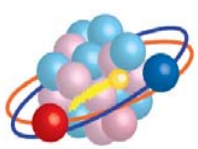
不安定核

－核構造の新天地、核構造とハドロン物理の架け橋－



Takaharu Otsuka
University of Tokyo / RIKEN / MSU

T. Suzuki	Nihon U.	A. Schwenk	TRIUMF
M. Honma	U. Aizu	B. Holt	TRIUMF
Y. Utsuno	JAEA		
Y. Akaishi	RIKEN		
H. Grawe	GSI		

14:46

アウトライン

1. 不安定核の物理を見る視点
    パラダイムシフト
    中性子過剰核で浮かび上がる核力の側面

2. テンソル力と殻進化の概観

3. 有効核力と Extended Weinberg Ansatz

4. 3体力が決めるドリップライン、不安定核が明かす3体力の謎

5. まとめと展望

３０年前頃の核物理

メゾスコピック系への応用：メタルクラスター、など

核物理としてはやや閉塞感

自分としては「応用」に活路を見出すことには抵抗感

１５年前頃の核物理

中性子ハローの発見： ドリップラインこそがフロンティア

原子核の半径は$A^{1/3}$ で決まるというパラダイム

（密度の飽和性）の変更

科学の革新的進歩にはパラダイムシフトが伴う

(Thomas Kuhn)

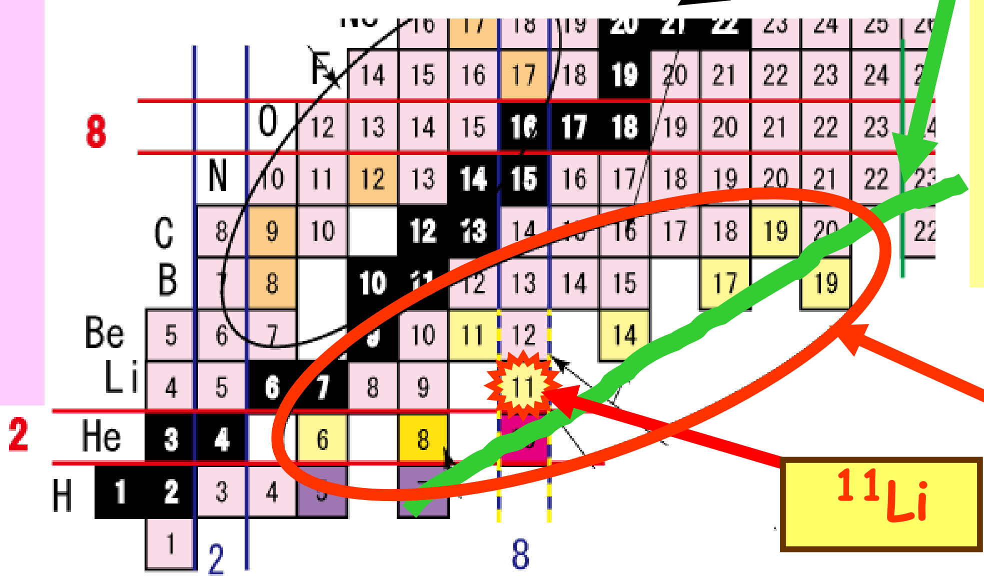
パラダイムシフトはそうそう起こるものではないが、他にもあり得るだろうか？

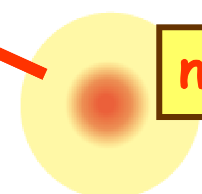
Studies on exotic nuclei in the 80~90's

Left-lower part of the Nuclear Chart

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**

Proton number →





neutron halo

Neutron number →

A nuclei (mass number)

stable

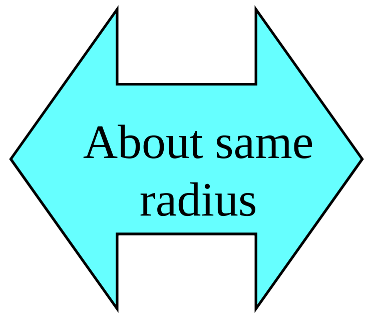
exotic

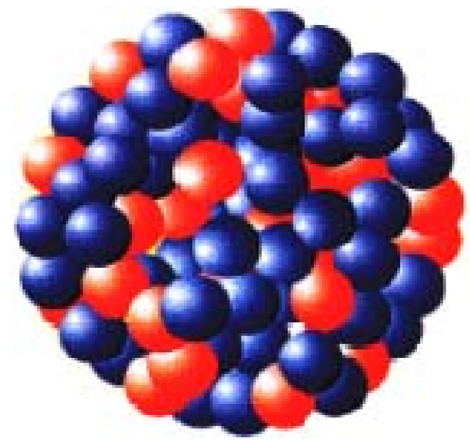
-- with halo

Neutron halo

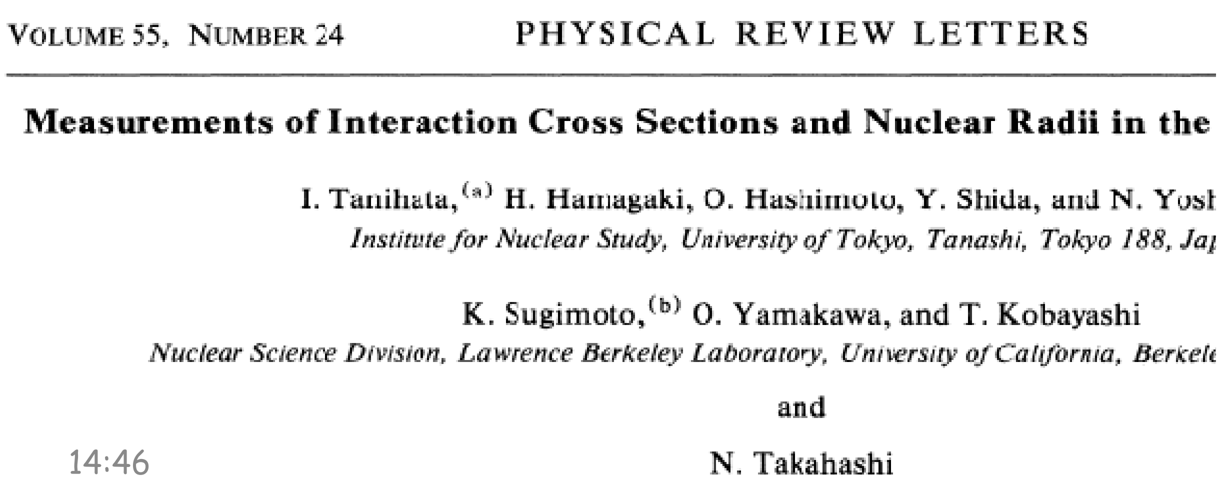
Strong tunneling of loosely bound excess neutrons

^{11}Li





^{208}Pb


VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS

Measurements of Interaction Cross Sections and Nuclear Radii in the

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K. Sugimoto,[b] O. Yamakawa, and T. Kobayashi
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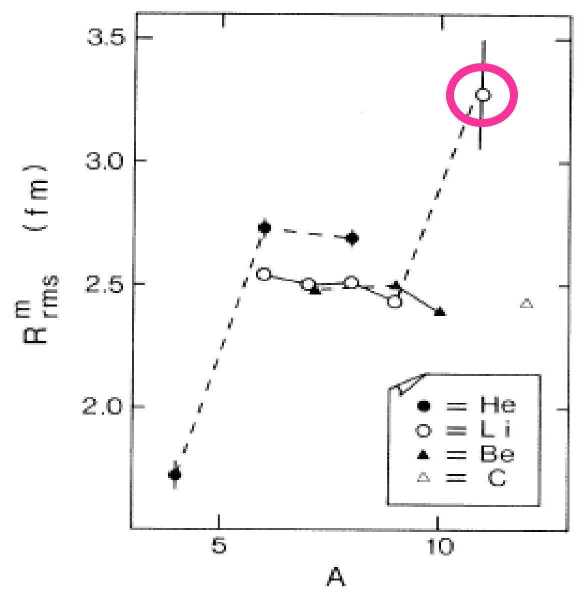
and

N. Takahashi



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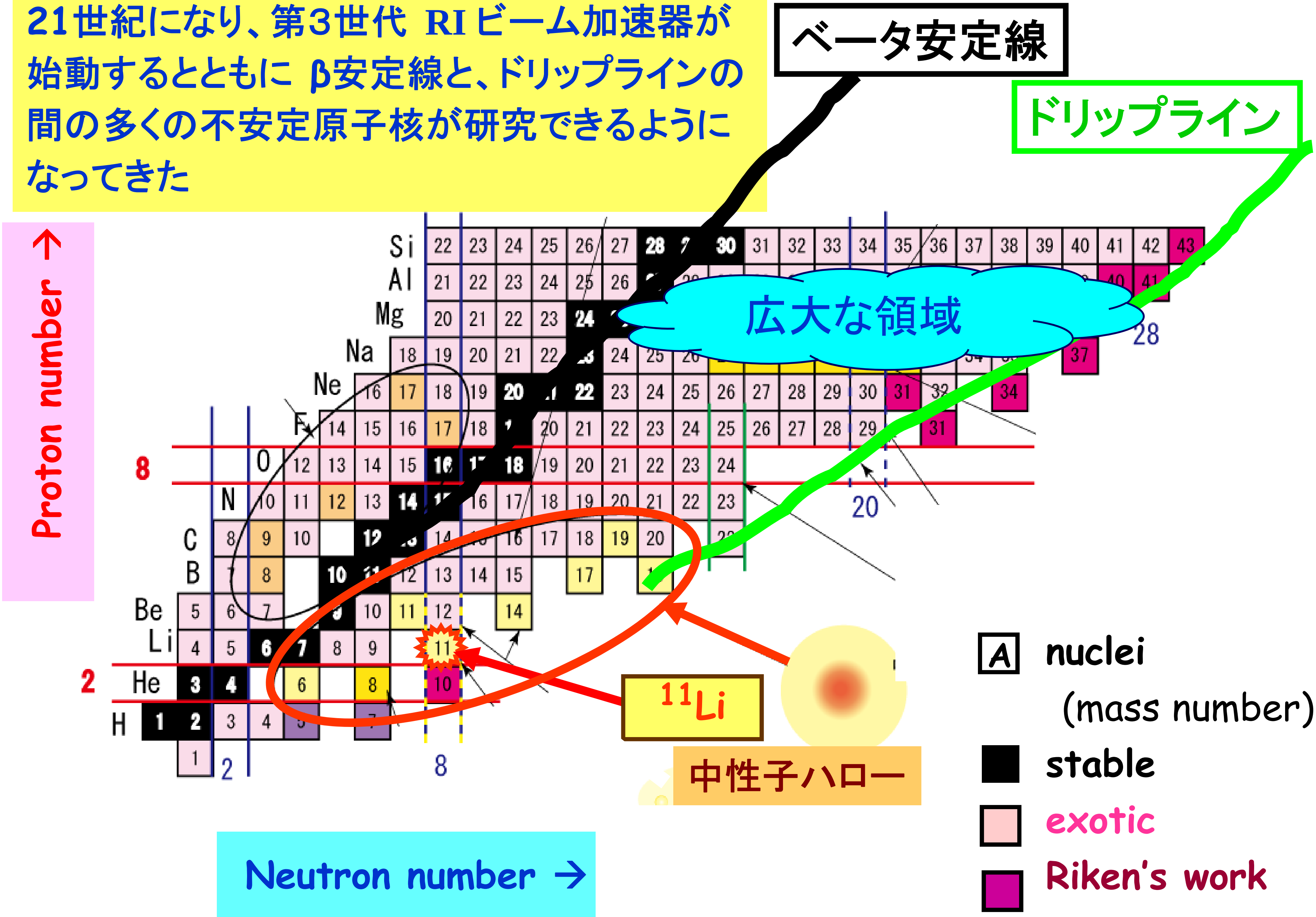
21世紀になり、第3世代 RI ビーム加速器が始動するとともに β安定線と、ドリップラインの間の多くの不安定原子核が研究できるようになってきた



このように核子数を大きく変えた場合に原子核構造を変える要素の一つとして、**Monopole Interaction** による **Effective Single-Particle Energy** の変化があげられる（殻進化、**Shell Evolution**)

Effective single particle energy

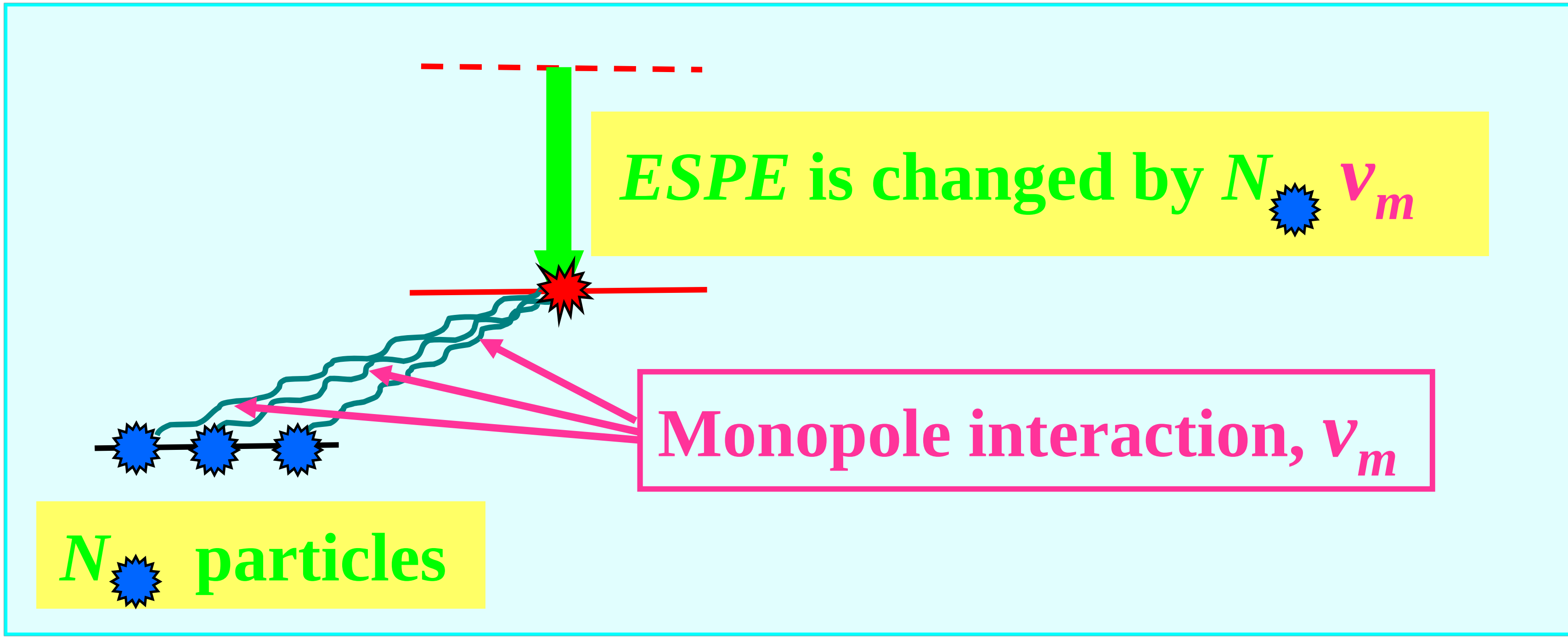
- Monopole part of the *NN* interaction

$$V_{ab}^{T} = \frac{\sum_J (2J+1) V_{abab}^{JT}}{\sum_J (2J+1)}$$

→ **Angular averaged interaction**

2核子の軌道運動の間の相対角度について
一般の相互作用を平均したもの

- Effective single-particle energy (*ESPE*)



このような lineariity は monopole interaction だけ。
他の multipole interaction は相手(上の図で●)の軌道が全部埋まると効果はゼロになる (trace=0)。 一方、monopole にはしばしば 10 のオーダーの係数がかかる。

この linearity は、中性子数だけ(又は陽子数だけ)を変えることができる不安定核の物性論では大変重要な役割。
（安定核だけをやっていた時には顕著でなかった。）

