Pion Nuclear Physics
-Importance of Tensor Interaction-

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with

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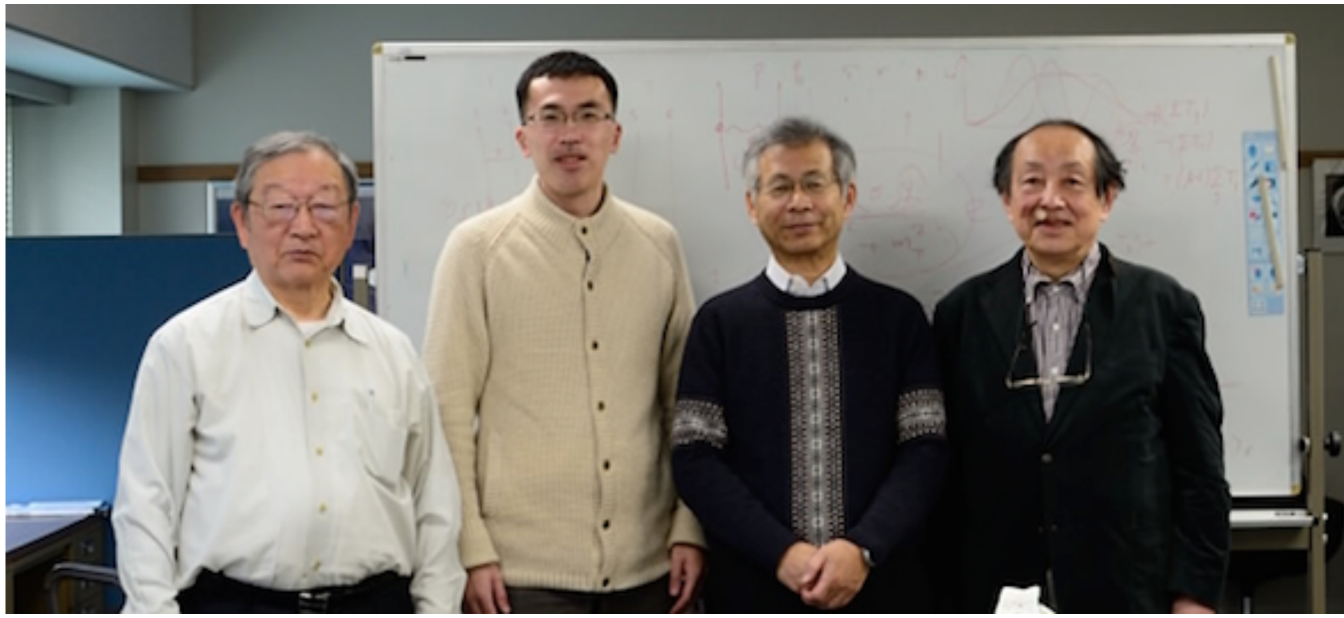
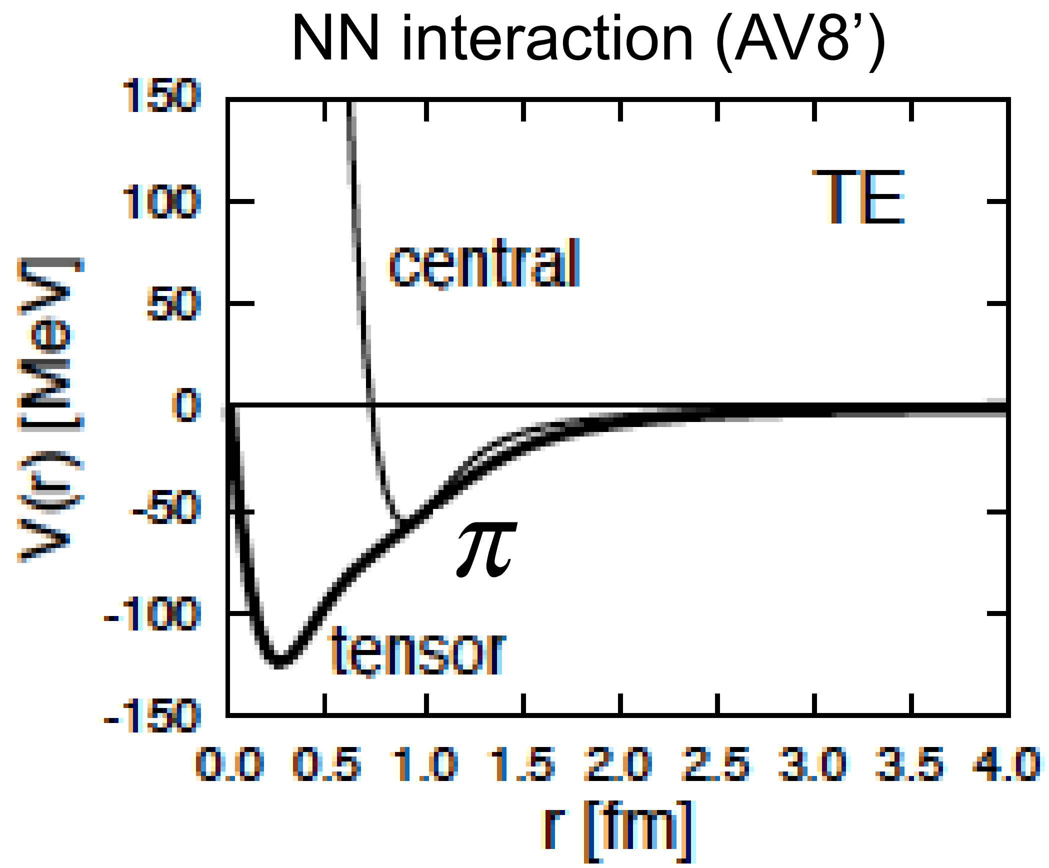
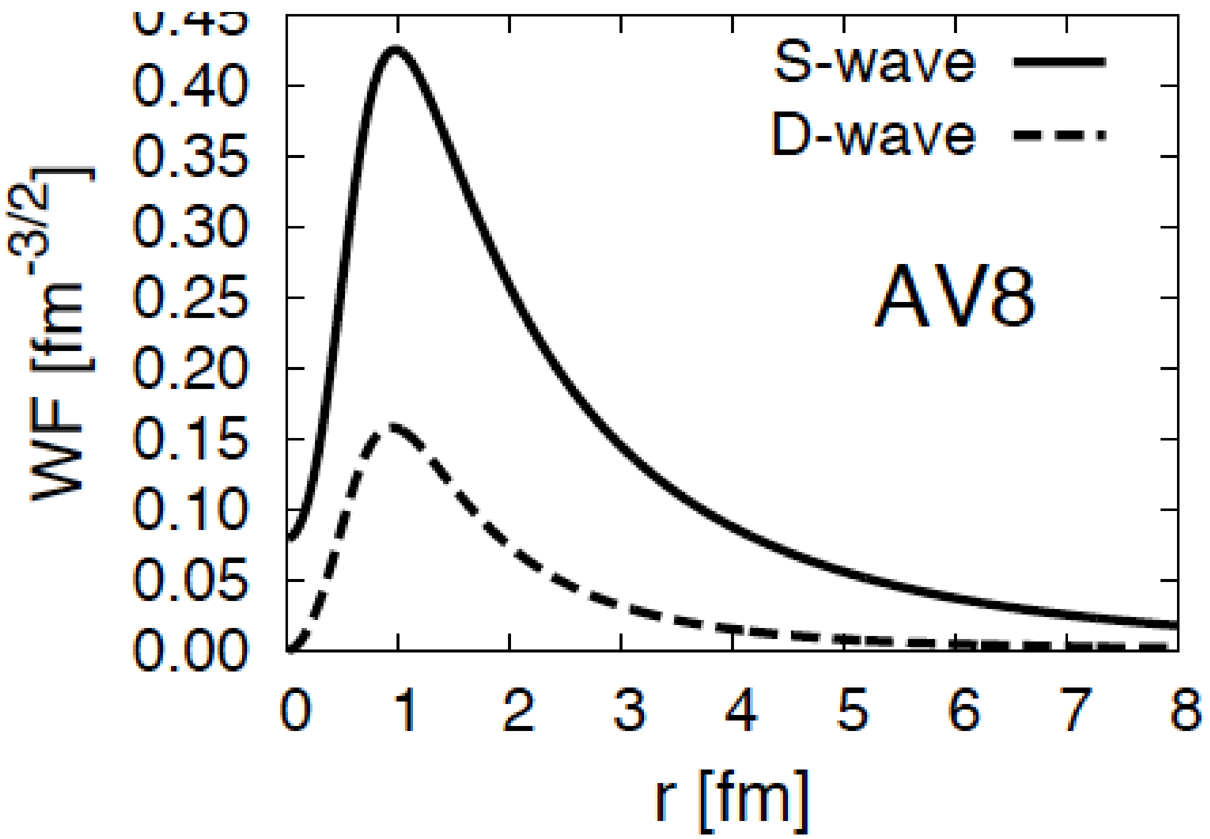


Deuteron (1^+)

S=1 and L=0 or 2

$$\Psi = \Phi_S + \Phi_D = (1+F_D)\Phi_S$$





Energy	−2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	−4.46
(SS)	−3.96
(DD)	−0.50
Tensor	−16.64
(SD)	−18.93
(DD)	2.29
LS	−1.02
P(*D*)	5.78 [%]
Radius	1.96 [fm]
(SS)	2.00 [fm]
(DD)	1.22 [fm]

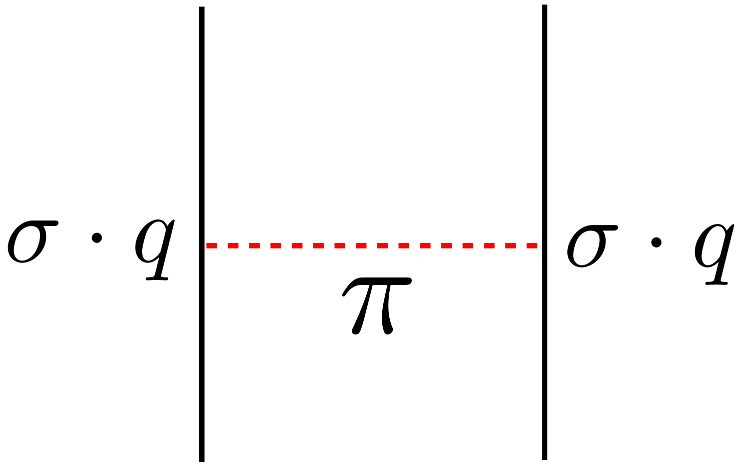
Tensor interaction is strong!!

Why tensor interaction is strong?

