High-Momentum correlated Nucleons and Tensor Blocking Effects Determine the shell structure in neutron-rich nuclei

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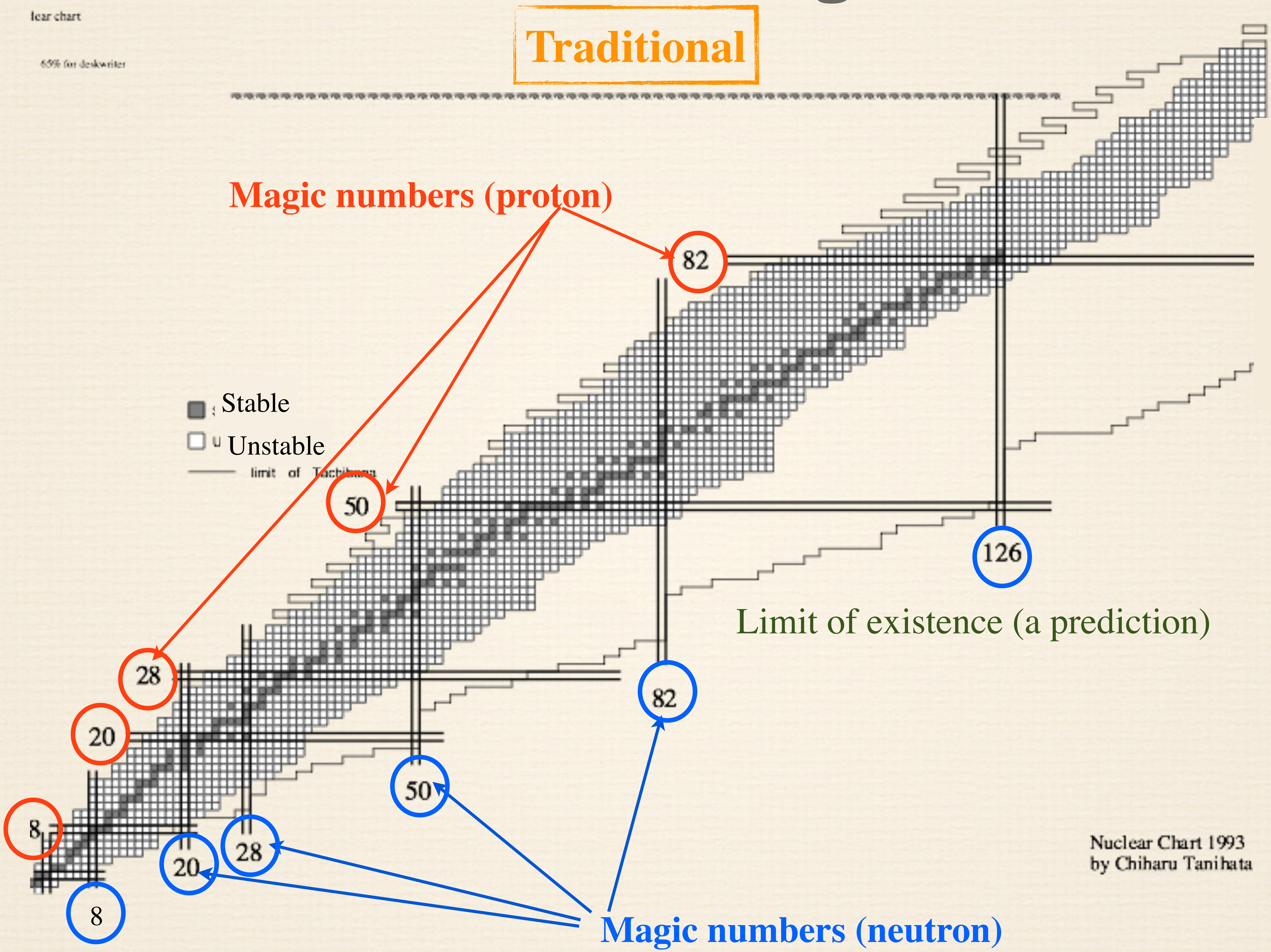
New Shell Structures observed in Neutron Rich Nuclei

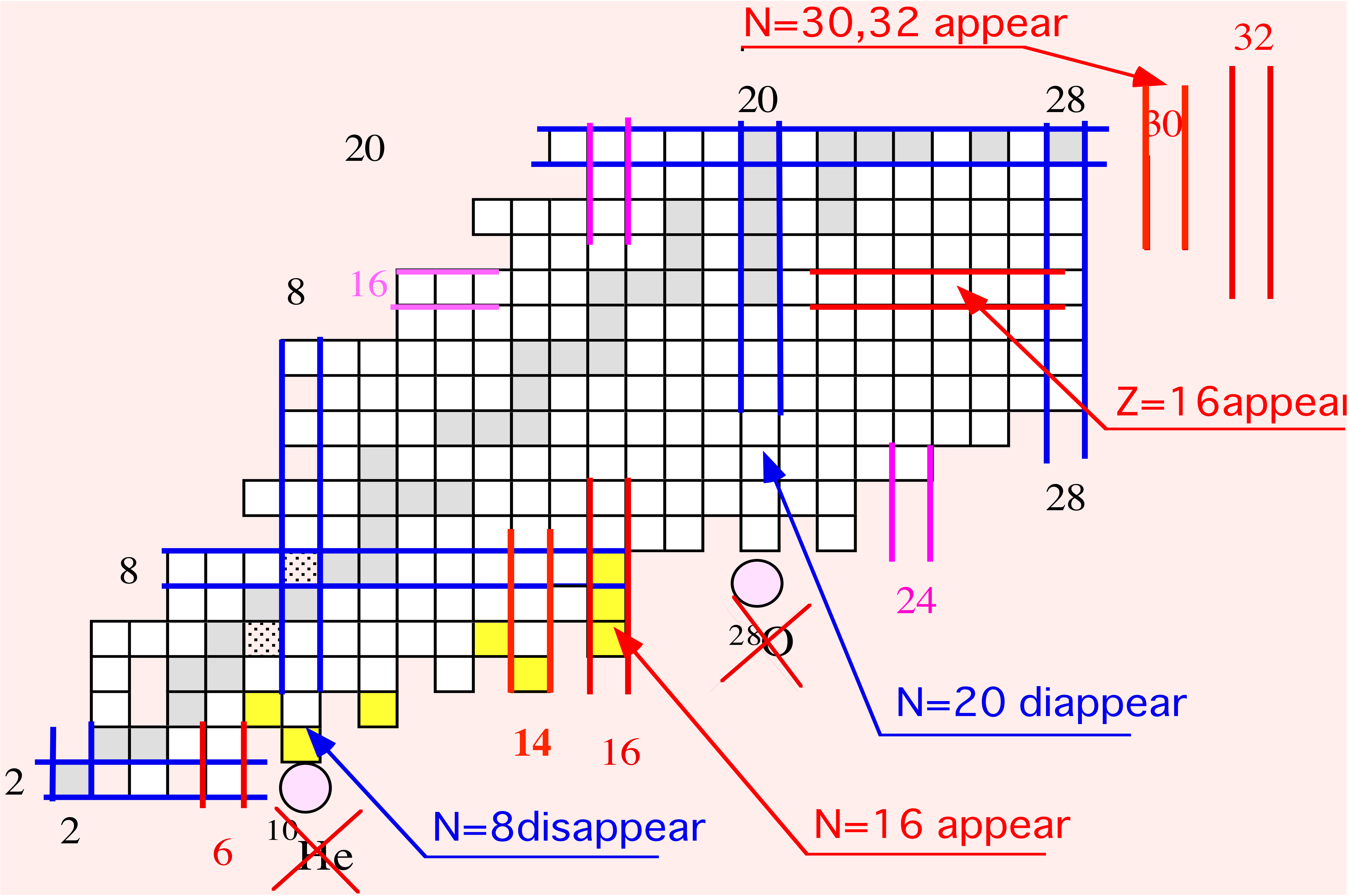
Discoveries in these 30 years

- "Doubly magic" ^{10}He and ^{28}O are not bound.
- New magic numbers N=6, 14, 16, 32, 34 emerge.
- Traditional magic numbers N=8 and N=20 disappear.
- The neutron dripline for O isotopes is N=16 but extend much more in F isotopes.
- The ground states of ^{11}Li and ^{11}Be are mainly $2s_{1/2}$ wave but the main component of ^{12}Be is $1d_{5/2}$.

Nuclear Chart and Magic Numbers



A New Chart

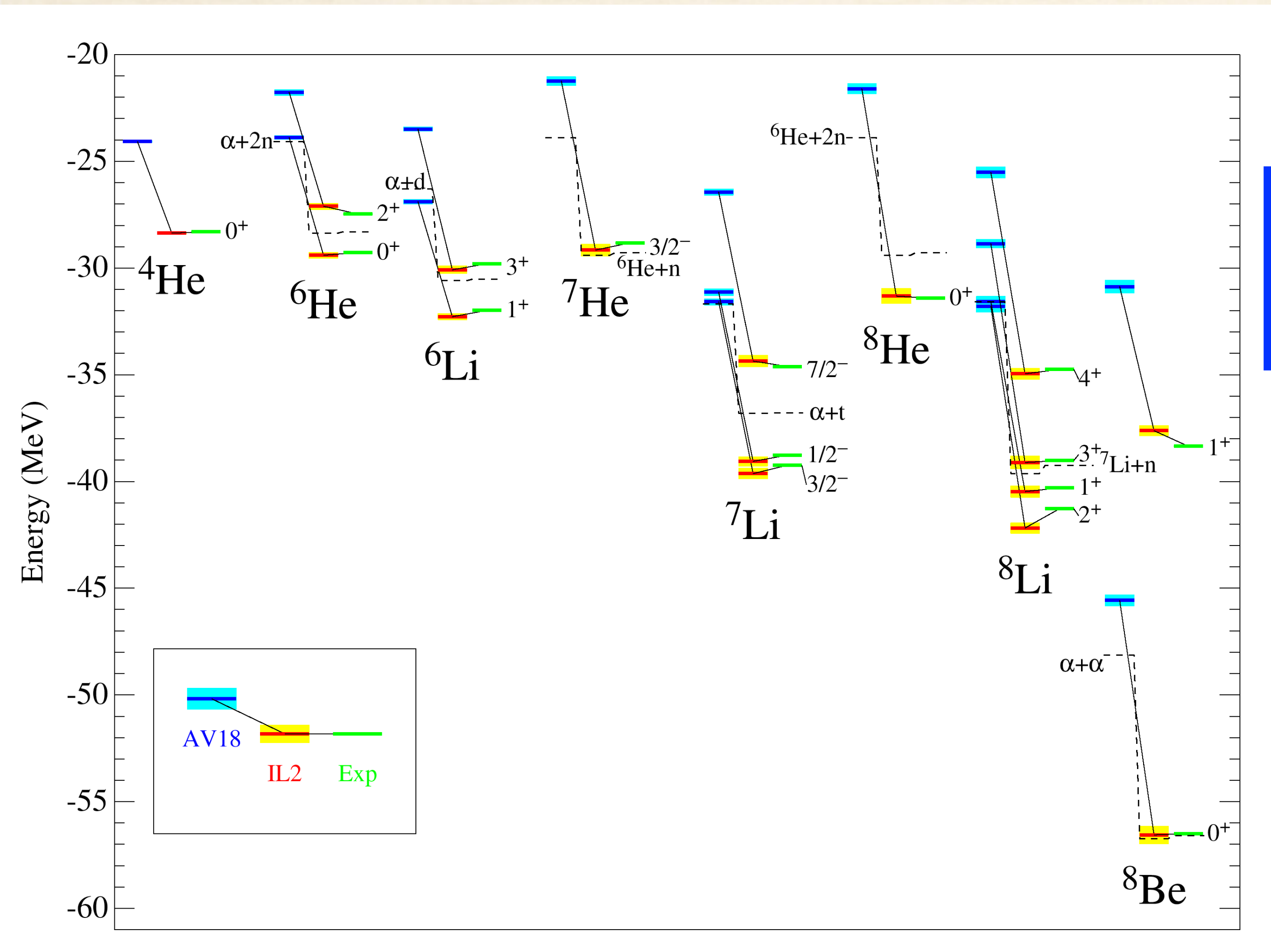


N=30,32 appear
32
20
28
30
20
16
8
Z=16appear
28
8
24
28O
N=20 diappear
2
2
6
10He
14
16
N=8disappear
N=16 appear

The most advanced,

An ab-initio calculations of nuclei from two-body interactions

Variational Calculation of few body systems with NN interactions

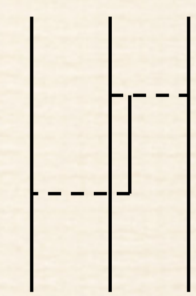


C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci.51(2001)

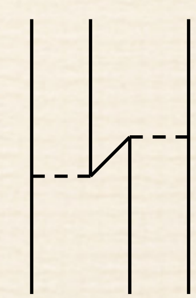
$$\Psi = \phi(r_{12})\phi(r_{23})\ldots\phi(r_{ij})$$

Tensor interactions are very important, also need 3-body interactions

V_{NNN}



Fujita-Miyazawa



Relativistic

Conclusion:
Pion exchange interactions are important

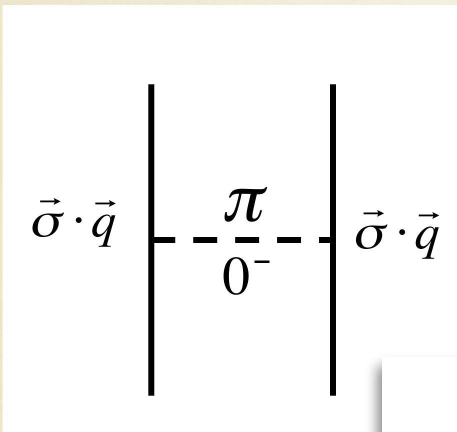
$$\frac{\langle \Psi | V_{\pi} | \Psi \rangle}{\langle \Psi | V_{NN} | \Psi \rangle} \sim 80\%$$

- 80% of attraction comes from pions.
  - *R. B. Wiringa: Ann. Rev. Nucl. Part. Sci.51(2001)*

Argonne GFMC

(Green Function Monte Carlo)

Pion exchange interaction



pion is a pseudo-scaler (0^-) meson

$$S_{12}(\hat{q}) = \sqrt{\frac{24\pi}{5}}\left[Y_2(\hat{q})\left[\sigma_1\sigma_2\right]_2\right]_0$$

$$\vec{\sigma}_1\cdot\vec{q}\,\frac{1}{m_\pi^2+q^2}\,\vec{\sigma}_2\cdot\vec{q}$$

$$= \frac{1}{3}\frac{q^2}{m_\pi^2+q^2}S_{12}(\hat{q}) + \frac{1}{3}\left(1-\frac{m_\pi^2}{m_\pi^2+q^2}\right)\vec{\sigma}_1\cdot\vec{\sigma}_2$$

Tensor **Spin-spin**

prefer high momentum **prefer low momentum**

Present days nuclear models

Interactions

- Nuclear interactions from QCD.
- Empirical interactions from nucleon-nucleon data.
- Effective Field theory
- Phenomenological interaction (Skyrme….)

Nuclear models

- Ab-initio models
- The shell model
- Mean field models (non-relativistic, relativistic)
- "Ab-initio" type models (no-core shell model…)

Present days nuclear models

Interactions

Non-of them treat tensor forces appropriately. (except 1)

(Inclusion of the interaction itself or treatment of high-momentum nucleons.)

ion

We need a theory to treat explicitly the tensor interactions!