問：　殻構造（象徴的には魔法数）は変わり得るか？

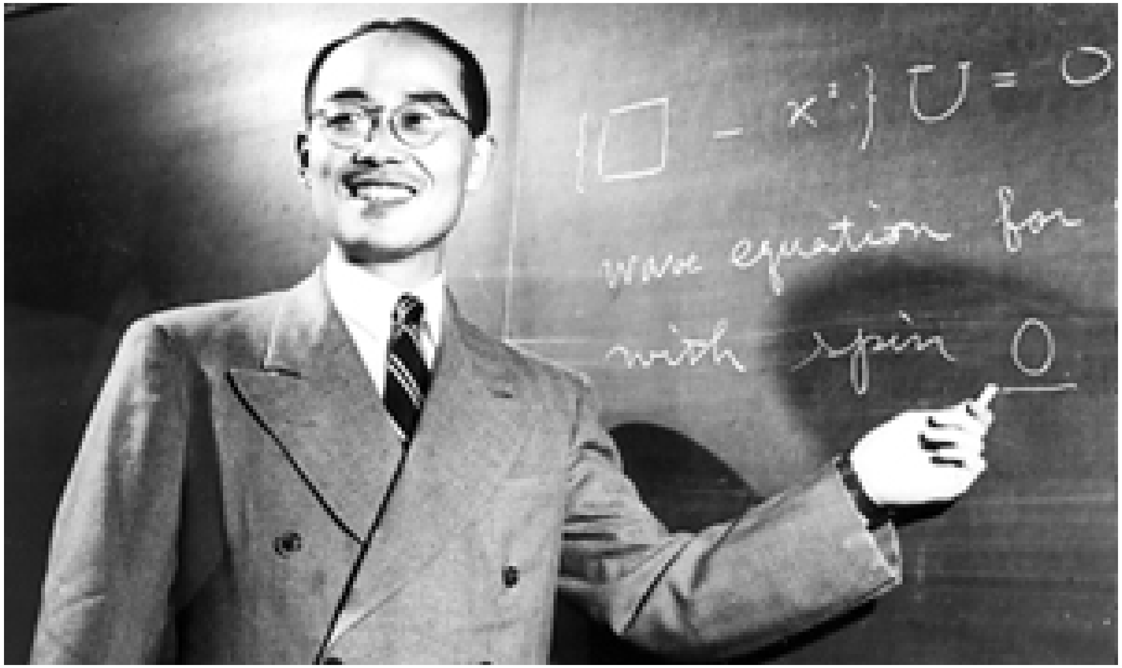
From undergraduate nuclear physics,

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

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

→上にないものが効かない限り変わらない
➔ だから変わらない（ギャップは変わらない）　10年前は私も

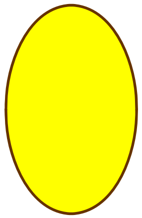
鍵＝テンソル力（1次の効果）



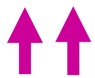
π中間子１個の交換 ~ テンソル力

複数のパイオンの交換 ➔ 有効中心力（σ 中間子）
原子核の結合エネルギーの主要部分

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

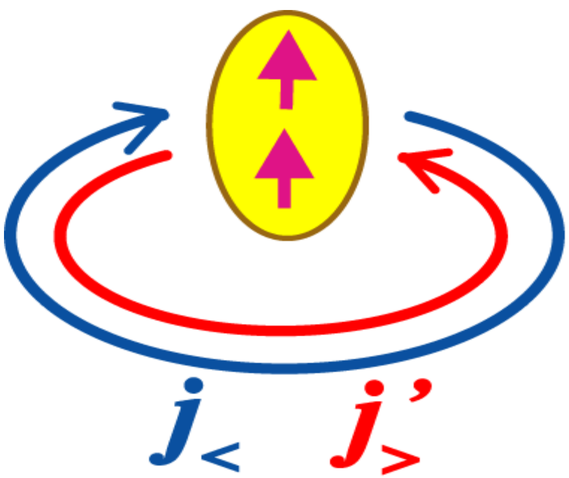


wave function of relative motion



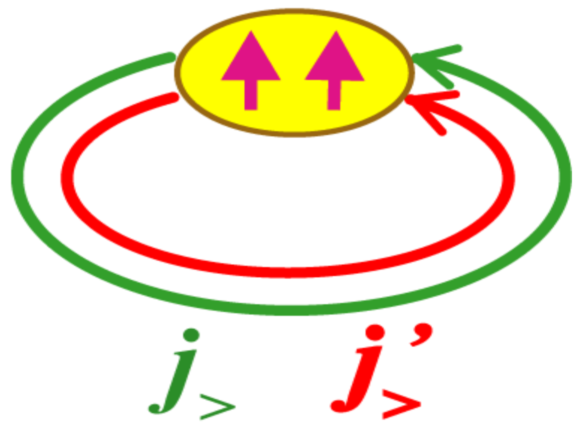
spin of nucleon

large relative momentum



attractive

small relative momentum



repulsive

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

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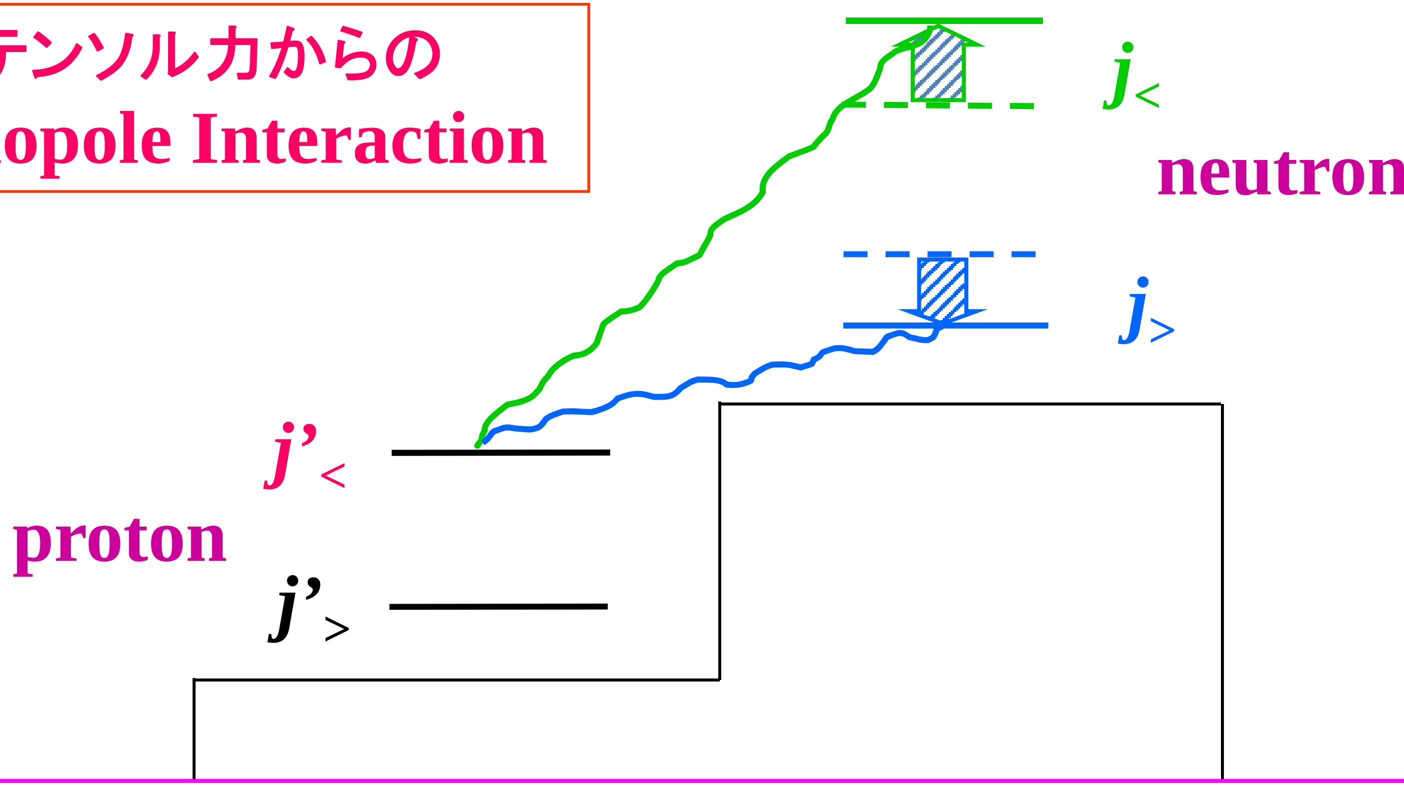
TO *et al.*, Phys. Rev. Lett. 95, 232502 (2005)

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

テンソル力からの Monopole Interaction



テンソル力の monopole interaction が満たす恒等式

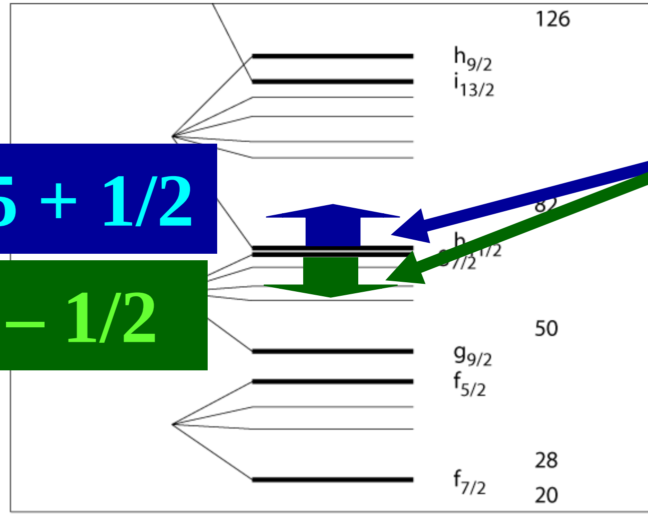
$$(2j_> +1)\ v_{m,T}^{(j' j_>)} + (2j_< +1)\ v_{m,T}^{(j' j_<)} = 0$$

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

$_{51}$Sb case

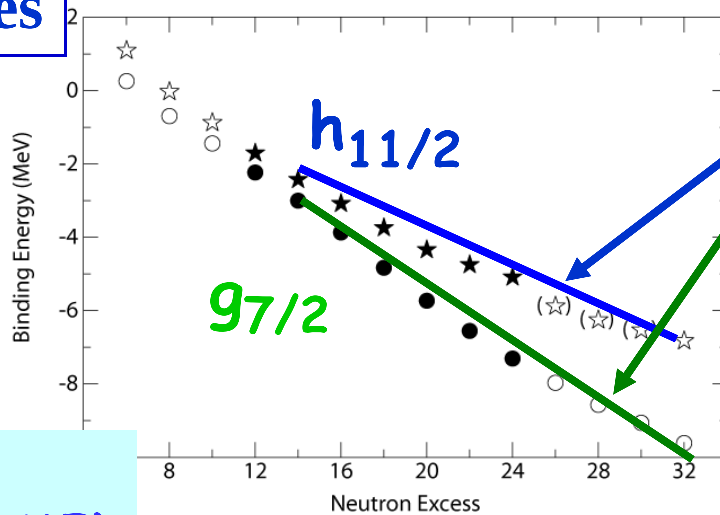
$1h_{11/2}$: 11/2 = 5 + 1/2

$1g_{7/2}$: 7/2 = 4 – 1/2



Opposite monopole effect from tensor force with neutrons in $h_{11/2}$.

Z=51 isotopes



Tensor by π+ ρ meson exchange

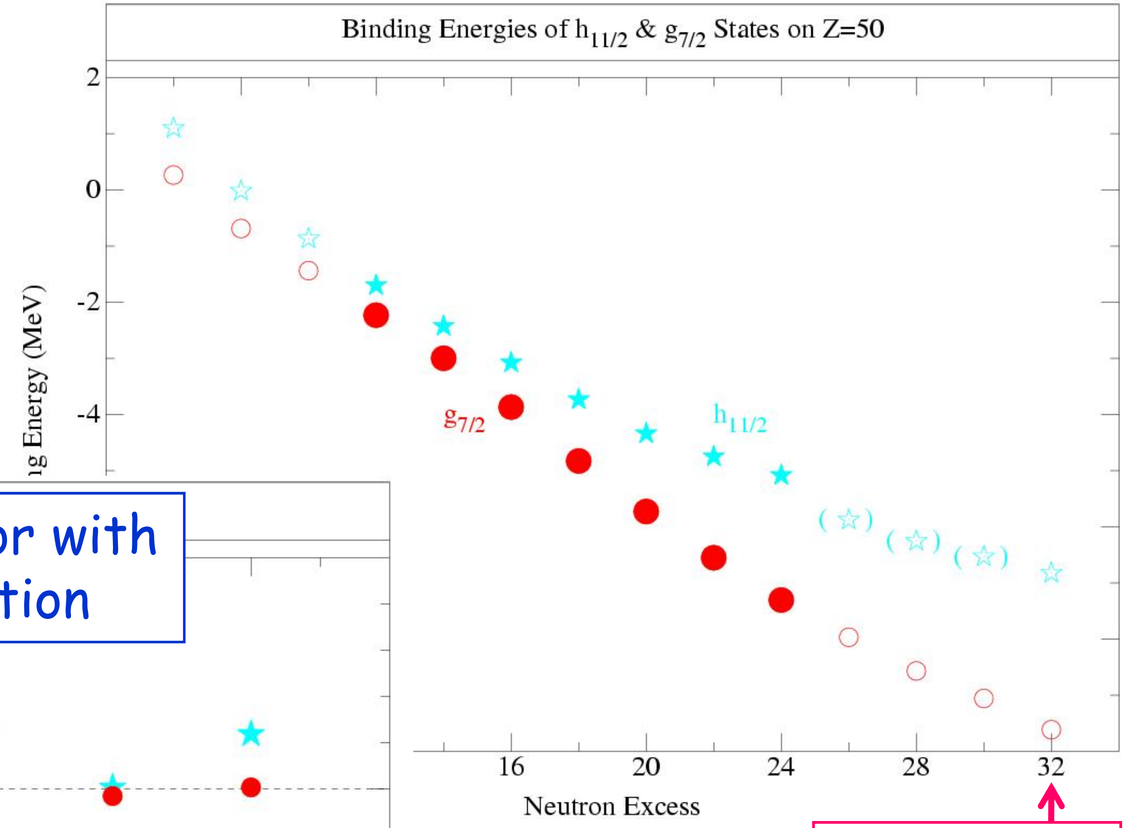
+ common effect (Woods-Saxon)

どの平均場理論でも (Skyrme, Gogny, RMF) 説明できなかった

$1h_{11/2}$ neutrons

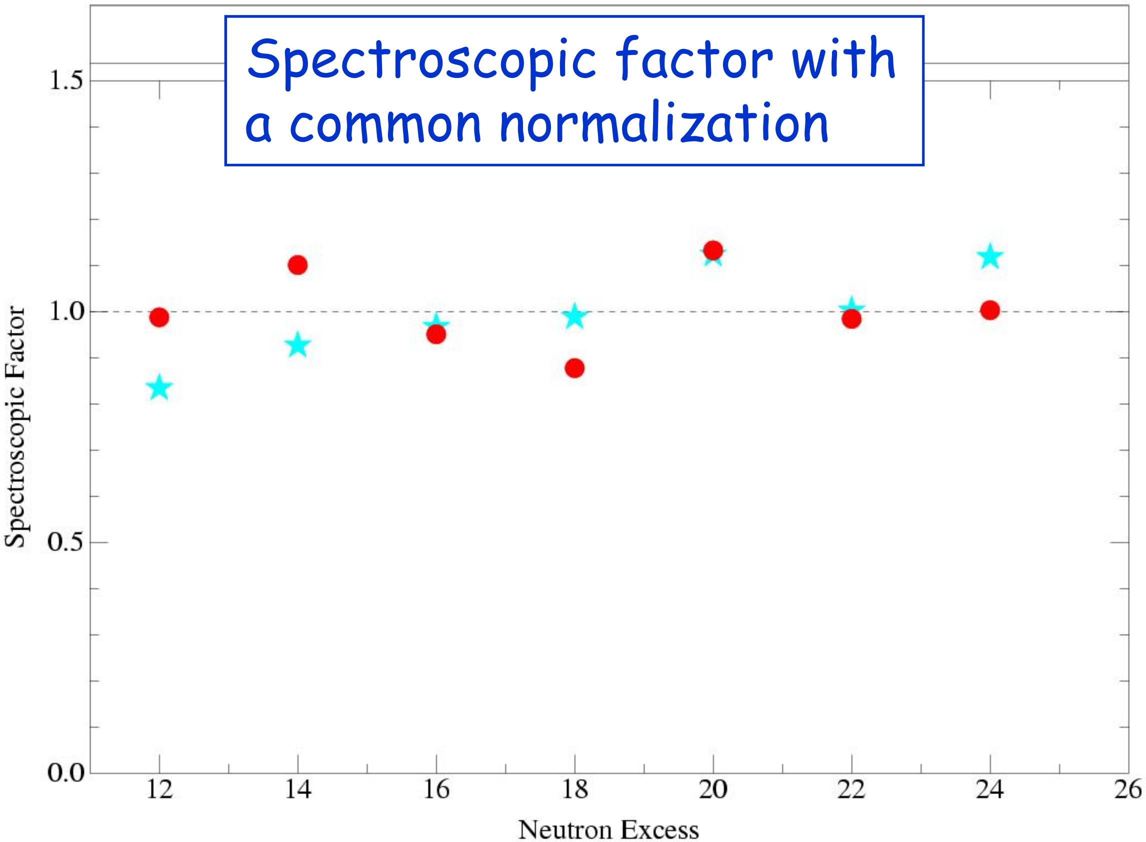
14:46 Exp. data from J.P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004)

These states are
of single-particle nature
to a similar extent.



closed shell

Spectroscopic factor with
a common normalization



Correlation effects do not
seem to change the story.

From the lecture note
by Schiffer for the 2008
CNS-EFES summer school

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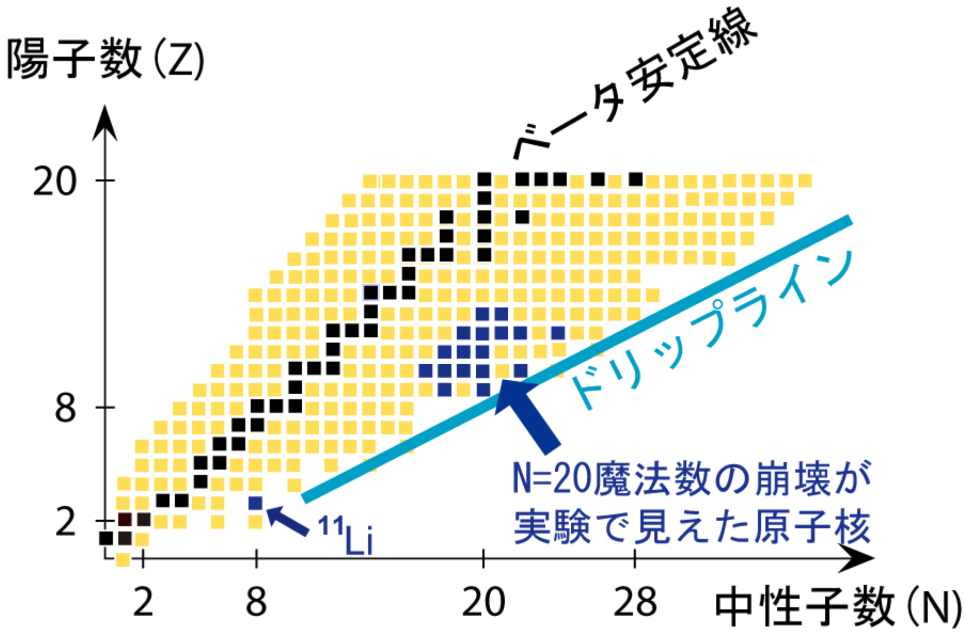
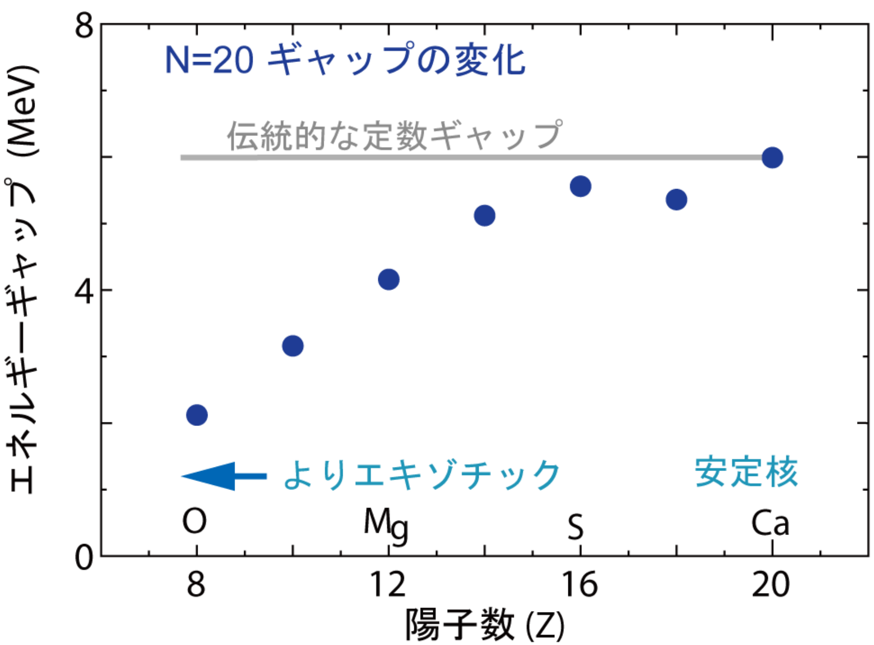
Island of Inversion の
隠された姿は？





テンソル力の monopole interaction の検証で
最近判明した例:

… ^{48}Ca (e,e'p)

テンソル力によるスピン軌道分岐の変化そのものを
見た(含むfragmentation)最初の例?