Pion is a pseudoscalar meson $J^\pi = 0^-$

Pion interaction ~ tensor interaction

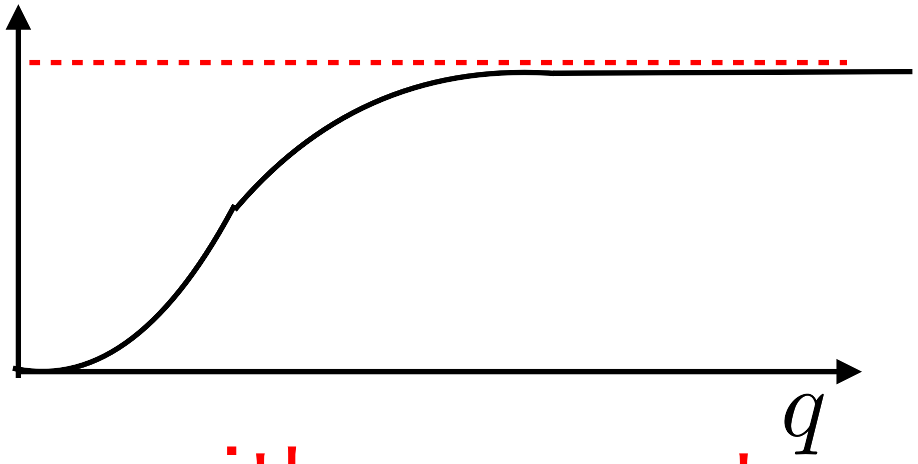
$$V_\pi = \frac{f_\pi^2}{m_\pi^2}\frac{(\sigma_1 \cdot q)(\sigma_2 \cdot q)}{m_\pi^2 + q^2}\tau_1\tau_2$$



$$\frac{(\sigma_1 \cdot q)(\sigma_2 \cdot q)}{m_\pi^2+q^2} = \frac{1}{3}\sigma_1\sigma_2\left[\cancel{\frac{m_\pi^2+q^2}{m_\pi^2+q^2}} - \frac{m_\pi^2}{m_\pi^2+q^2}\right] + \frac{1}{3}S_{12}(q)\frac{q^2}{m_\pi^2+q^2}$$

δ関数 Yukawa Tensor

$$S_{12}(q) = [[\sigma_1\sigma_2]_2 \times Y_2(q)]_0$$

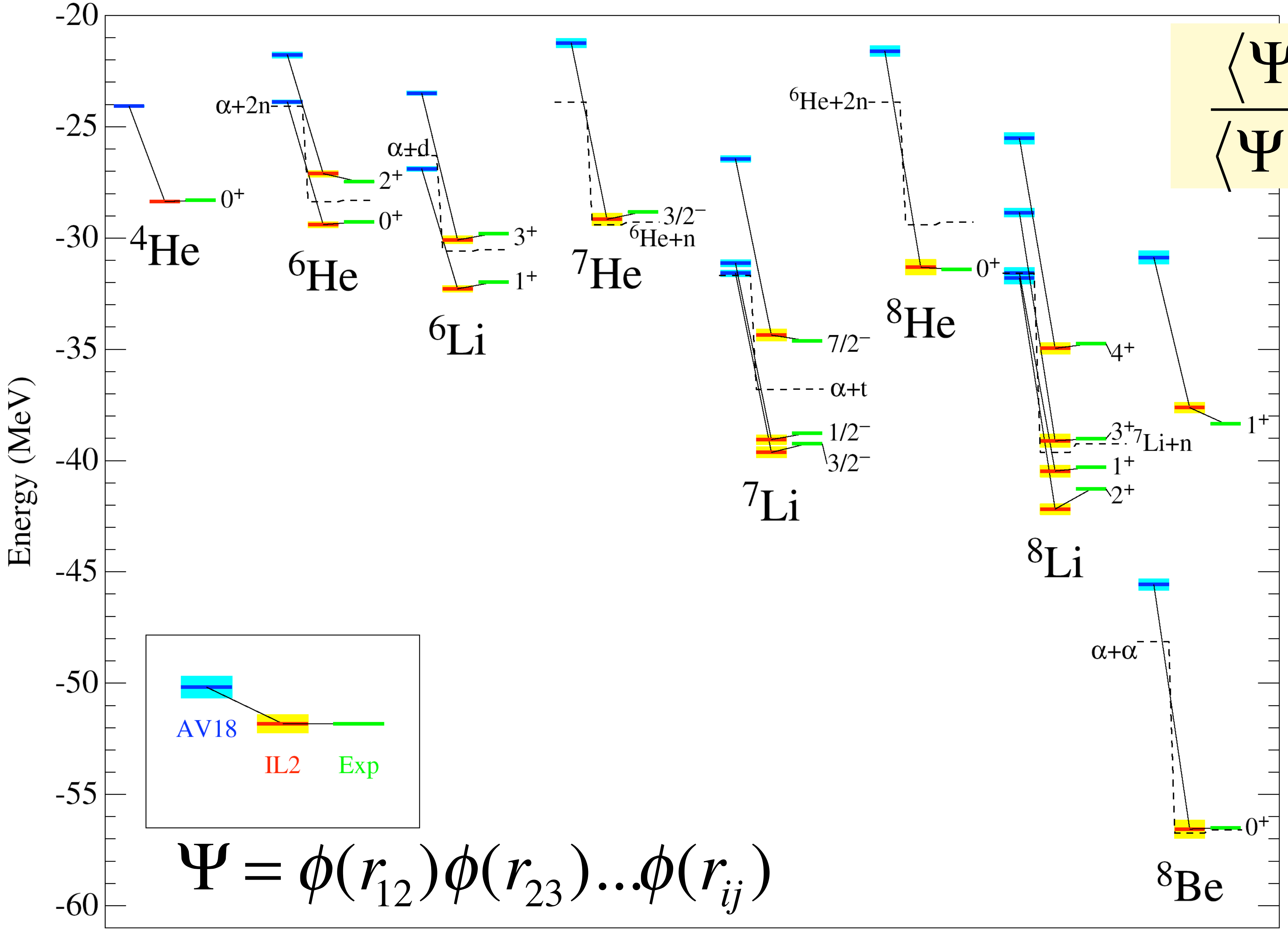


Tensor interaction increases with momentum

Variational calculation of light nuclei with NN interaction

VMC+GFMC

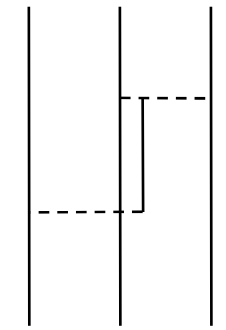
$$\frac{\langle\Psi|V_\pi|\Psi\rangle}{\langle\Psi|V_{NN}|\Psi\rangle} \sim 80\%$$



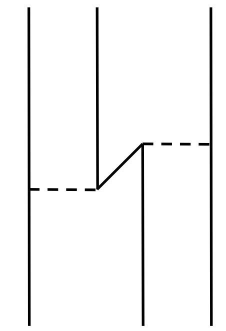
$$\Psi = \phi(r_{12})\phi(r_{23})\ldots\phi(r_{ij})$$

C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci.51(2001)

V_{NNN}



Fujita-Miyazawa



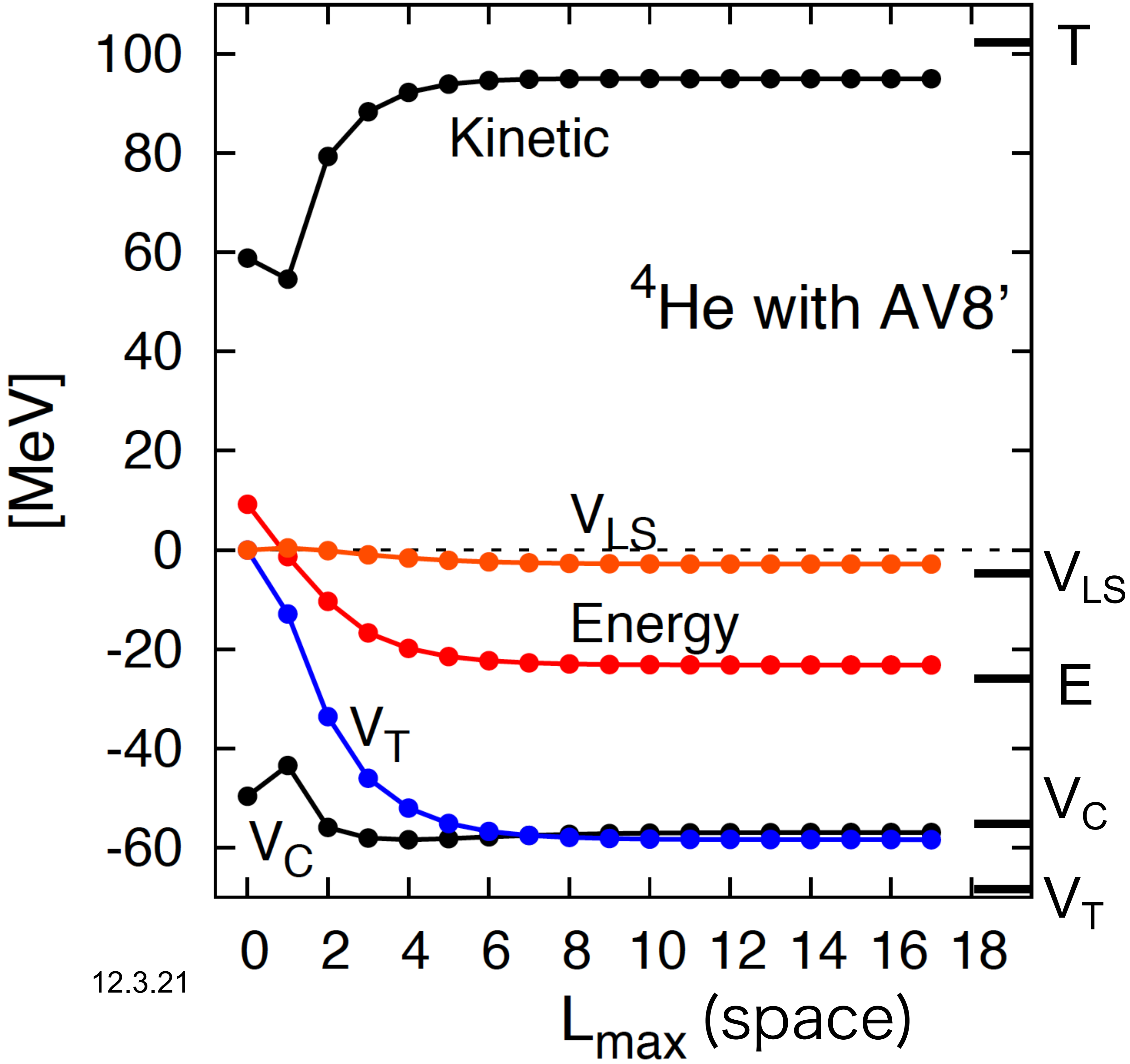
Relativistic

Heavy nuclei (Super model)