2. The s

3. Mea

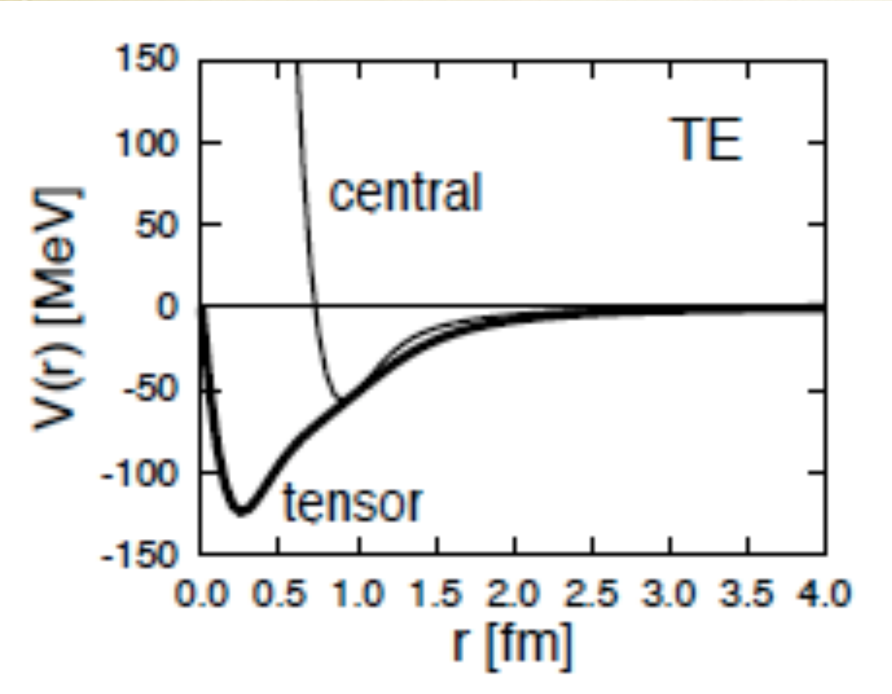
4. "Ab-

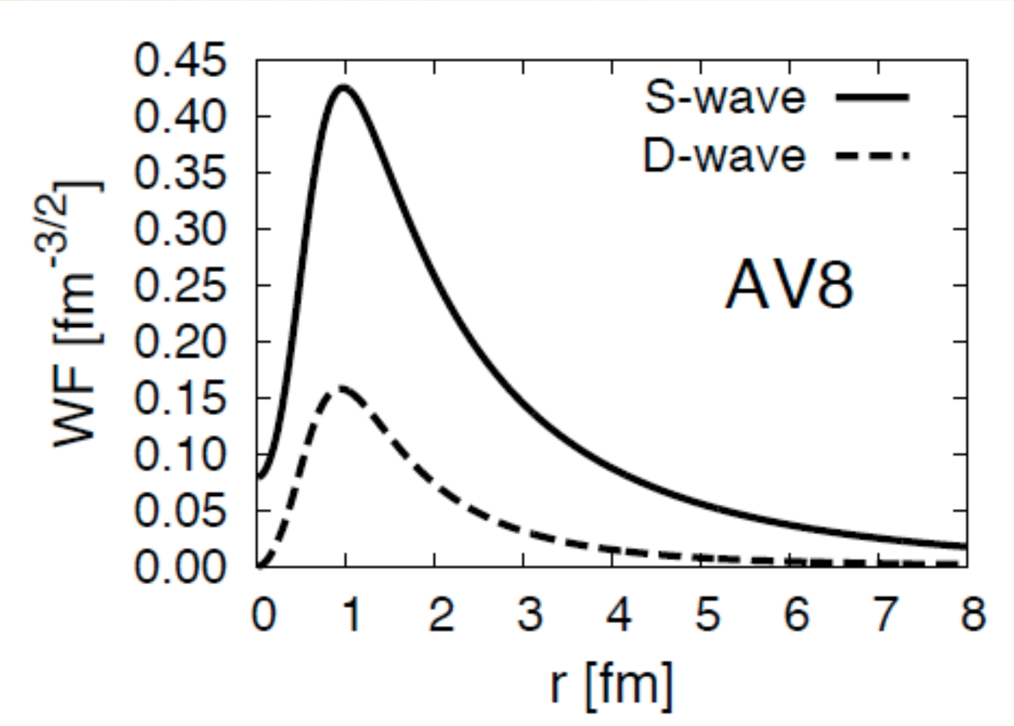
Ab-initio calculations can not be extended to nuclei of A>12!

Importance of tensor interactions (known facts)

- Deuteron
- Saturation properties of the nuclear matter.
- As an origin of spin-orbit (*l*•*s*) interactions.
- Magnetic moments of doubly-closed±1 nuclei

Deuteron = a Nucleon Bound State

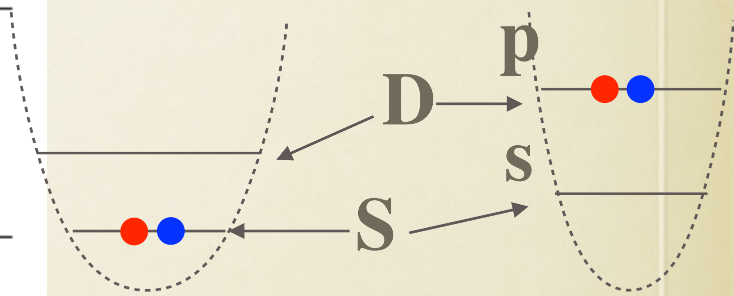




S=1 and L=0 or 2

Binding of deuteron (1^+)

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]



shell model式

D wave has a large relative momentum

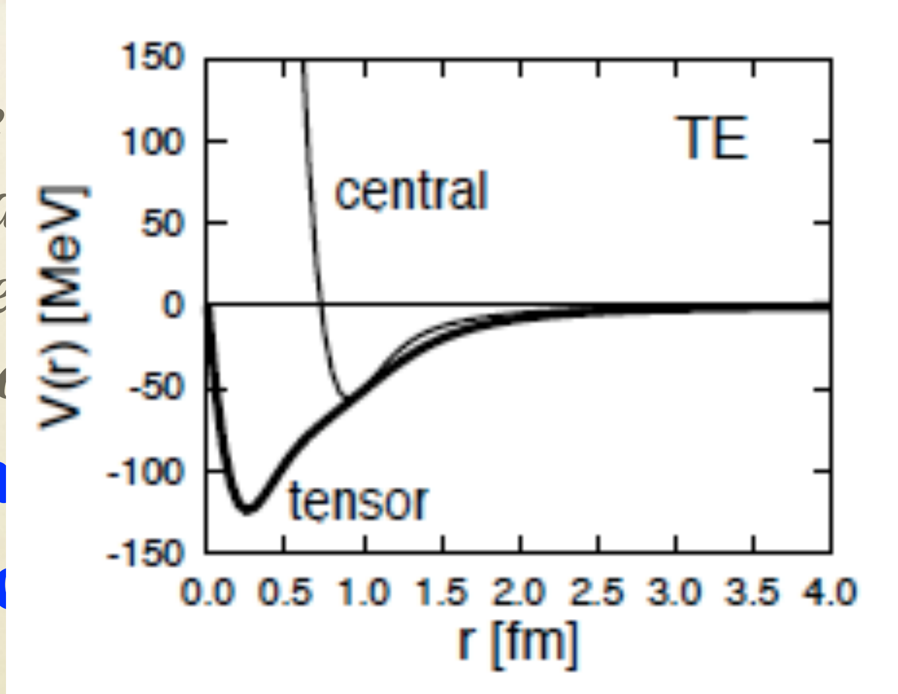
Why nuclear matter density Saturate?

- **Nuclear matter**
  - *E/A=16 MeV, ρ=1.6 nucleons/fm^{-3}.P$_F$~1.2 fm^{-1}.*
    - average nucleon distance~1.6 fm.

The repulsive core of the central interaction is not the main cause!

- *The practical saturation problem then re saturation occurs at the right density and we have seen above, the saturation in the three factors, in decreasing order of imp*

(a) tensor force; (b) exchange chara and (c) repulsive



Excitation to D state and Blocking

- Two nucleons are initially in states *B* and *C*. When they interact they are shifted to state *D* and *E* outside the Fermi sphere. If they are initially in a ^3S state and interaction with tensor force, then they are in a $^3D_1$ state in *DE*.
- This one of the important mechanism to gain binding energy by the tensor force.

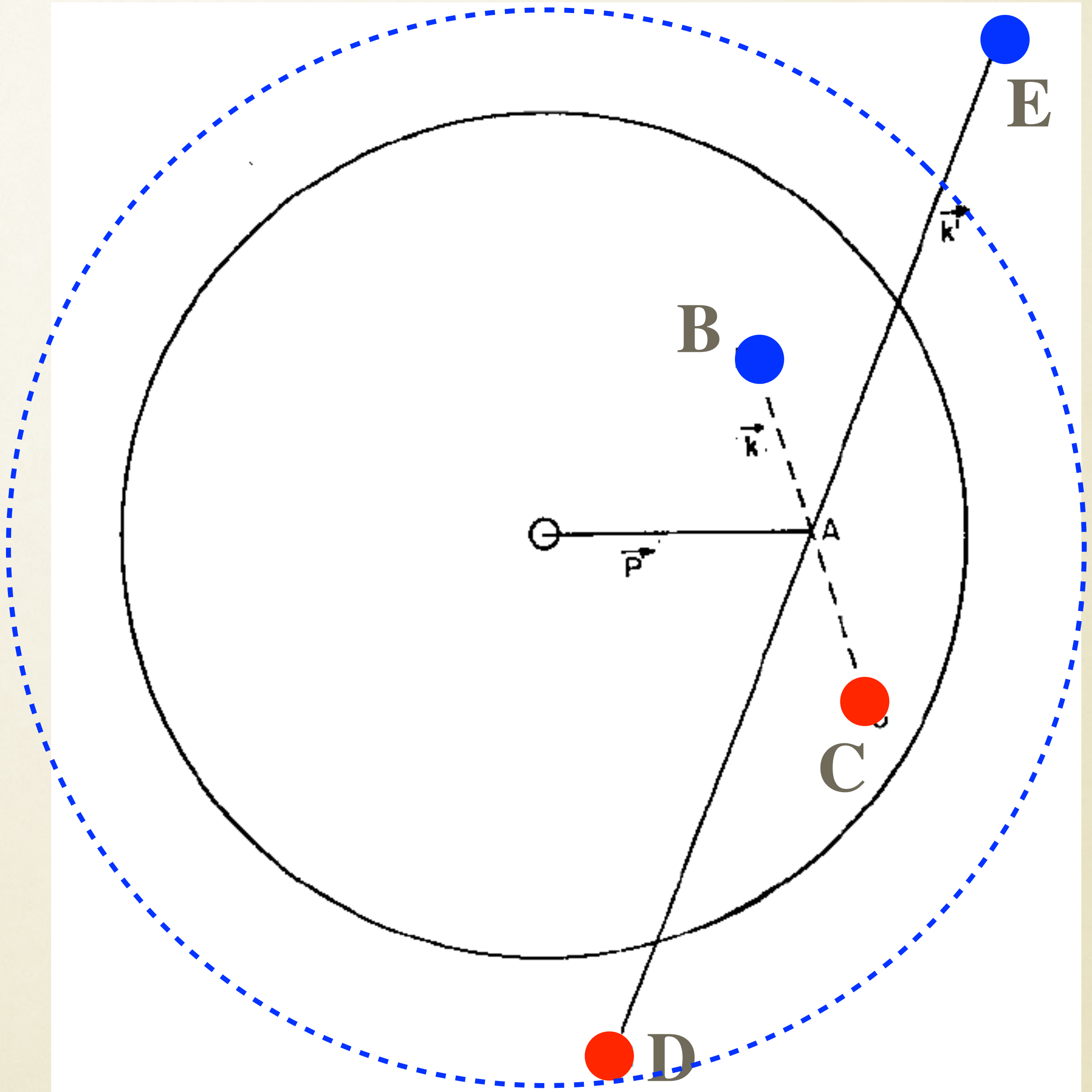


FIGURE 10. Two nucleons are initially in states *B* and *C*, having average momentum ***P*** and relative momentum ***k***. When they interact they are shifted to states *D* and *E* outside the Fermi sphere, with relative momentum ***k***'. If they are initially in a ^3S state and interact by tensor force, then they are in a $^3D_1$ state in *DE*.

- **When the density comes higher, Fermi sphere comes larger. A part of the open space for this excitation is blocked and thus the energy gain, unless otherwise obtained, is lost. This is the mechanism of <u>Saturation</u> by blocking of the tensor interaction.**

Tensor force as an origin of *l·s* interactions

- T. Terasawa, Progr. Theo. Phys. vol.23, 87 (1960).
- A. Arima and T. Terasawa, Progr. Theo. Phys. vol.23, 115 (1960).

- We will see the mechanism later

Magnetic moments of Doubly closed shell±1 nuclei

- **Please refer:**

  K. Shimizu, M. Ichimura, A. Arima, Nucl. Phys. A, 226, p282 (1974)

Explicit treatment of Tensor interactions in nuclei

- **Tensor optimized shell model**
  - ***T. Myo, Y. Kikuchi, K. Kato, H. Toki, K. Ikeda, Progr. Theo. Phys. 119, 561 (2008).***
  - ***T. Myo, H. Toki, and K. Ikeda, Progr. Theo. Phys. 121, 511 (2009).***
- **Binding of ^{4}He.**
- **Saturation properties of the nuclei. (energy and density)**
- **Two-particle excitations and high-momentum nucleons.**

Tensor Optimized Shell Model (TOSM)

Myo, Toki, Ikeda, Kato, Sugimoto, PTP 117 (2006)

0p-0h + 2p-2h

$$\Phi(^4\mathrm{He}) = \Sigma_i C_i \psi_i(\{b_\alpha\}) = C_1 (0s)^4 + C_2 (0s)^2(\overline{0p_{1/2}})^2 + \cdots$$

size parameter: $b_{0s} \neq b_{\overline{0p}}$

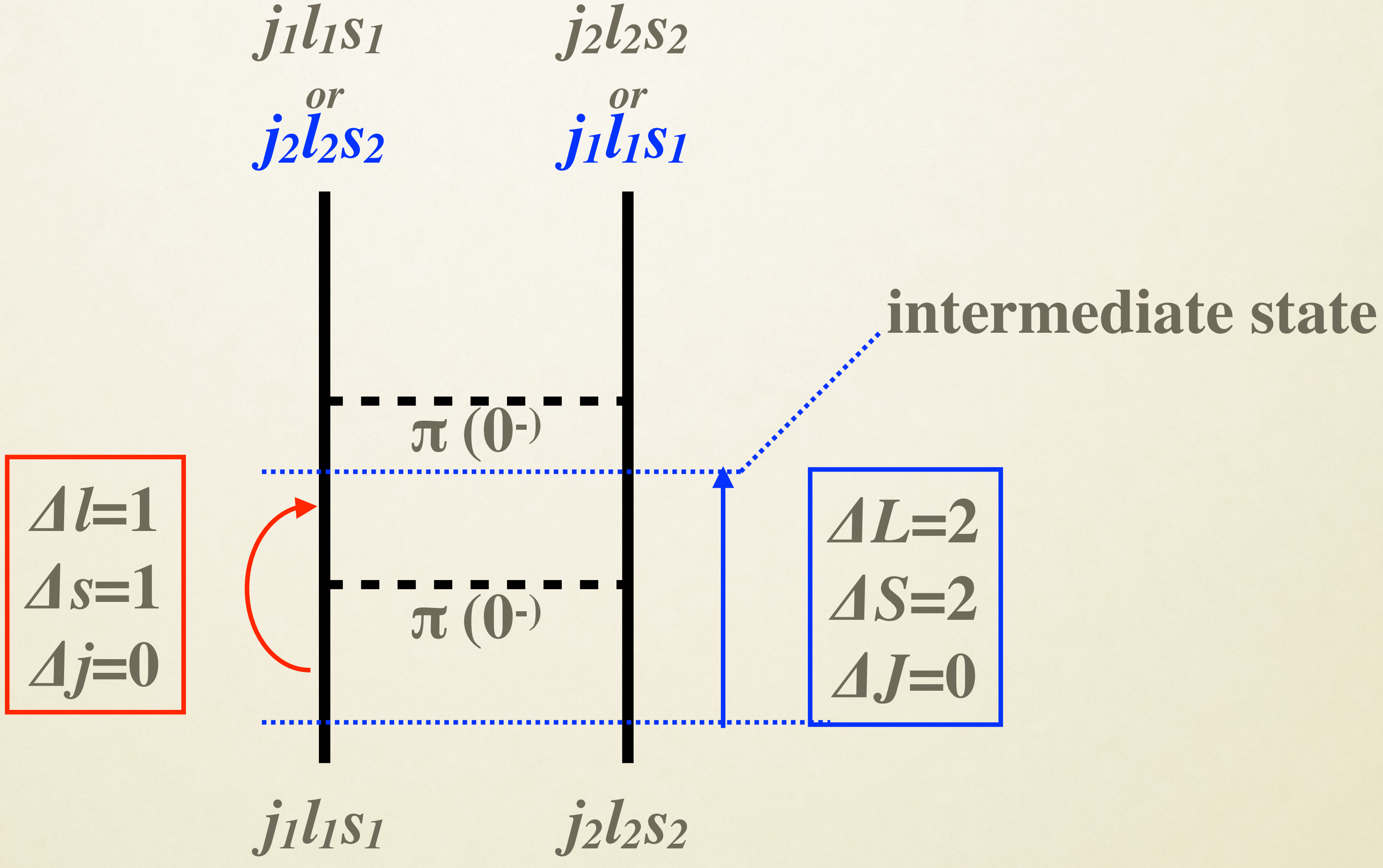
It is not a perturbation model!