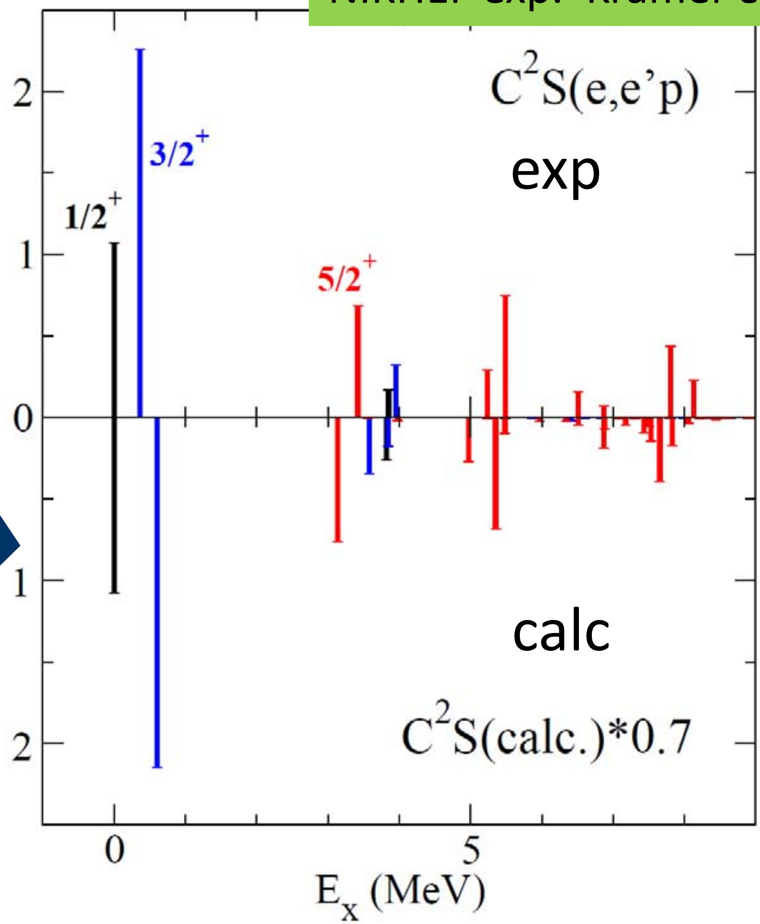
電子散乱実験 ⇒ 不安定核での殻進化
J-Labなどでできるといいのだが
RIビームでできるのはだいぶ先の話?

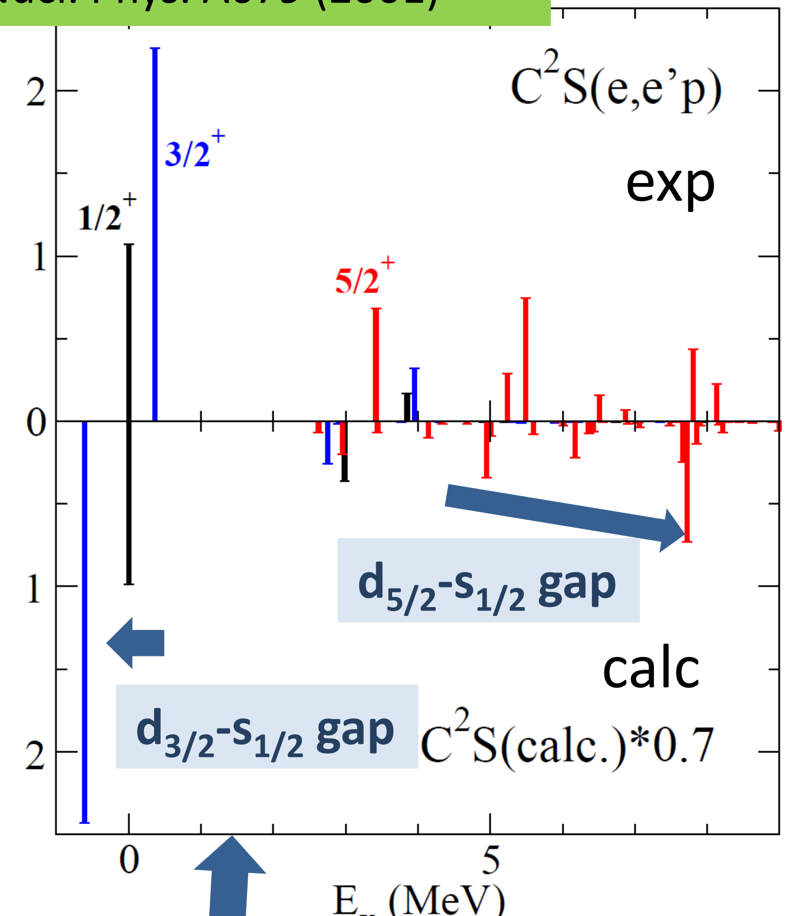
Spectroscopic factor for -1p from ^{48}Ca:

probing the change of spin-orbit splitting

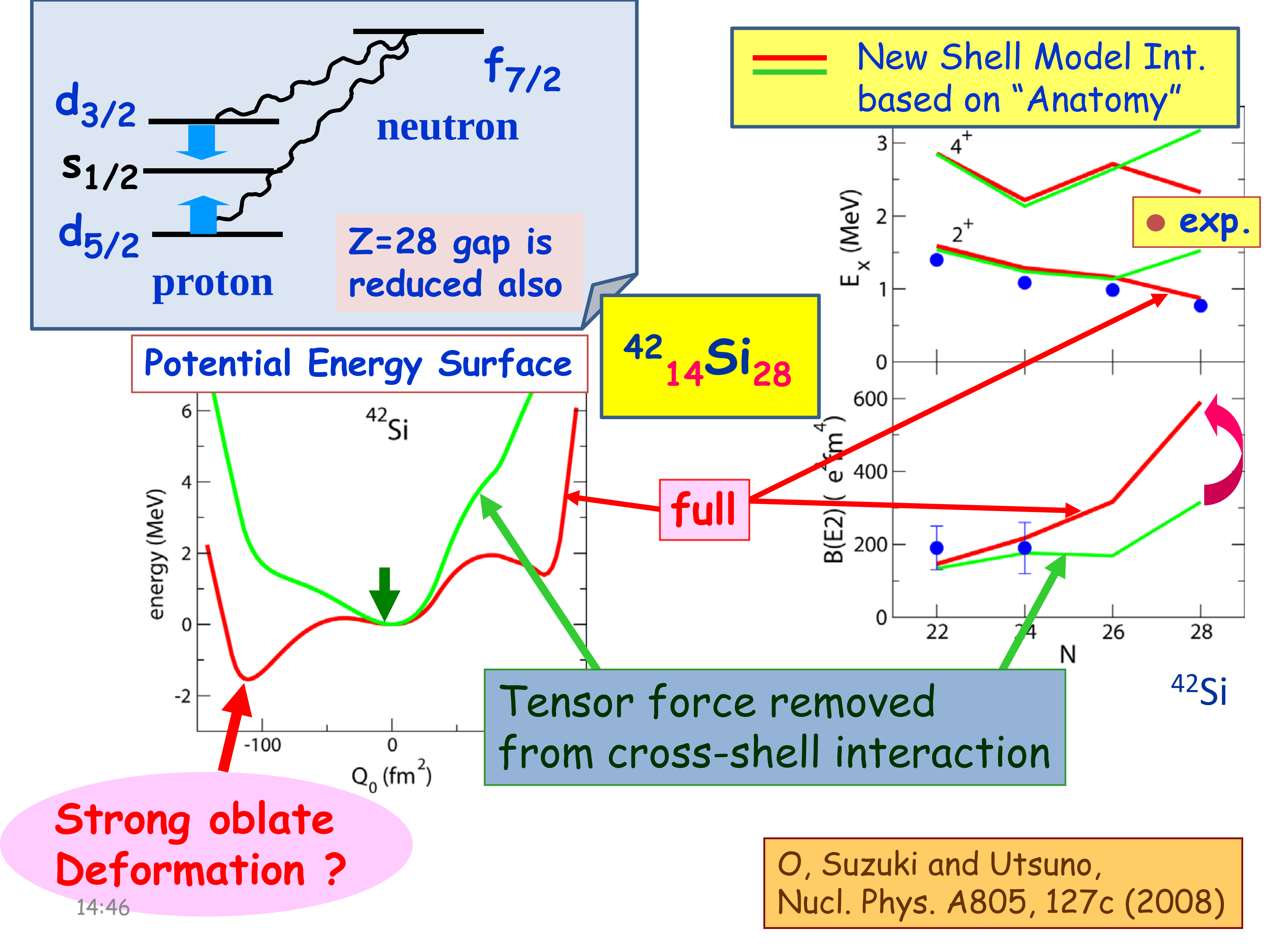
The same interaction as the one for ^{42}Si

NIKHEF exp. Kramer *et al.* Nucl. Phys. A679 (2001)





If the tensor force is taken away



d3/2
s1/2
d5/2
f7/2
neutron
proton
Z=28 gap is reduced also
New Shell Model Int. based on "Anatomy"
exp.
42 14 Si 28
Potential Energy Surface
42Si
energy (MeV)
6
4
2
0
-2
-100
0
Q0 (fm2)
full
Ex (MeV)
3
2
1
0
4+
2+
B(E2) (e2fm4)
600
400
200
0
22
24
26
28
N
42Si
Tensor force removed from cross-shell interaction
Strong oblate Deformation ?
O, Suzuki and Utsuno, Nucl. Phys. A805, 127c (2008)
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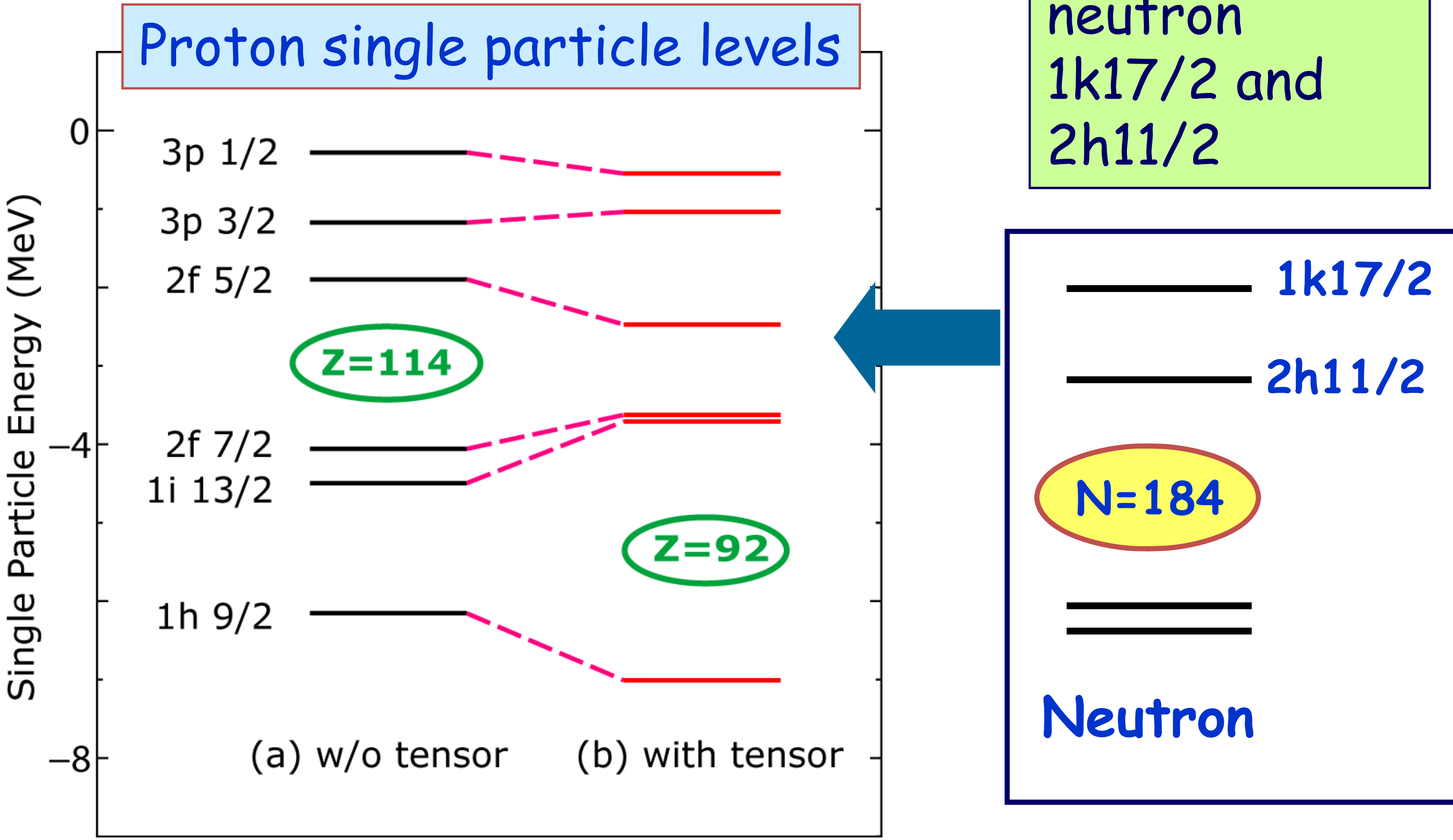
Effect of tensor force on (spherical) superheavy magic numbers

Occupation of neutron 1k17/2 and 2h11/2



Woods-Saxon potential

Tensor force added

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

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戦いはまだ終わっていない．．．．

PRL 100, 062501 (2008) PHYSICAL REVIEW LETTERS week ending 15 FEBRUARY 2008

Shell Model Description of the ^{14}C Dating β Decay with Brown-Rho-Scaled NN Interactions

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[3]*Department of Physics, University of Idaho, Moscow, Idaho 83844, USA*
(Received 21 September 2007; published 15 February 2008)

We present shell model calculations for the beta decay of ^{14}C to the ^{14}N ground state, treating the states of the $A = 14$ multiplet as two $0p$ holes in an ^{16}O core. We employ low-momentum nucleon-nucleon (NN) interactions derived from the realistic Bonn-B potential and find that the Gamow-Teller (GT) matrix element is too large to describe the known lifetime. By using a modified version of this potential that incorporates the effects of Brown-Rho scaling medium modifications, we find that the GT matrix element vanishes for a nuclear density around 85% that of nuclear matter. We find that the splitting between the $(J^\pi, T) = (1^+, 0)$ and $(J^\pi, T) = (0^+, 1)$ states in ^{14}N is improved using the medium-modified Bonn-B potential and that the transition strengths from excited states of ^{14}C to the ^{14}N ground state are compatible with recent experiments.

In-medium ではテンソル力（による相関）は弱い
と言っている。（実は configuration space が狭いだけ？）

有効核力とExtended Weinberg Ansatz

成功している有効相互作用の解剖学

pf殻に対する GXPF1

本間、他　2002年~　最新の公開バージョン GXPF1A

G-matrix (H.-Jensen) から得られた微視的相互作用
（199個の独立な量）

その内約70個に現象論的な補正

699個の実験データを使用＋その後のマイナーな改訂

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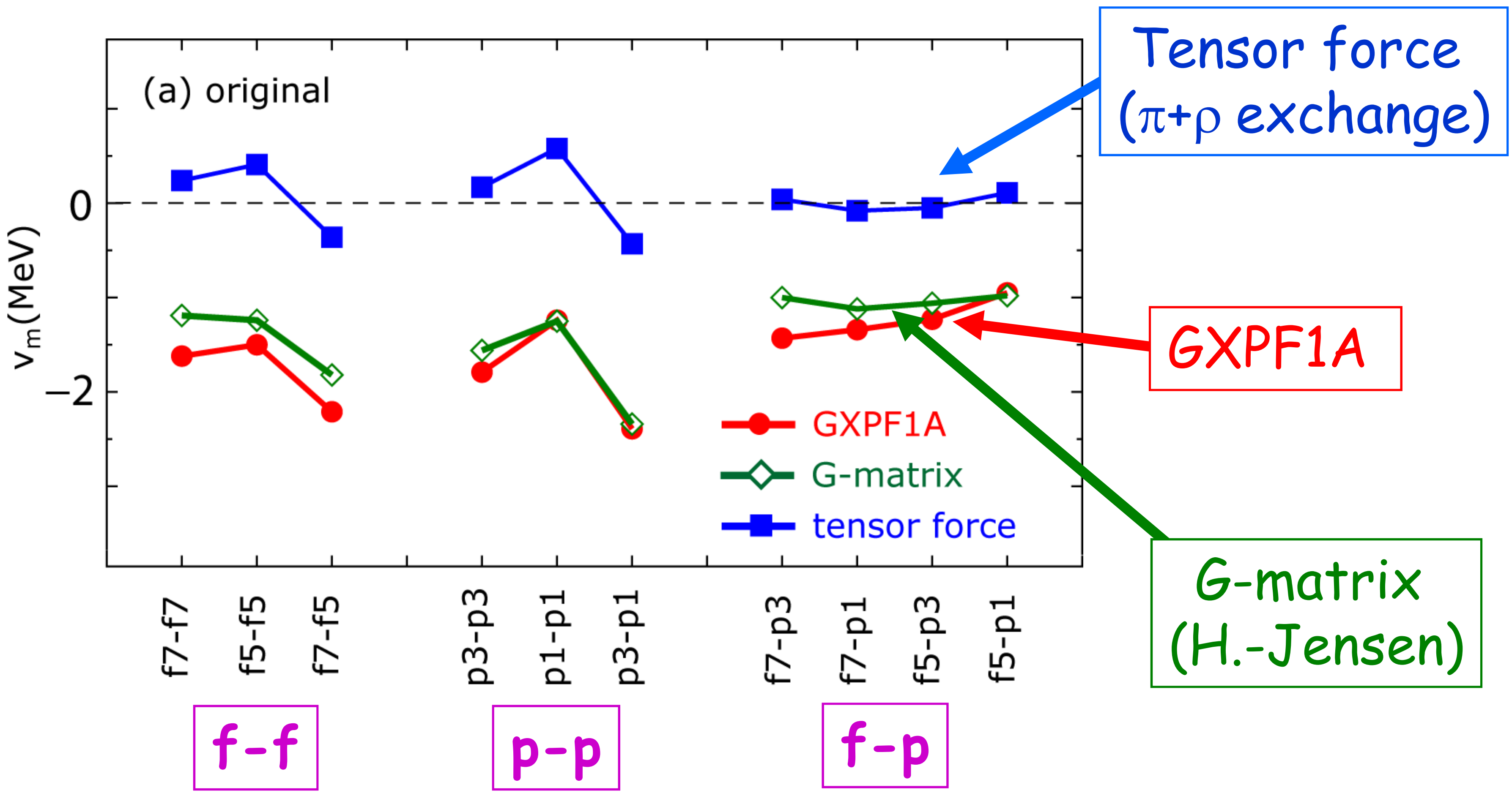
T=0 monopole interactions in the pf shell



