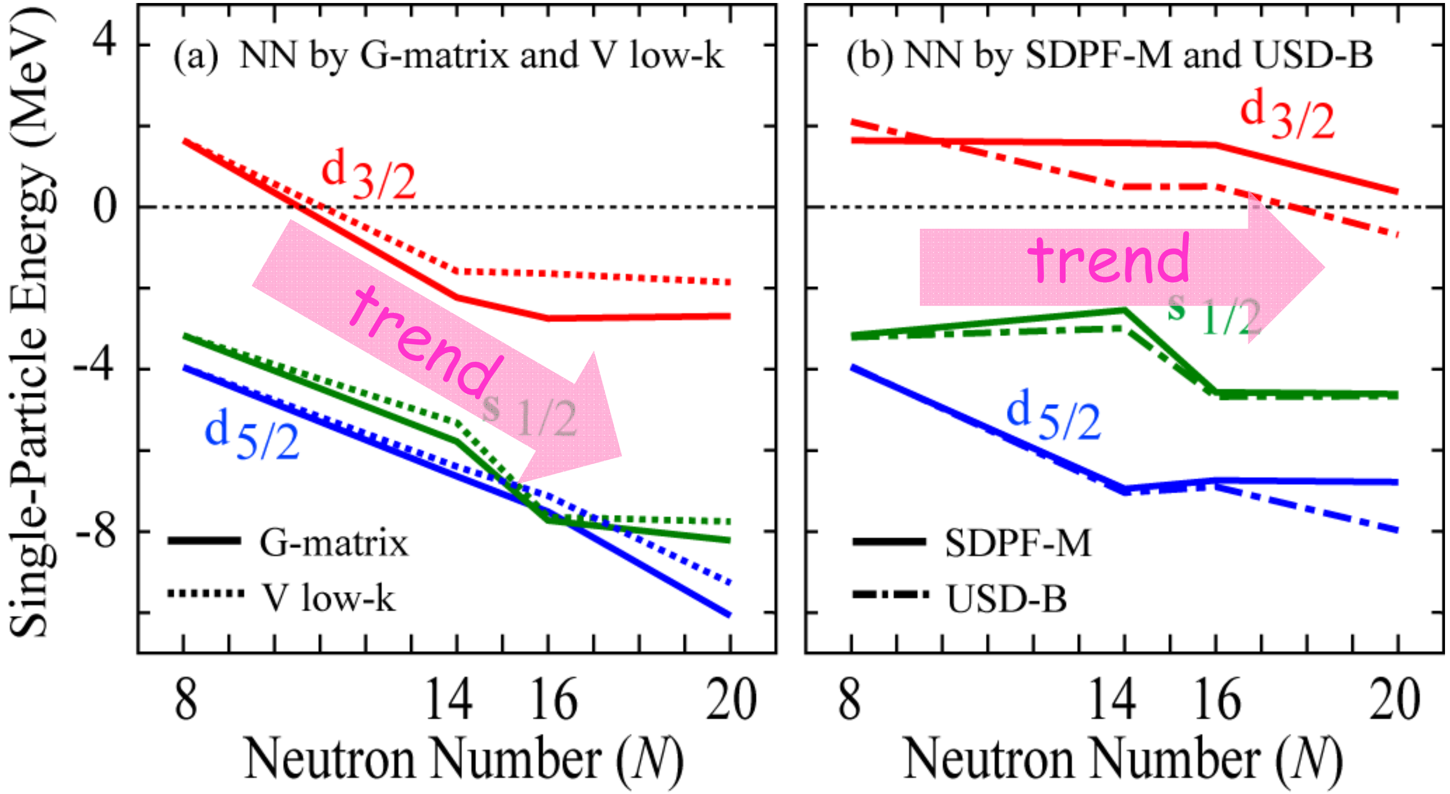
G-matrix+ core-pol. : Kuo, Brown

V low-k : Bogner, Kuo, Schwenk

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)



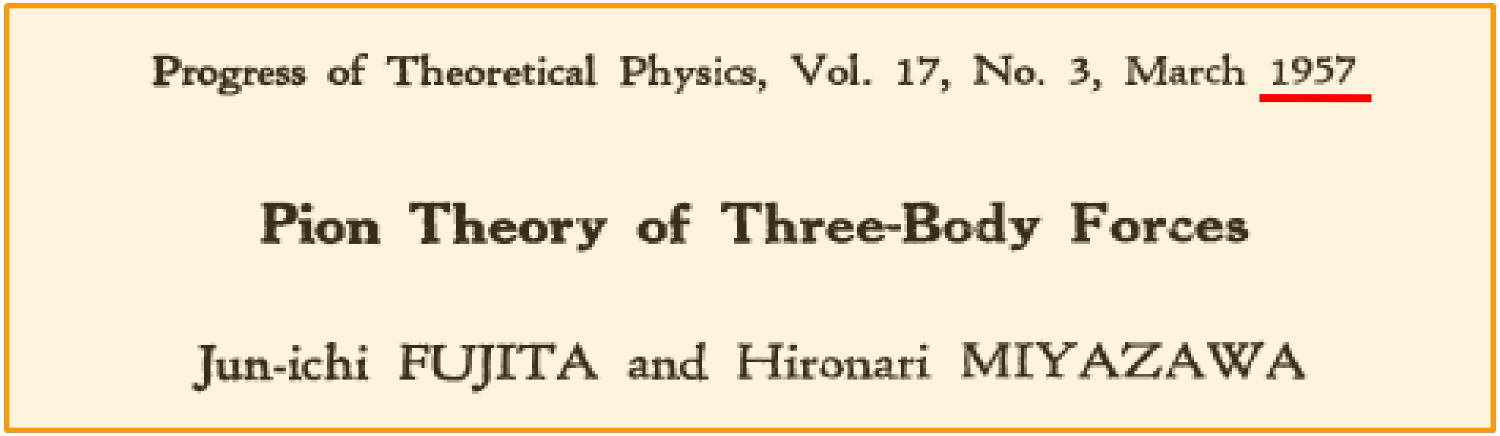
What is the origin of the ***repulsive modification*** of ***T=1*** monopole matrix elements ?

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)