Pion is key

TOSM+UCOM with AV8'

$$\Psi = C_0|0\rangle + \sum_{\alpha} C_{\alpha}|2p2h:\alpha\rangle$$



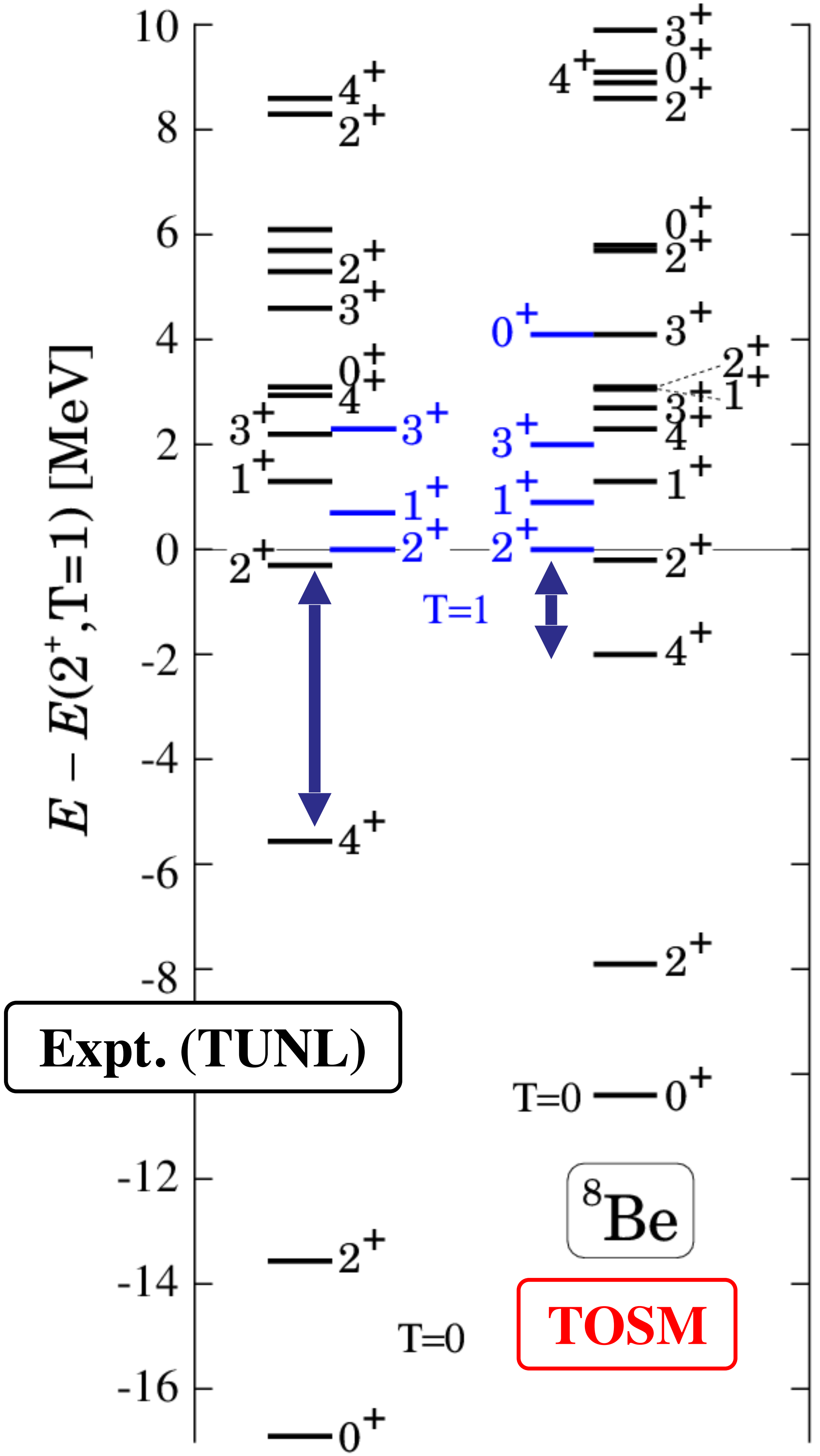
T.Myo H.Toki K.Ikeda
PTP121(2009)511

TOSM

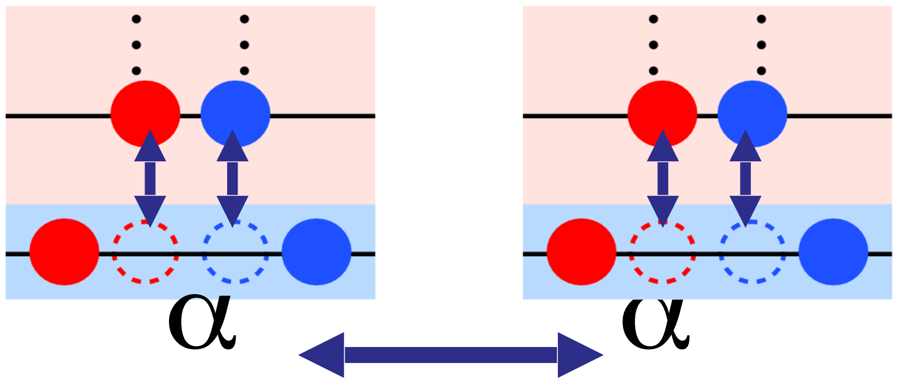
Tensor optimized
Shell model

Few body
Calculation
(Kamda et al)

^{8}Be in TOSM – AV8’ –



- correct level order (*T*=0,1)
- tensor contribution : *T*=0 > *T*=1
- α : 0p0h+2p2h with high-k
  - – 2α needs 4p4h.
  - – spatial asymptotic form of 2α



clustering

⇒ TOAMD

Tensor Optimized Antisymmetrized Molecular Dynamics (TOAMD)

Myo Toki Ikeda

Tensor optimized shell model (TOSM)

1. We include tensor interaction most effectively to shell model
2. Difficult to treat cluster structure

+

Horiuchi Enyo Kimura..

Antisymmetrized molecular dynamics (AMD)

1. Cluster+shell structure is handled on the same footing using effective interaction
2. Difficult to treat bare nucleon-nucleon interaction

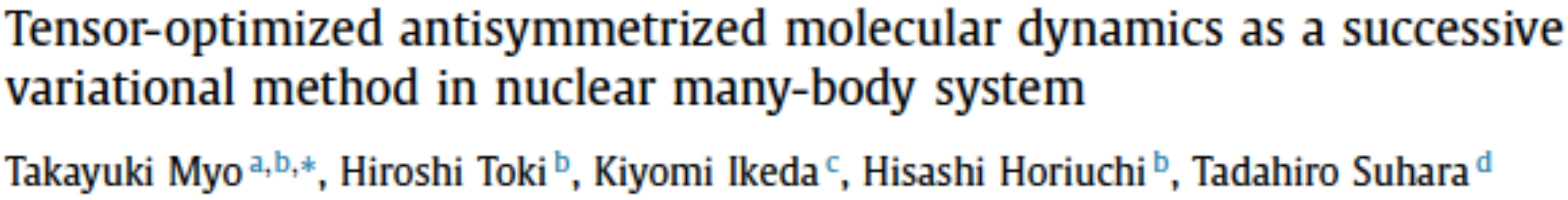
↓

Study nuclear structure based on bare NN interaction

Prog. Theor. Exp. Phys. **2015**, 073D02 (38 pages)
DOI: 10.1093/ptep/ptv087

Tensor-optimized antisymmetrized molecular dynamics in nuclear physics

Takayuki Myo[1,2,*], Hiroshi Toki[2], Kiyomi Ikeda[3], Hisashi Horiuchi[2],
and Tadahiro Suhara[4]



Tensor-optimized antisymmetrized molecular dynamics as a successive variational method in nuclear many-body system

Takayuki Myo[a,b,*], Hiroshi Toki[b], Kiyomi Ikeda[c], Hisashi Horiuchi[b], Tadahiro Suhara[d]

Phys. Lett. B769 (2017) 213

PHYSICAL REVIEW C **95**, 044314 (2017)

Successive variational method of the tensor-optimized antisymmetrized molecular dynamics for central interaction in finite nuclei

Takayuki Myo,[1,2,*] Hiroshi Toki,[2,†] Kiyomi Ikeda,[3,‡] Hisashi Horiuchi,[2,§] and Tadahiro Suhara[4,‖]

Hybridization of tensor-optimized and high-momentum antisymmetrized molecular dynamics for light nuclei with bare interaction

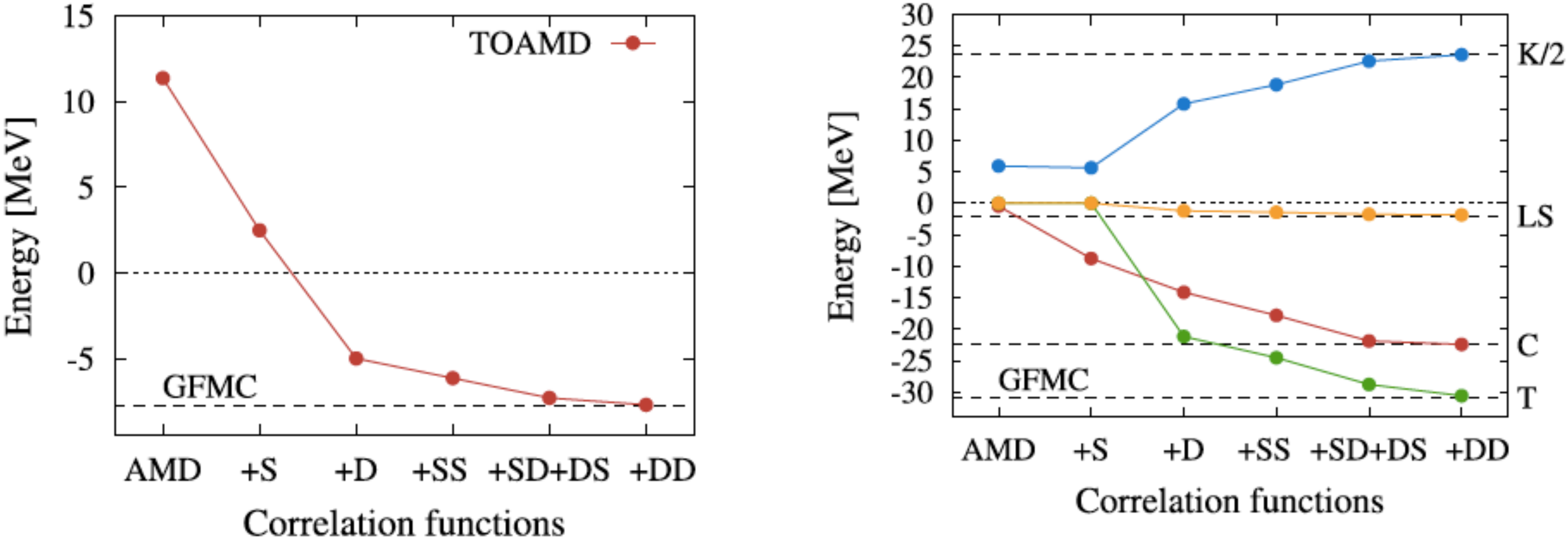
Prog. Theor. Exp. Phys. **2018**, 011D01 (9 pages)