Energy variation

$$H = \sum_{i=1}^{A} t_i - T_G + \sum_{i<j}^{A} v_{ij}, \qquad v_{ij} = v_{ij}^{C} + v_{ij}^{T} + v_{ij}^{LS} + v_{ij}^{Clmb},$$

$$\delta \frac{\langle\Phi|\, H\,|\Phi\rangle}{\langle\Phi|\Phi\rangle} = 0 \quad \Rightarrow \quad \frac{\partial\langle H-E\rangle}{\partial b_\alpha} = 0\ , \quad \frac{\partial\langle H-E\rangle}{\partial C_i} = 0.$$

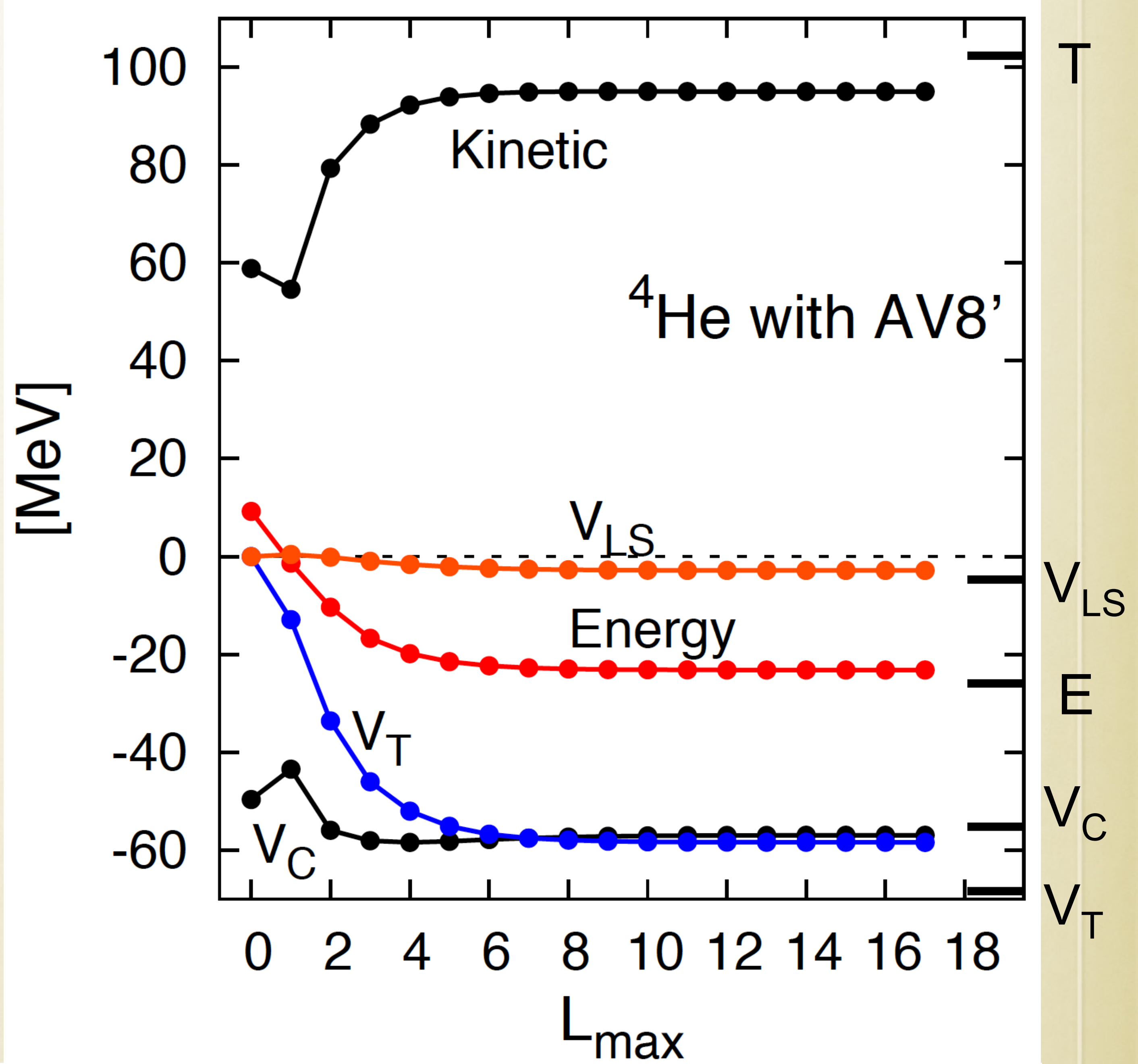
Selection rule of the tensor interaction



Tensor interaction in nucleus ^{4}He

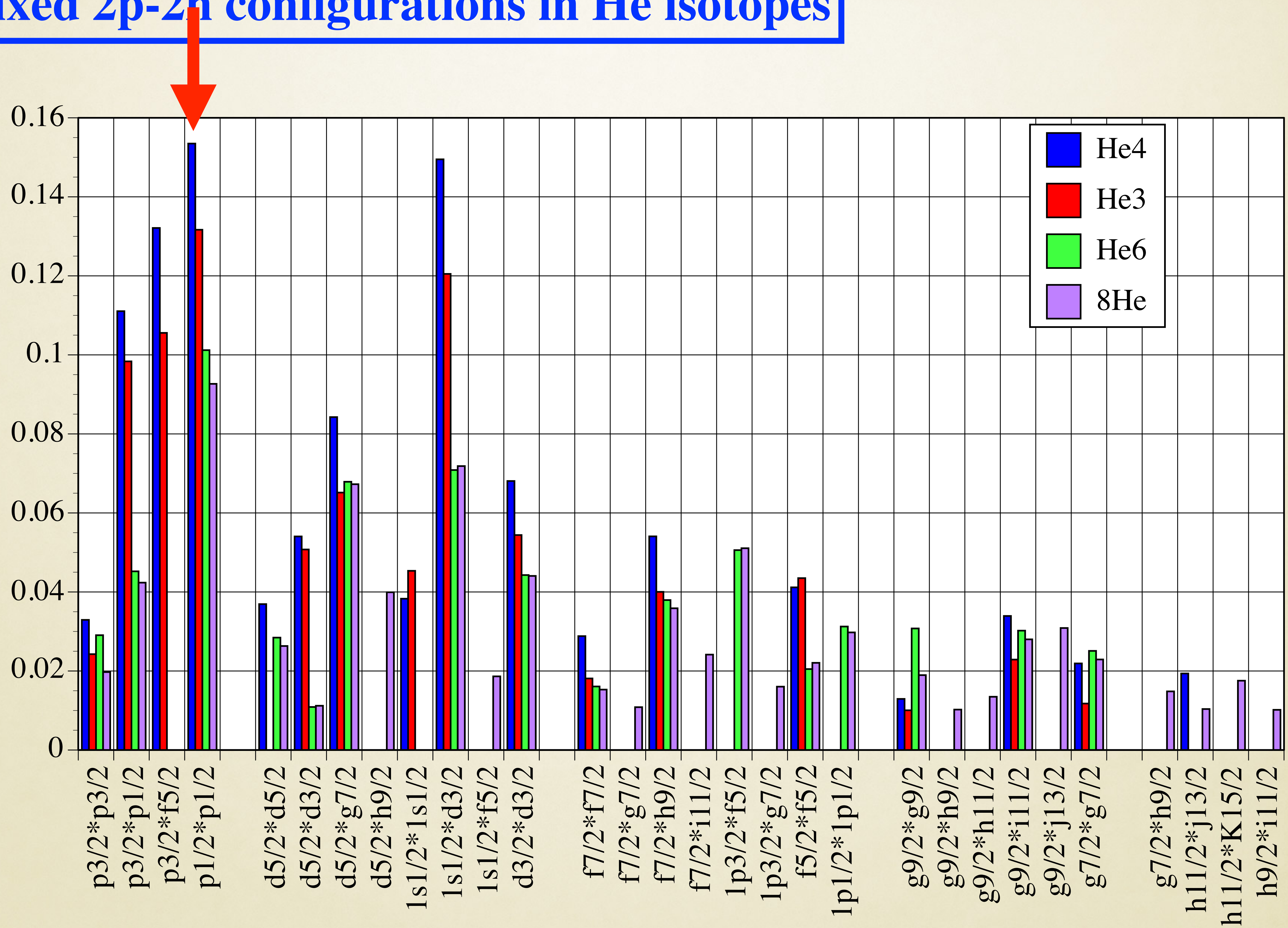
- V_T contribute from higher *l* orbitals and convergence is slow.
- 2p-2h excitations of p-n pair under ΔS=2, ΔL=2 provide tensor energies.

- Tensor interactions give ~60 MeV of potential energy.
- **Remember** *L*=1 excitation already gives 8 MeV of potential energy.



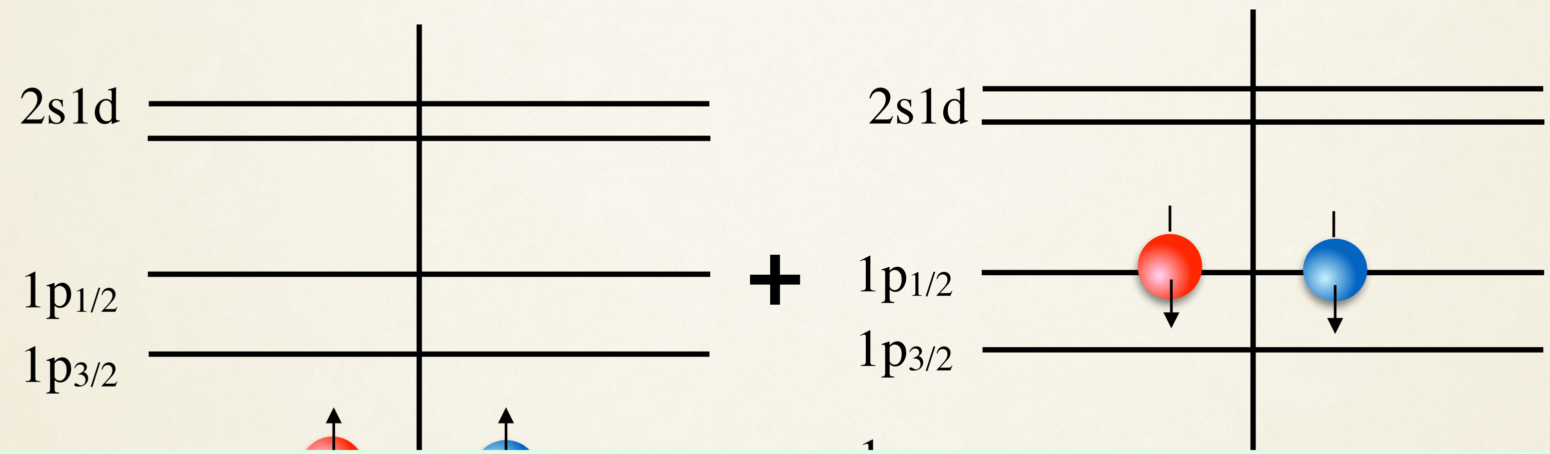
Tensor Optimized Shell Model by T. Myo, H. Toki and K. Ikeda, Progr. Theor. Phys. **121** 511 (2009)

Mixed 2p-2h configurations in He isotopes



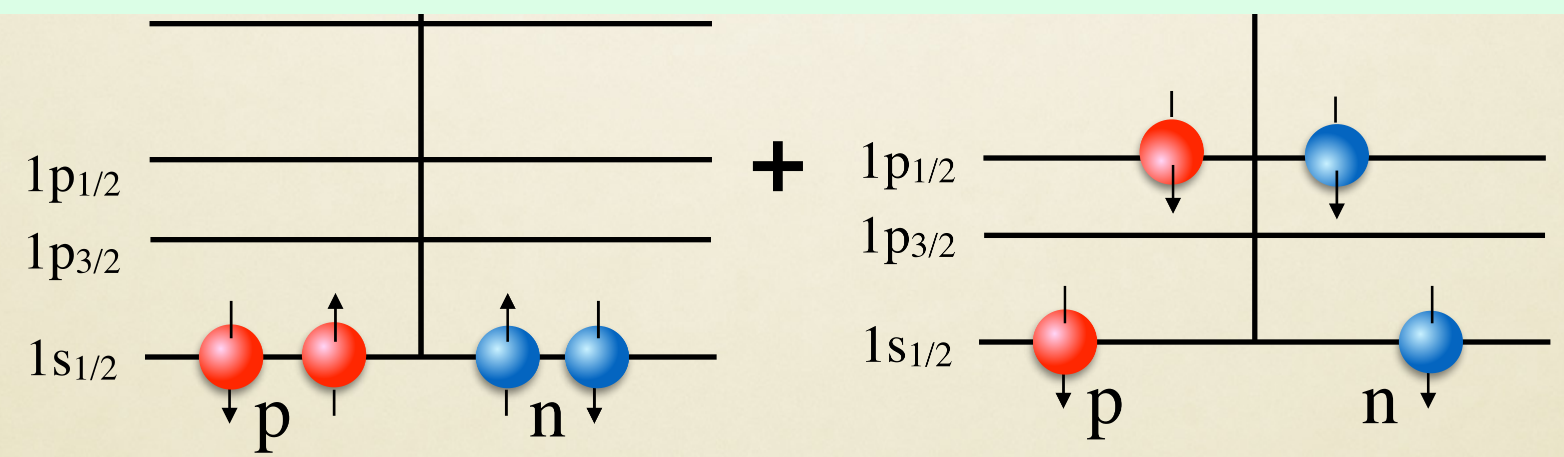
The most important mixing

d:



Highest spin orbital ($j_>$) in a major shell is not used for the tensor interaction.
An example is $1p_{3/2}$ orbital in ^{4}He and deuteron.