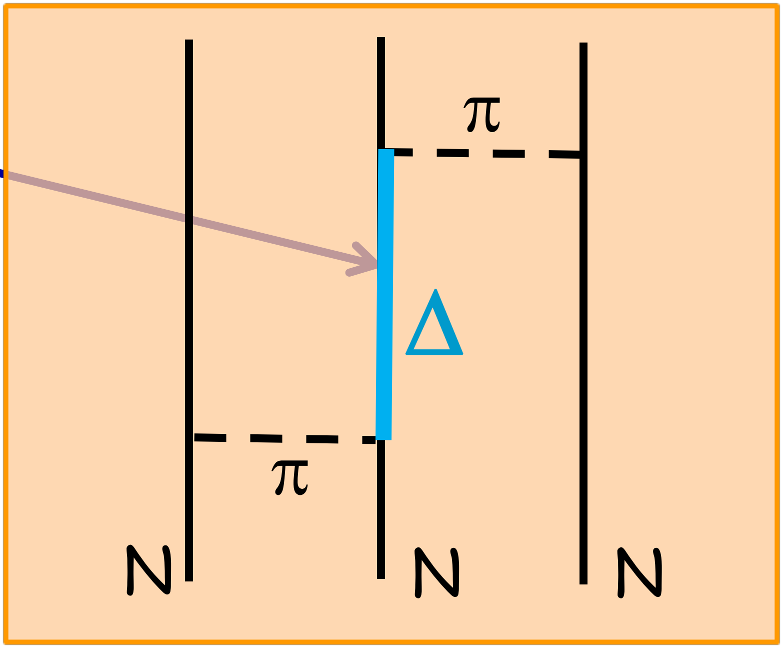


Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

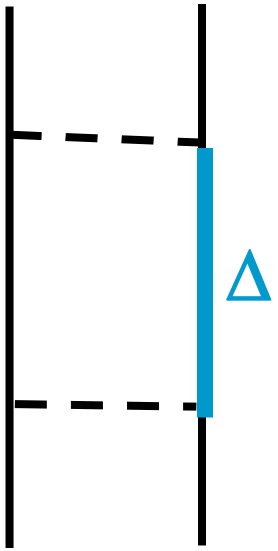
Pion Theory of Three-Body Forces

Jun-ichi FUJITA and Hironari MIYAZAWA

Δ particle
m=1232 MeV
S=3/2, I=3/2



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

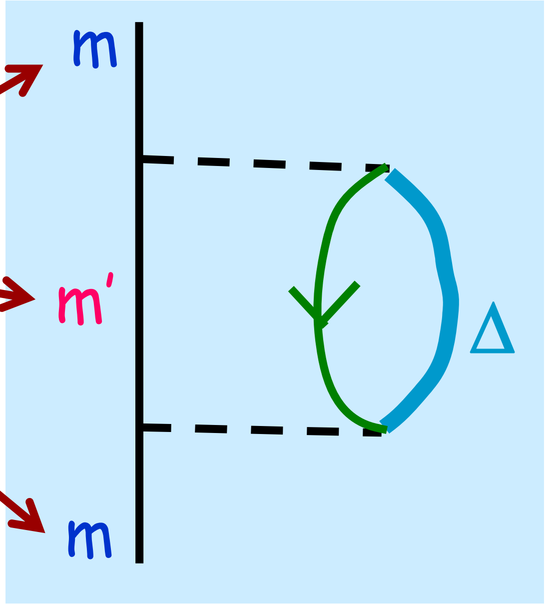


T=1
attraction
between *NN*
effectively

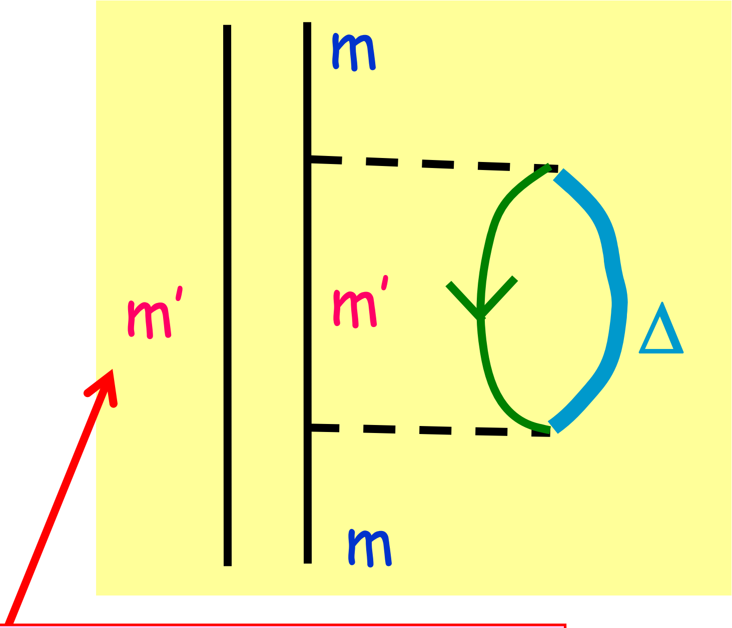
Modification to bare *NN* interaction (for *NN* scattering)

Pauli blocking effect on the renormalization of single-particle energy

single
particle
states



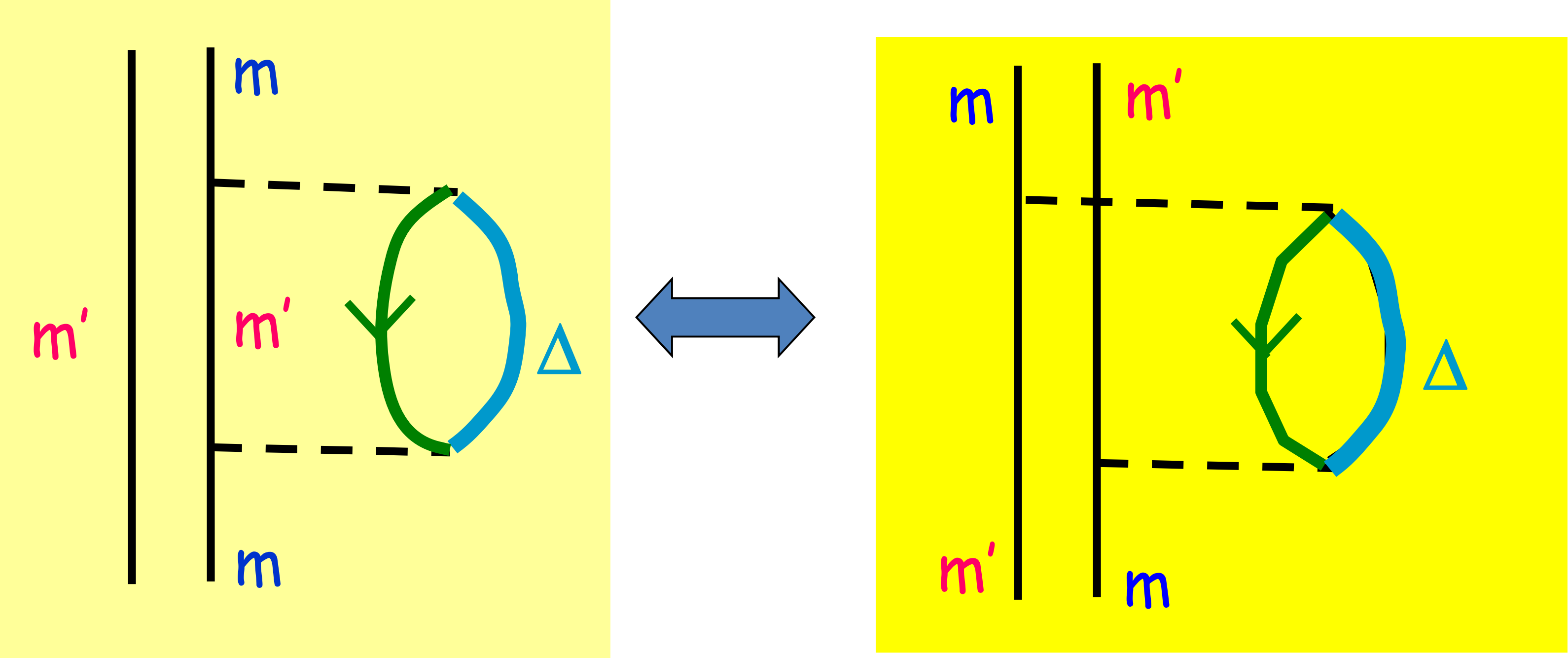
Renormalization of
single particle energy
due to
Δ-hole excitation
→ more binding (attractive)