"Local pattern" ← tensor force

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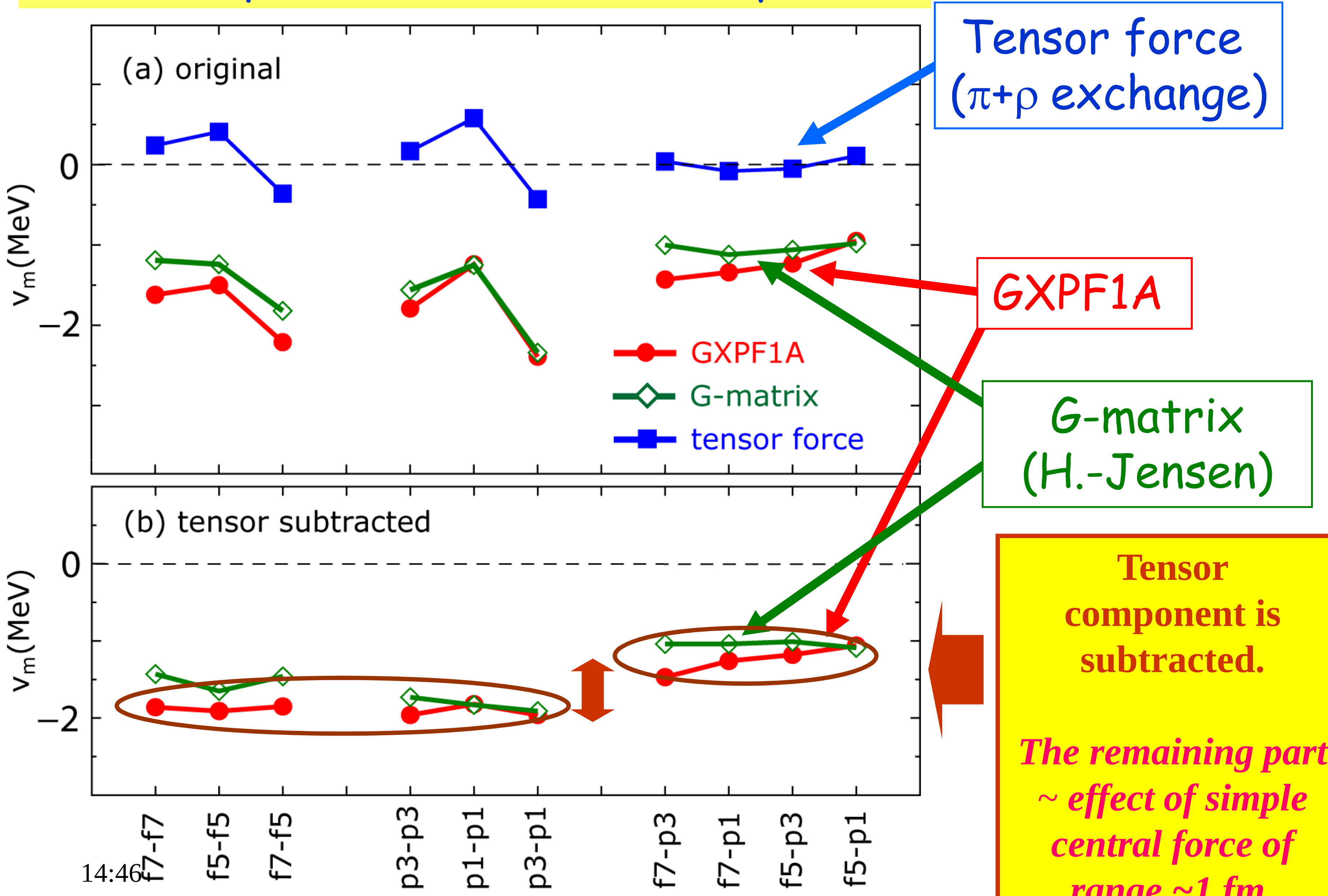
T=0 monopole interactions in the pf shell



Tensor component is subtracted.

The remaining part ~ effect of simple central force of range ~1 fm.

Monopole interaction

1 fm 程度のレンジ(ガウス関数)を持つ中心力
結合力の源、概ね定数
繰り込みの効果

動径波動関数による → ノード数が違うと弱くなる

π＋ρ中間子交換から来る bare のテンソル力
大きさは中心力より小さい
斥力になることがあるので、殻構造に大きな影響

２体 LS 力 (今日は省略） 限られた場合に効果

The central force is modeled by a Gaussian function

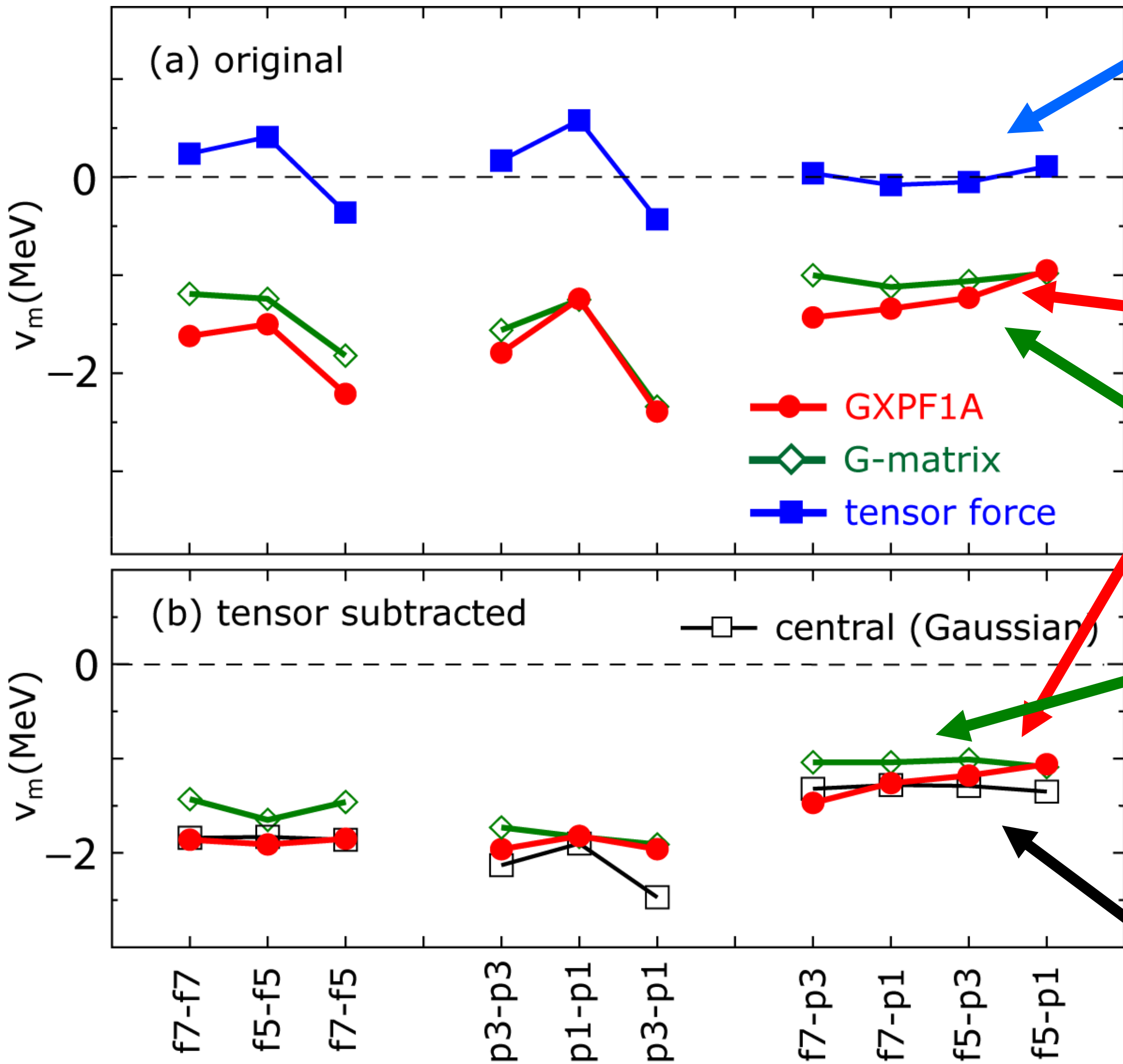
$$V = V_0 \ \exp(-(r/\mu)^2) \quad (S,T \text{ dependences})$$

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 ?

T=0 monopole interactions in the pf shell



Tensor force (π+ρ exchange)

GXPF1

G-matrix (H.-Jensen)

Central (Gaussian) - Reflecting radial overlap -

14:46

f-f p-p f-p

This is not a very lonely idea → Chiral Perturbation of QCD

Short range central forces have complicated origins and should be adjusted.

S. Weinberg,
PLB 251, 288 (1990)

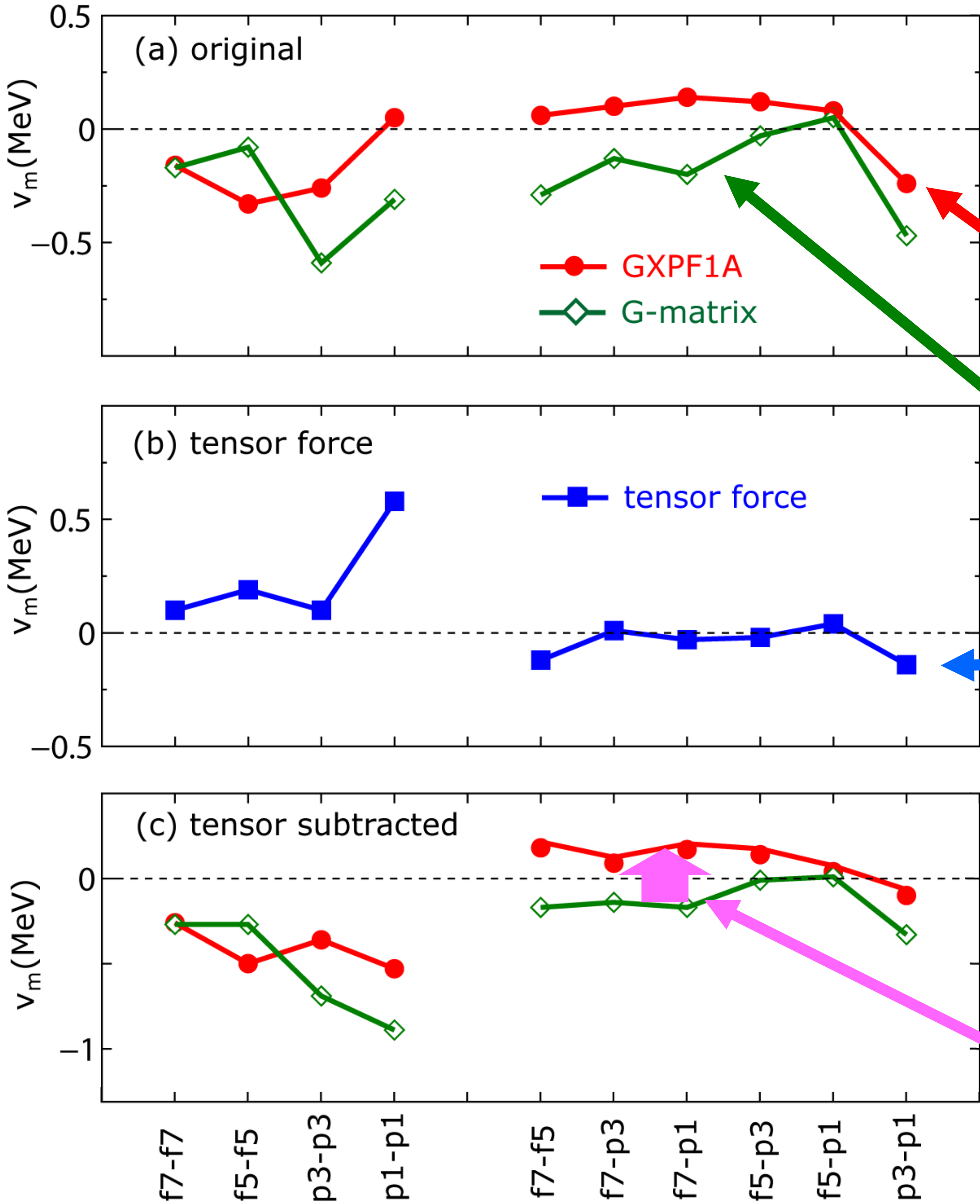
tive potential gives a local coordinate-space two-nucleon potential:

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

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.]

T=1 monopole interaction



T=1 monopole interactions in the pf shell

GXPF1A

G-matrix (H.-Jensen)

Tensor force (π+ρ exchange)

Basic scale ~ 1/10 of T=0

Repulsive corrections to G-matrix

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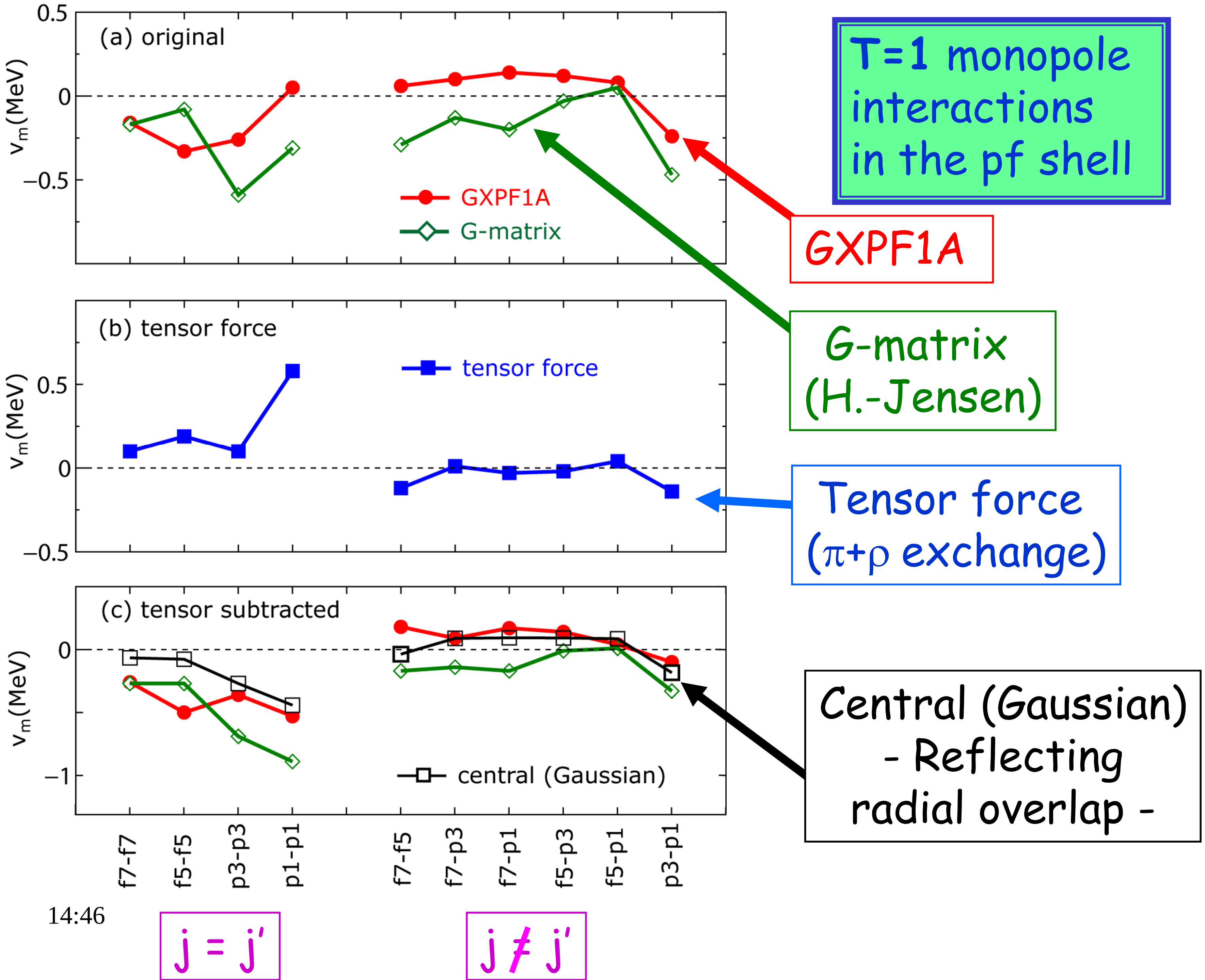
j = j'

j ≠ j'



T=1 monopole interactions in the pf shell
(a) original
GXPF1A
G-matrix
(b) tensor force
tensor force
(c) tensor subtracted
central (Gaussian)
v_m(MeV)
f7-f7
f5-f5
p3-p3
p1-p1
f7-f5
f7-p3
f7-p1
f5-p3
f5-p1
p3-p1
GXPF1A
G-matrix (H.-Jensen)
Tensor force (π+ρ exchange)
Central (Gaussian) - Reflecting radial overlap -
j = j'
j ≠ j'

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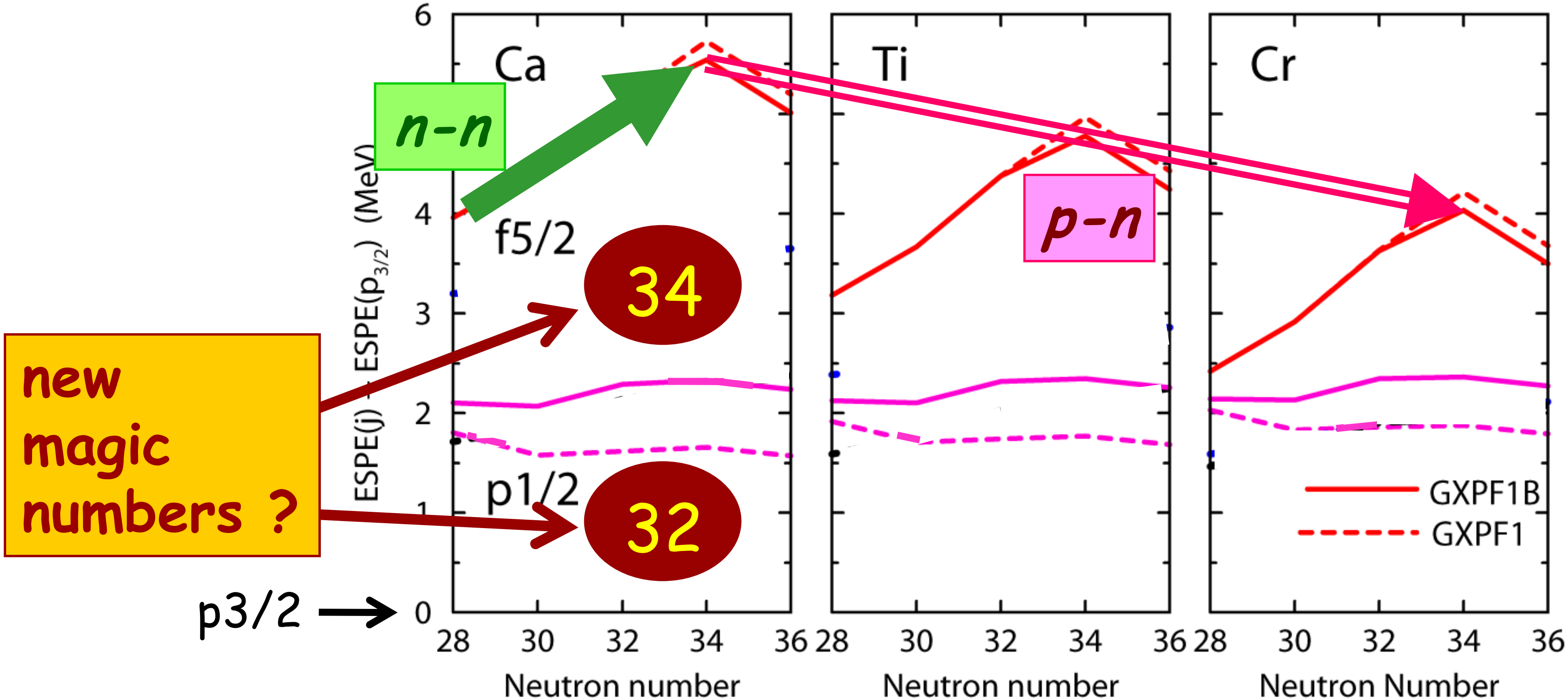
(effective) single-particle energies relative to $p_{3/2}$