^{4}He:

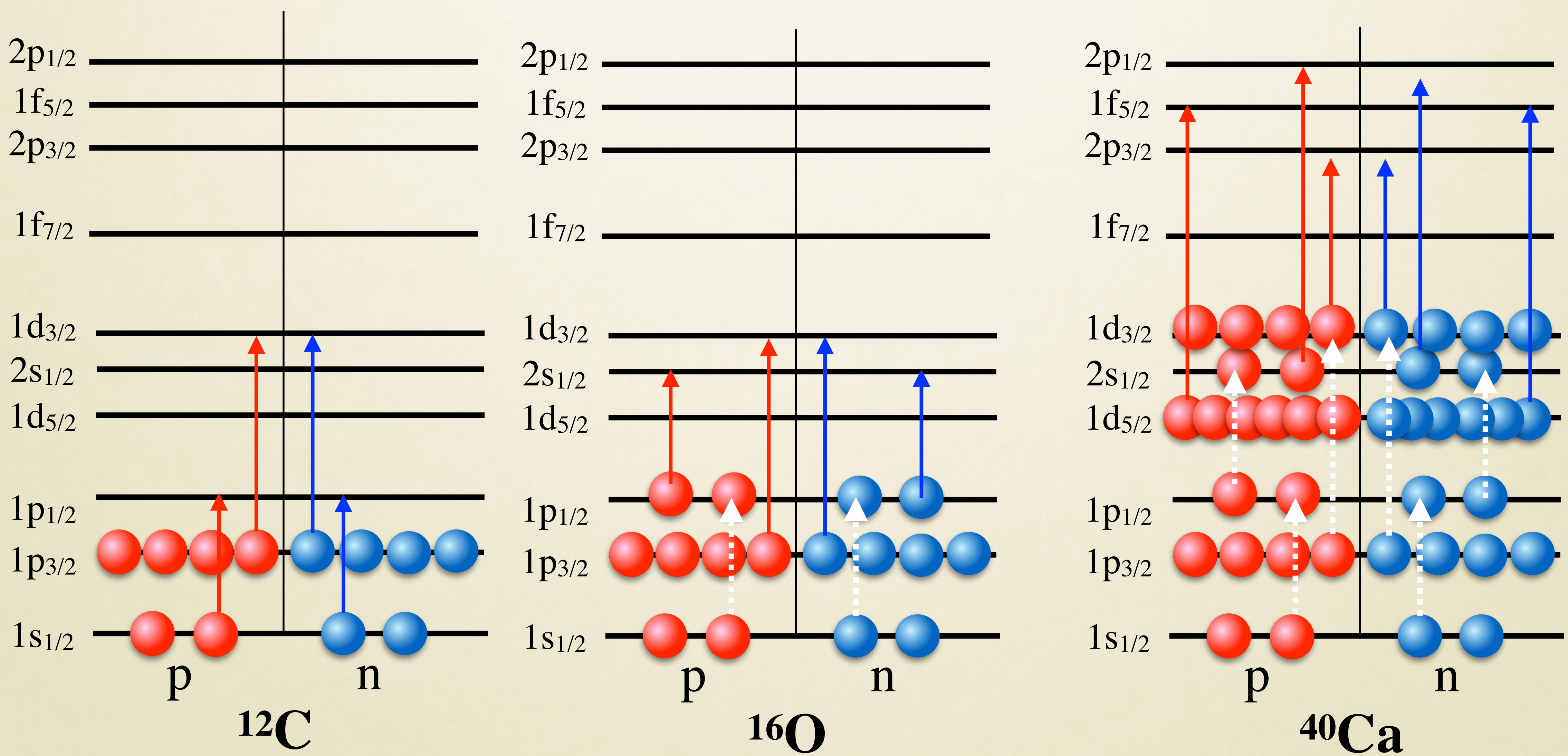


~10%

In more general p-n pairs from (nlj)^2 configuration to (n+1l+1j)^2 or (n+1l-1j)^2

Nuclear Saturation by Tensor Blocking

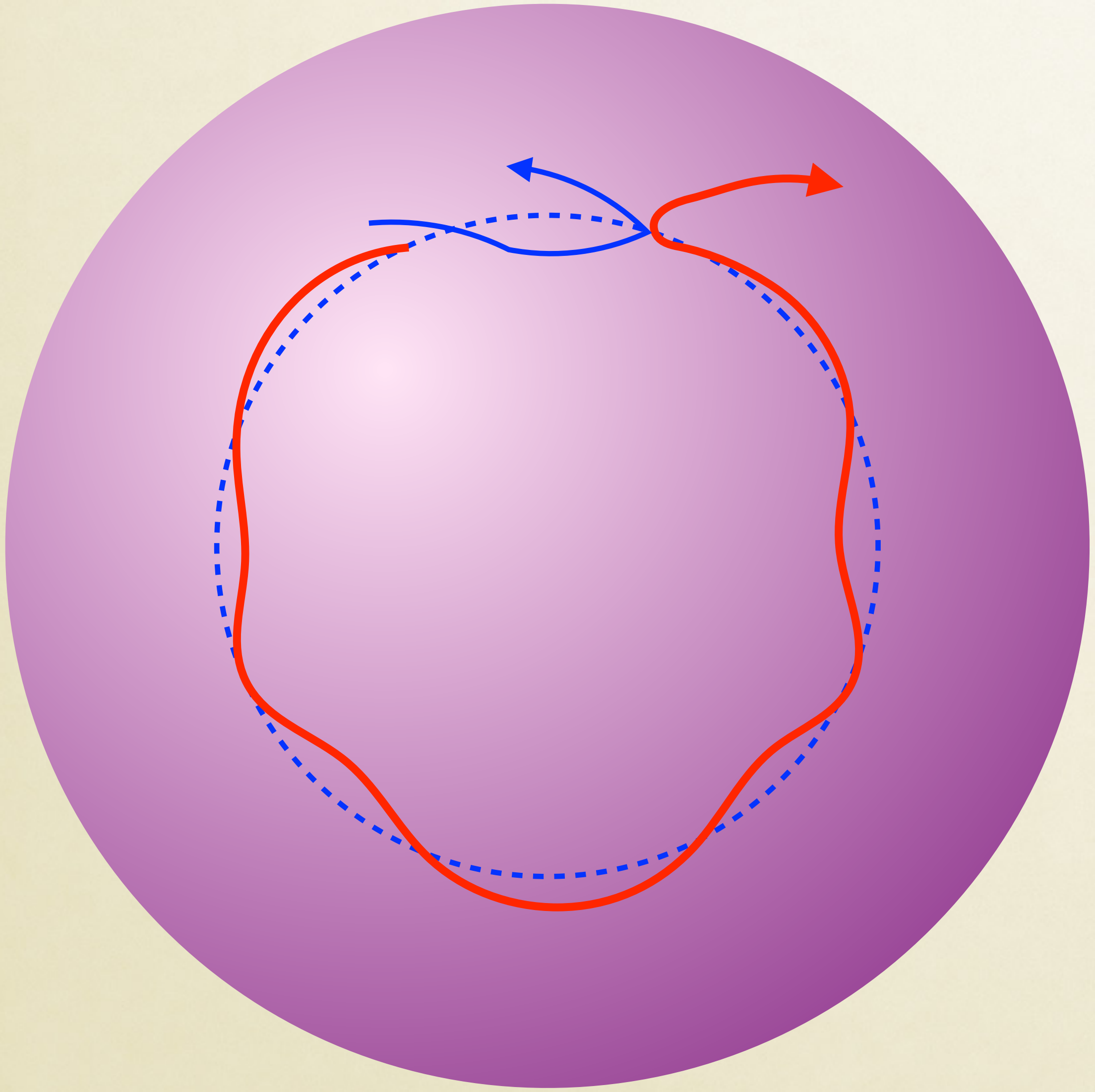
Blocking and Opening occurs simultaneously and keep the binding per nucleon to be almost constant.



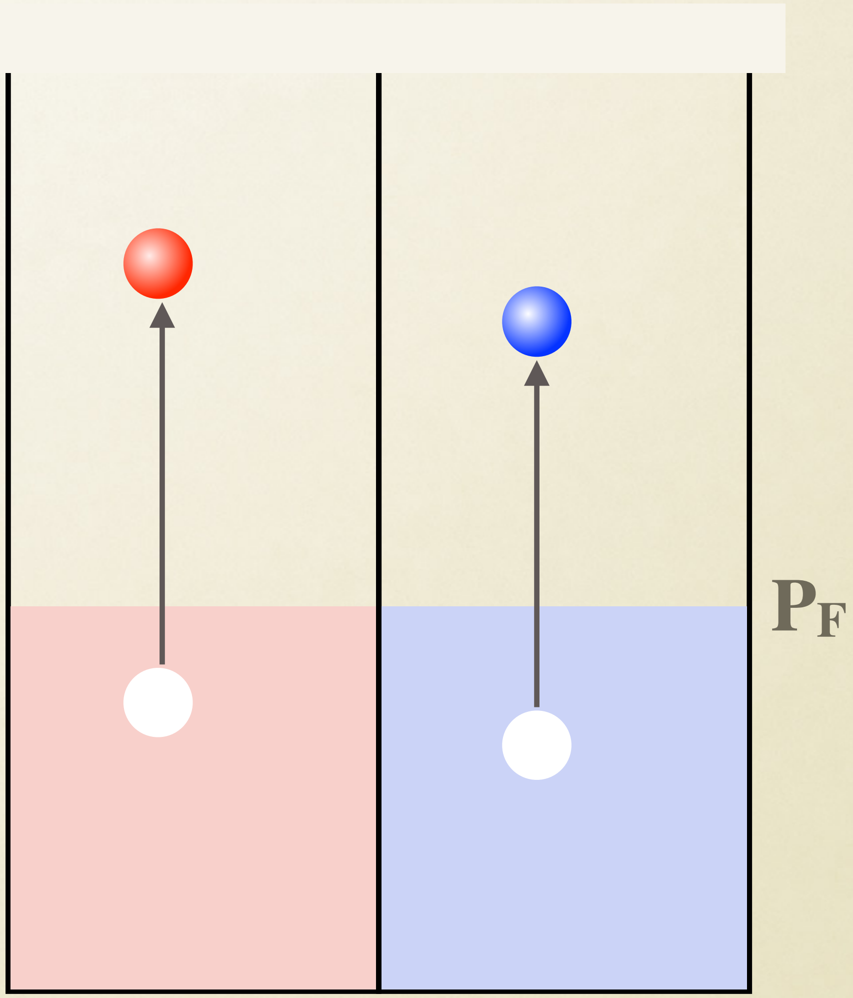
^{12}C do not suffer blocking o

^{16}O suffer blocking from $1s_{1/2}$ to $1p_{1/2}$.
But open new excitation from $1p_{1/2}$ to $2s_{1/2}$.

- **and, 2p-2h excitations by tensor interactions make nucleons with much higher momentum than usual Fermi motion.**



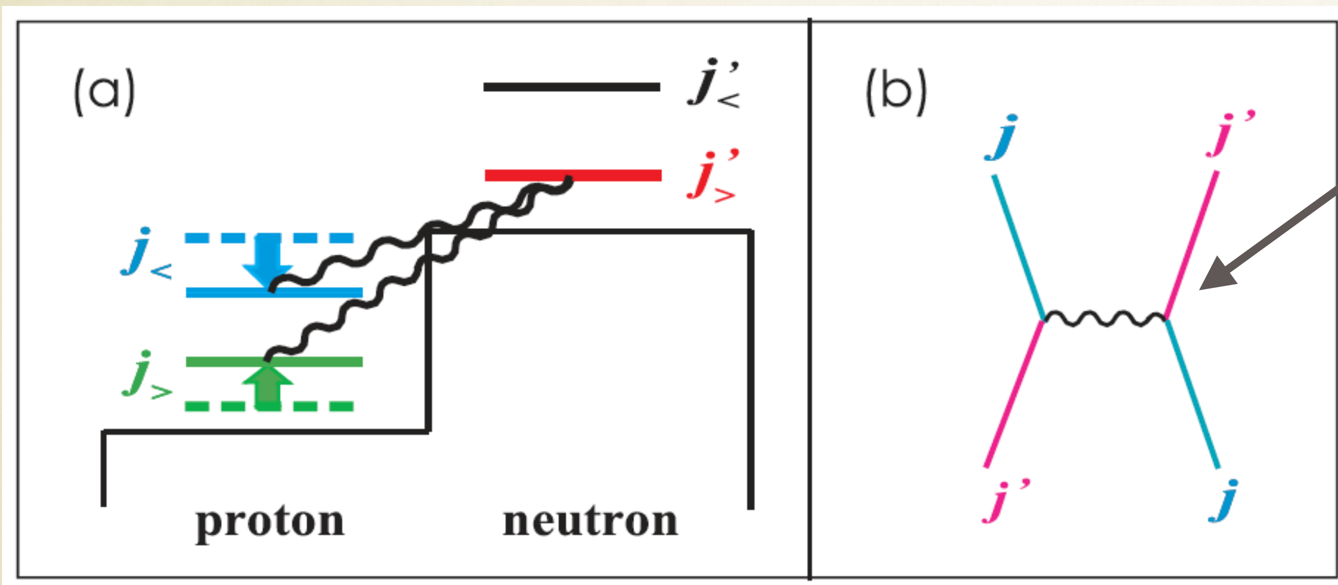
Coordinate space



Momentum space

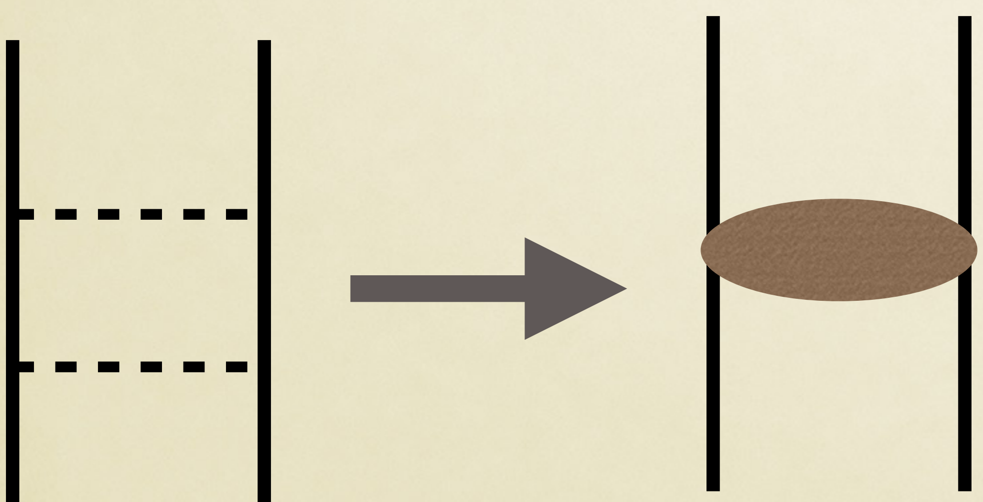
Inclusion of tensor interaction into shell model (first order perturbation) $<\Psi|V_T|\Psi>$ Monopole interaction

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



Only exchange terms contribute. (First order perturbation)

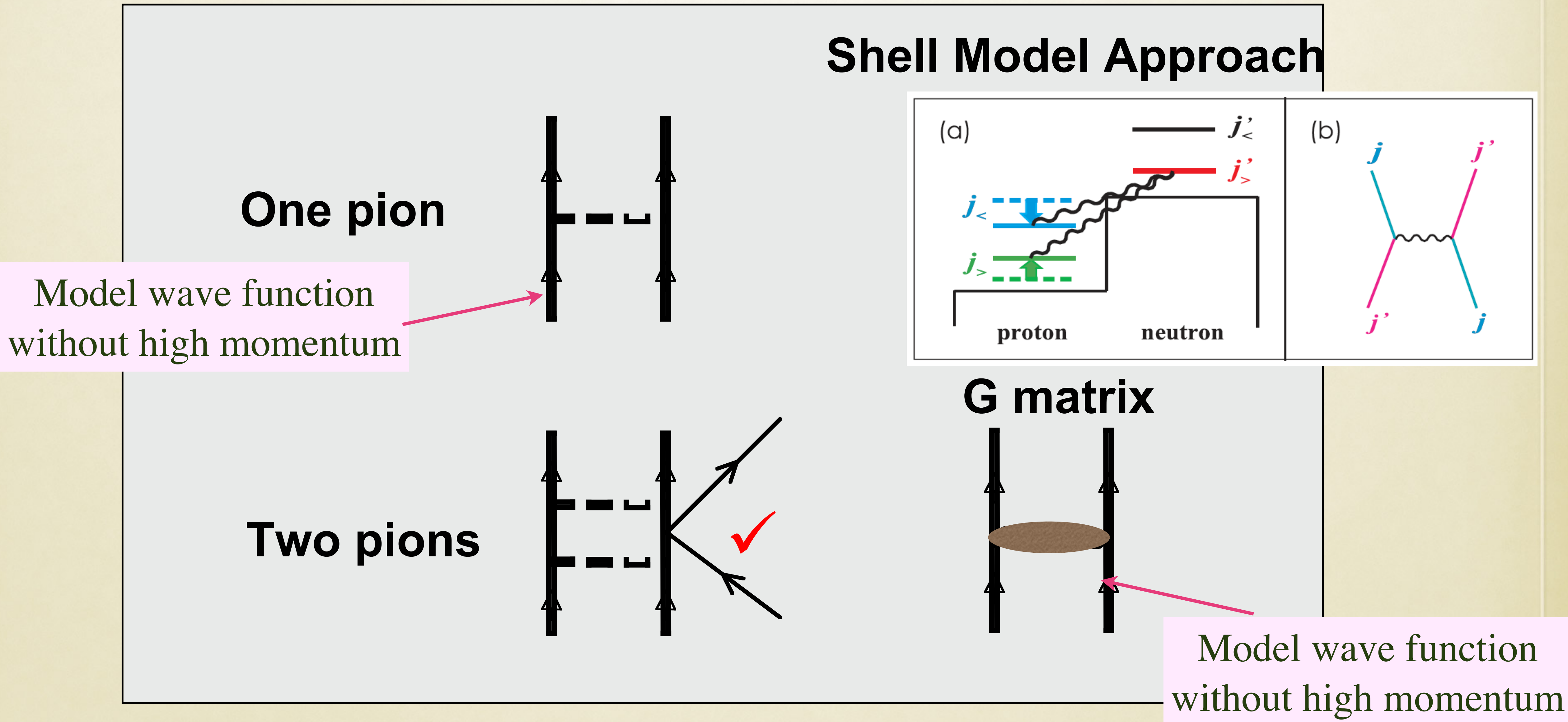
It does not contribute to doubly closed shell nuclei.