Another valence
particle in state m′

Pauli Forbidden
→ *The effect is*
suppressed

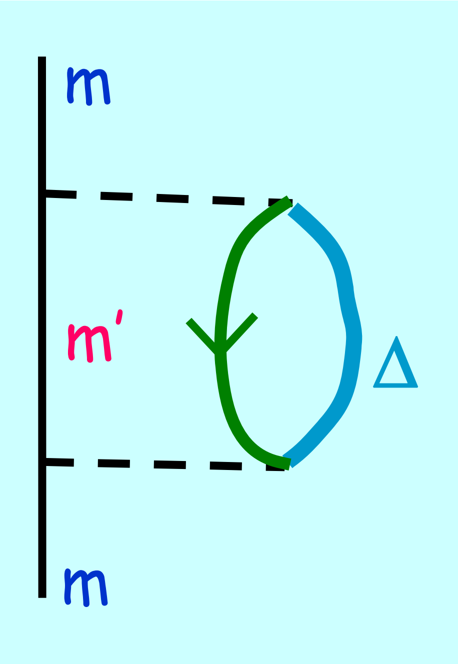
Inclusion of Pauli blocking



Pauli forbidden
(from previous page)

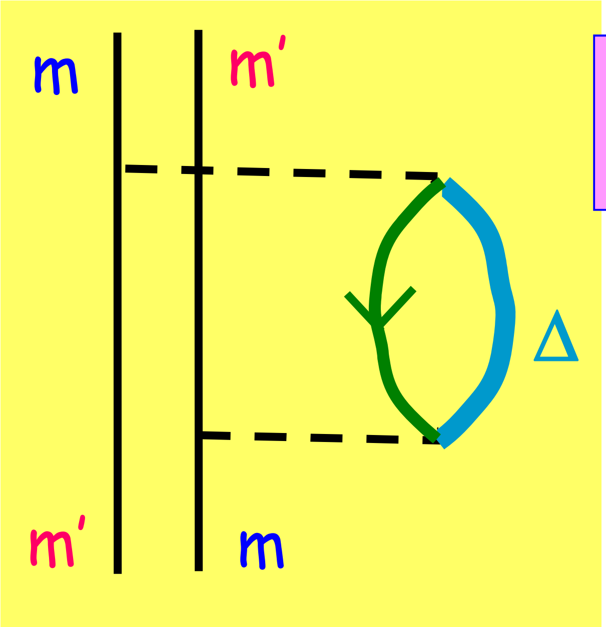
This Pauli effect is included automatically by the exchange term.

Most important message with Fujita-Miyazawa 3NF



Renormalization of single particle energy

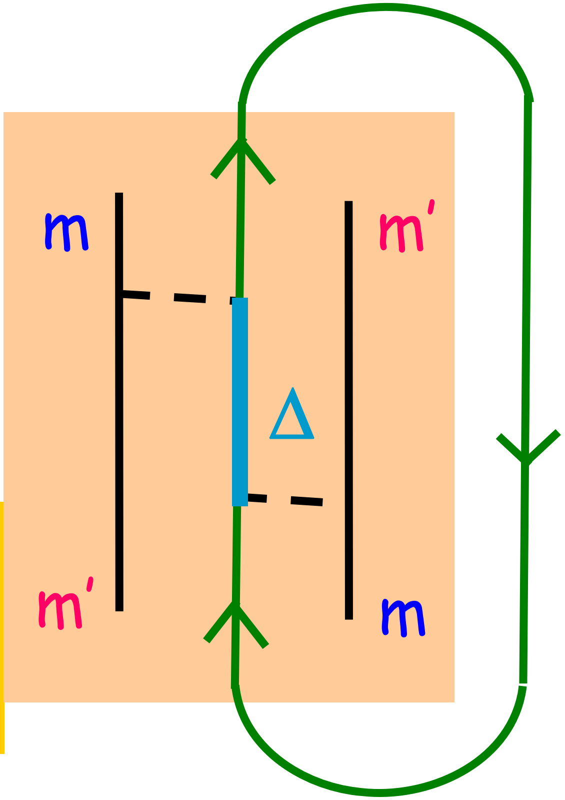
+



Pauli blocking

Effective monopole repulsive interaction

same

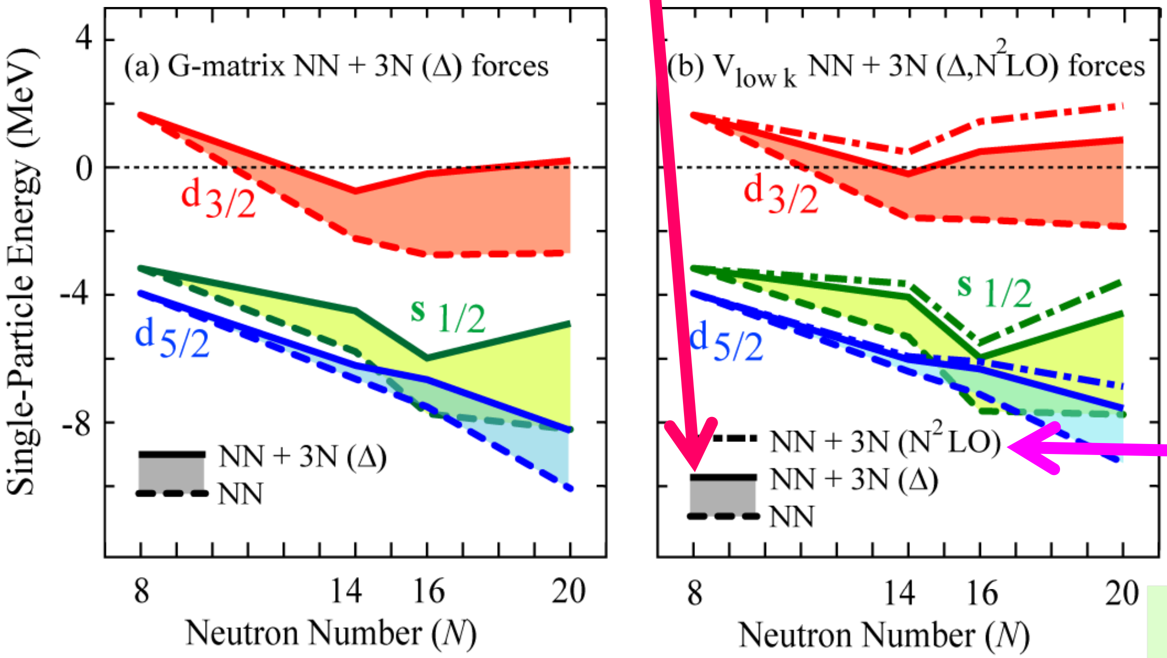


Monopole part of Fujita-Miyazawa 3-body force

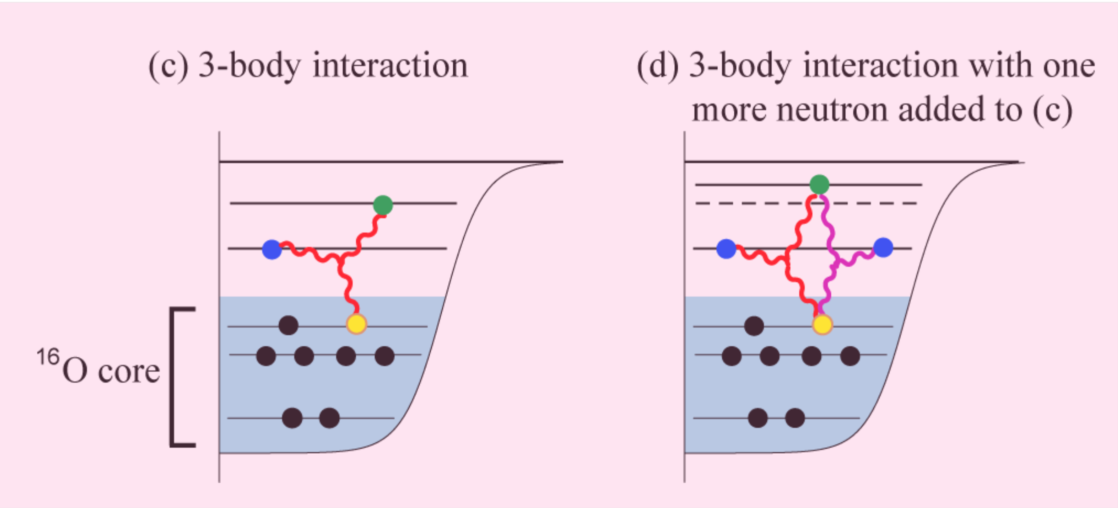
(i) Δ-hole excitation in a conventional way

