Tensor Force Prompts New Magic Numbers

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Story

- **Tensor force - “short” range correlation - high momentum nucleon - binding energy**
- **Expression in shell model space**
  - ***Mixing of 2p-2h states with high momentum***
- **Experimentally**
  - **(p,d*) reaction***
  - **(p,pd*) reaction***
- **Difference of tensor blocking in *N~Z* nuclei and neutron rich nuclei**
  - ***Tensor blocking is the most important ingredient for saturation property of nuclear matter***
  - ***Tensor blocking in shell model space and a difference between stable and neutron rich nuclei.***
- **Changes of magic numbers**
  - ***Qualitative consideration on the shell orbitals***

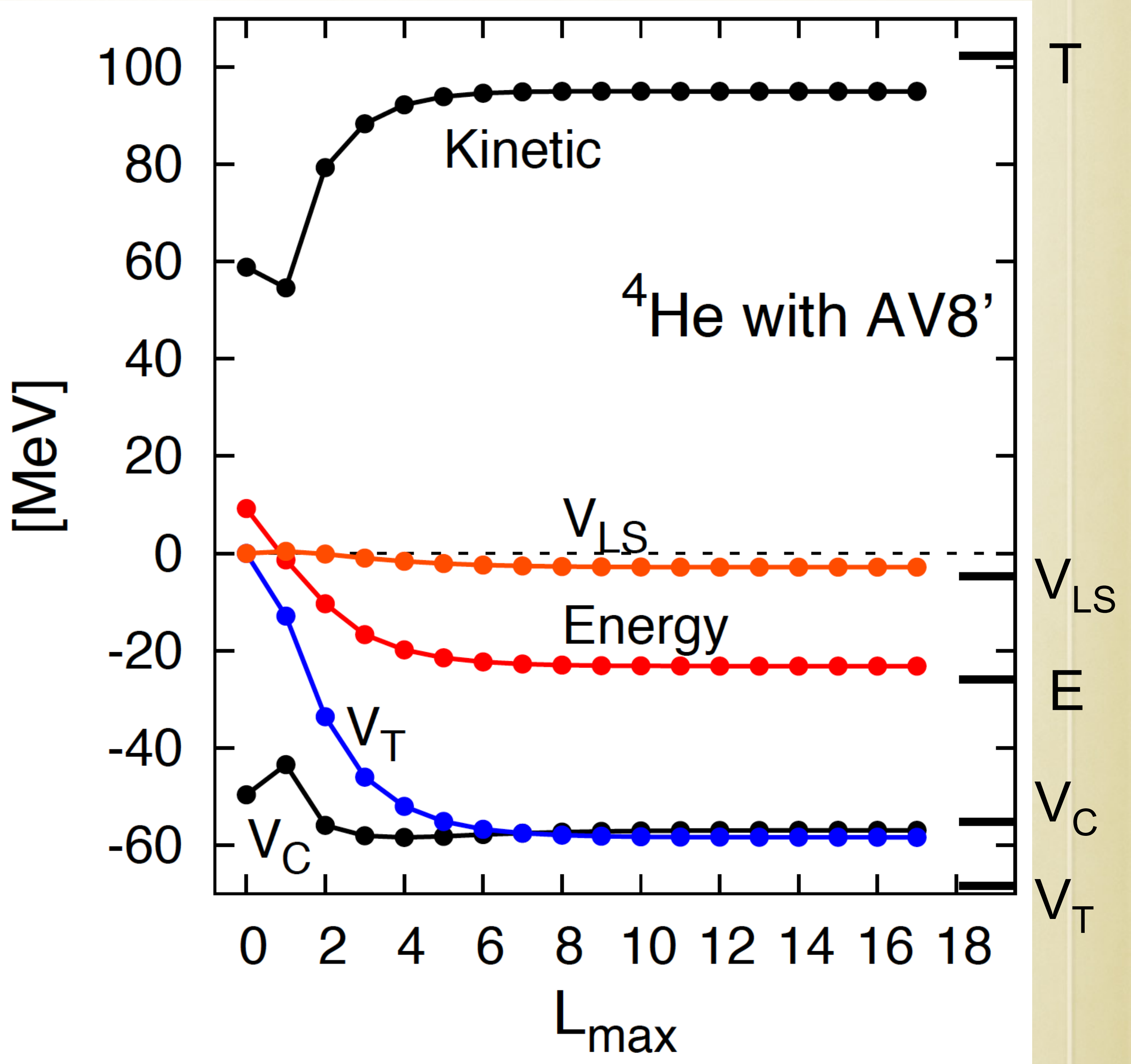
Tensor force in nuclei

- Pion exchange interaction includes tensor force with same amplitude as central forces.
- Tensor interaction produce correlated pairs of short distance. It therefore produce high-momentum nucleons.
- This high-momentum pair give large binding energy similar to D-wave in deuteron.