Mengjiao Lyu[1,*], Masahiro Isaka[1], Takayuki Myo[1,2,*], Hiroshi Toki[1], Kiyomi Ikeda[3],
Hisashi Horiuchi[1], Tadahiro Suhara[4], and Taiichi Yamada[5]

He(A=3)

Interaction is AV8’

TOAMD group: Phys. Lett. B769 (2017) 213



$$\Phi_{TOAMD} = (1 + F_S + F_D + F_S F_S + F_S F_D + F_D F_D)\Phi_{AMD}$$

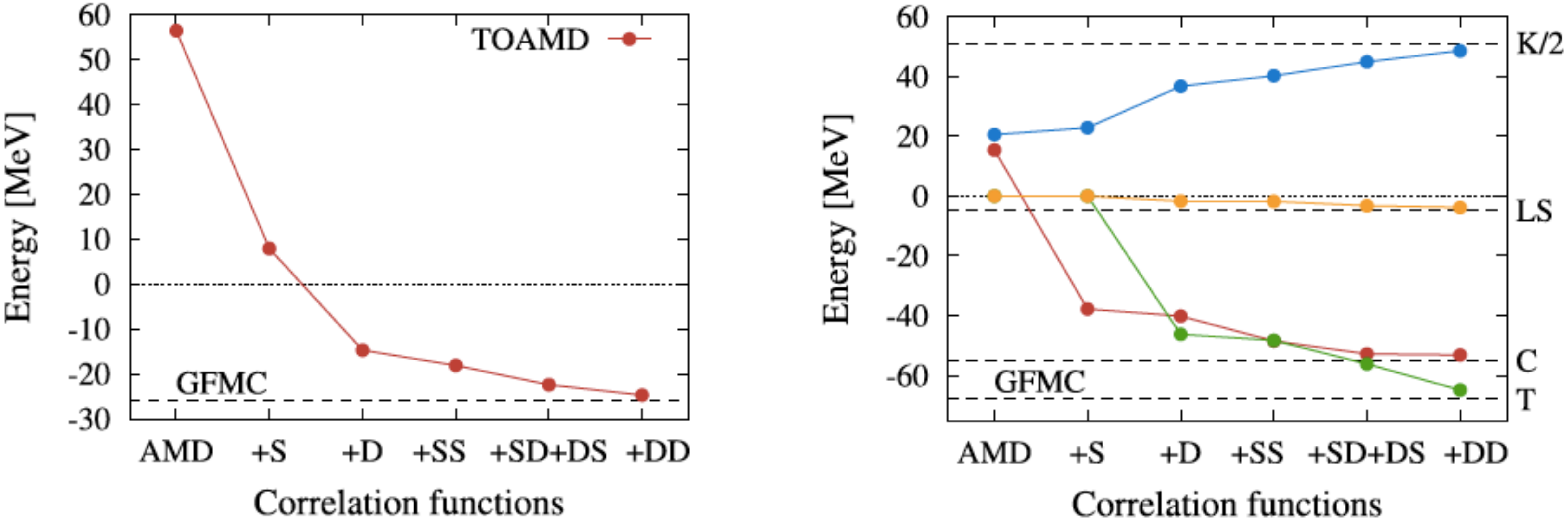
We achieve convergence successively.

(Successive variational method)

He(A=4)

Interaction is AV8’

TOAMD group: Phys. Lett. B769 (2017) 213



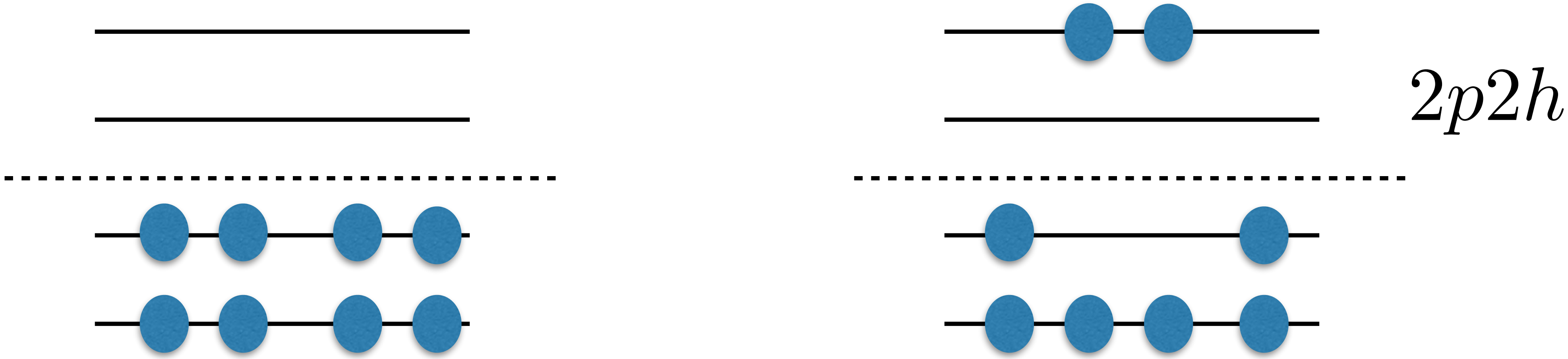
$$\Phi_{TOAMD} = (1 + F_S + F_D + F_S F_S + F_S F_D + F_D F_D)\Phi_{AMD}$$

We work on p-shell nuclei.

Experiments

We have wave function of ground state

$$|A\rangle = (1 + F_D)|0\rangle$$



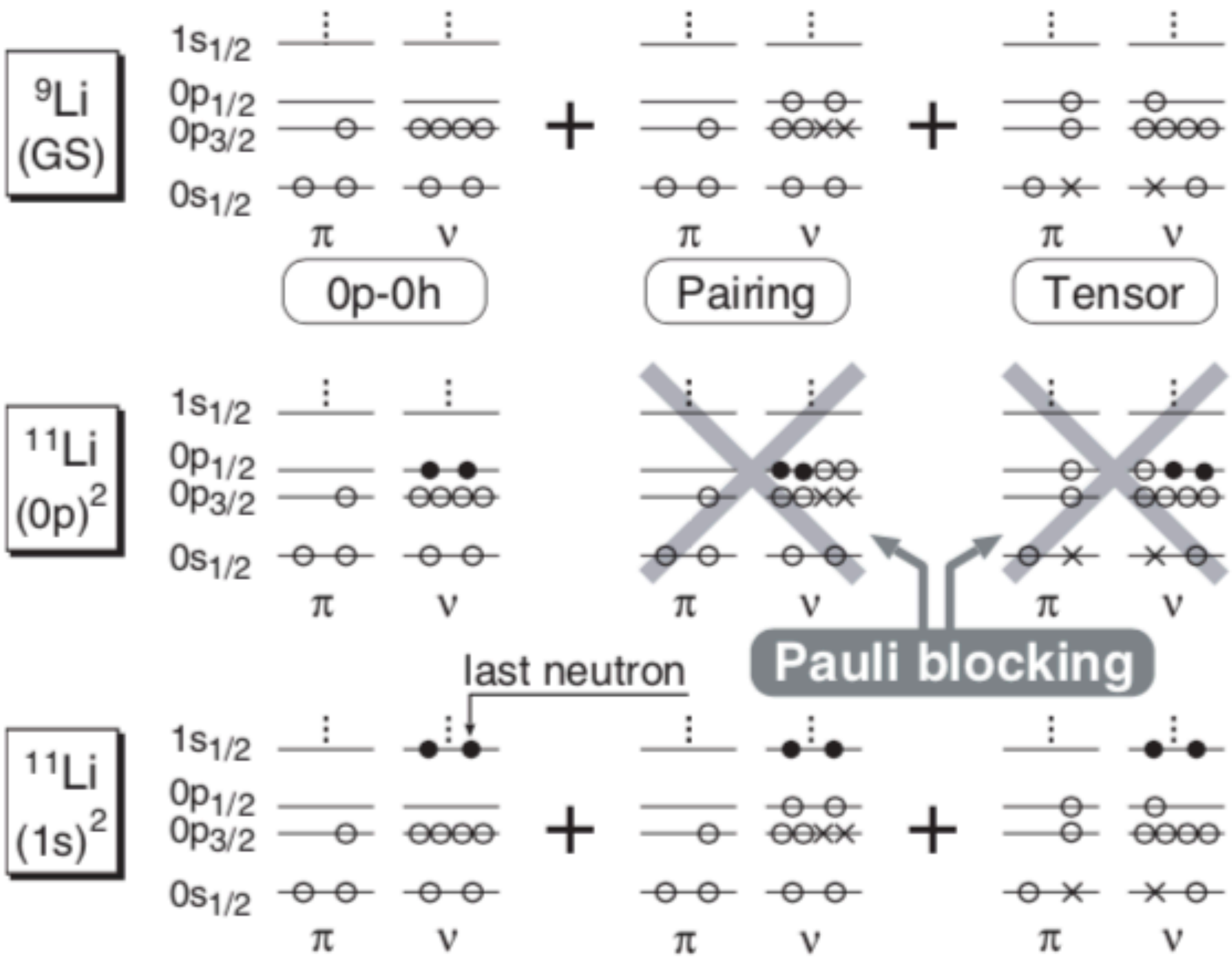
$$\langle A|O|A\rangle \approx \langle \text{model:A}|O|\text{model:A}\rangle + \langle \text{model:A}|F_D O F_D|\text{model:A}\rangle$$