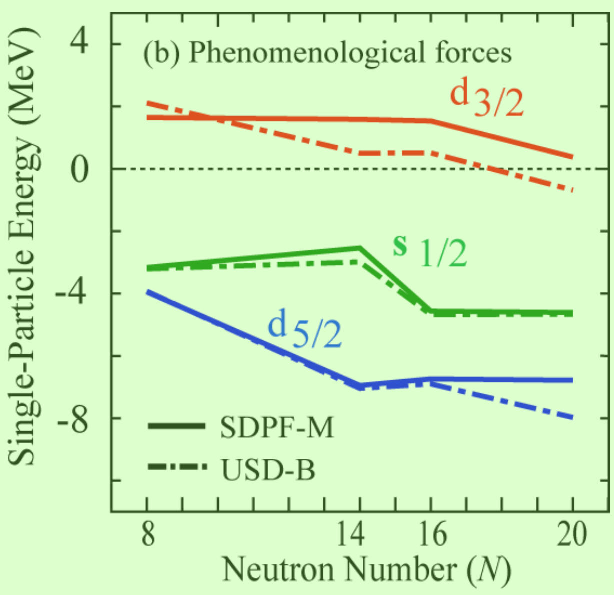
(ii) EFT with Δ

Δ-hole dominant role in determining oxygen drip line



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



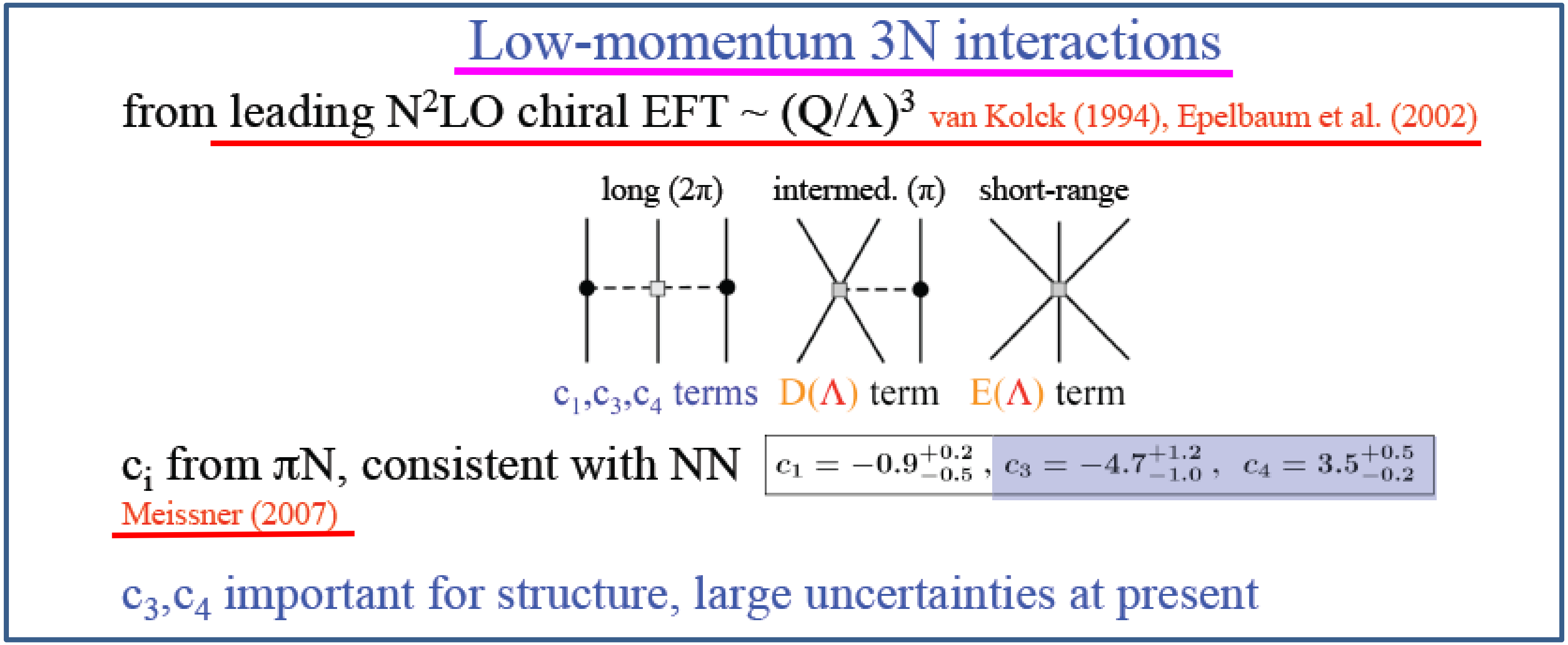


Conventional calculation with πNΔ coupling

π exchange with radial cut-off at 0.5 fm , ΔE =293 MeV

f_{πNΔ}/f_{πNN} = ¥sqrt{9/2}

A.M. Green, Rep. Prog. Phys. 39, 1109 (1976)



Low-momentum 3N interactions

from leading N^2LO chiral EFT ~ $(Q/\Lambda)^3$ van Kolck (1994), Epelbaum et al. (2002)

c_i from πN, consistent with NN $c_1 = -0.9^{+0.2}_{-0.5}$, $c_3 = -4.7^{+1.2}_{-1.0}$, $c_4 = 3.5^{+0.5}_{-0.2}$

Meissner (2007)

c_3,c_4 important for structure, large uncertainties at present

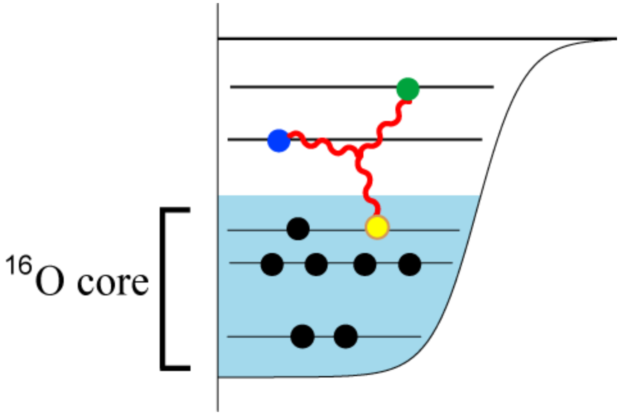
NN for smooth cutoff $V_{\mathrm{low}\,k}$ (n_exp=4) from N^3LO(500)