Expression of tensor correlated pairs in shell model

Tensor force in ^{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 >10 MeV of potential energy.



The most important 2p-2h configuration

Configurations up to *l*=1

T. Myo, K. Kato, and K. Ikeda, PTP 113, (2005) 763.

$$\Psi(^4\mathrm{He}) = \sum_{i=1}^{6} a_i \, \Phi_i \ ,$$

$$\begin{aligned}
\Phi_1 &= (0s_{1/2})^4_{00} \ , \\
\Phi_2 &= \left[(0s_{1/2})^2_{01}, (0p_{1/2})^2_{01}\right]_{00} \ , \\
\Phi_3 &= \left[(0s_{1/2})^2_{10}, (0p_{1/2})^2_{10}\right]_{00} \ , \\
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	V_T [MeV]
$\Phi_1 = (0s_{1/2})^4_{00}\ ,$	
$\Phi_2 = \left[(0s_{1/2})^2_{01}, (0p_{1/2})^2_{01}\right]_{00}\ ,$	0.37
$\Phi_3 = \left[(0s_{1/2})^2_{10}, (0p_{1/2})^2_{10}\right]_{00}\ ,$	14.49
$\Phi_4 = \left[(0s_{1/2})^2_{01}, (0p_{3/2})^2_{01}\right]_{00}\ ,$	0.19
$\Phi_5 = \left[(0s_{1/2})^2_{10}, (0p_{3/2})^2_{10}\right]_{00}\ ,$	1.67
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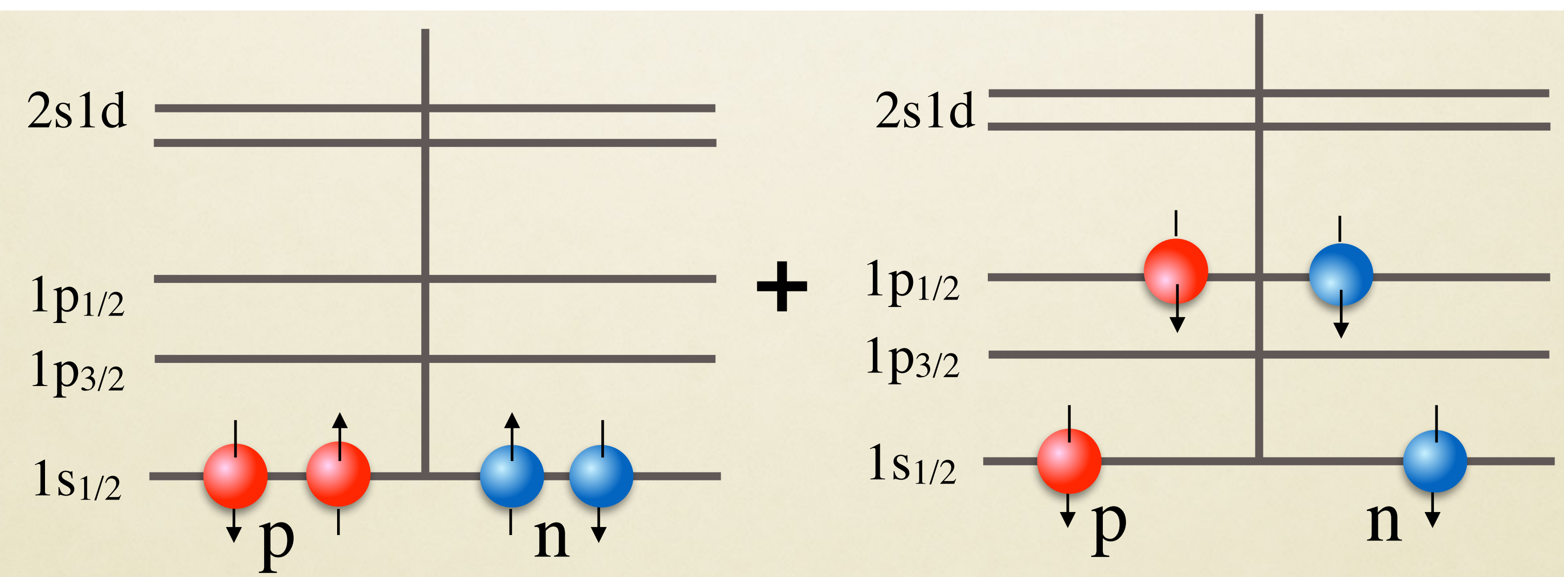
	V_T [MeV]
Φ_2	0.37
Φ_3	14.49
Φ_4	0.19
Φ_5	1.67
Φ_6	0.09