G-matrix and perturbation

Difference between Shell model treatment and reality

pion exchange: $\propto S_{12} \frac{q^2}{m^2 + q^2}$



✓ **High Momentum Component**

Breathe deeply

- **Pion exchange provides the Central and the Tensor Forces.**
- **The central force prefer a low momentum.**
- **The tensor force prefer a high momentum.**
- **Attraction by the tensor force is gained by a transition of a *pn* pair to higher orbitals under selection rule $\Delta S=2, \Delta L=2$. (in shell model language)**
- **Tensor interaction is blocked when nucleon occupy higher orbitals and thus nuclear saturation occurs.**

High-momentum nucleons in ground states of a nucleus?

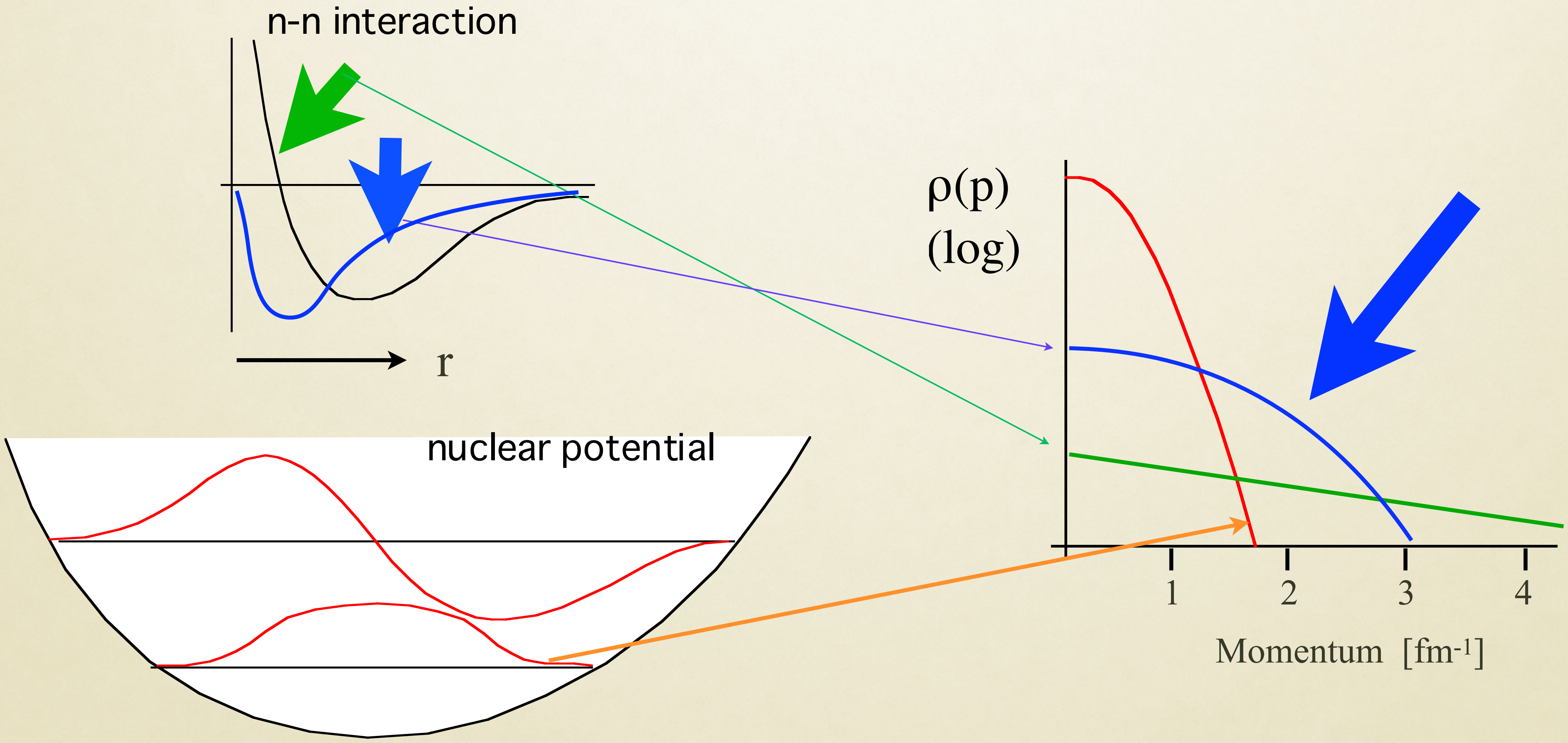
- Recently confirmed by (p, n) and (p, pd) reactions of ^{16}O at RCNP. see
  - H.-J. Ong et al., Phys. Lett. B 725, 277-281 (2013)
  - S. Terashima et. al., Phys. Rev. Lett. 121, 242501 (2018)
- Also observed in quasi-free electron scattering.
  - (e, e'pn)

This paper tells, for the first time,
a high-momentum nucleon pair is S=1 and T=0,
consistent with tensor correlated pair.

Tensor forces as high momentum

Wave functions

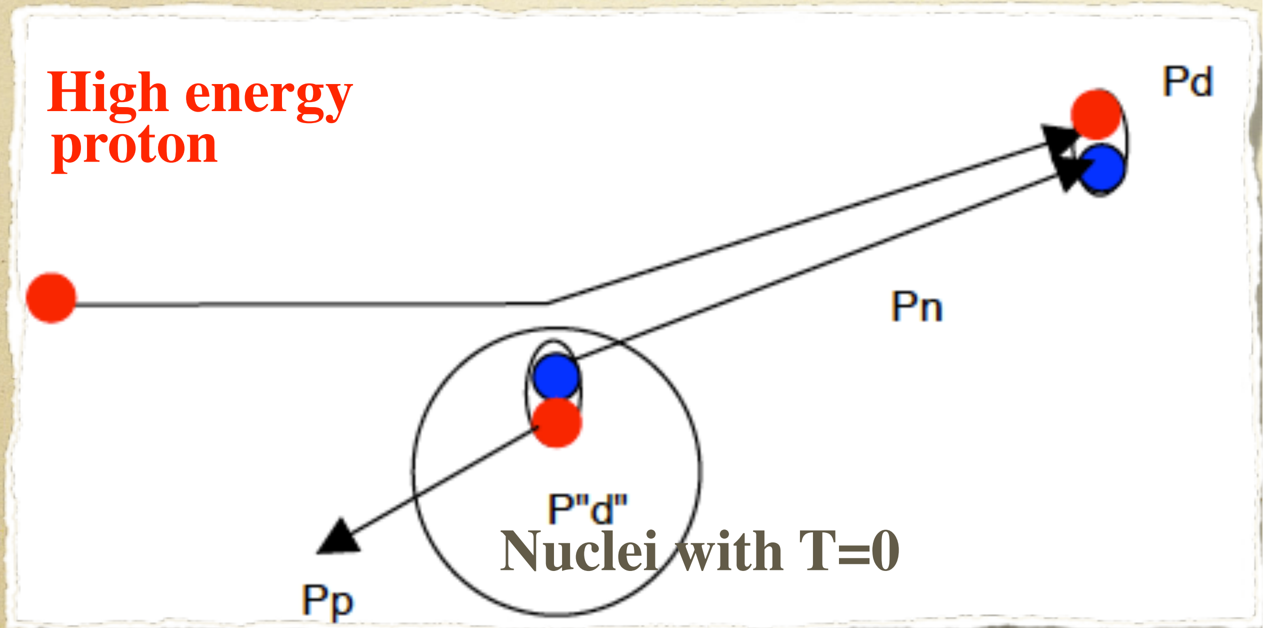
- Range of tensor force is about the distance of pion exchange, and thus gives momentum component specific to it.



$^{16}O(p,pd)^{14}N$

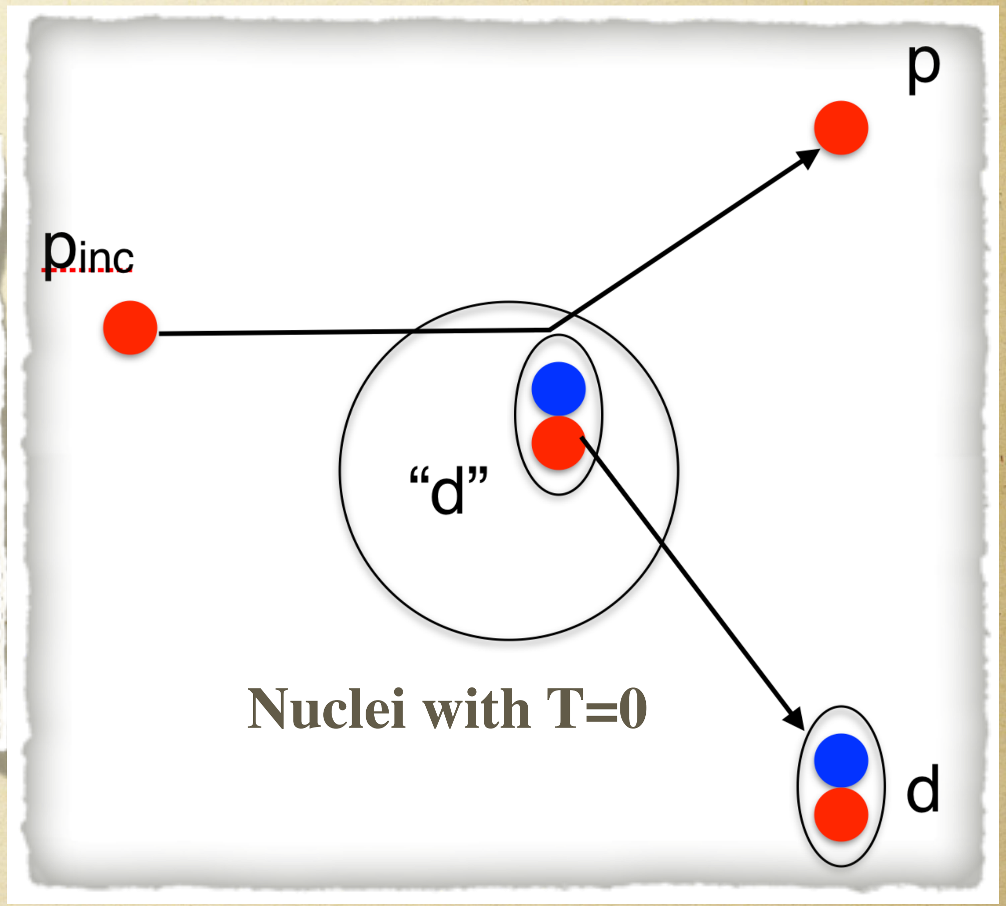
- A measurement of correlated pn pairs in nuclei with large relative momenta.

Pick up



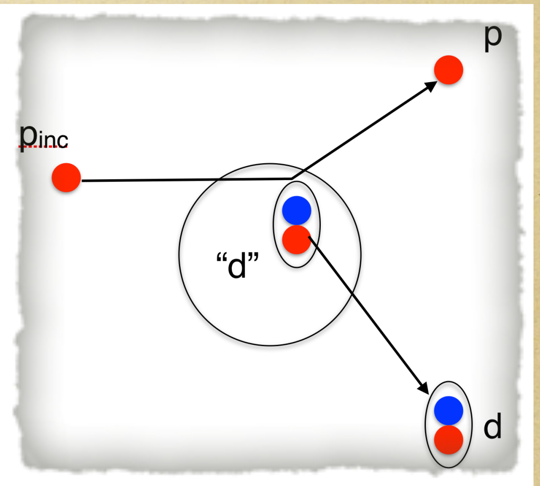
T of residual nuclei = *T* of "d"

Knock out

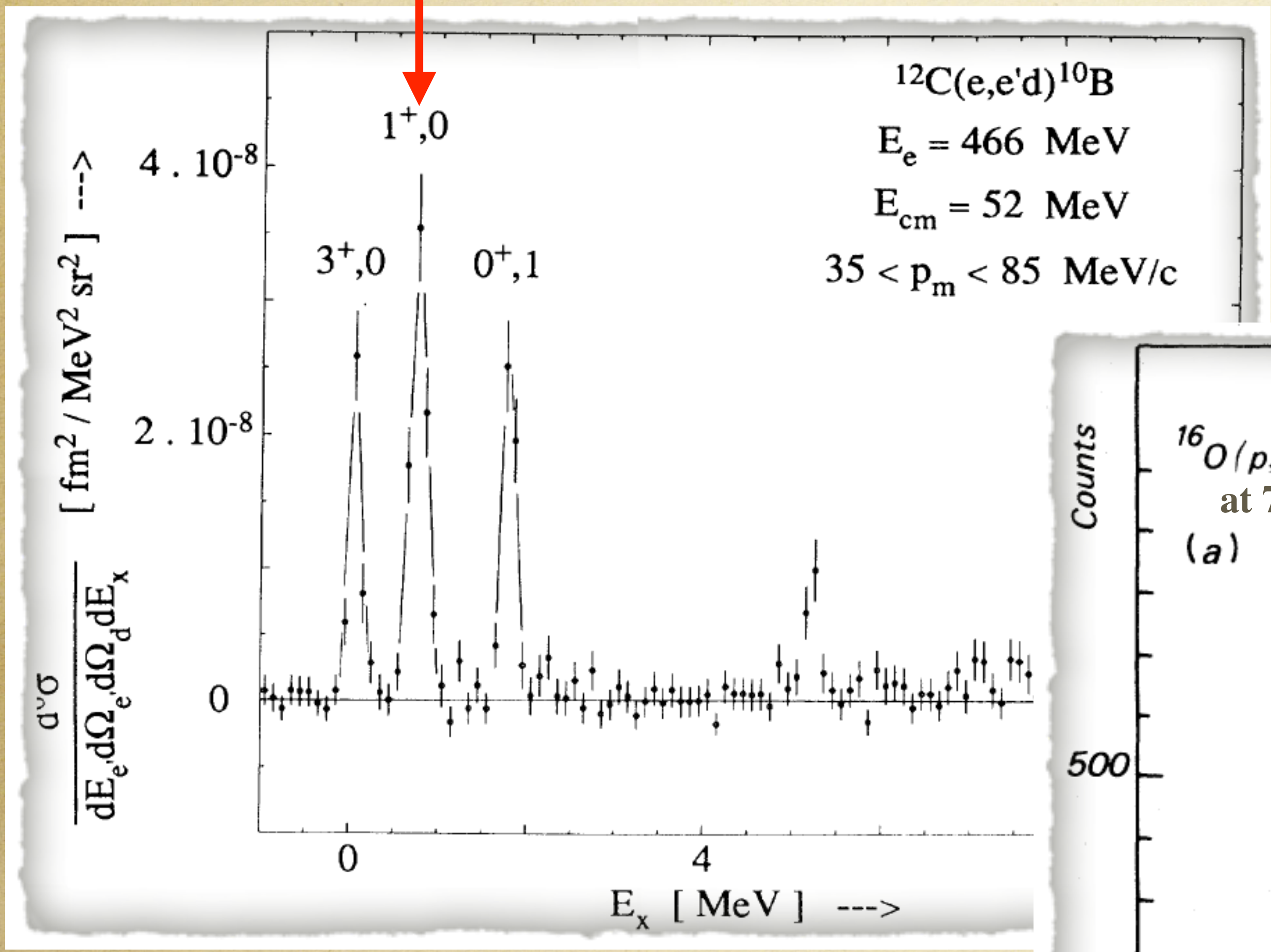


T of residual nuclei = 0 or 1
: independent from *T* of "d"