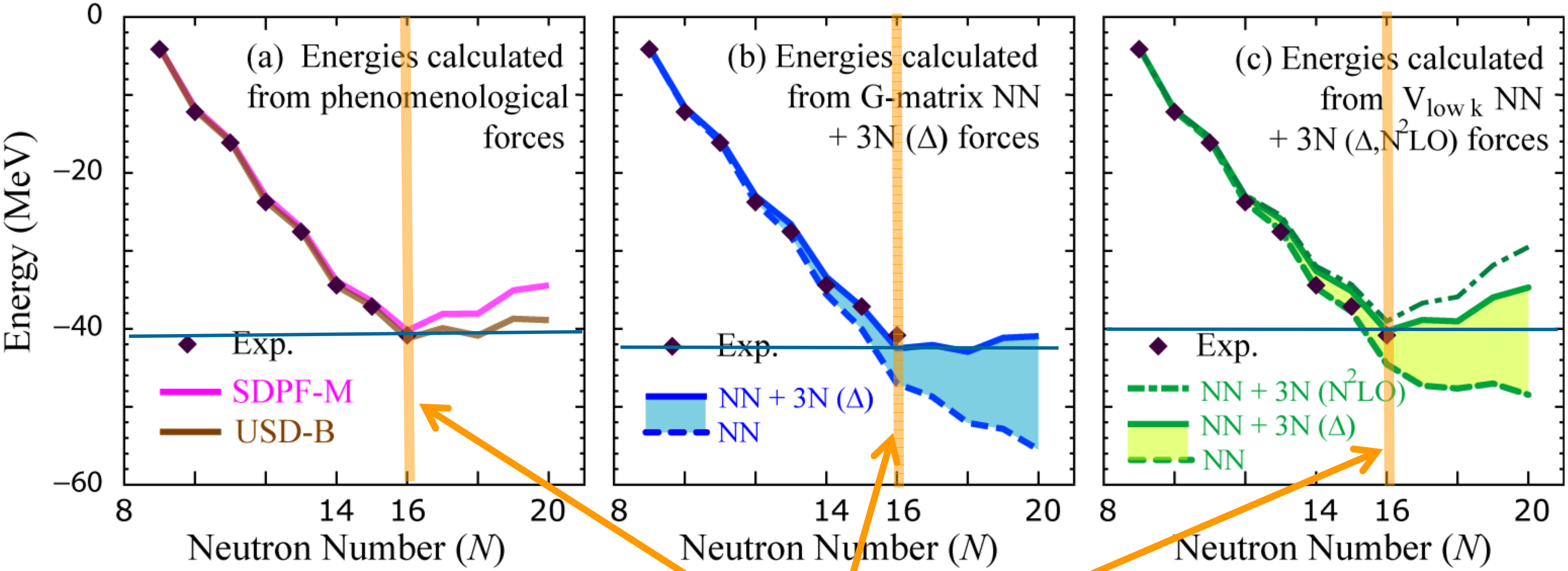
D, E terms fitted to E(3H) and radius(4He)

Ground-state energies of oxygen isotopes

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

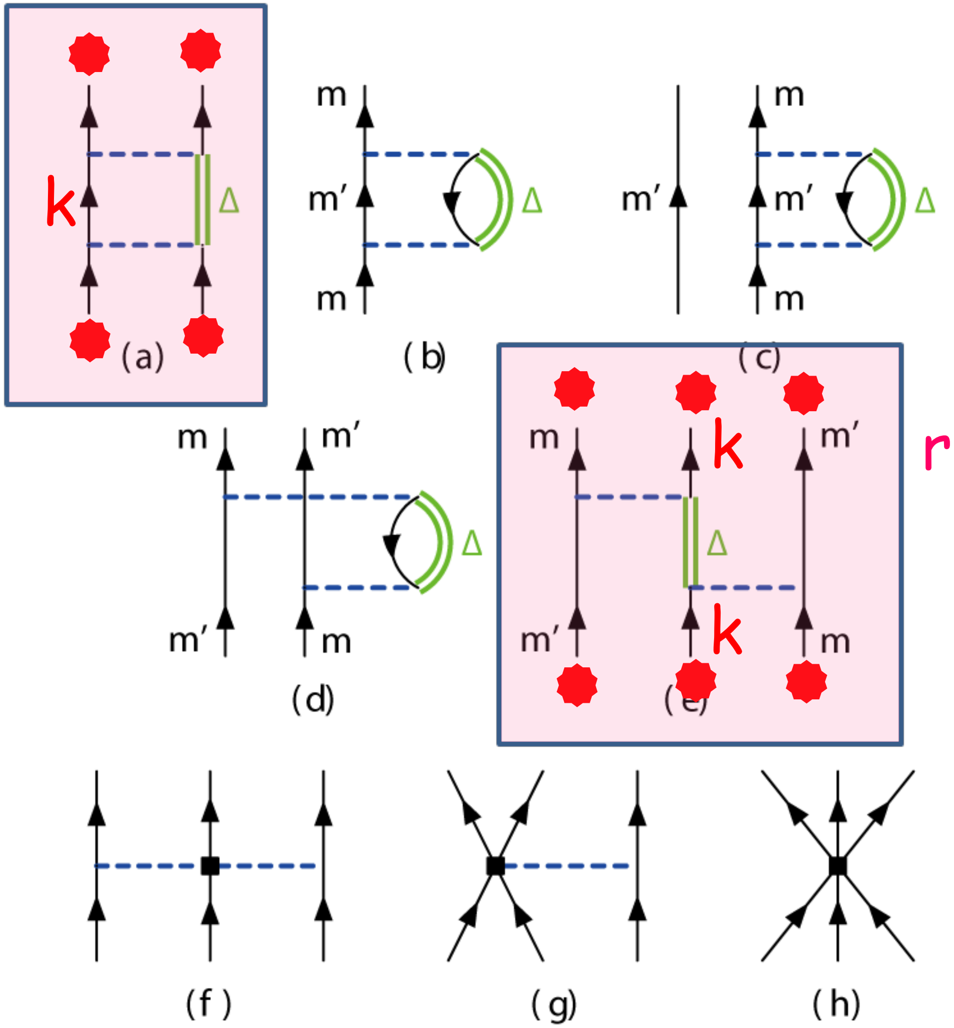
(Fujita-Miyazawa force)