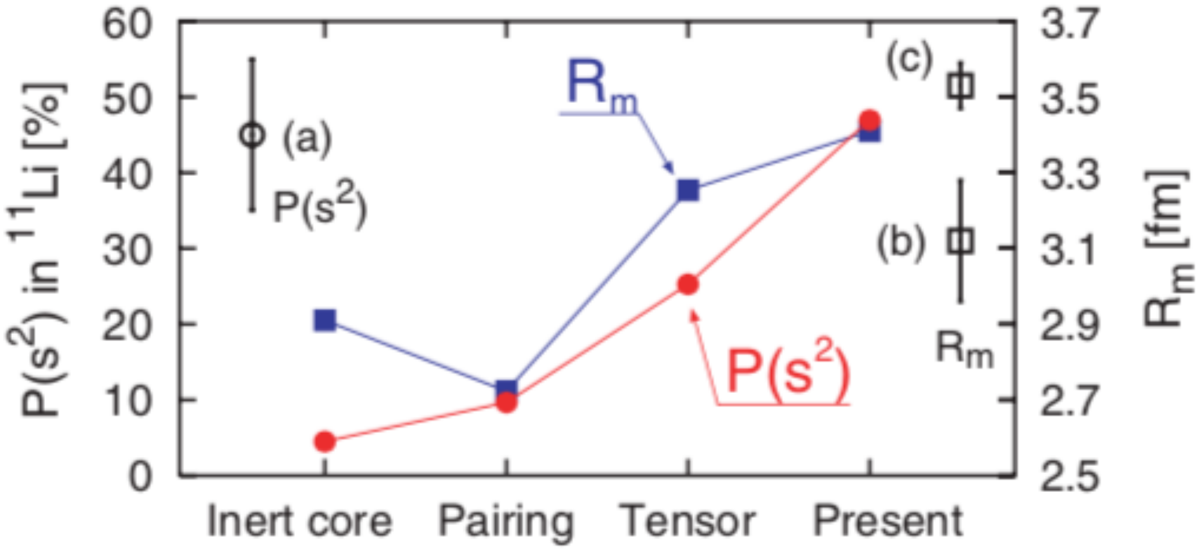
μ	Magnetic moment
$M1$	M1 transition
e^{ikr}	Form factor

PHYSICAL REVIEW C **76**, 024305 (2007)

Roles of tensor and pairing correlations on halo formation in ^{11}Li

Takayuki Myo,[1,*] Kiyoshi Katō,[2,†] Hiroshi Toki,[1,‡] and Kiyomi Ikeda[3,§]

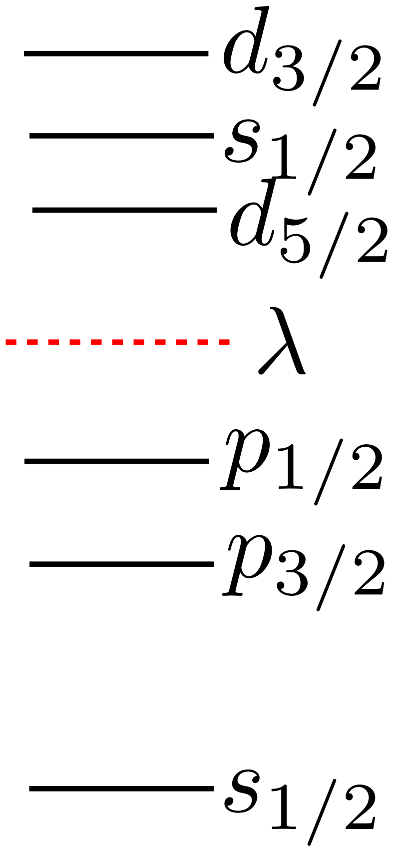




Tensor correlation reproduces the halo structure of ^{11}Li

^{15}O
Level scheme

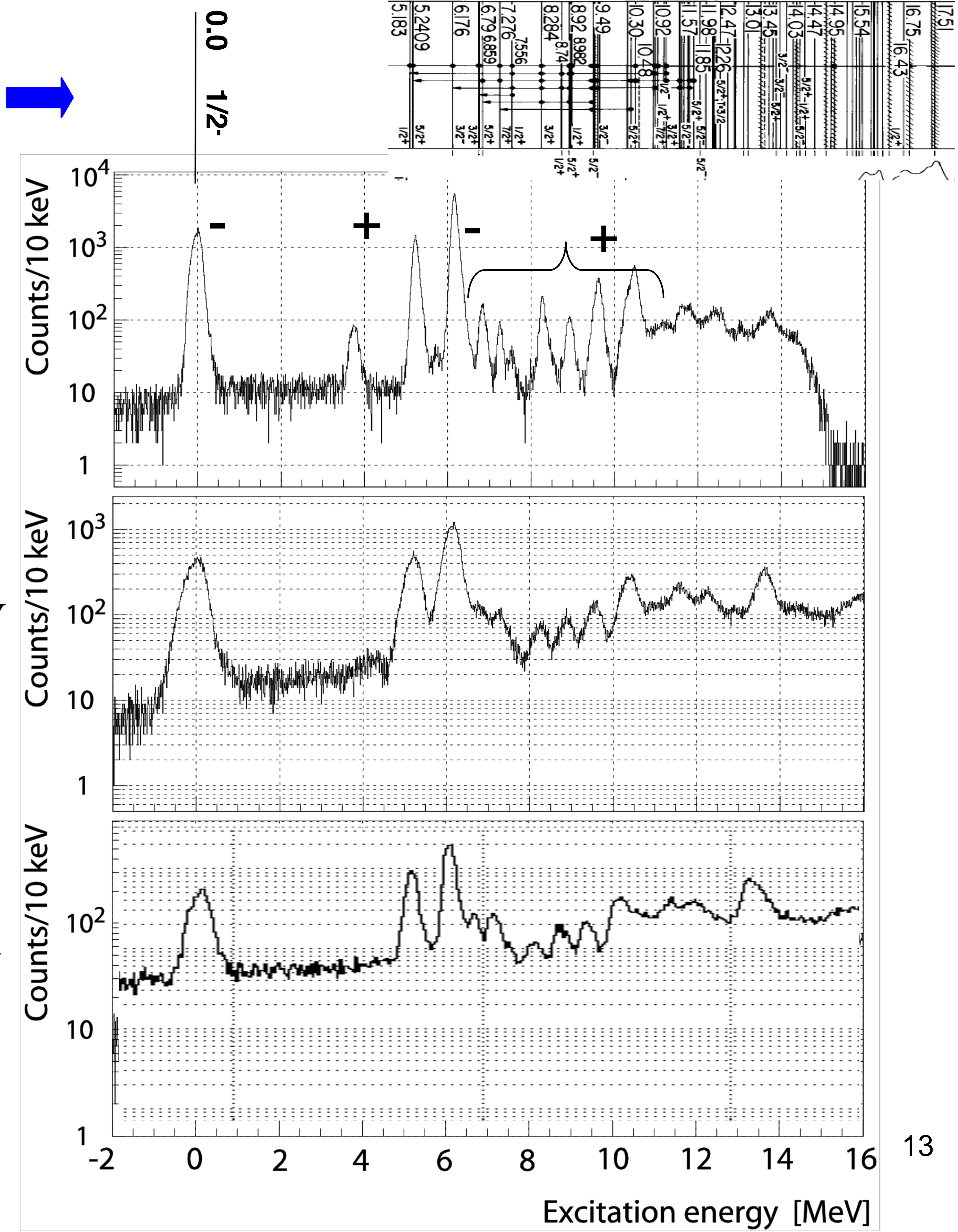
Ong, Tanihata et al



^{16}O (*p*,*d*)
E_p = 198 MeV
Θ_d = 10°

^{16}O (*p*,*d*)
E_p = 295 MeV
Θ_d = 10°

^{16}O (*p*,*d*)
E_p = 392 MeV
Θ_d = 10°



12.3.21

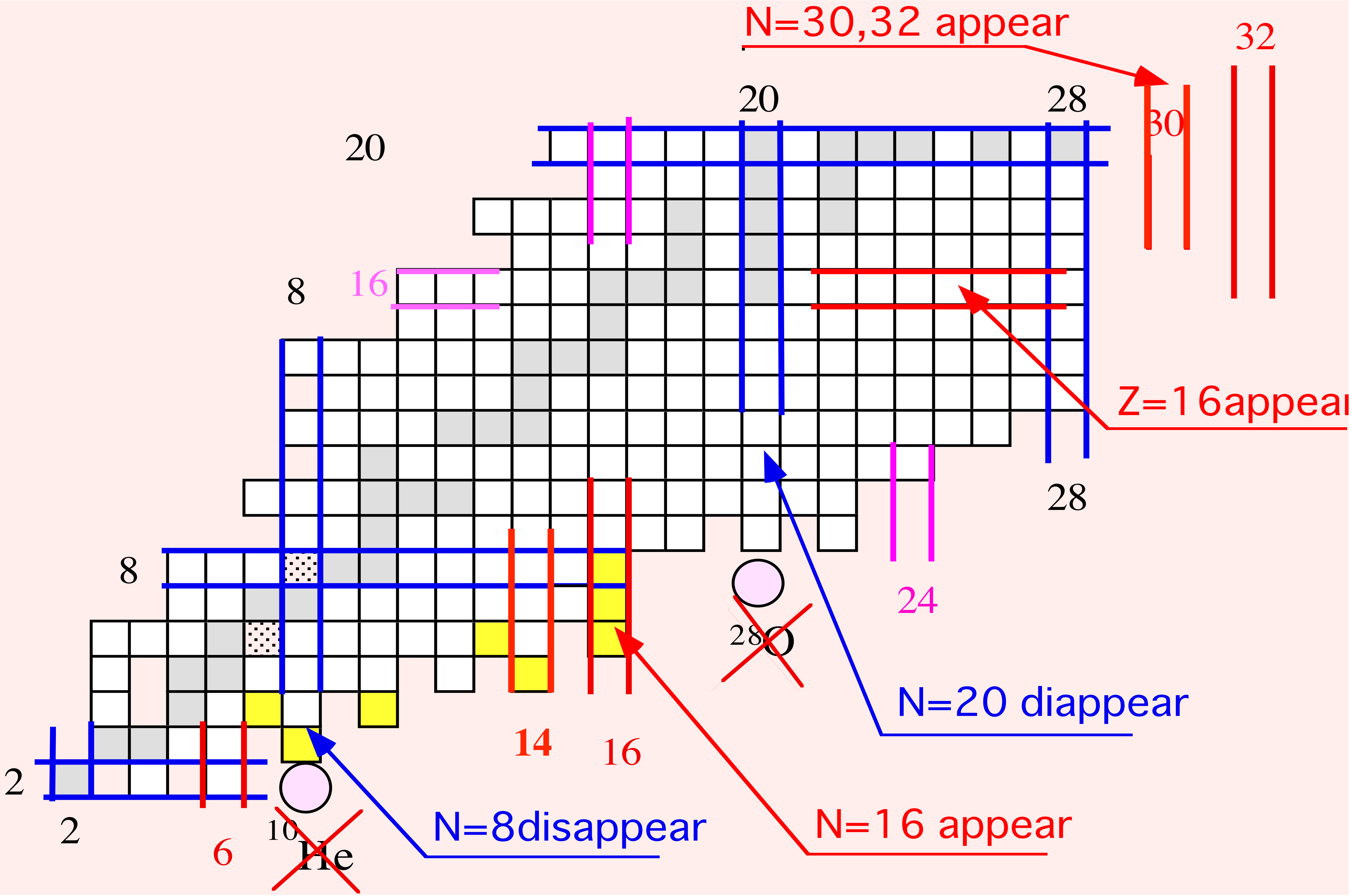
Tensor Blocking and Nuclear Shell Structure
Understanding Magic Numbers in Neutron Rich Nuclei by Tensor Blocking Mechanism