Reduction of f5/2-p3/2 from Ca to Cr *p-n* **force:**
~ 1.5 MeV = 1.0 MeV (tensor) + 0.5 MeV (central)

Rising of f5/2 from ^{48}Ca to ^{54}Ca *nn* **force:**
~ p3/2-p3/2 attraction + p3/2-f5/2 repulsion

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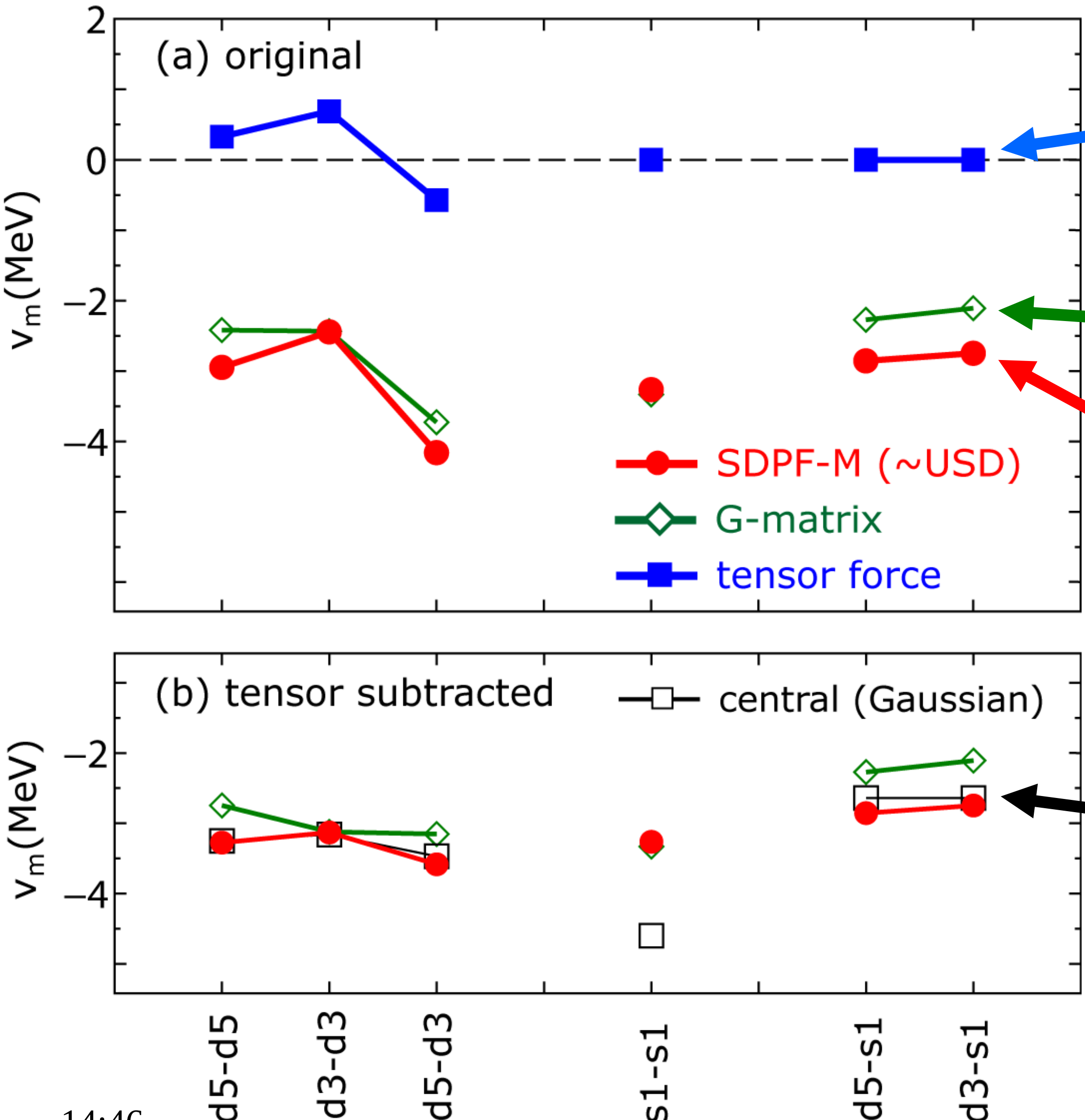
T=0 monopole interactions in the sd shell



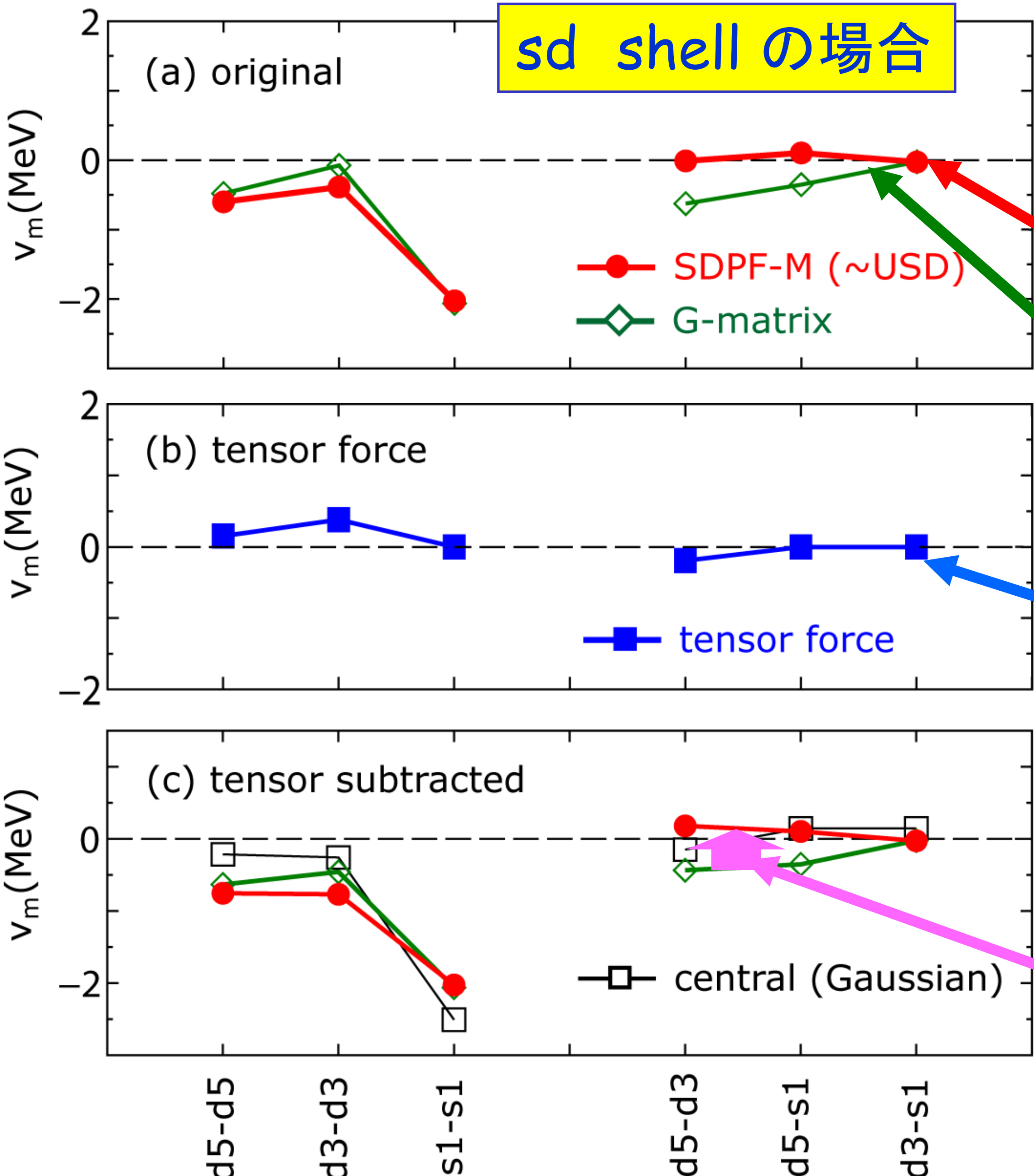
Tensor force
(π+ρ exchange)

G-matrix
(H.-Jensen)

SDPF-M
(~USD)

Central (Gaussian)
- Reflecting
radial overlap -

sd shell の場合



T=1 monopole interactions in the sd shell

SDPF-M (~USD)

G-matrix (H.-Jensen)

Tensor force (π+ρ exchange)

Basic scale ~ 1/10 of T=0

Repulsive corrections to G-matrix

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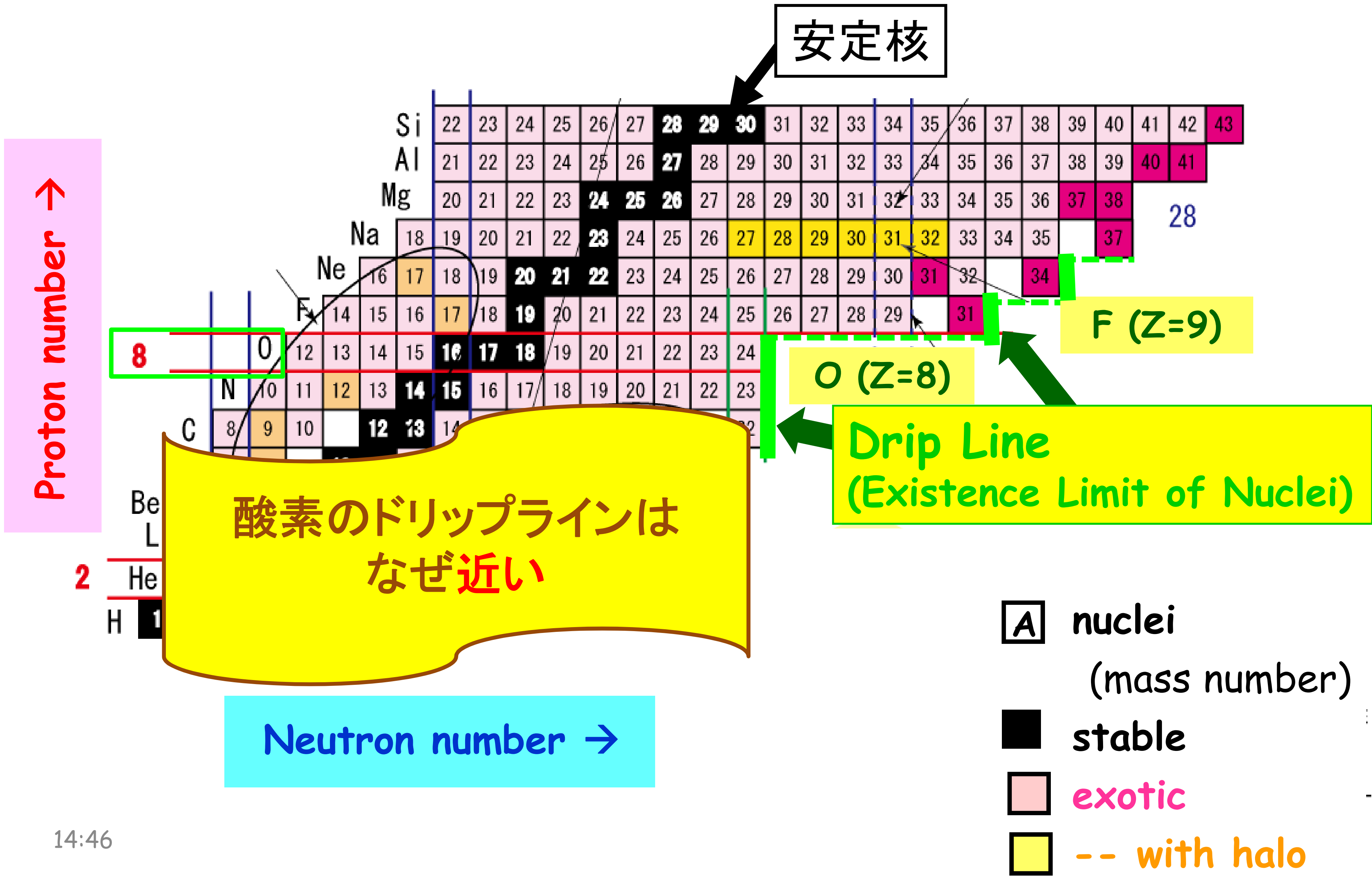
j = j'

j ≠ j'

T=1 の斥力補正とドリップライン



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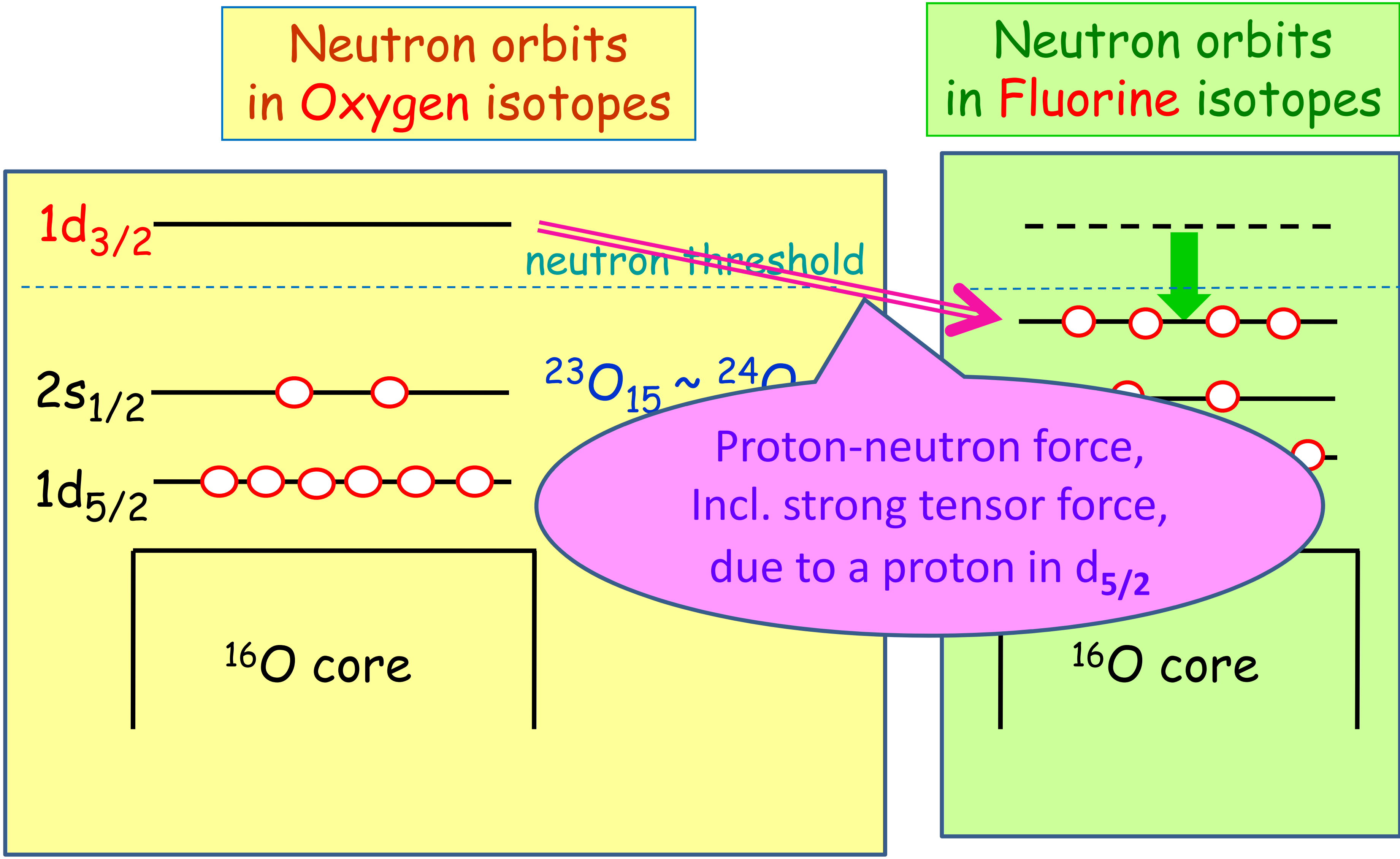
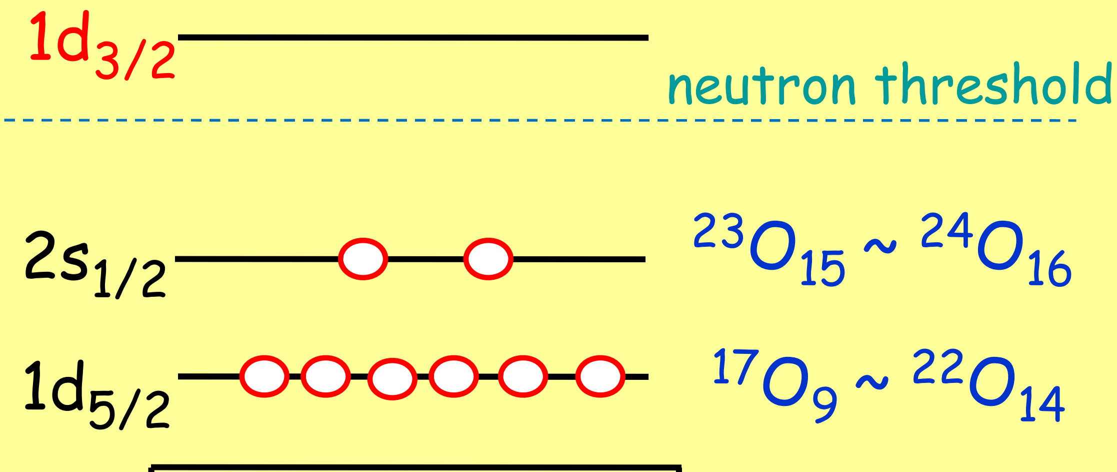
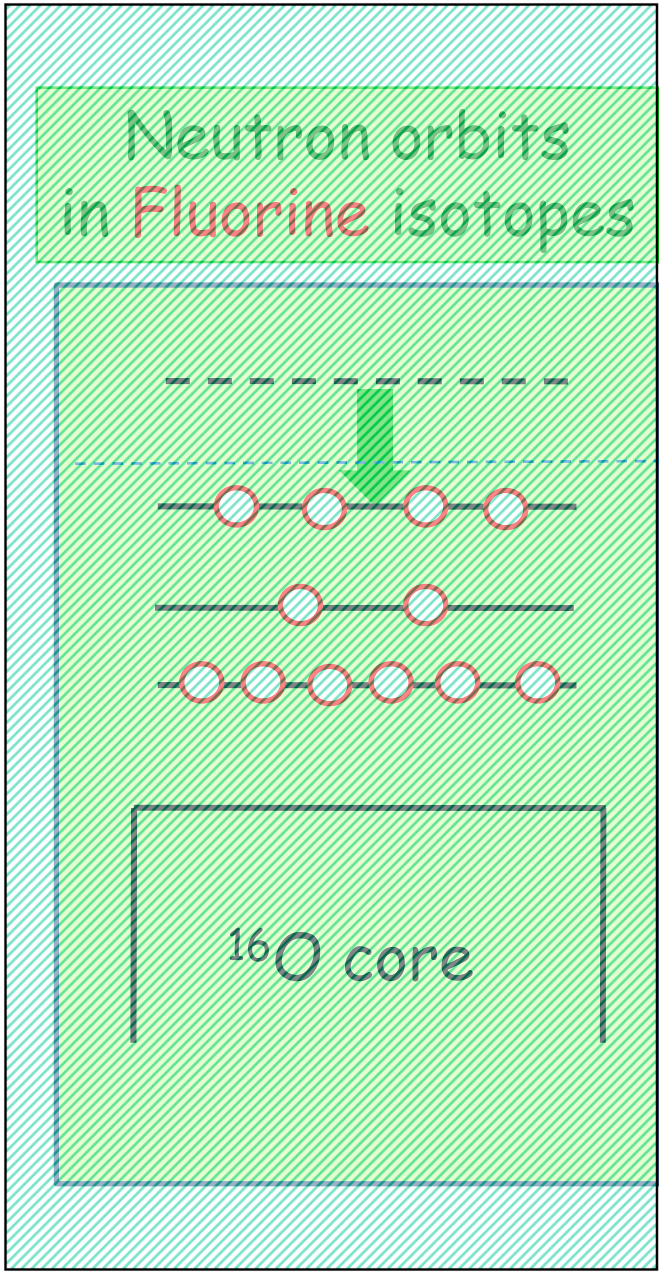
This is because the neutron $d_{3/2}$ orbit is high for Oxygen.