Drip line

For neutron matter : ● k states below Fermi level



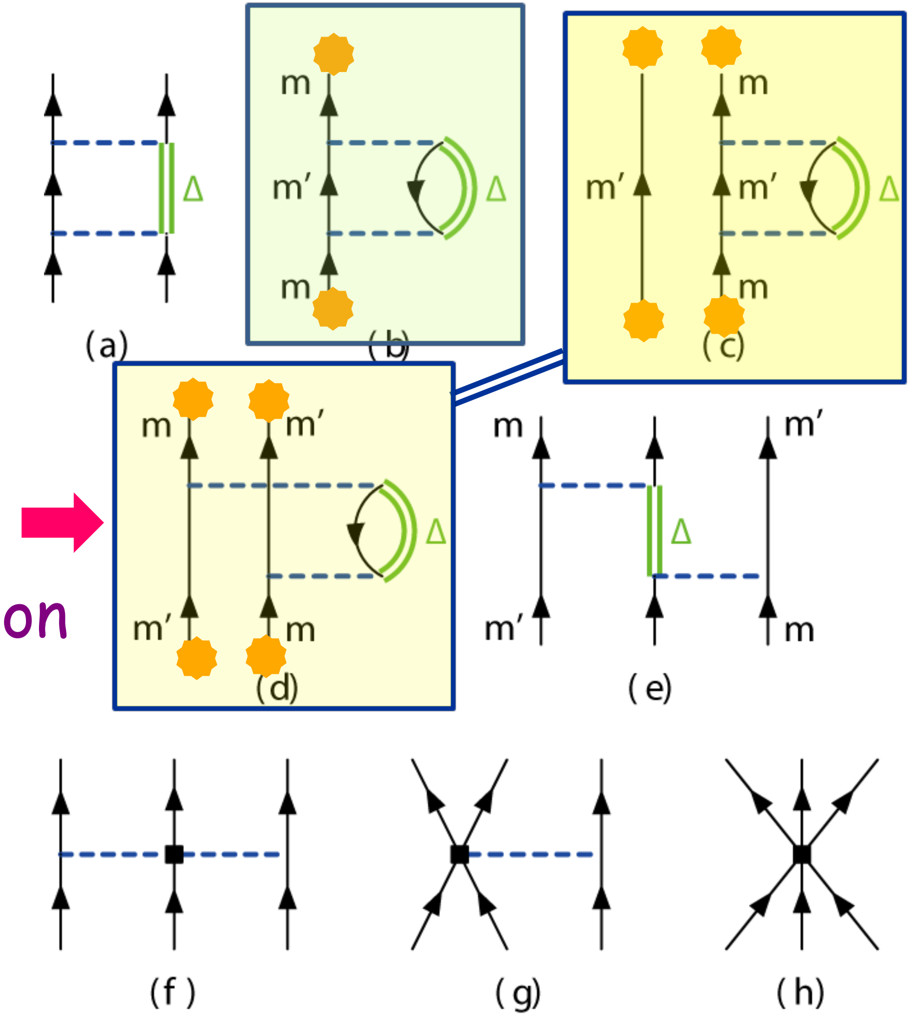
attractive

repulsive

Brown and Green, Nucl.Phys. A137, 1 (1969
Fritsch, Kaiser and Weise, Nucl. Phys. A750, 259 (2005);
Tolos, Friman and Schwenk, Nucl.Phys. A806}, 105 (2008);
Hebeler and Schwenk, arXiv:0911.0483 [nucl-th]

For valence neutrons: ✹ states outside the core

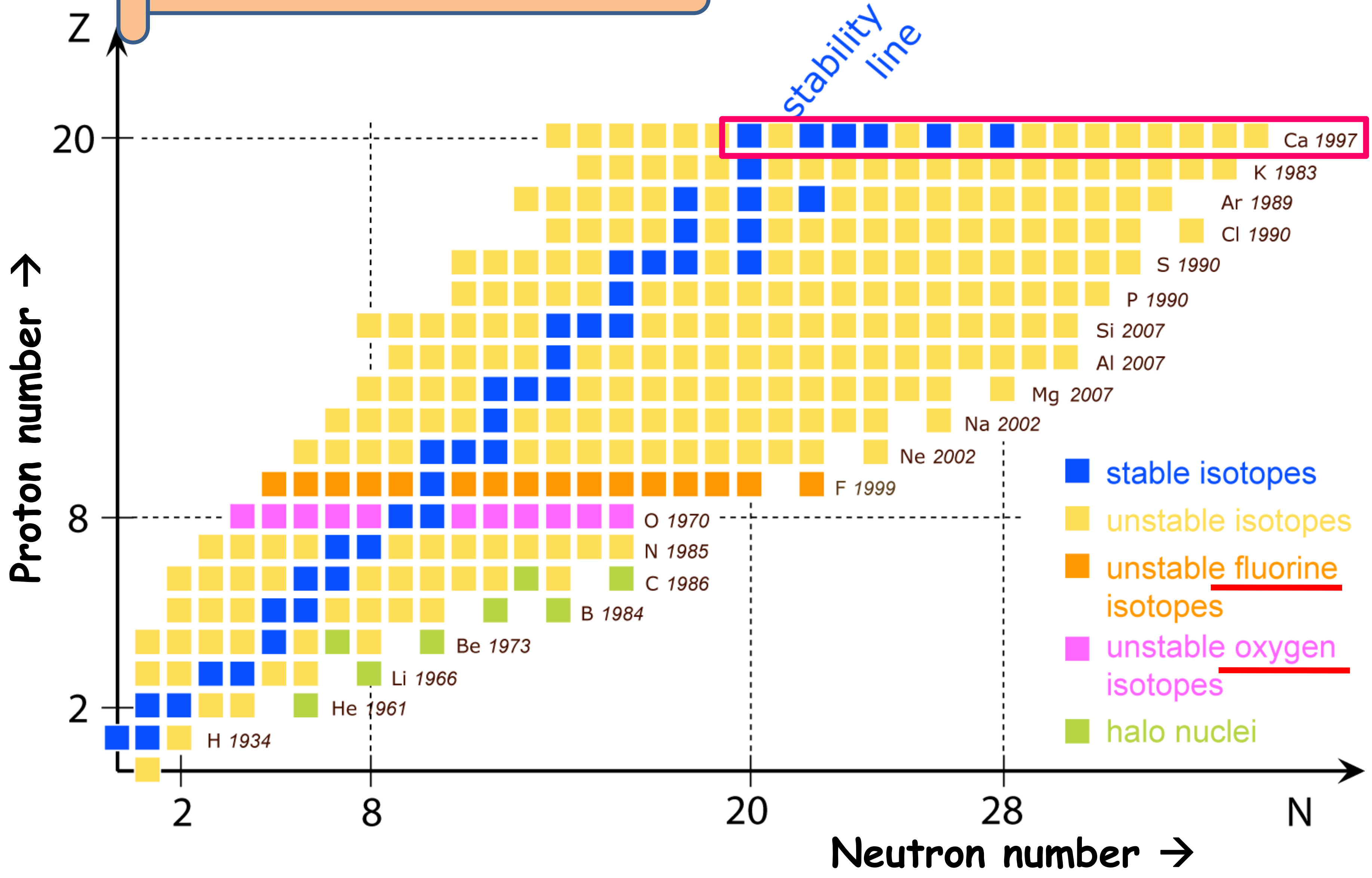
Attractive (single-particle energy renormalization)



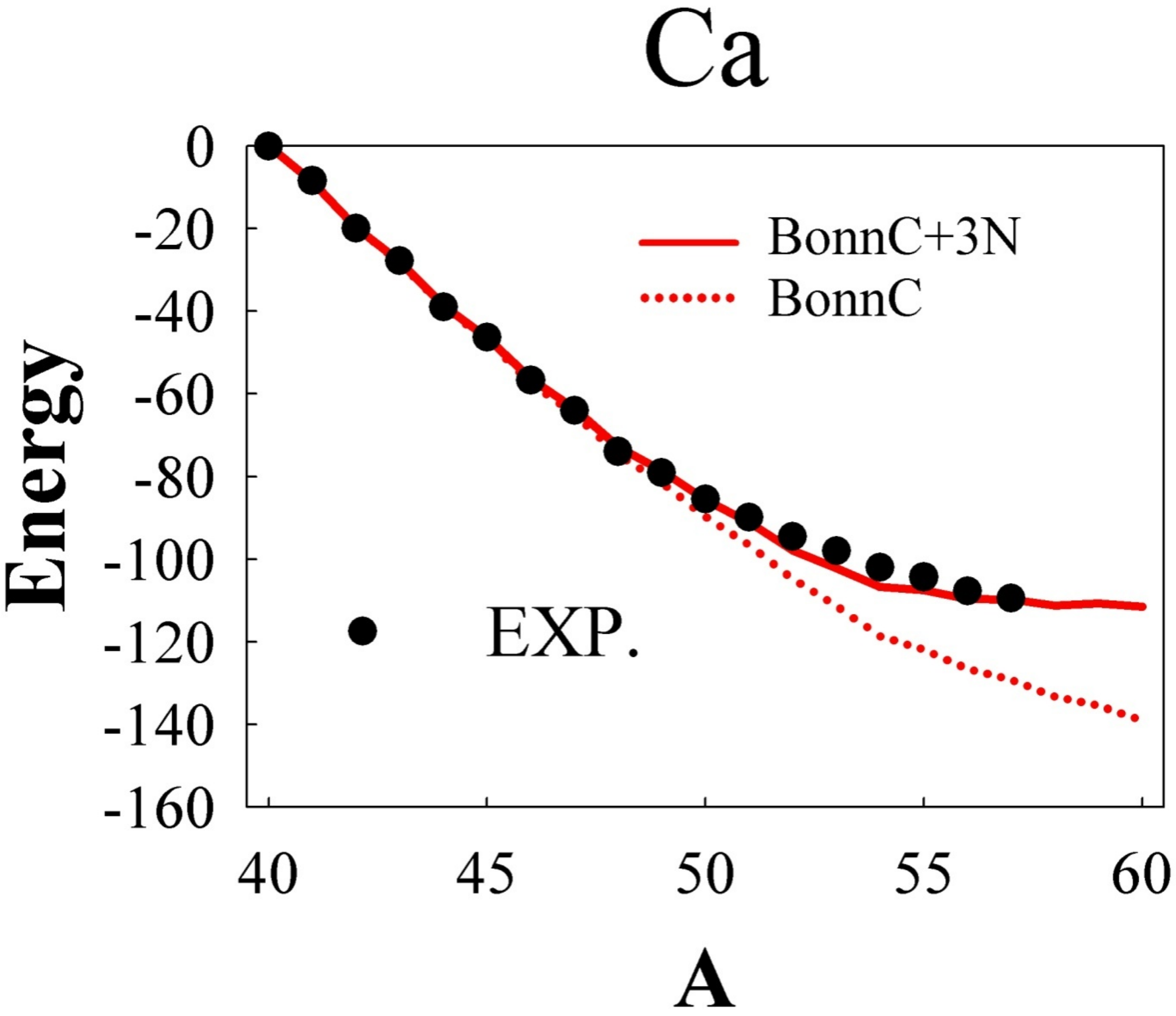
repulsive (valence neutron interaction)