I. Tanihata[a,b], H. Toki[b], S. Terashima[a], and H.-J. Ong[b]
a) IRCNPC and School of Physics, Beihang University, Beijing 100191 , P. R. China
b) RCNP Osaka University, Osaka 567-0047, Japan

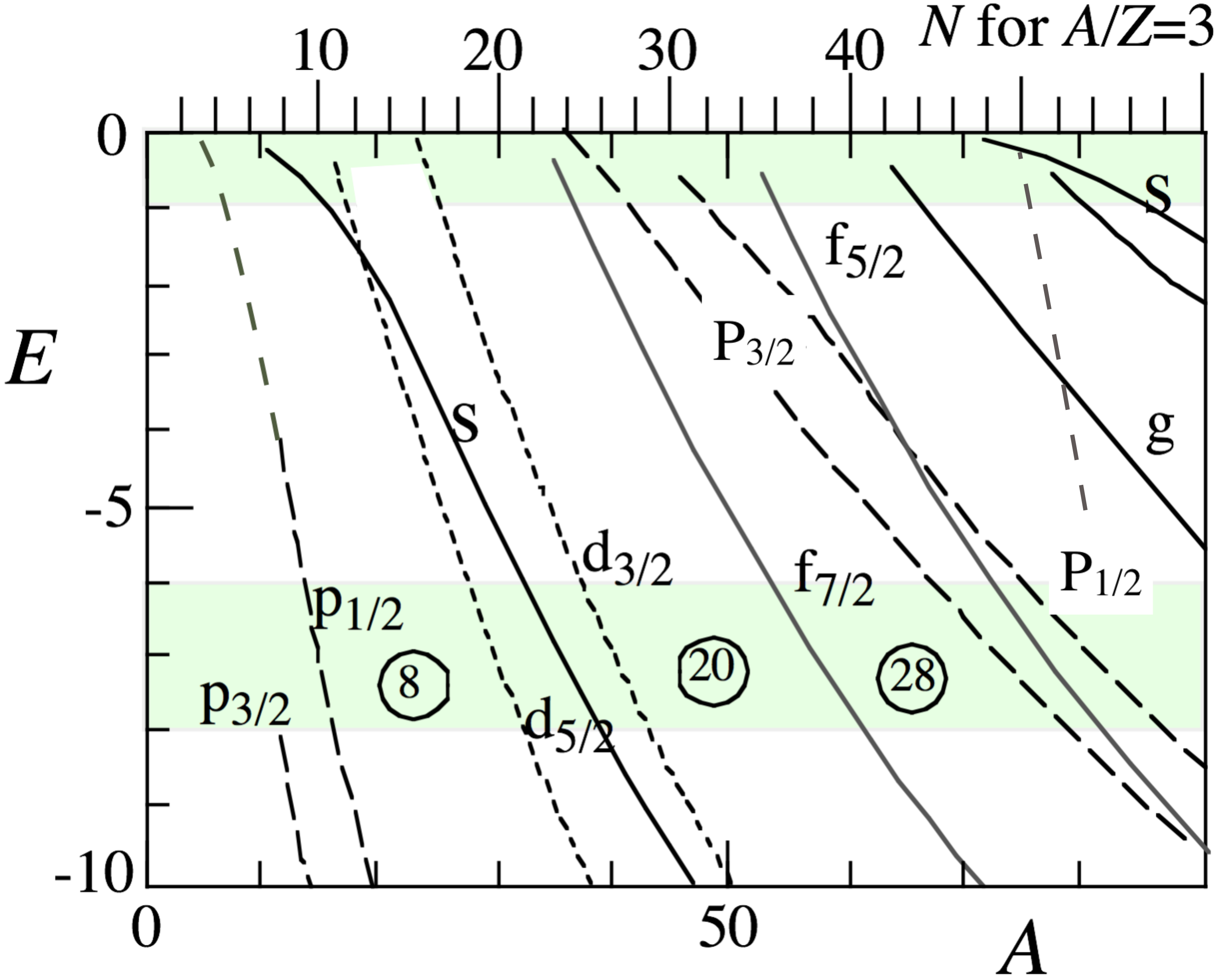
Tensor blocking shell model

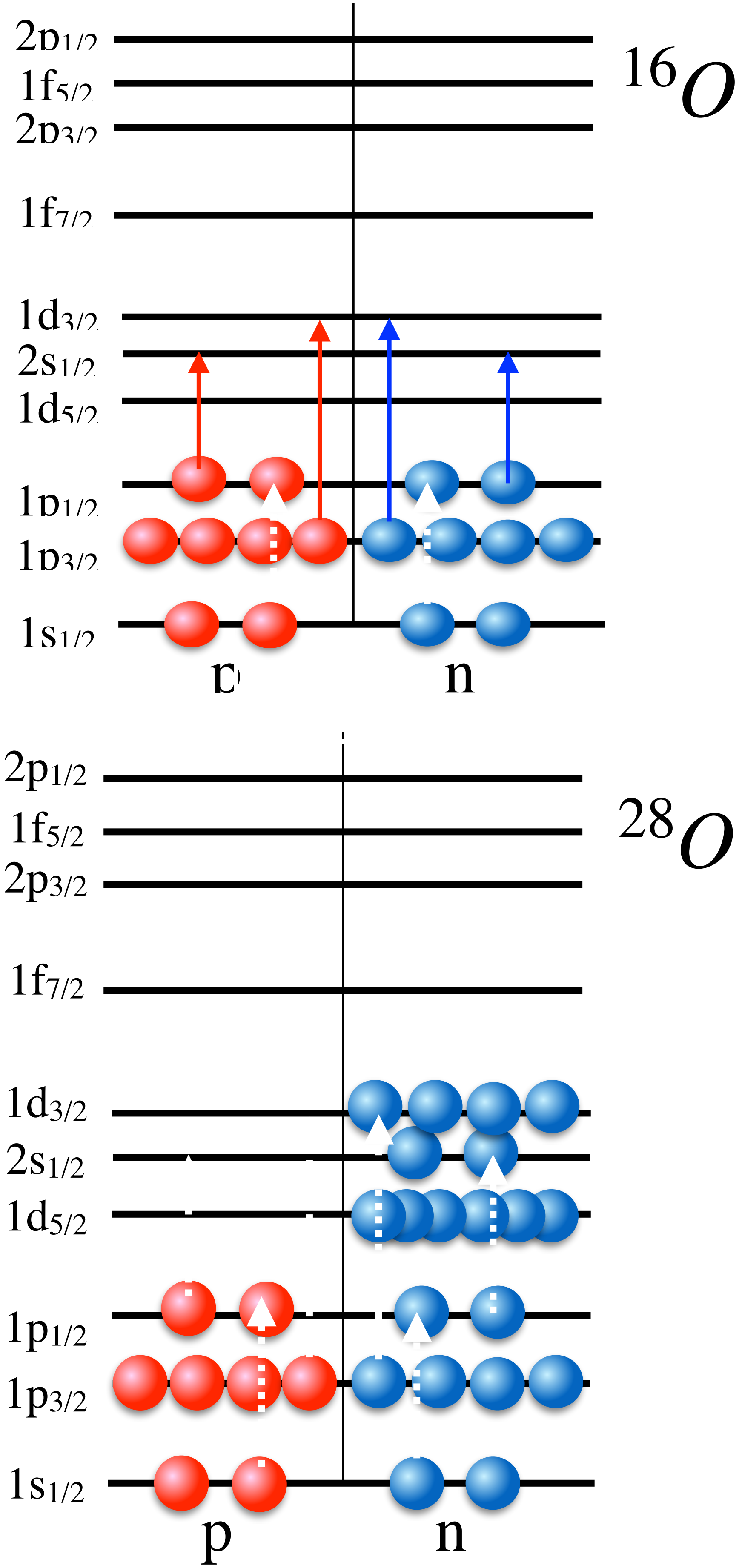
I. Tanihata
H. Toki

A New Chart


N=30,32 appear
32
20
28
30
20
8
16
Z=16appear
28
8
28O
24
N=20 diappear
2
14
16
2
6
10He
N=8disappear
N=16 appear

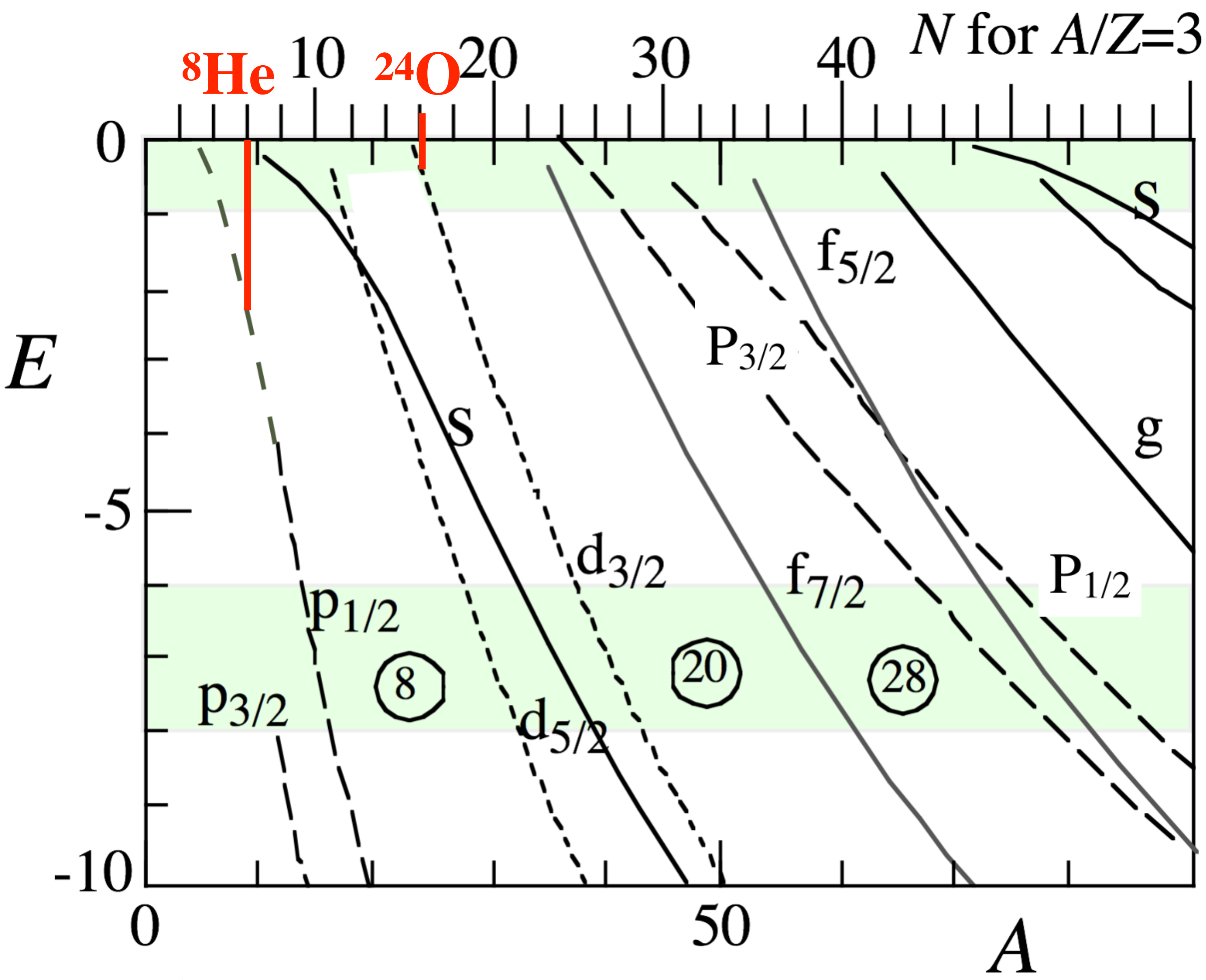
1. Single particle spectrum
2. Tensor blocking energy





Woods-Saxon potential parameters are from the book of Bohr and Mottelson.
Calculations are made for A/Z=3 nuclei.