Neutron orbits in Oxygen isotopes



Why do those neutrons *NOT* pull down $d_{3/2}$?



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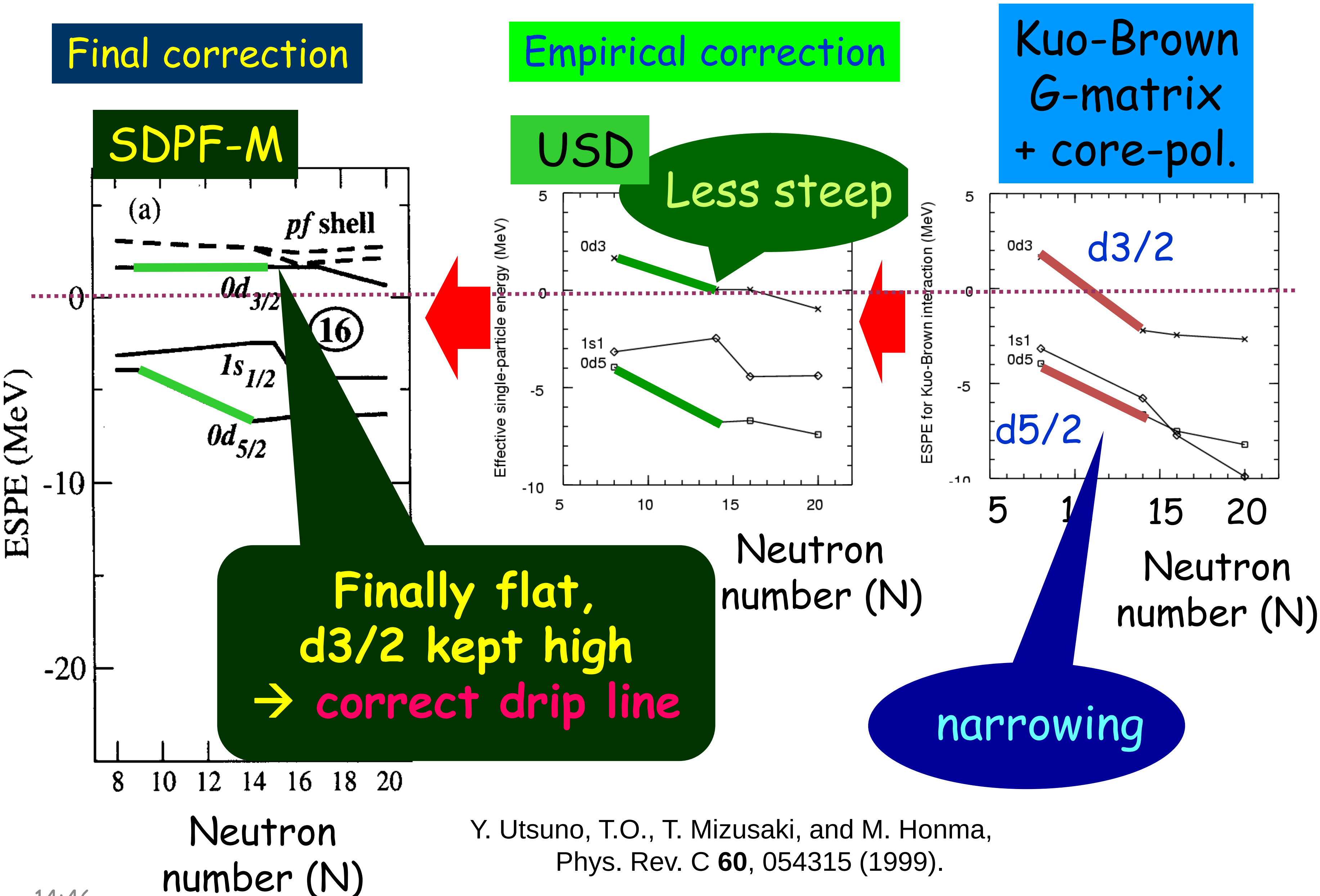
Effective Single-Particle Energy for Oxygen isotopes



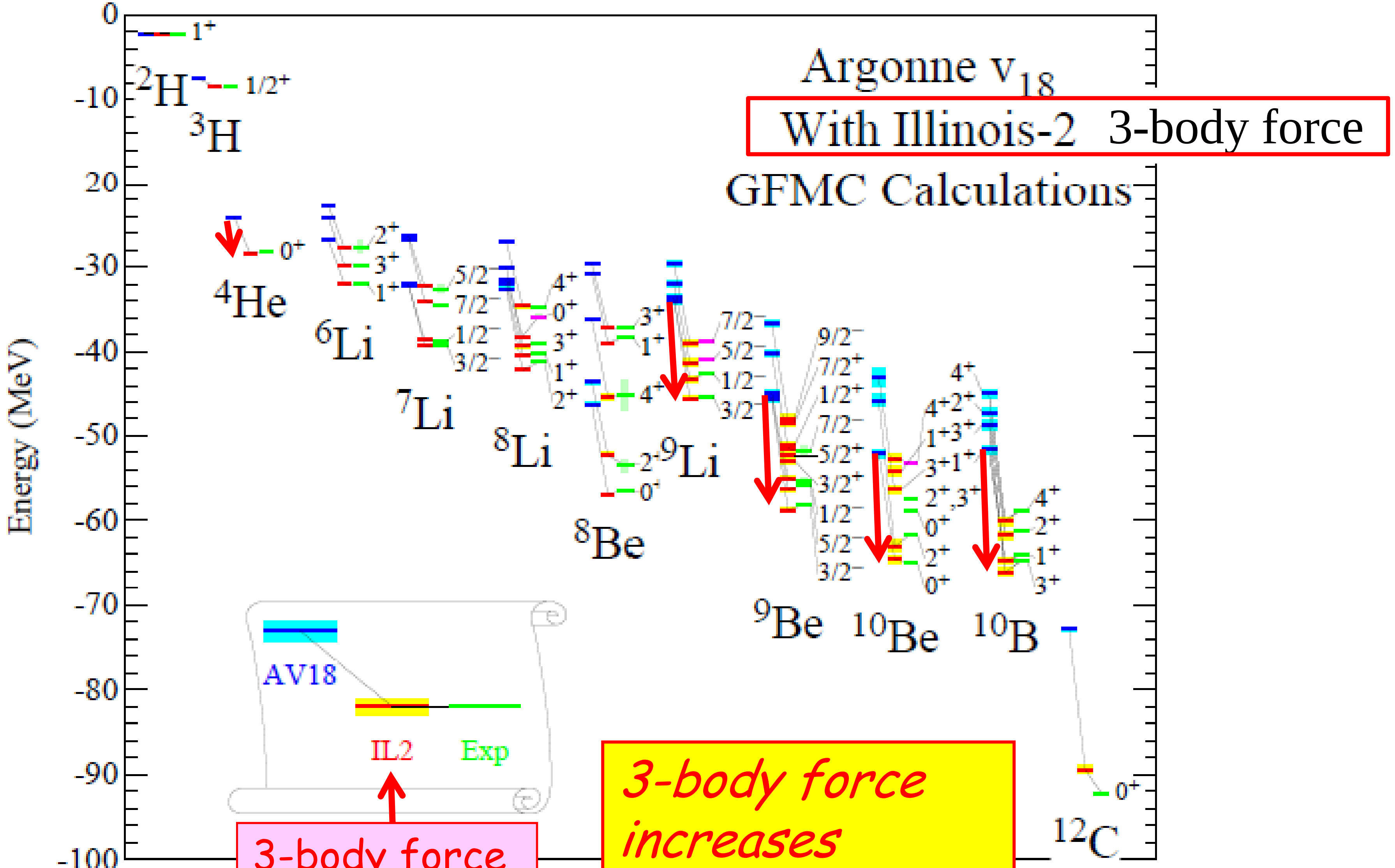
Y. Utsuno, T.O., T. Mizusaki, and M. Honma,
Phys. Rev. C **60**, 054315 (1999).

斥力補正の起源は、これだけ2体力を考えても
見つからないという状況証拠からも

→ ３体力に起源？

3NF -> attractive effects
systematics in results of GFMC, NCSM
CC (Hagen et al., Phys. Rev. C76, 034302 (2007))

GFMC (Green Function Monte Carlo) by Argonne group



3-body force included

3-body force increases binding energies

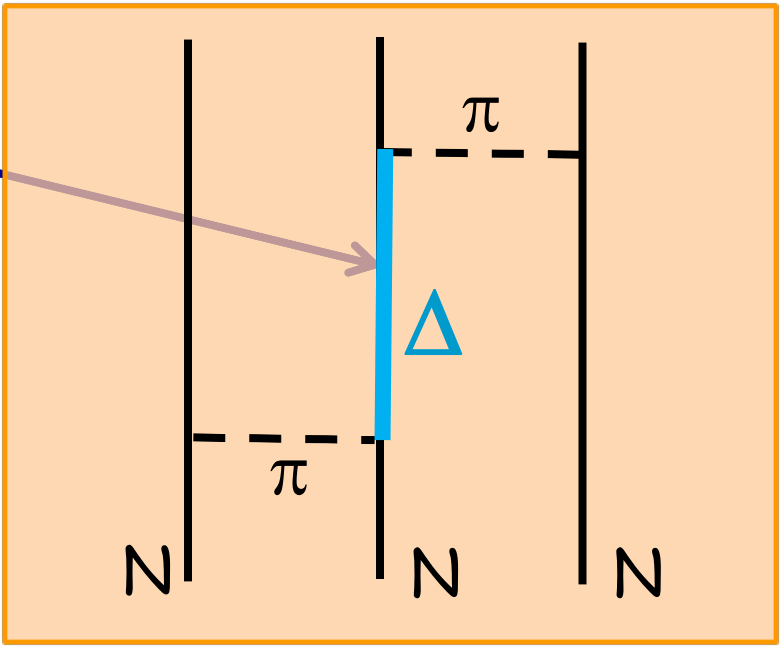
The key : Fujita-Miyazawa 3N mechanism (Δ-hole excitation)

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

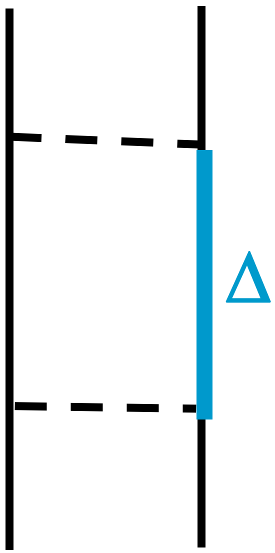
Pion Theory of Three-Body Forces

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

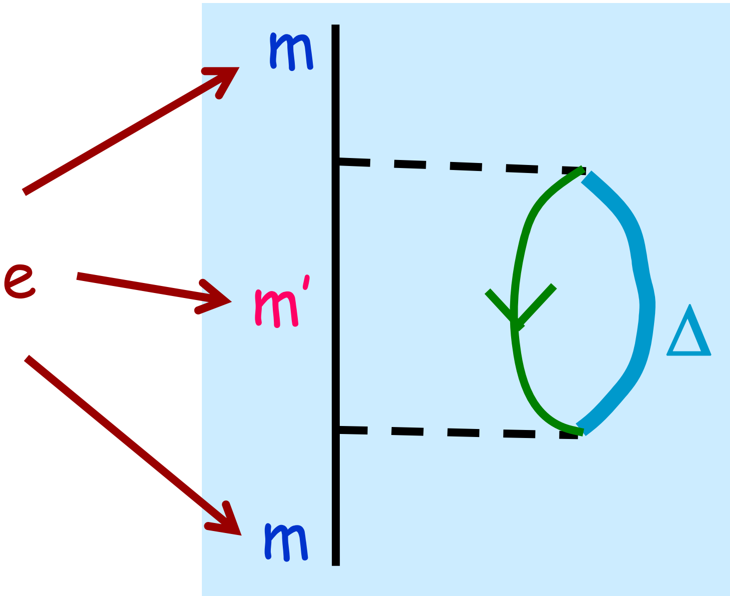


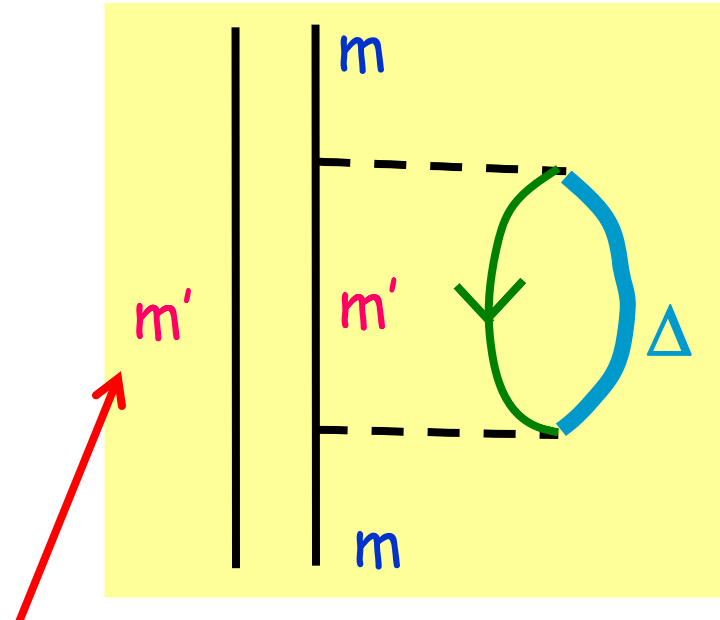
T=1
attraction
between *NN*
effectively

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*

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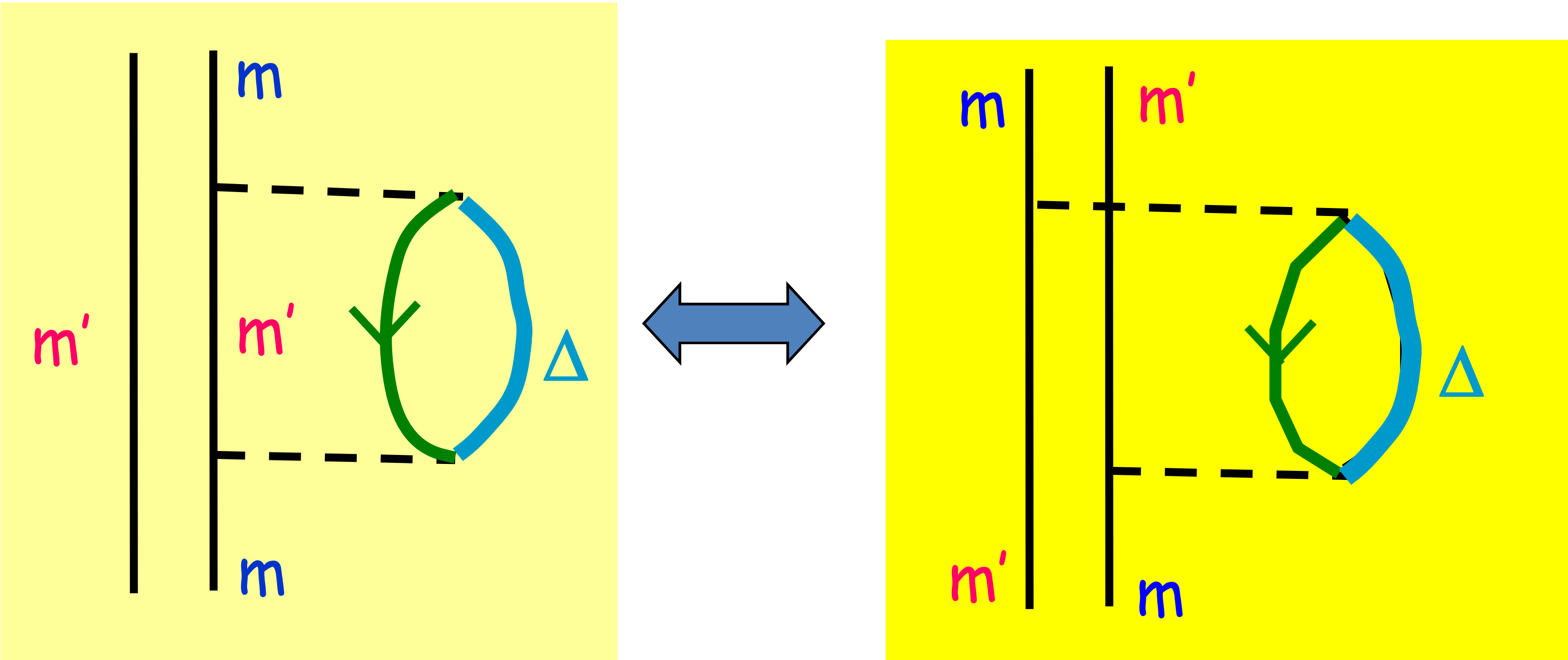
Inclusion of Pauli blocking



Pauli forbidden
(from previous page)

This Pauli effect is included automatically by the exchange term.