Nuclear Chart
- Left Lower Part -

Ca isotopes

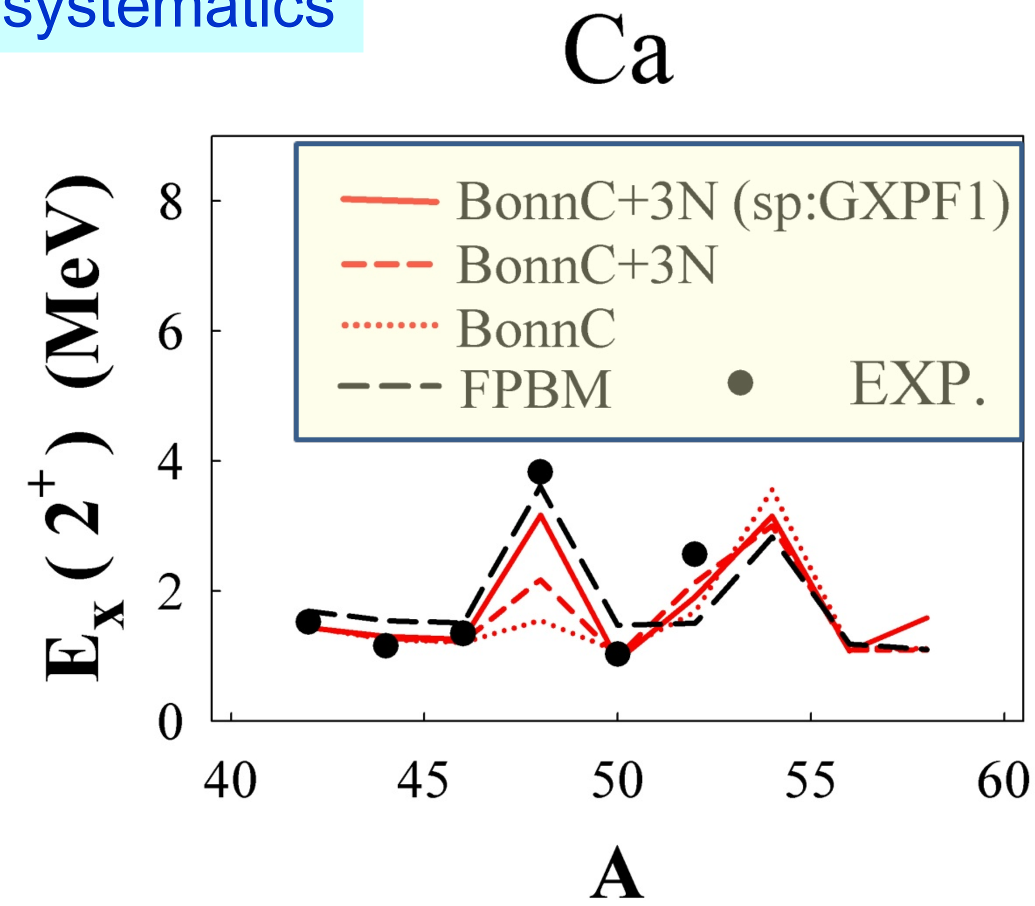


Ca ground-state energy *cont'd*



SPE : GXPF1 f7:-8.62 f5: -1.38 p3: -5.68 p1: -4.14

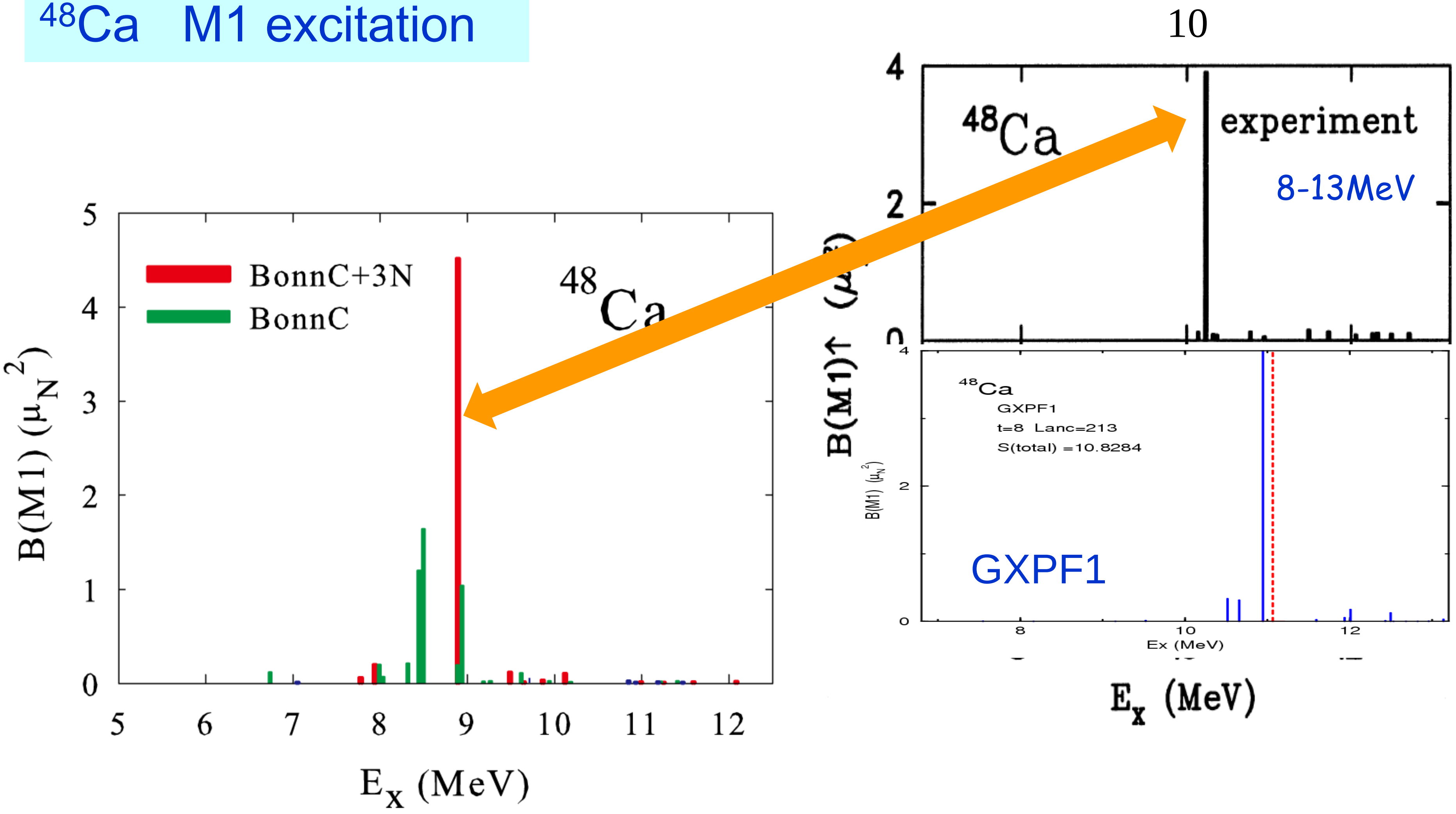
Ca 2+ level systematics



2^+ of ^{48}Ca rises by 3N
becomes about right by using GXPF1A SPE

N=32, 34 higher 2^+ levels

^{48}Ca M1 excitation



spe : GXPF1

Spin quenching factor 0.8

Summary

1. 核力のモノポール成分の効果は粒子数とともにリニアに増大
レンズのようなもので、中性子過剰核で核力を究めることを可能にする

2. メイヤー・イェンゼンの“原子核によらない普遍な魔法数・殻構造”のパラダイムは
エキゾチック核（不安定核）では崩れる。２体、３体の核力はその主な原動力。

殻構造は一粒子の性質を決めるだけでなく、Jahn-Teller効果に他ならない
基底状態近辺の変形を決め、スピンに関わる性質にも影響

3. テンソル力と中心力はワインバーグ型の有効力を構成。テンソル力は原子核中
でも bare と同じ （様々な現代風核力で同様、もちろん現代的理論で）。
陽子-中性子間の相互作用をよく表す
N＝20近傍の island of inversion、^{78}Ni, ^{100}Sn などの key issue を解く

4. 藤田-宮沢3体力は、バレンス中性子間に有効斥力を生じる。
中性子数を増やすと一粒子エネルギーの間は広がる
新たな魔法数の発生、shell quenching 仮説とは逆のこと
酸素のドリップラインの説明、殻模型有効相互作用の最後の謎を解明？
カルシウムなどで、ゆるく束縛された中性子物質を形成か？

5. 核力による多体問題が核物理であるならば、本当の核物理はこれから始まると
言っても過言でない （安定核はプロローグ？）

Summary

1. Effects of monopole component increase linearly as the particle number. This works like a lens, which enables us to study nuclear forces deeply in neutron-rich nuclei.

2. Meyer-Jensen's paradigm that magic number and shell structure remain (topologically) unchanged for all nuclei has been destroyed for exotic nuclei. 2- and 3-body forces are driving forces.

   Shell structure determines not only single-particle properties but also deformations, which are nothing but Jahn-Teller effect, and spin properties as well.