Knock out data

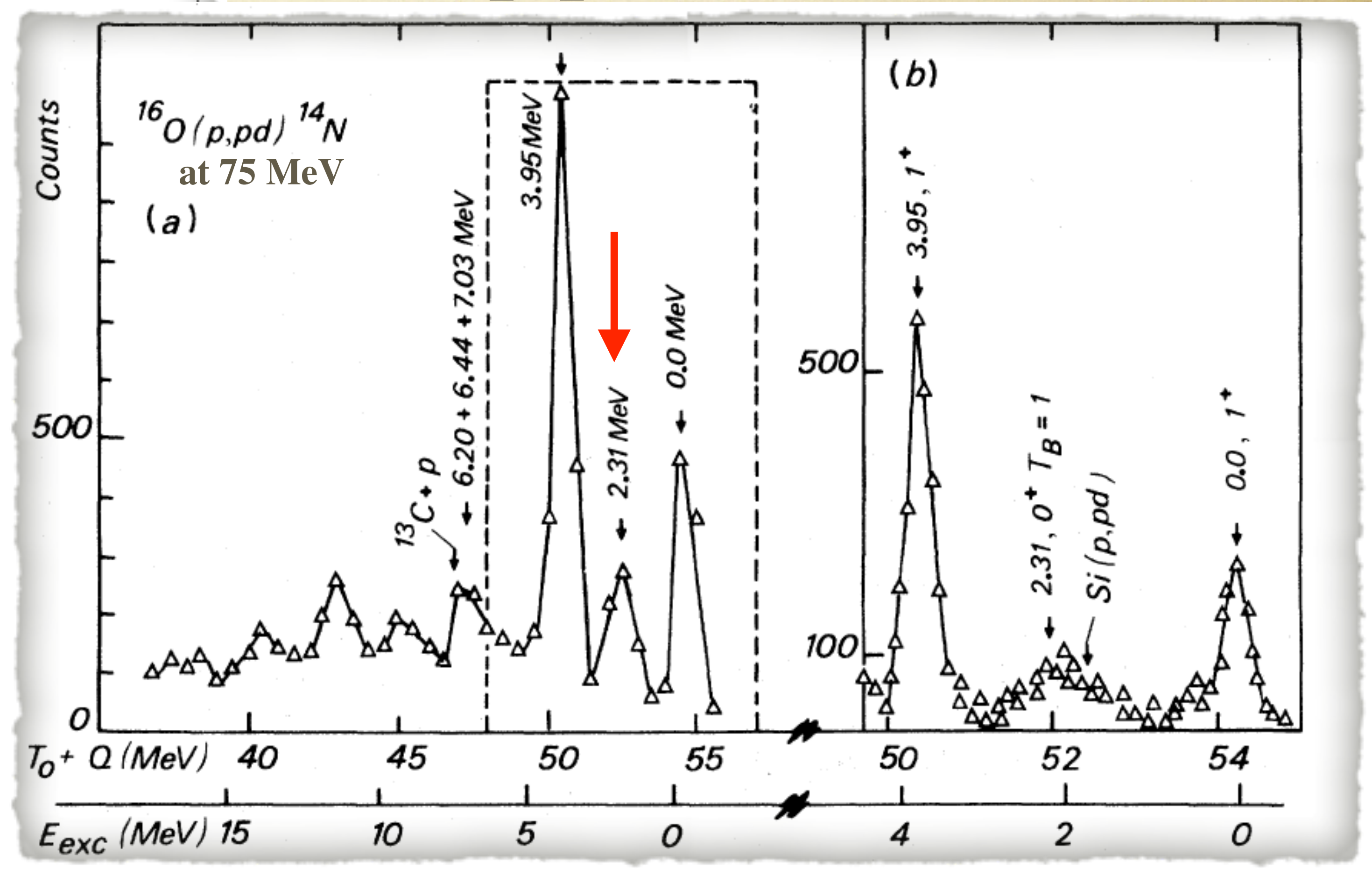


$^{12}C(e,e'd)^{10}B$ @466MeV



E. Ent et al., Phys. Rev. Lett. 62 (1989) 24

$^{16}O(p,pd)^{14}N$ at 75 MeV



J. Y. Grossiord et al., Phys. Rev. C 15 (1977) 843.

^{16}O(p, pd)^{14}N reaction at a large momentum transfer

E_p=400 MeV

Terashima et al. Phys. Rev. Lett. 121, 242501 (2018)

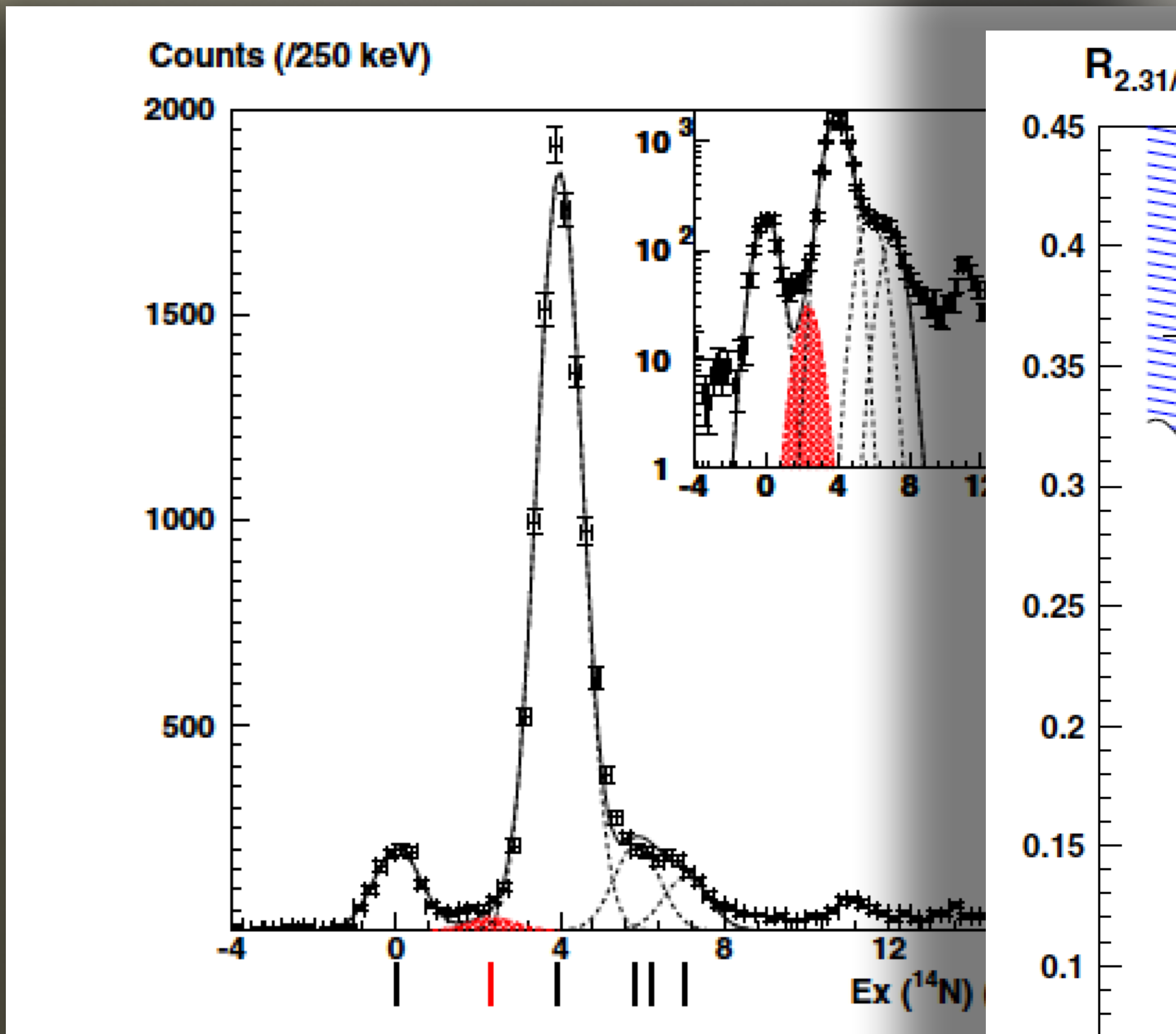
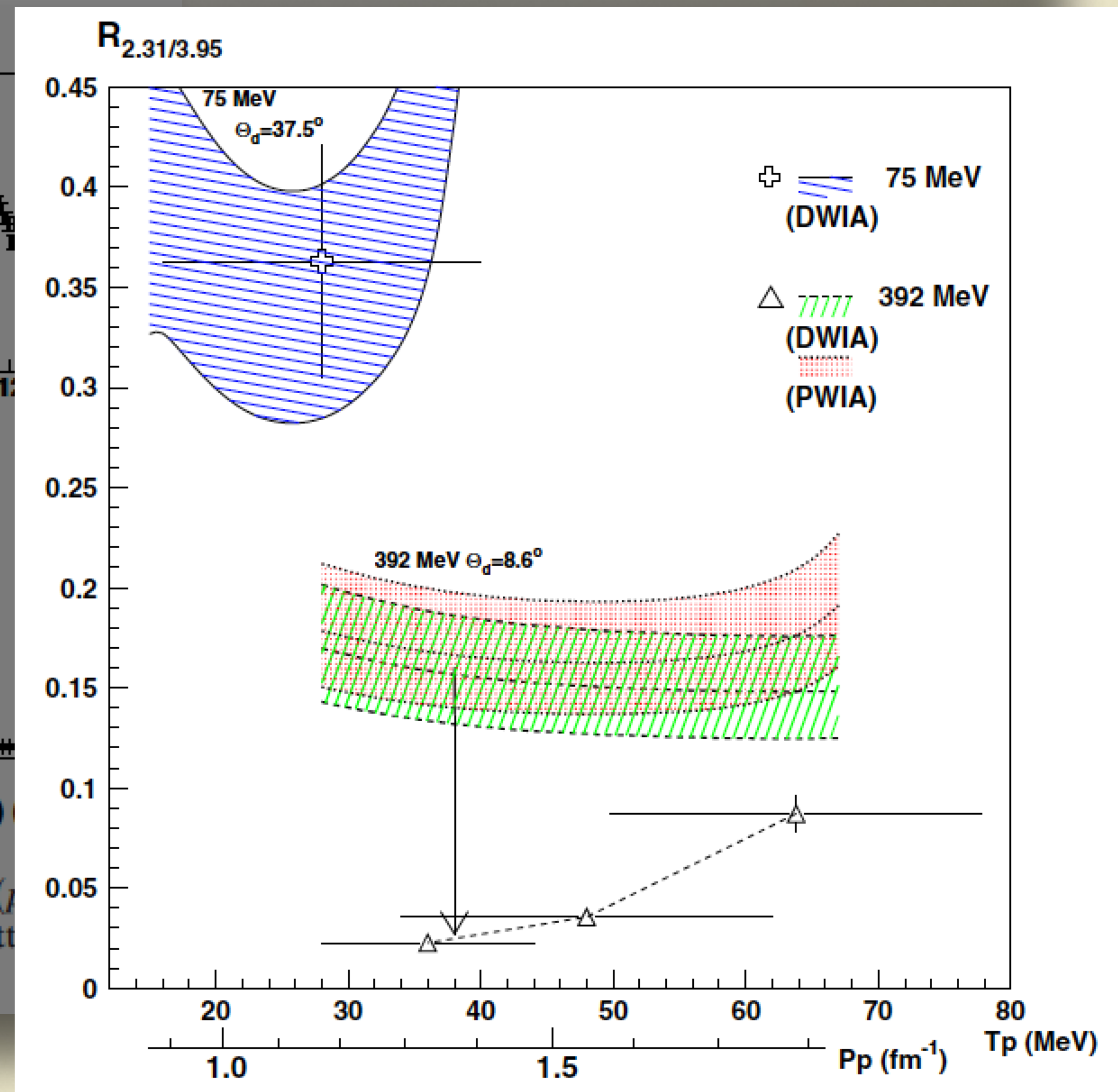


FIG. 2. The excitation energy spectrum of ^{16}O(
$\theta_d = 8.6°/\theta_p = 138.4°$ with the total and individual fitt
shown by the solid and dashed lines, respectively.



So

- High-momentum pair is there in ground states of nuclei.
- High-momentum pn pair is important to provide a large amount of binding in nuclei though the tensor interaction.
- But no nuclear model include such nucleons explicitly.

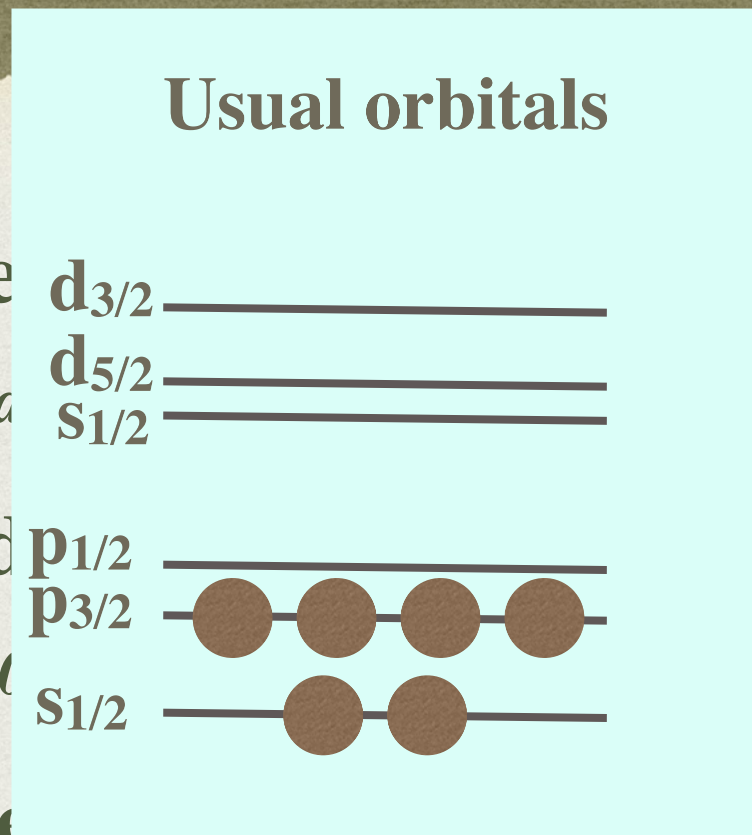
In general this effect is considered just to cut the shell model space restricting only low momentum nucleons.
Missing strength of 20%

That is not true!

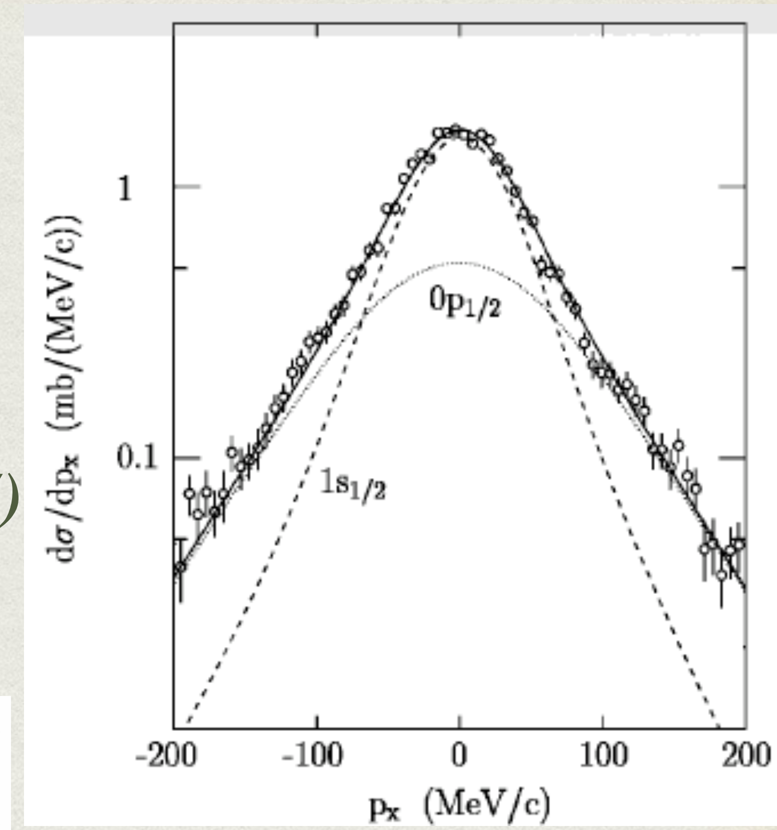
Ground state properties are strongly affected by High-Momentum Nucleons

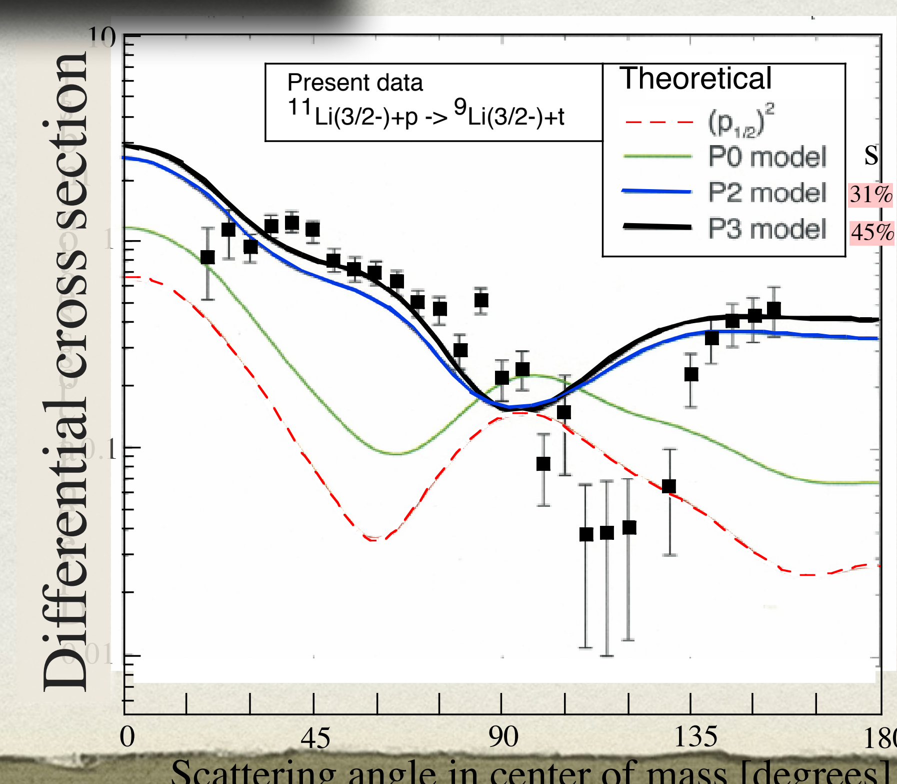
and an effect of high-momentum component explains structure of a halo nucleus ^{11}Li!