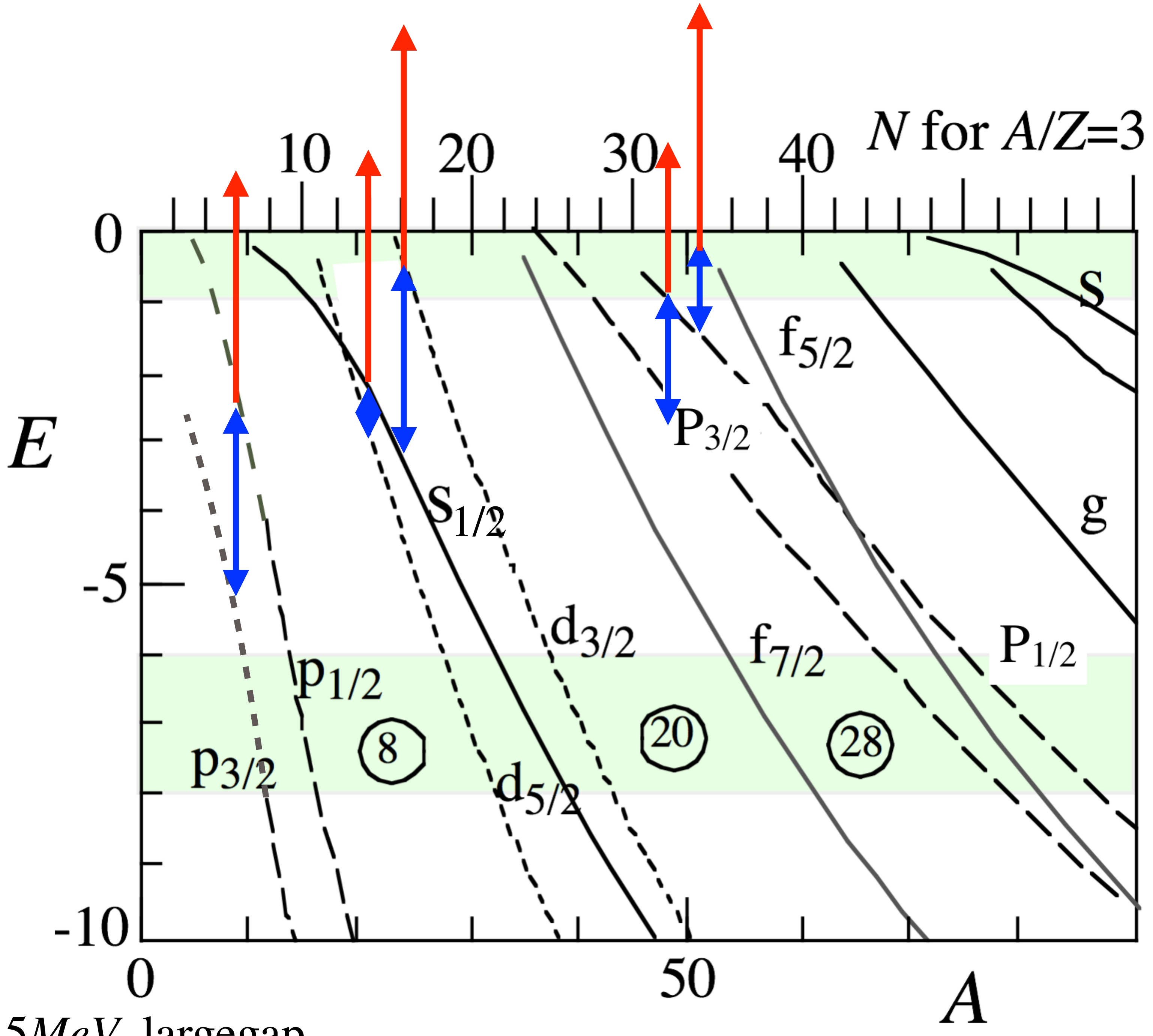
Why doubly magic ^{10}He and ^{28}O are not bound?



$2\Delta E(p_{1/2}) = 5MeV$ unbound

$2\Delta E(d_{3/2}) = 5MeV$ unbound

How are new magic numbers N=6,14,16,32,34 made?



energy gaps become more than factor of two larger due to the tensor blocking.

$\Delta E(p_{1/2}) = 2.5MeV$ largegap

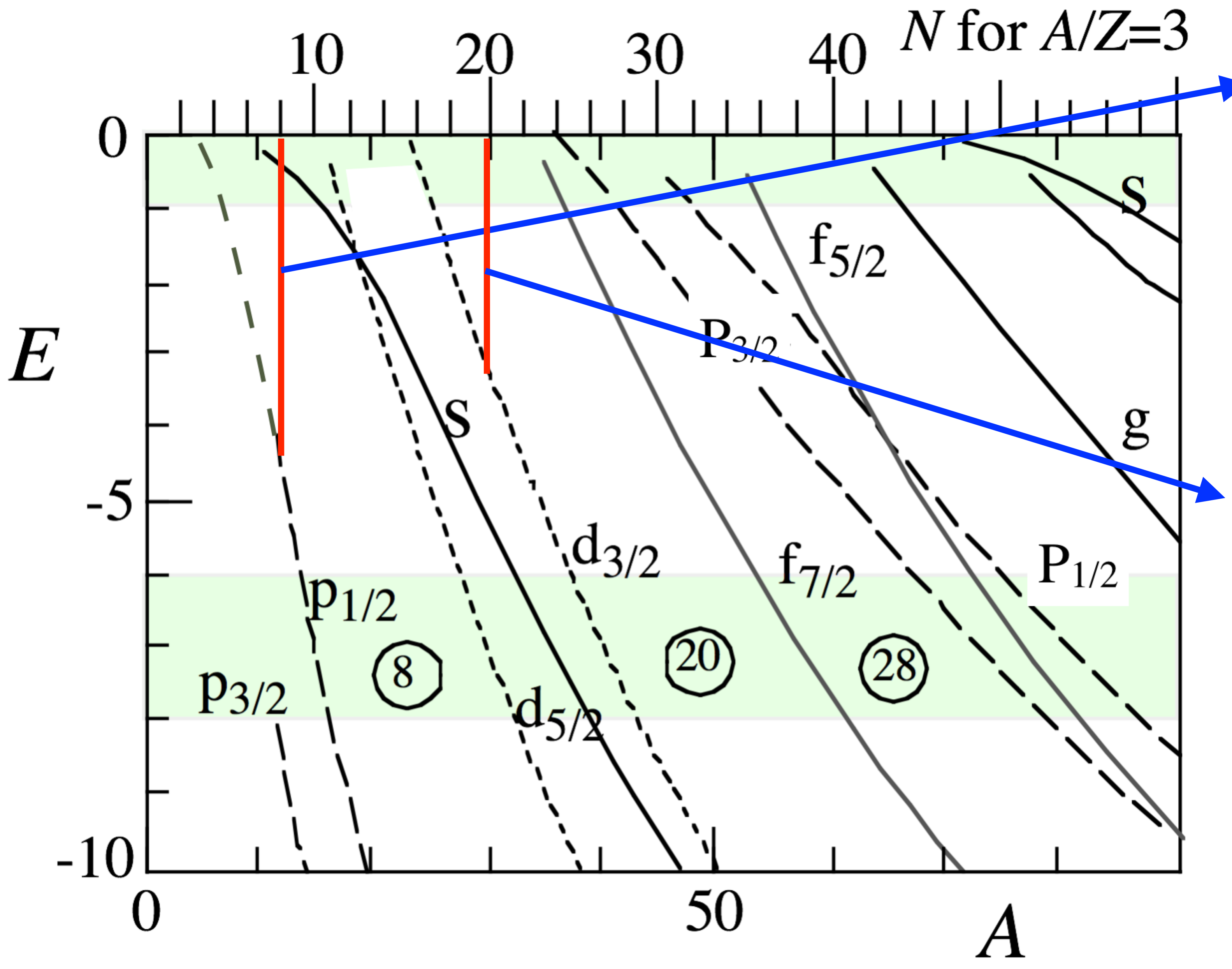
$\Delta E(s_{1/2}) = 2.5MeV$ largegap

$\Delta E(d_{3/2}) = 2.5MeV$ largegap

$\Delta E(p_{3/2}) = 2.5MeV$ largegap

$\Delta E(p_{1/2}) = 2.5MeV$ largegap

Why magic numbers N=8 and N=20 disappear in neutron-rich nuclei?



Originally a large gap but the tensor blocking effectively bring $p_{1/2}$ much loosely bound and mixes with sd-shell. Blocking does not occur for $s_{1/2}$ until proton fills $p_{1/2}$.