3. Tensor force and central force constitute an effective force of Weinberg type. Tensor force appears, in its monopole channel, to be the same between in nuclei and in free space (as proved by modern thoerys) .

Summary (continued)

Proton-neutron forces are well modeled.
N=20 island of inversion, key issues like 78Ni, 100Sn

4. Fujita-Miyazawa force generates effective repulsive forces between valence neutrons.
The spacing between single-particle levels gets wider as the neutron number increases.
new magic number; opposite to shell quenching
Drip line of oxygen
Last puzzle of SM eff. interaction solved ?
Loosely bound neutron matter in Ca isotopes ?

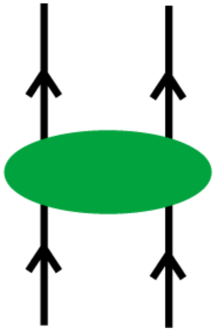
5. If nuclear physics implies many-body problems due to nuclear forces, it may be said that the real nuclear physics starts now (stable nuclei are prolog ?)

Summary-2

Dominant monopole forces are due to

V =

(a) central force :
Gaussian
(strongly renormalized)

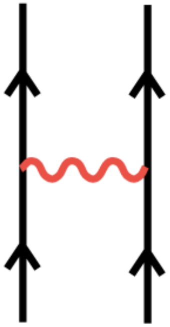


μ=1 fm

basic binding

+

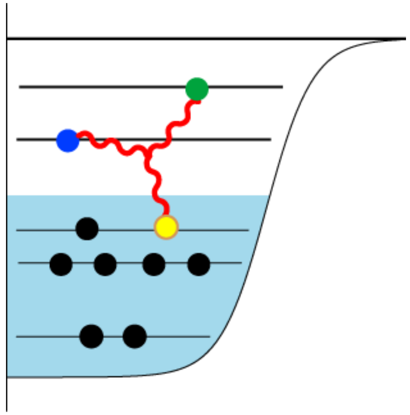
(b) tensor force :
π + ρ meson
exchange



variation of
shell structure

+

FM 3NF



limit of
existence

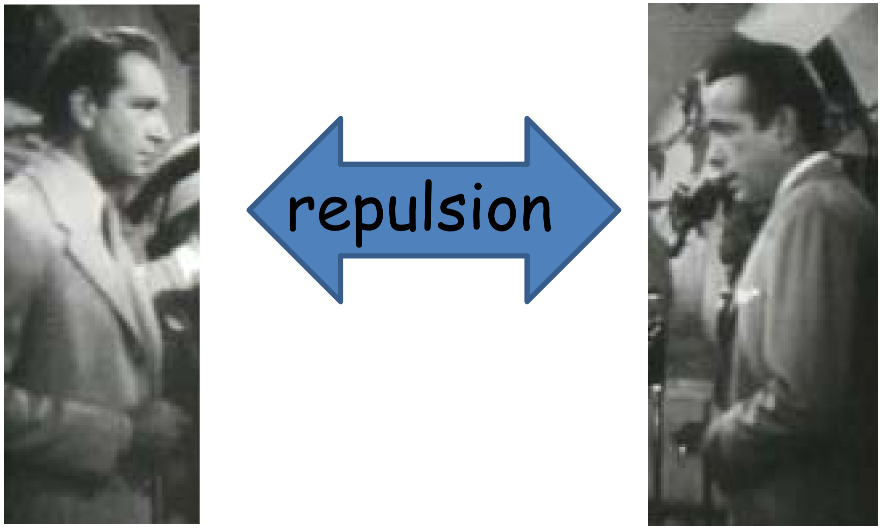
+

Casablanca mechanism

Love = attractive force

This love is reduced
by the presence of Rick

This love is reduced
by the presence of Victor



repulsion

Collaborators

T. Suzuki	Nihon U.
M. Honma	Aizu
Y. Utsuno	JAEA
N. Tsunoda	Tokyo
K. Tsukiyama	Tokyo
M. H.-Jensen	Oslo

A. Schwenk	TRIUMF/Darmstadt
J. Holt	ORNL
K. Akaishi	RIKEN