s- and p- waves mixing in ^{11}Li



- Mome… fragments ^{10}Li
  - *Equa… mon 1999)*
- Beta-d…
  - *30-4… nt of $p_{1/2}$ (Borge 1997)*
- two-ne… ion
  - *(^{11}Li+p --> ^{9}Li+t)*
  - *31-45% $s_{1/2}$ and $p_{1/2}$*
  - *(2008)*



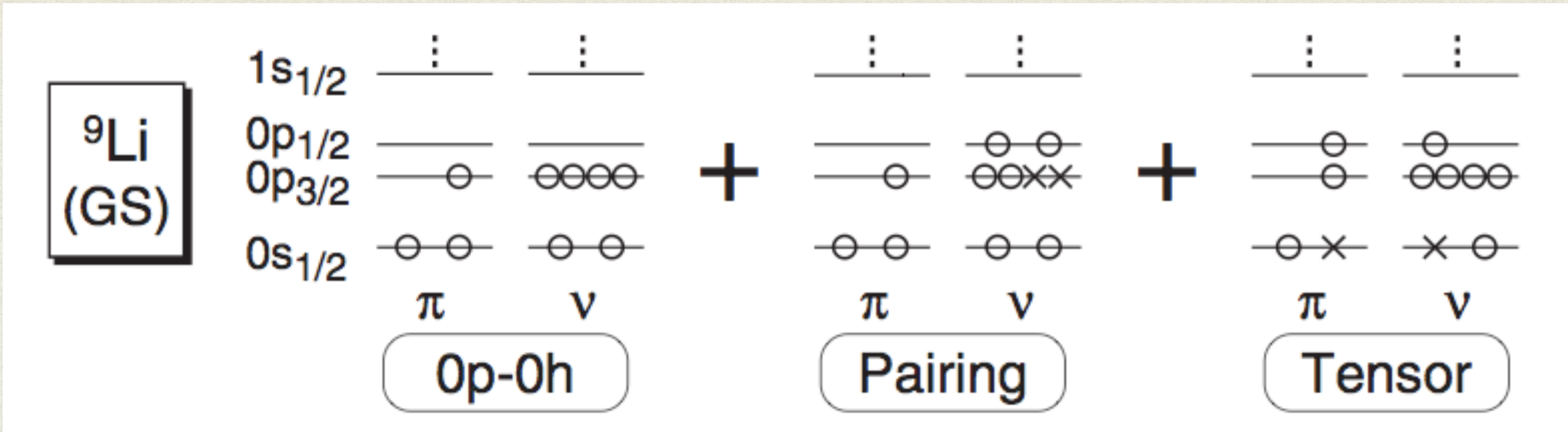


41% s

35% s

I. Tanihata et al., Phys. Rev. Lett 100 (2008) 192502..

Mixing of $s_{1/2}$ and $p_{1/2}$ in ^{11}Li



T. Myo, K. Kato, H. Toki, K. Ikeda, Phys. Rev. 76 (2007) 024305.

TOSM

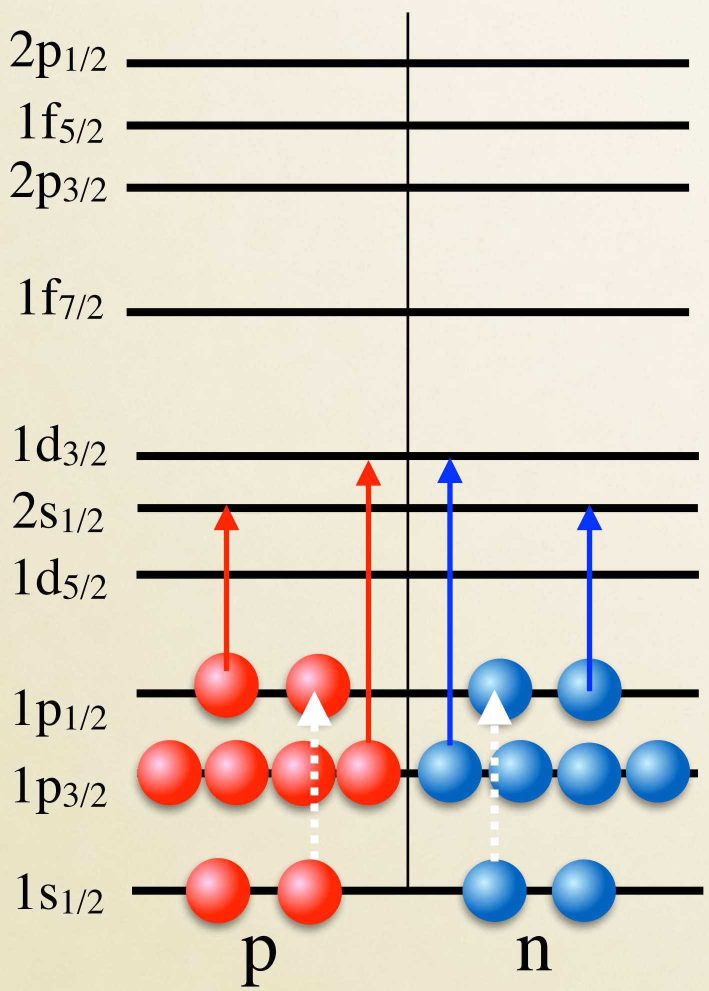
Myo, Toki, Ikeda, Kato, Sugimoto, PTP 117 (2006)

- It provides good account of ground and low excited states up to Be isotopes.
- It explains, for the first time, the s-p mixing in halo ^{11}Li nucleus.

- However it needs extensive computer power and it is difficult to extend the calculations above Be presently.
- But now we know that the tensor blocking is important to explain the structure of neutron rich nuclei.

What is the difference between stable and neutron rich nuclei?

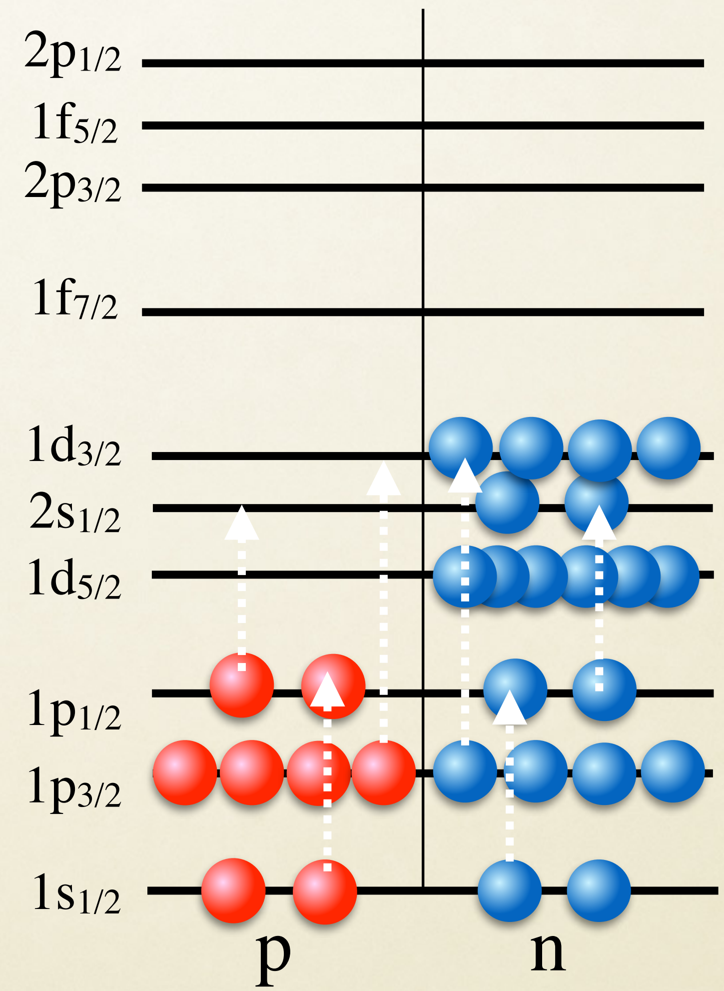
Symmetric nuclei



^{16}O

Blocking and Opening occur simultaneously.

Neutron rich nuclei



^{28}O

Only tensor blocking occurs.

Tensor Blocking Shell Model

New!

- Use spirit of TOSM (include 2p-2h excitation explicitly so that tensor force is treated well).
- Treat only $\Delta l=1$ orbital separately. All light nuclei so far fills only up to $\Delta l=1$ orbitals.
- Higher excitations $\Delta l \geq 2$ is treated in Q-space and consider only to contribute to the mean field potential.

Tensor Blocking Shell Model

Relation to the shell model

$$H = \sum T^i + \sum v_C^{ij} + \sum v_T^{ij}$$

residual interactions and treated them as perturbation.

$$H = \sum T^i + V_{sh} + \sum v_{sh}^{ij}$$

We write tensor part explicitly, then

$$V = H - \sum T^i = V_C + V_T + \sum v_c^{ij} + \sum v_T^{ij}$$

$$V_{sh} = V_C + V_T$$

$$\sum v_{sh}^{ij} = \sum v_c^{ij} + \sum v_T^{ij}$$

In the shell model tensor blocking is not treated then so we separate blocking part, (Blocking occurs only in Δl=1 transition)

$$V_T = V_{T1} - V_{T1}^0 + (V_{T1}^0 + \sum_{l=2\ldots} V_{Tl})$$

$$= V_{T1} - V_{T1}^0 + V_T^0$$

$$V = V_{sh} + (V_{T_1} - V_{T_1}^0) + \sum \bar{v}_{sh}^{ij}$$

->We can use (Woods-Saxon potential + Blocking)

$$(V_{T_1} - V_{T_1}^0)$$

The difference of the potential energy between an open shell and the occupied shell.

If you include high-momentum correlated nucleons, you can not forget this term.

wl

ar

$V_C + V_T^0$ is exactly the shell model potential (V_{sh}) at the closed shell.

Tensor Blocking Shell Model

$H = T + V_C + V_T$ $\qquad \Psi = \psi_{Sh} + \psi_{2p-2h}$

ψ_{sh} only low momentum
$\psi_{2p\text{-}2h}$ includes high-momentum

Otsuka's monopole term

Potential energy

$$\langle \Psi | V_C + V_T | \Psi \rangle = \langle \psi_{Sh} | V_C | \psi_{Sh} \rangle + \langle \psi_{Sh} | V_T | \psi_{Sh} \rangle + 2\langle \psi_{Sh} | V_T | \psi_{2p-2h} \rangle + \langle \psi_{2p-2h} | V | \psi_{2p-2h} \rangle$$

$$\langle \psi_{Sh} | V_T | \psi_{2p-2h} \rangle = \langle \psi_{Sh} | V_T | \psi_{2p-2h}^{\Delta l=1} \rangle + \langle \psi_{Sh} | V_T | \psi_{2p-2h}^{\Delta l \geq 2} \rangle$$

Δl=1 gives 5~8 MeV additional energy in the binding.

So we treat all other term as a mean field potential given by phenomenologically accepted Woods-Saxon potential.

Usual shell model

$$H_{Sh} = \sum_{i,j} v_{ij}$$

$$= V_{mf} + \sum_{i,j} \bar{v}_{i,j}$$

mean field potential
and
residual interactions

V_{mf}: includes tensor
$\bar{v}_{i,j}$: does not!

Take a depth breathe for the last sections

- **We start from single-particle orbitals obtained from a classical Woods-Saxon potential.**
- **Then we follow the change of binding energy by the change of tensor interactions when nucleons are added to a new orbital.**
- **The magic number is where energy gap to next nucleus is large.**