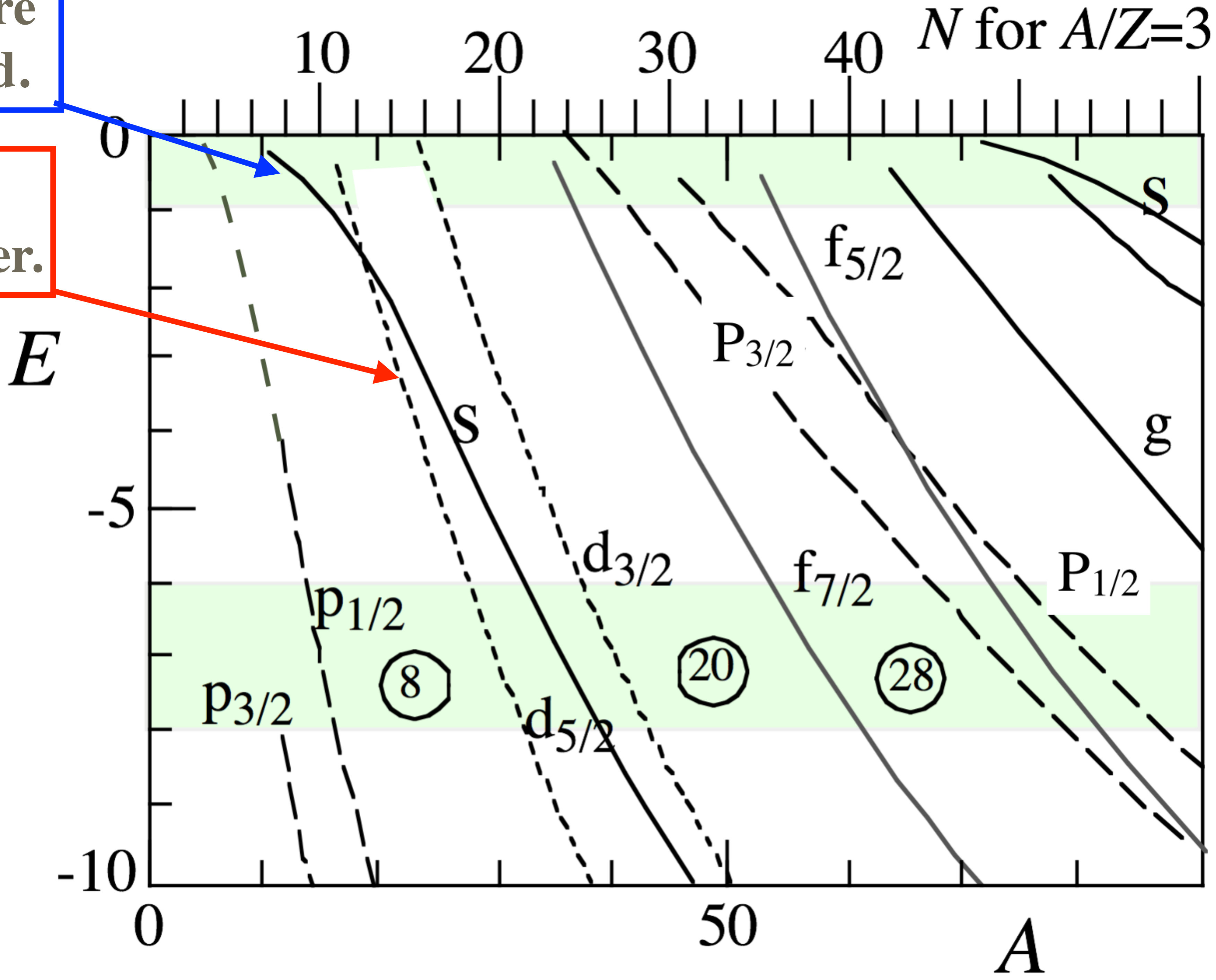
Originally the energy gap is larger than ~4 MeV but the tensor blocking effectively bring $d_{3/2}$ much loosely bound and mixes with fp-shell. For loosely bound nuclei not only $f_{7/2}$ but also $p_{3/2}$ comes closer. $f_{7/2}$ has no blocking effect and $p_{3/2}$ do not until proton fills $d_{3/2}$.

^{11}Li$_{gs}$, ^{11}Be$_{gs}$ are s-wave dominated,

Why ^{12}Be$_{gs}$ is $d_{5/2}$ dominated?

^{11}Li$_{gs}$, ^{11}Be$_{gs}$ are weakly bound.

^{12}Be$_{gs}$ is bound stronger.



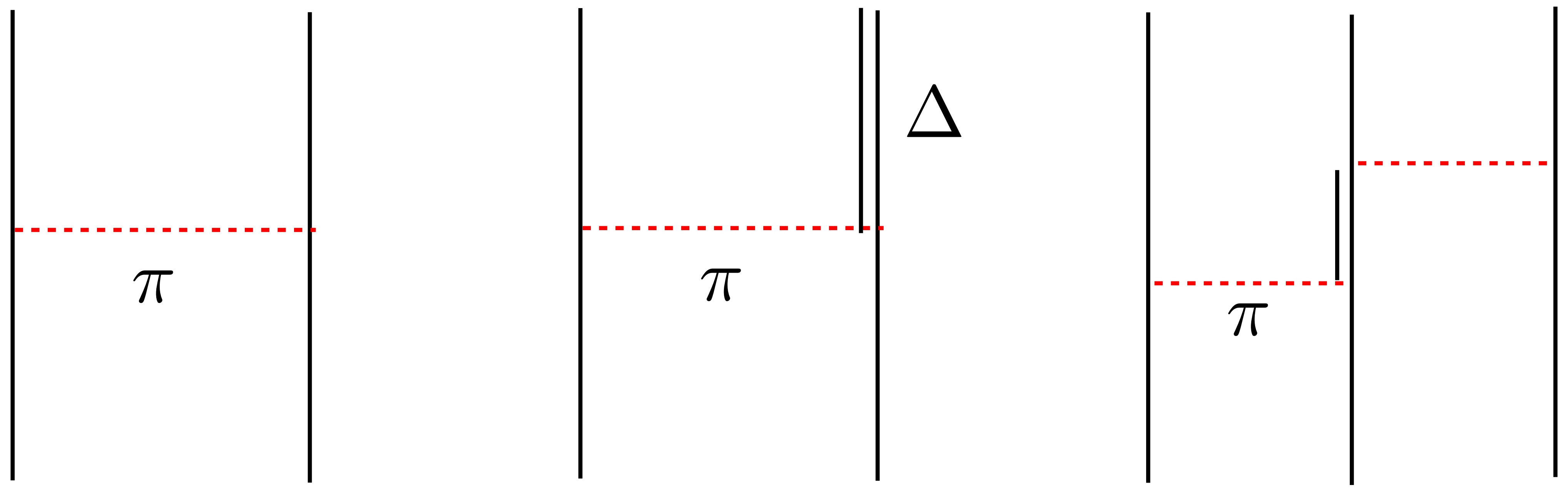
Three body interaction (Deltas in nuclei)

$$L_{QCD} = \bar{\psi}(i\gamma_\mu(\partial^\mu - eA^\mu) - m)\psi + \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a}$$

Chiral symmetry $m \sim 0$

$m \to M$

Chiral symmetry breaking (Nambu-Jana-Lasinio)

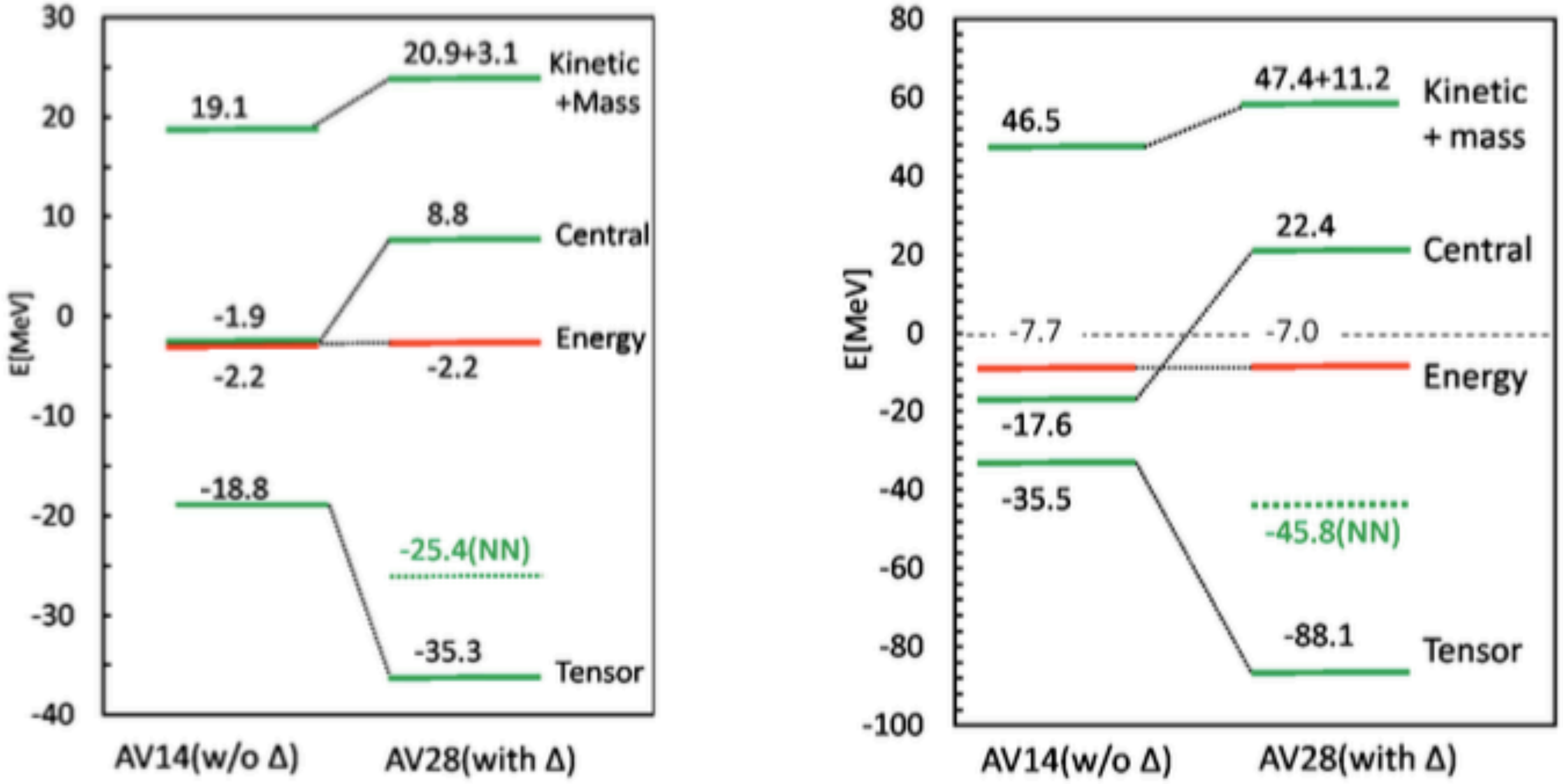


Three body
Interaction

Tensor force and delta excitation for the structure of light nuclei

Journal of Physics: Conference Series **569** (2014) 012076

K. Horii[1], T. Myo[2,3], and H. Toki[3]



All the attraction comes from the tensor interaction due to the delta excitations

Conclusion:

Pion Nuclear Physics = Tensor physics

Pion generates strong tensor interaction

We formulate TOSM + TOAMD

We calculated He3 and He4 using TOAMD

We treat delta excitation explicitly for He3

We will work p-shell nuclei using TOAMD

We develop Tensor Blocking Shell Model

Hadron nuclear physics