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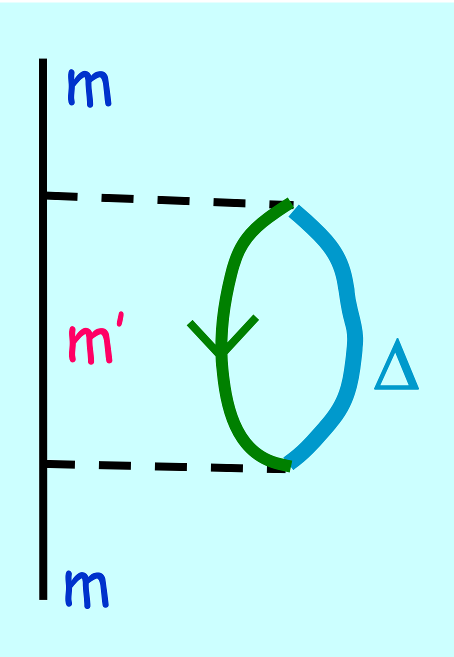
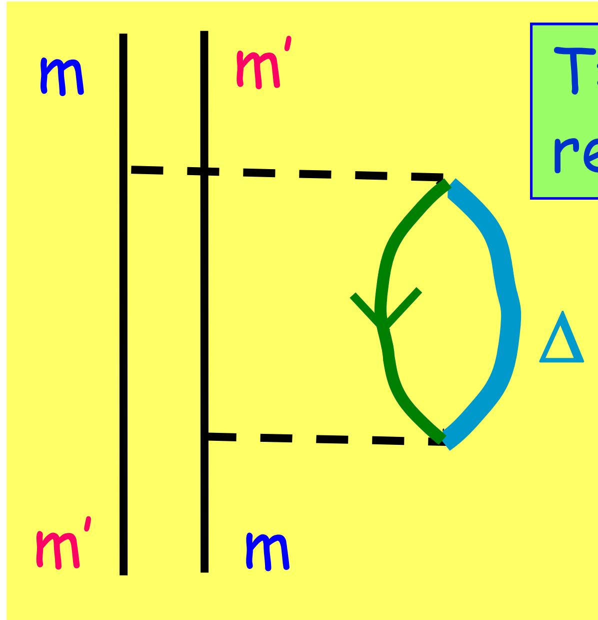
Realization in terms of 3-body interaction



+



T=1 effective monopole repulsive interaction

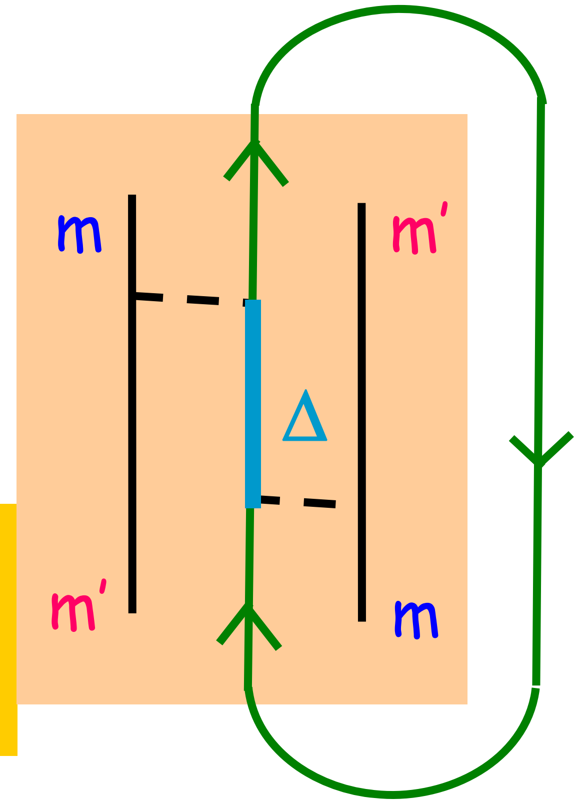
T=0 does not survive
3rd order (Akaishi et al.)

Renormalization of single particle energy

Pauli blocking

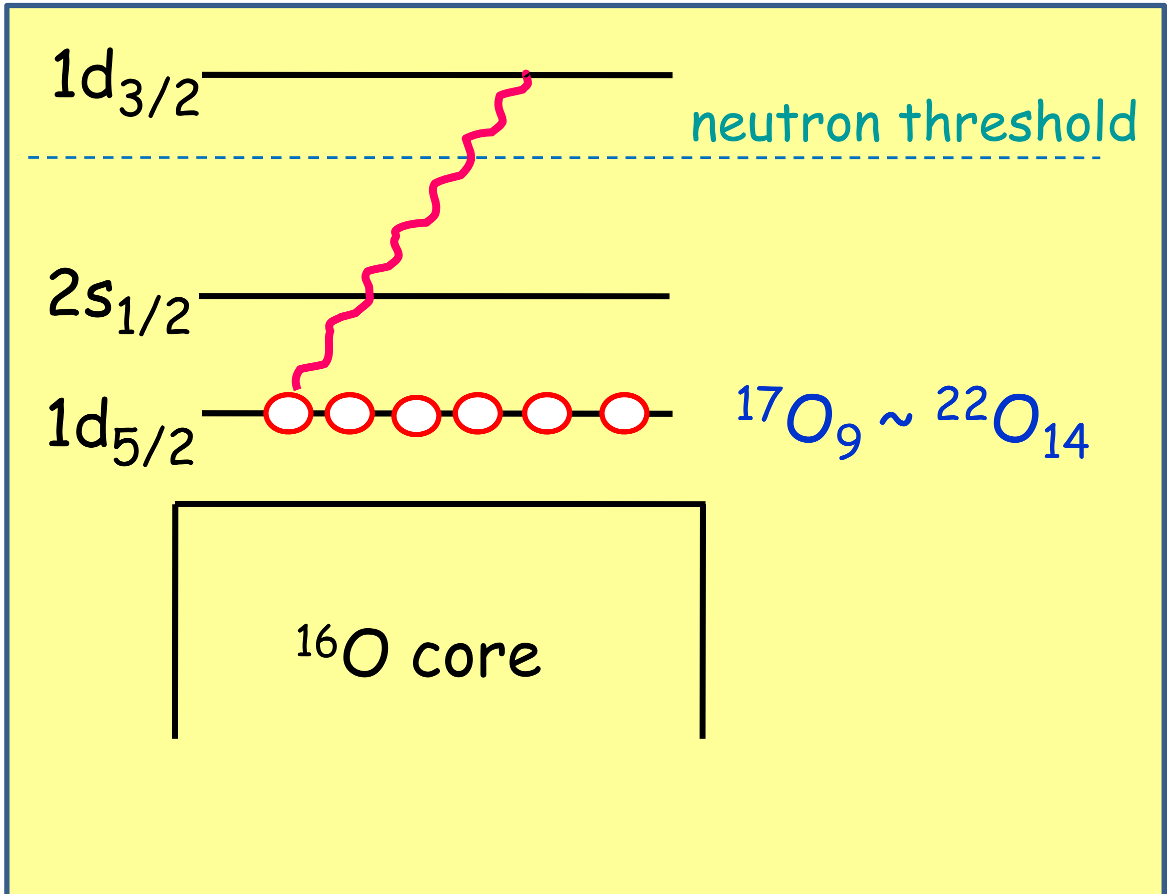
same

Monopole part of Fujita-Miyazawa 3-body force



Back to the question of high-lying $d_{3/2}$

Neutron orbits
in Oxygen isotopes



Central :
attractive
(generally)

Tensor :
attractive
- 0.9 MeV
(next page)

Δ-hole induced
repulsion
(> tensor)
Next page

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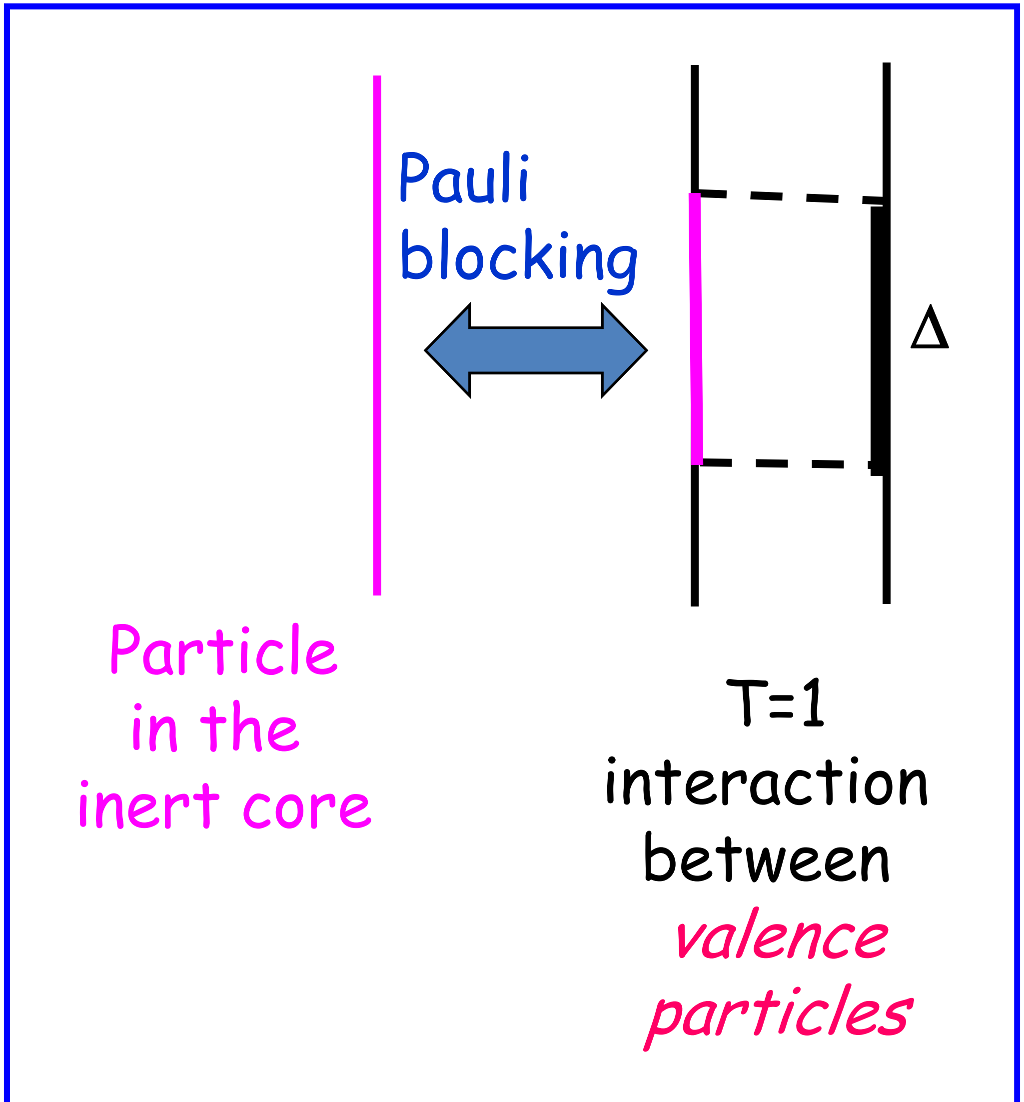
Other diagram included



Related effect was discussed by Frisch, **Kaiser** and **Weise** for **neutron matter**

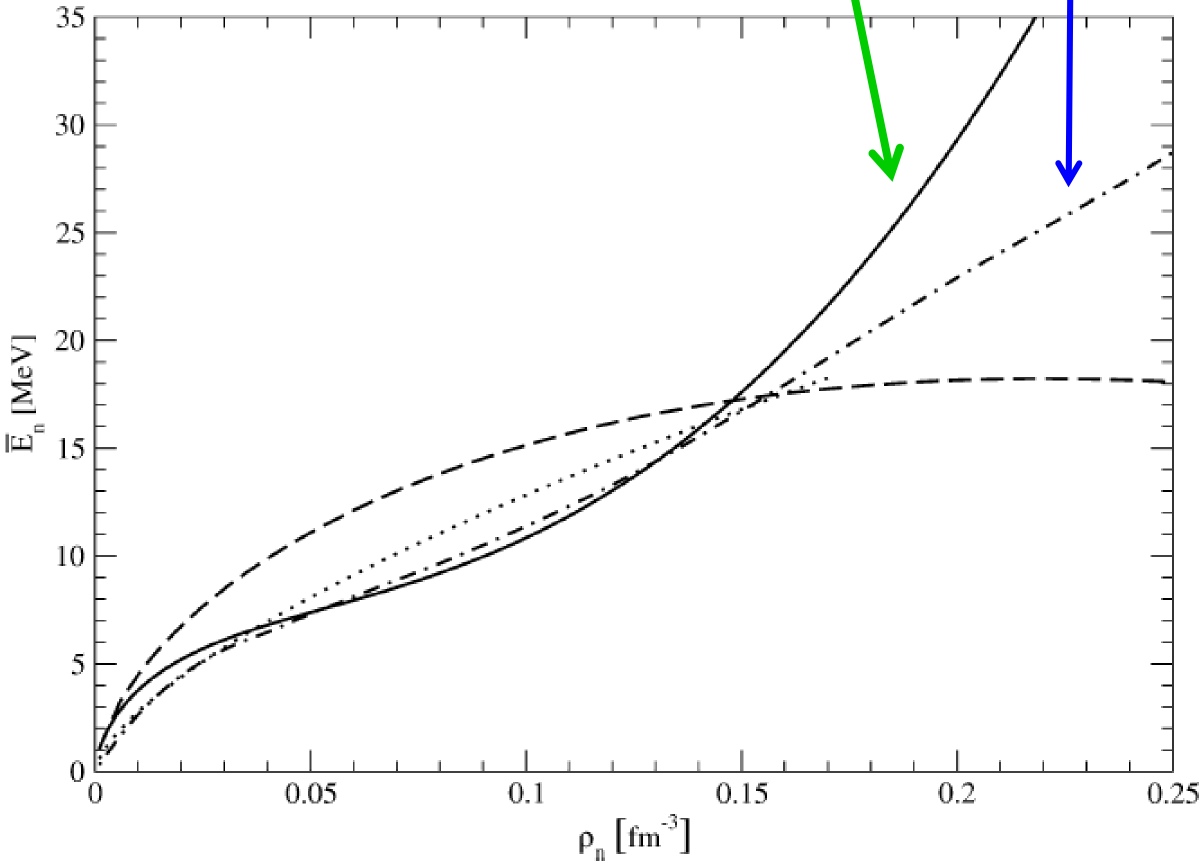
See also **Nishizaki, Takatsuka and Hiura** PTP 92, 93 (1994)

Δ-hole excitation may be crucial to neutron matter property

Chiral Perturbation incl. Δ : Frisch, Kaiser and Weise

A. Akmal, V.R. Pandharipande, D.G. Ravenhall, Phys. Rev. C 58 (1998) 1804.

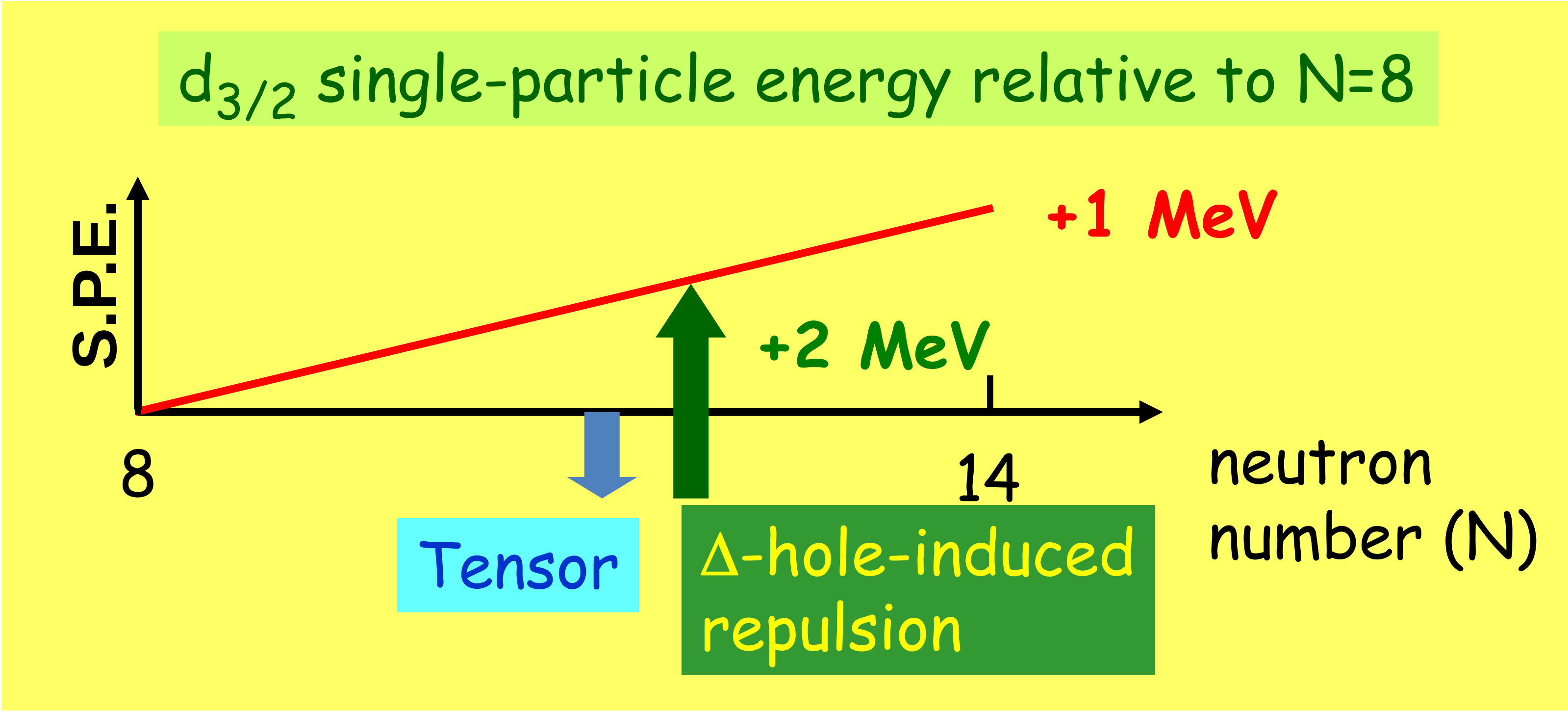
S. Fritsch et al. / Nuclear Physics A 750 (2005) 259–293