Now it's become very simple

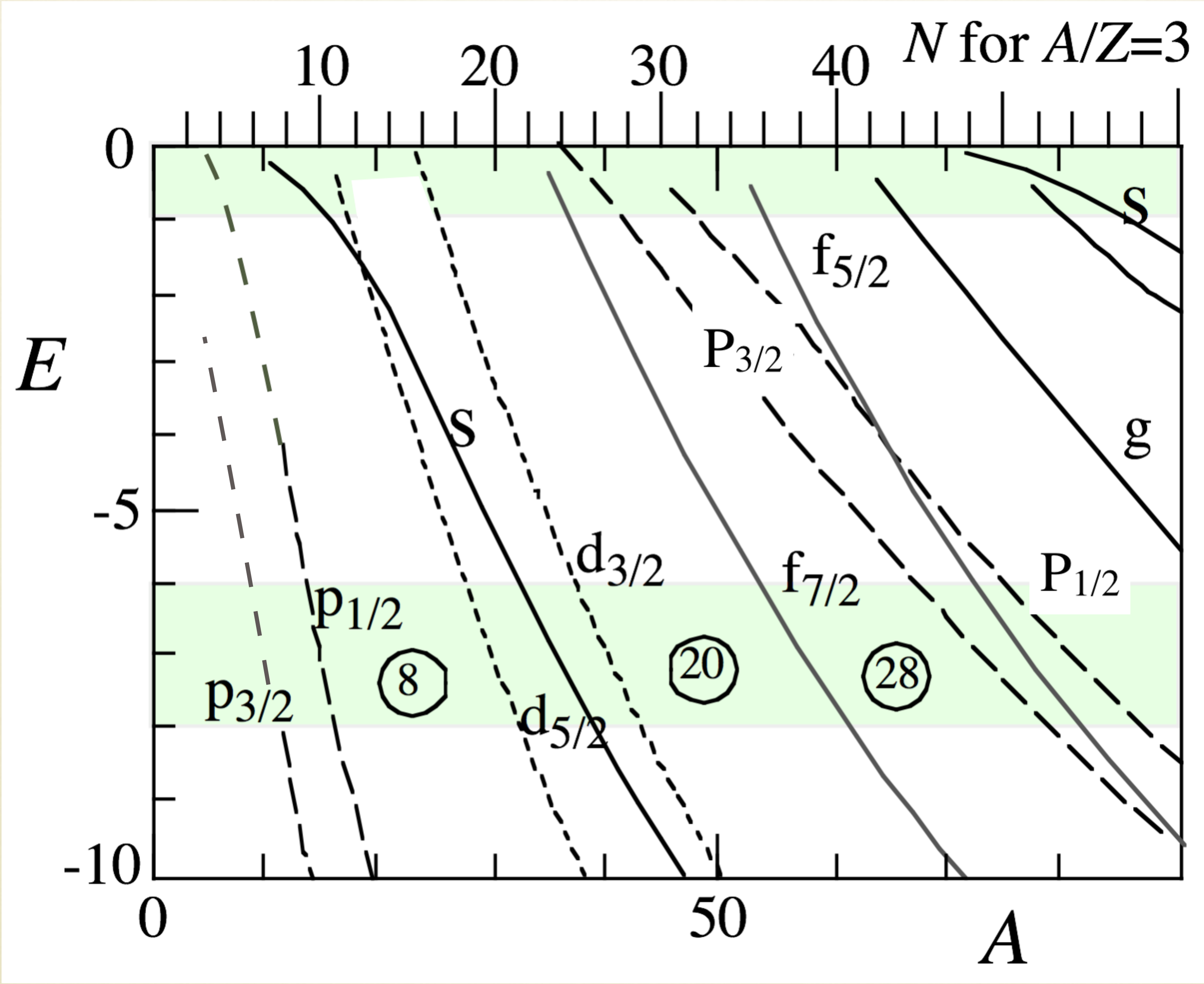
- Only two ingredients,

mean filed

and

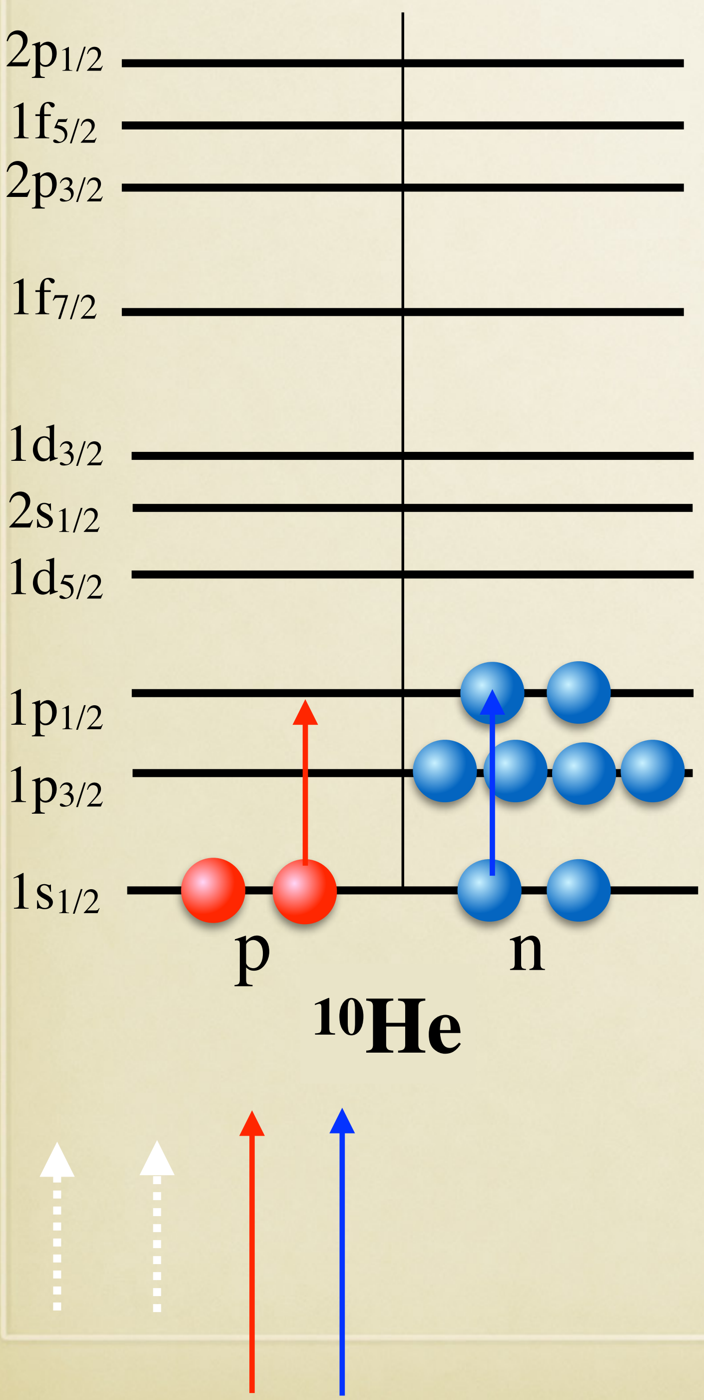
Δl=1 tensor.

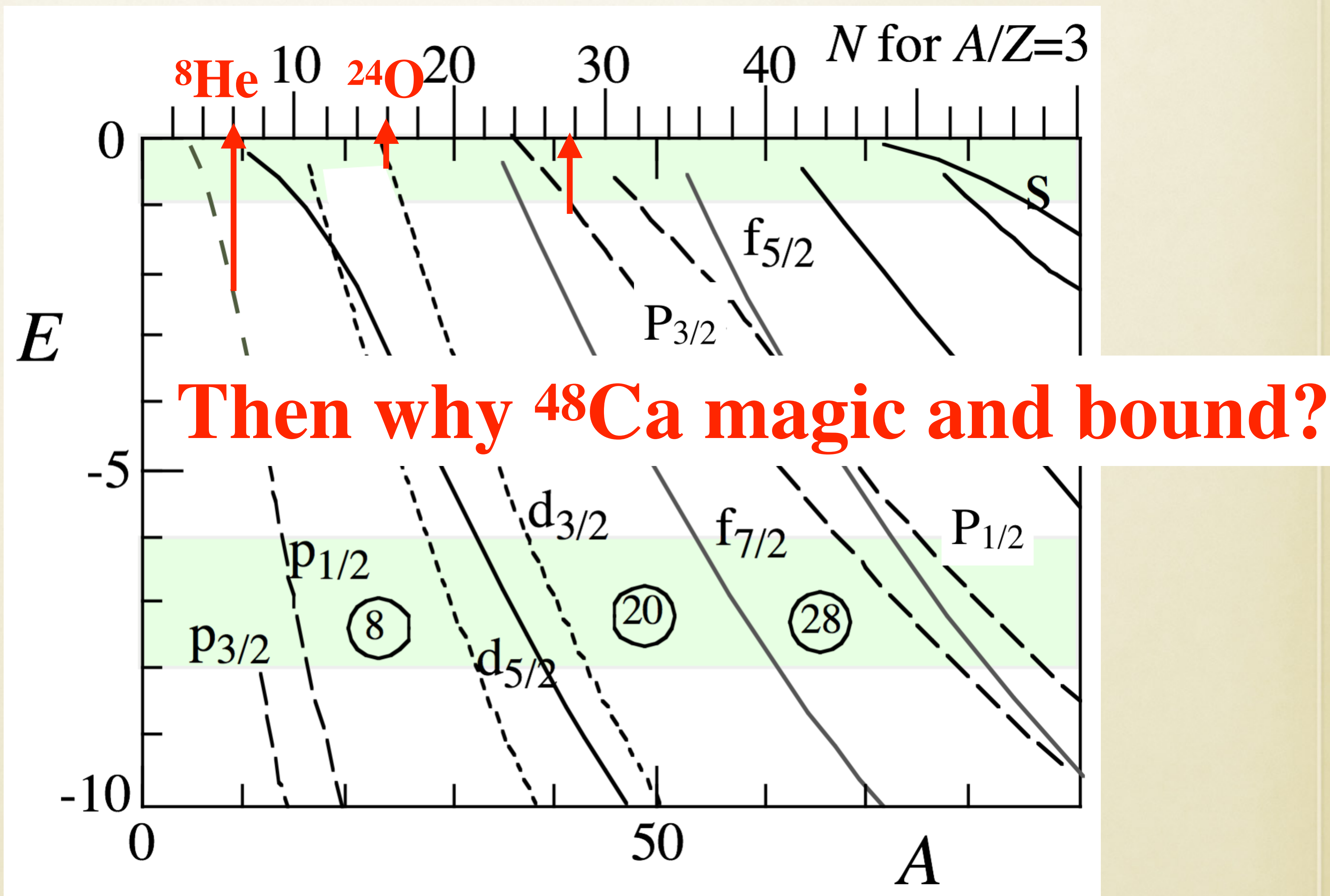
Orbitals in W-S potential
A blocking of 2p-2h excitation looses >5 MeV



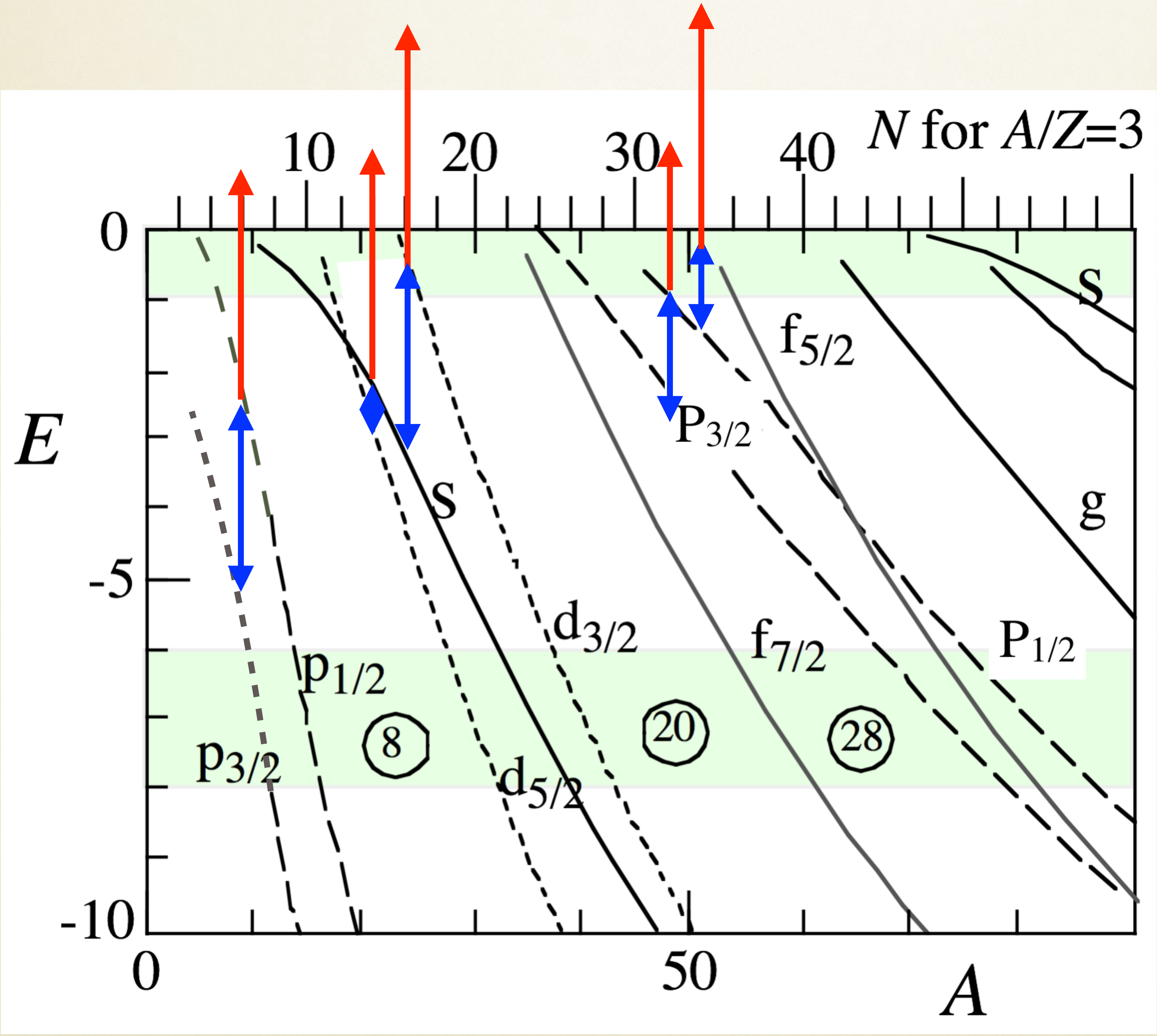
Woods-Saxon potential parameters are from the book of Bohr and Mottelson.
Calculations are made for A/Z=3 nuclei.

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



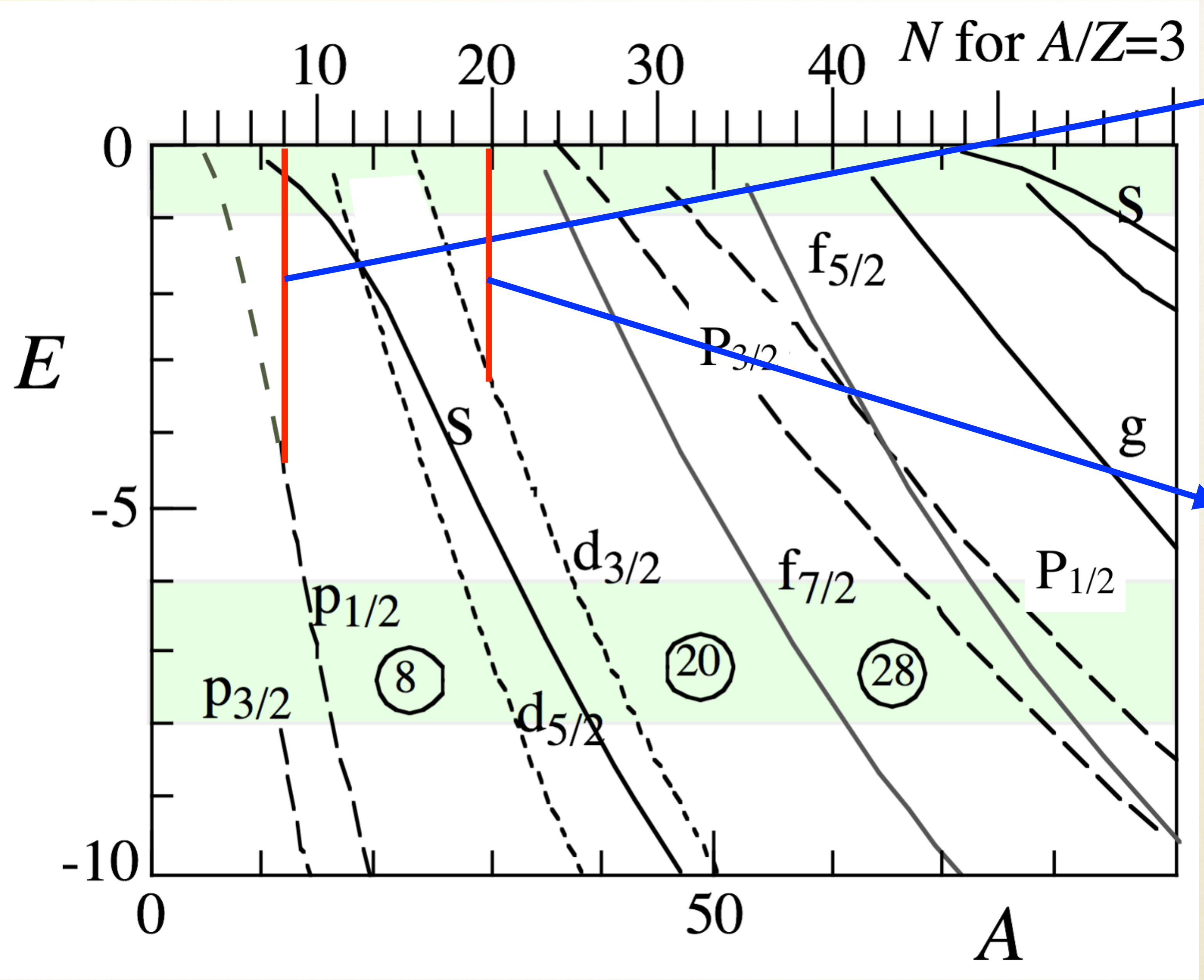


How are new magic numbers N=6,14,16,32,34 made?



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

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 $d_{3/2}$.

Why the neutron drip line suddenly extend very much in F isotopes?

- Tensor opening occurs in F and binding energy is back to normal.

Summary

- Importance of the tensor interaction is reviewed.
- Effects of recently observed high-momentum pn pair are considered in relation to the nuclear structures.
- Importance of the tensor blocking, that is significant in neutron rich nuclei, are discussed.
- A new model of nuclei "Tensor Blocking Shell Model" is introduced and used to examine new behaviors of neutron rich nuclei.

Conclusion

- All new magic numbers appeared in neutron rich nuclei are consistently explained.
- Disappearance of traditional magic numbers and non binding of ^{8}He and ^{28}O are explained.
- Sudden extension of dripline in F is understood.
- A peculiar change of GS configurations is understood.

Some related matters

- Neutron dripline may be closer than present predictions.
- Next magic number in neutron rich nuclei is 56 or 58.
- Magic numbers in neutron rich region affect the R-process.
- Effect of tensor blocking near the stability line may give new views to residual interactions.
- Relation to the *l•s* interactions

l·*s* splitting in ^{5}He

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Spin-Orbit Splitting and Tensor Force. I*

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It has been shown that about **a half of the experimental values of the doublet splittings in ^{5}He and ^{15}N can be derived,** using the meson-theoretic potential or the Serber one, **through the second order effect of perturbation theory**. The splitting energies have been shown to be mainly ascribed to the facts that

(1) the tensor force is strong and, especially, is stronger in the triplet even states than in the triplet odd states, and

(2) the deformation of the closed shell core induced by the tensor force between the core-nucleons is restricted so as to satisfy the Pauli principle with the outside nucleon.

Fig. 1 … (IIIb)

Collaborators

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Thank you for your attention

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Like a change from the geocentric system to heliocentric system!

Thank you for your kind attention