Repulsive effective monopole interaction assuming ^{16}O core

π exchange with radial cut-off at 0.7 fm , ΔE =293 MeV
f_{πNΔ}/f_{πNN} = ¥sqrt{9/2}

j	j'	Monopole interaction pion tensor
$d_{5/2}$	$d_{3/2}$	250 keV



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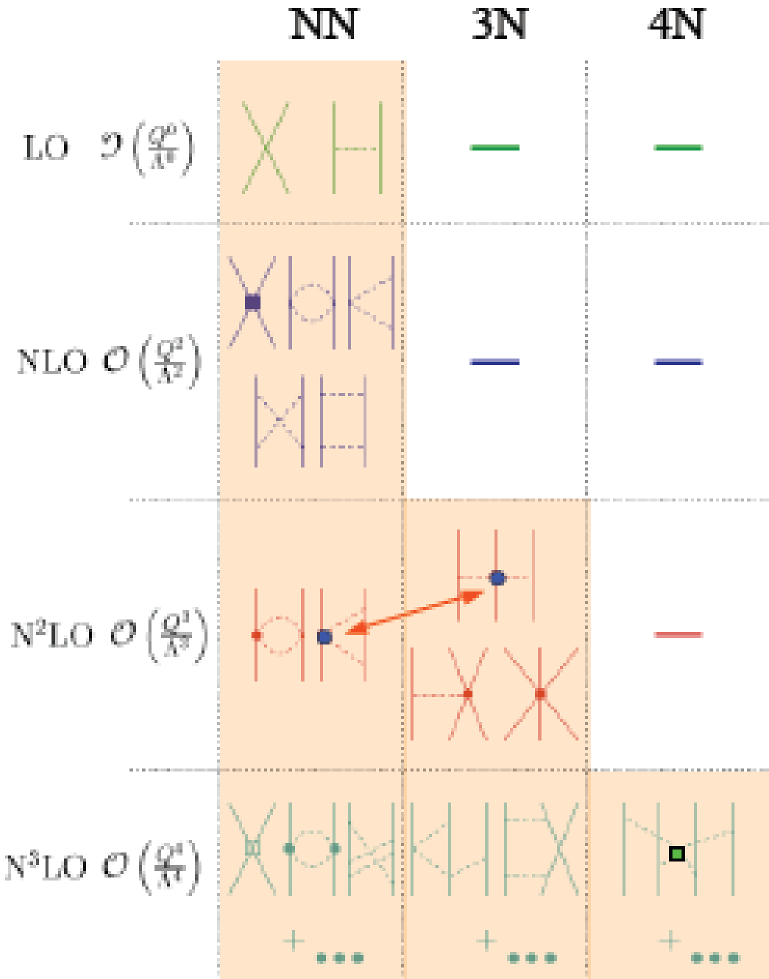
Chiral EFT for nuclear forces

Separation of scales: low momenta $\frac{1}{\lambda} = Q \ll \Lambda_b$ breakdown scale Λ_b



explains pheno hierarchy:
NN > 3N > 4N > …

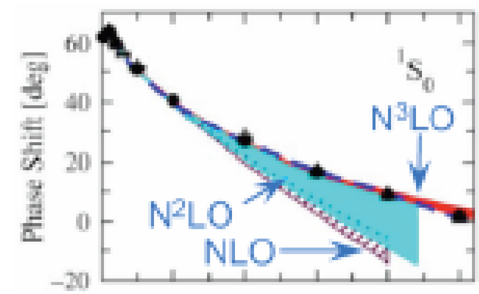
NN-3N, πN, ππ, electro-weak,… consistency

3N,4N: 2 new couplings to N³LO

resolution/Λ-dependent couplings

error estimates from truncation order, lower bound from Λ variation

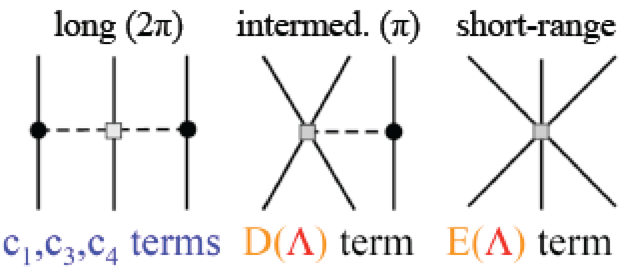
open problems:
power counting
Δ-less vs. full
…



Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum, Meissner, Nogga, Machleidt,…

Low-momentum 3N interactions

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



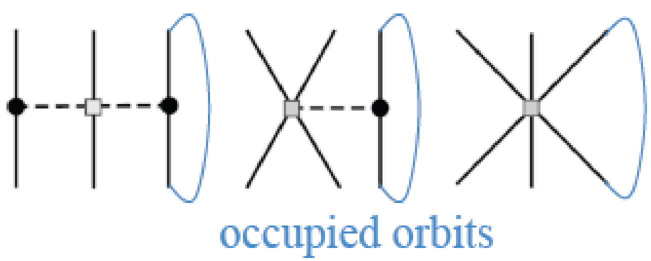
c_i from πN, consistent with NN $c_1 = -0.9^{+0.2}_{-0.5}\,,\; c_3 = -4.7^{+1.2}_{-1.0}\,,\; c_4 = 3.5^{+0.5}_{-0.2}$

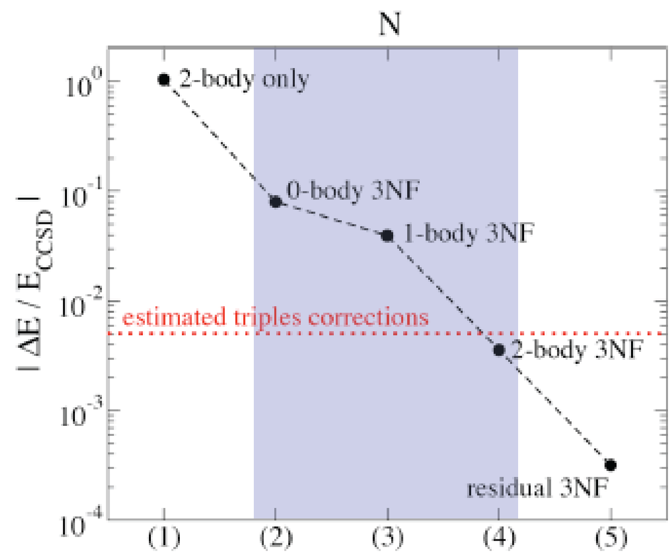
Meissner (2007)

c_3, c_4 important for structure, large uncertainties at present

Results show that 0-, 1- and 2-body parts of 3N interaction dominate

2-body part





residual 3N interaction can be neglected

very promising and practical

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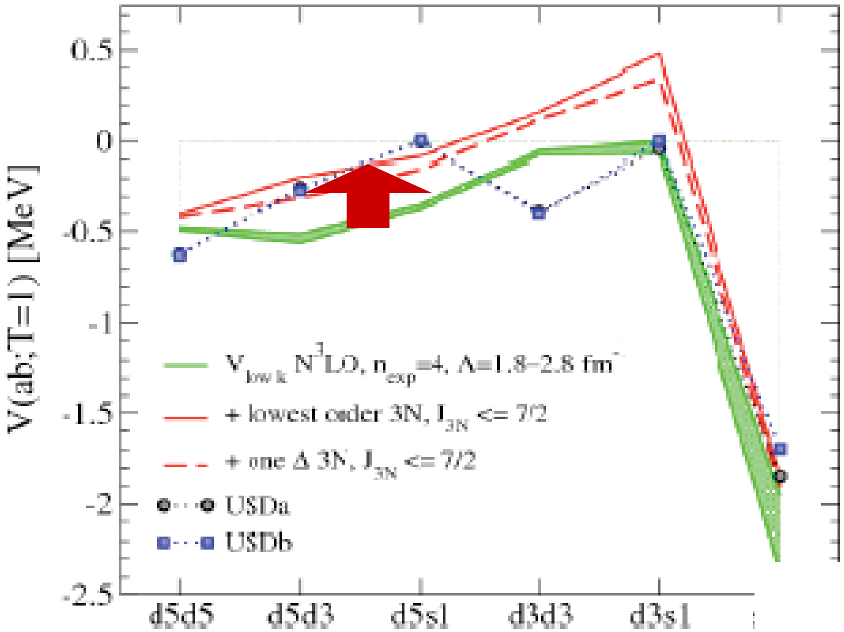
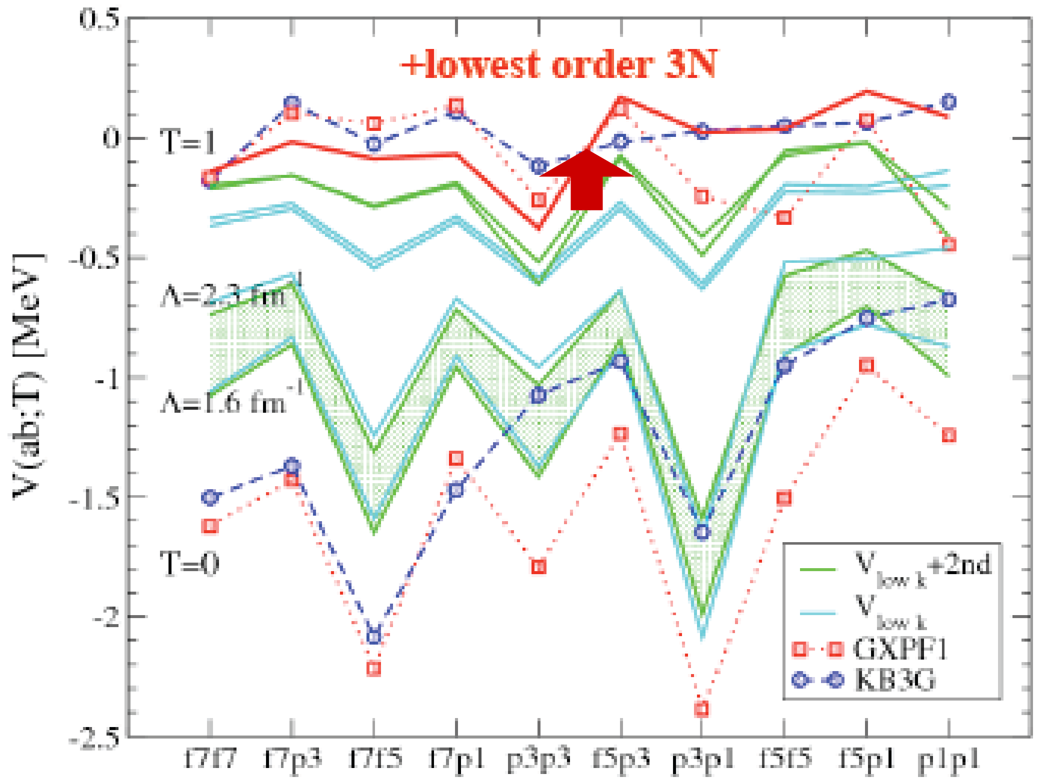
More binding by 3NF Is this always true ?



From EFT (Effective Field Theory)

sd shell

pf shell



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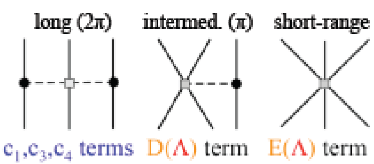

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Meissner (2007)

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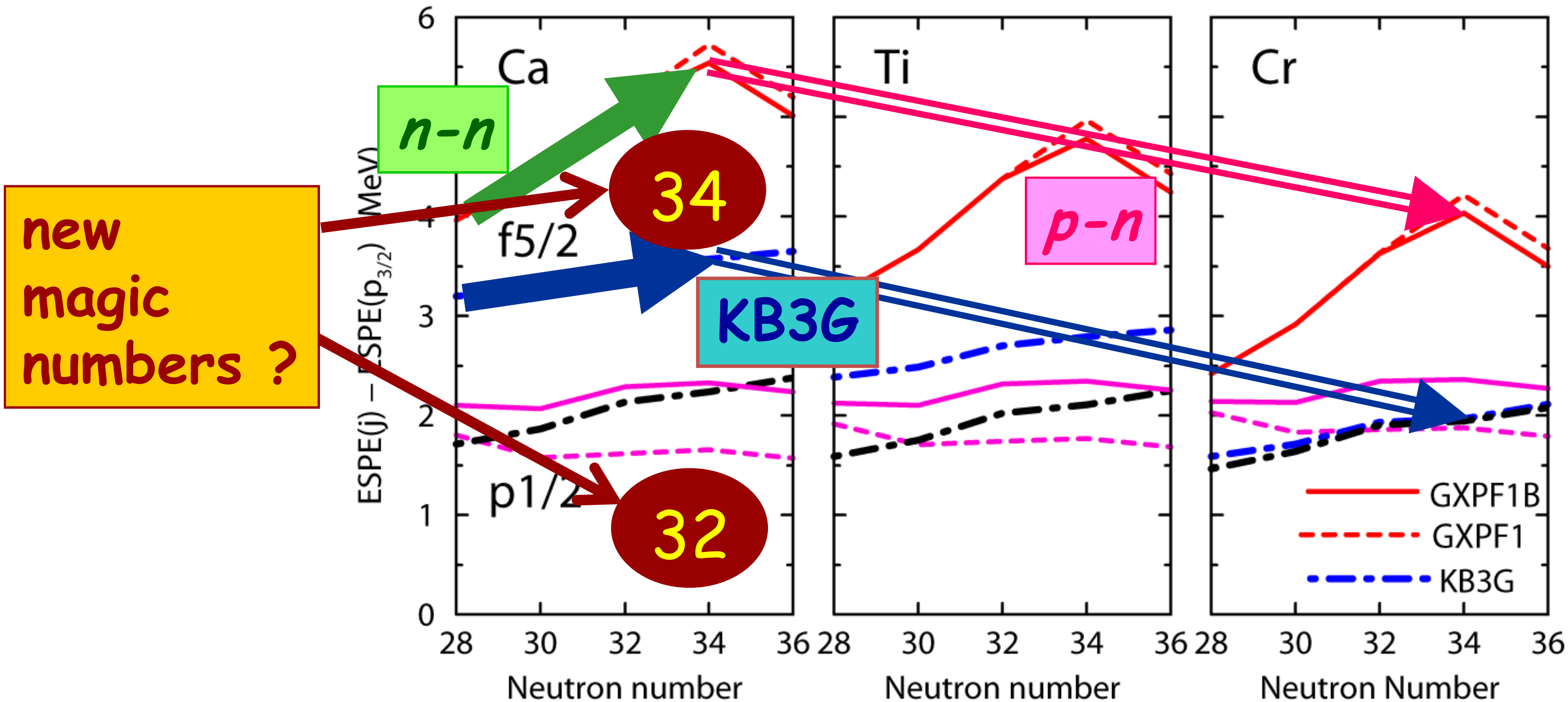
(Effective) single-particle energies



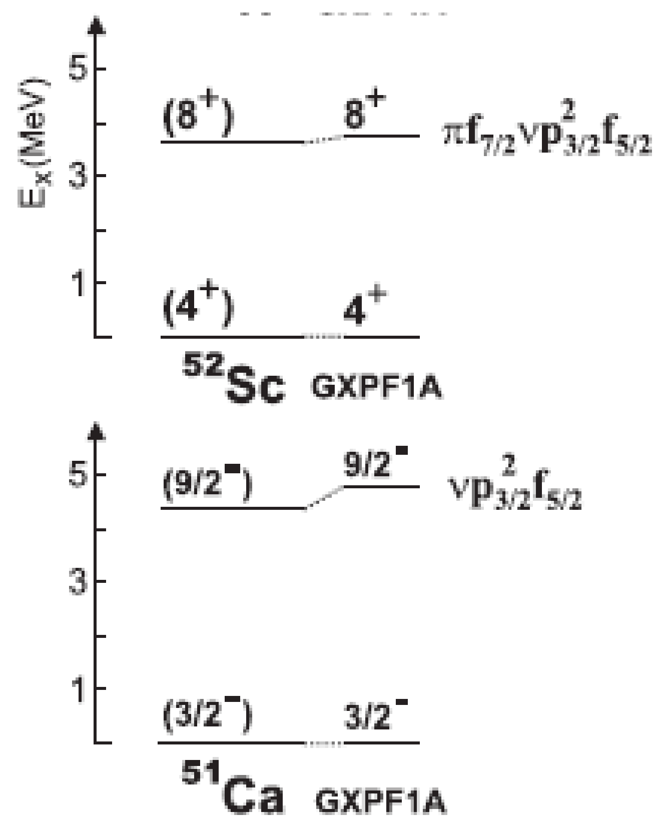
Lowering of f5/2 from Ca to Cr :
~ 1.6 MeV = 1.1 MeV (tensor) + 0.5 MeV (central)

Rising of f5/2 from ^{48}Ca to ^{54}Ca :
p3/2-p3/2 attraction ⟺ p3/2-f5/2 repulsion

KB interactions : Poves, Sanchez-Solano, Caurier and Nowacki, Nucl. Phys. A694, 157 (01)

- **N=34 magic number**

The same mechanism widens N=34 gap.



Recently more (indirect) experimental indications, e.g., Fornal et al. PR C77 (2008)

まとめ

殻構造は原子核構造の根幹

例:　低励起での変形はヤーンテラー効果　→　殻効果

殻構造は不安定核で変わり、核力（ハドロン間相互作用）の特定の成分が特徴的なパターンで関与

1.　テンソル力　(→ *ls* splitting の変化: hw と同程度のオーダー、グルーピング)
2.　中心力　(→ 動径波動関数のノード)
3.　3体力 (藤田ー宮沢力の Monopole 成分＝robust に斥力
　　⇒ バレンス核子間のT=1 斥力補正)

帰結

1. →　^{42}Si ←→ ^{48}Ca (e,e'p)

　　N=20 魔法数の消滅　×ギャップは大きいままで、ギャップ越えの励起が大
　　　　（**WBB の Island of Inversion のアイデア**）
　　○　ギャップそのものが変動し、小さくなる

2. →　exotic Ni, Cu (lowering of $f_{5/2}$) …　R プロセスでのN=50

3. →　O dripline,　新魔法核 ^{54}Ca ?
　　3NF ~ EFT ~ neutron matter　　**不安定核がハドロン力理論の検証の場**

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