^{4}He:



~10%

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	V_T [MeV]
Φ_2	0.37
Φ_3	14.49
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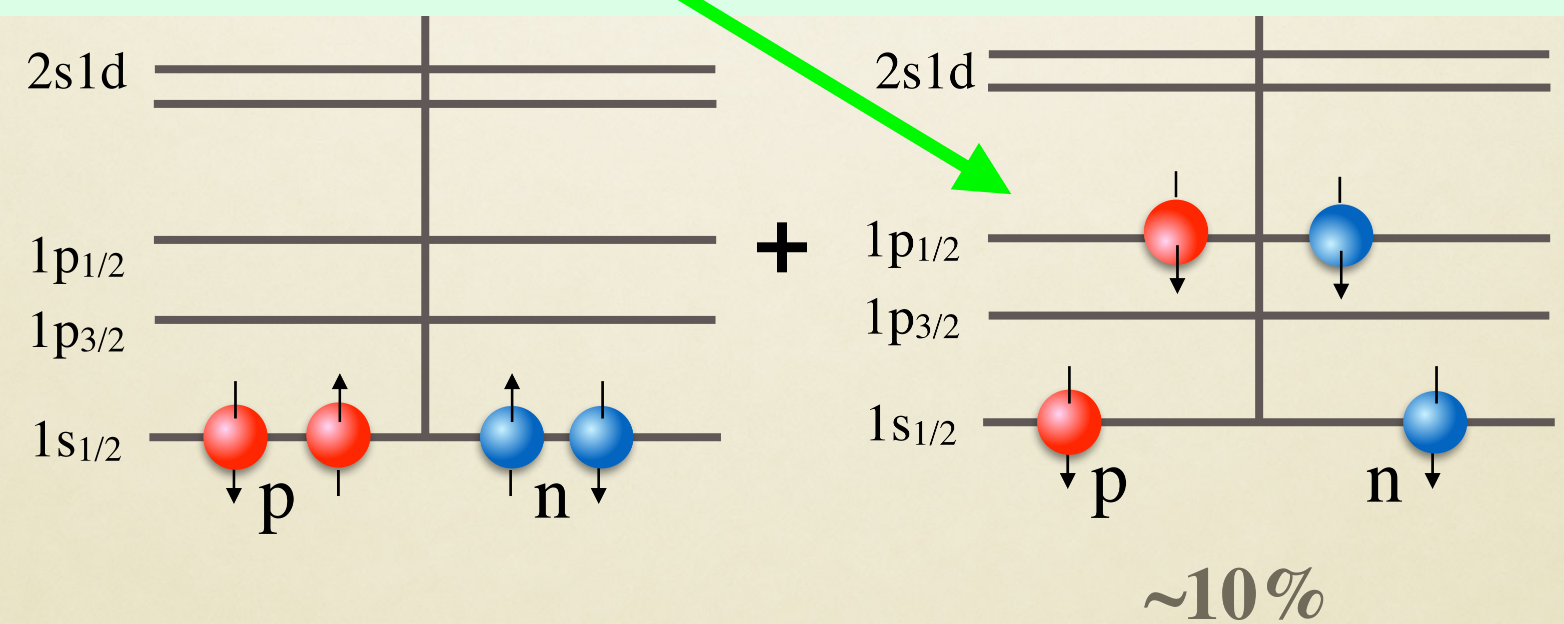
Highest spin orbital ($j_>$) in a major shell is not used for the tensor interaction.
An example is $1p_{3/2}$ orbital in ^{4}He and deuteron.

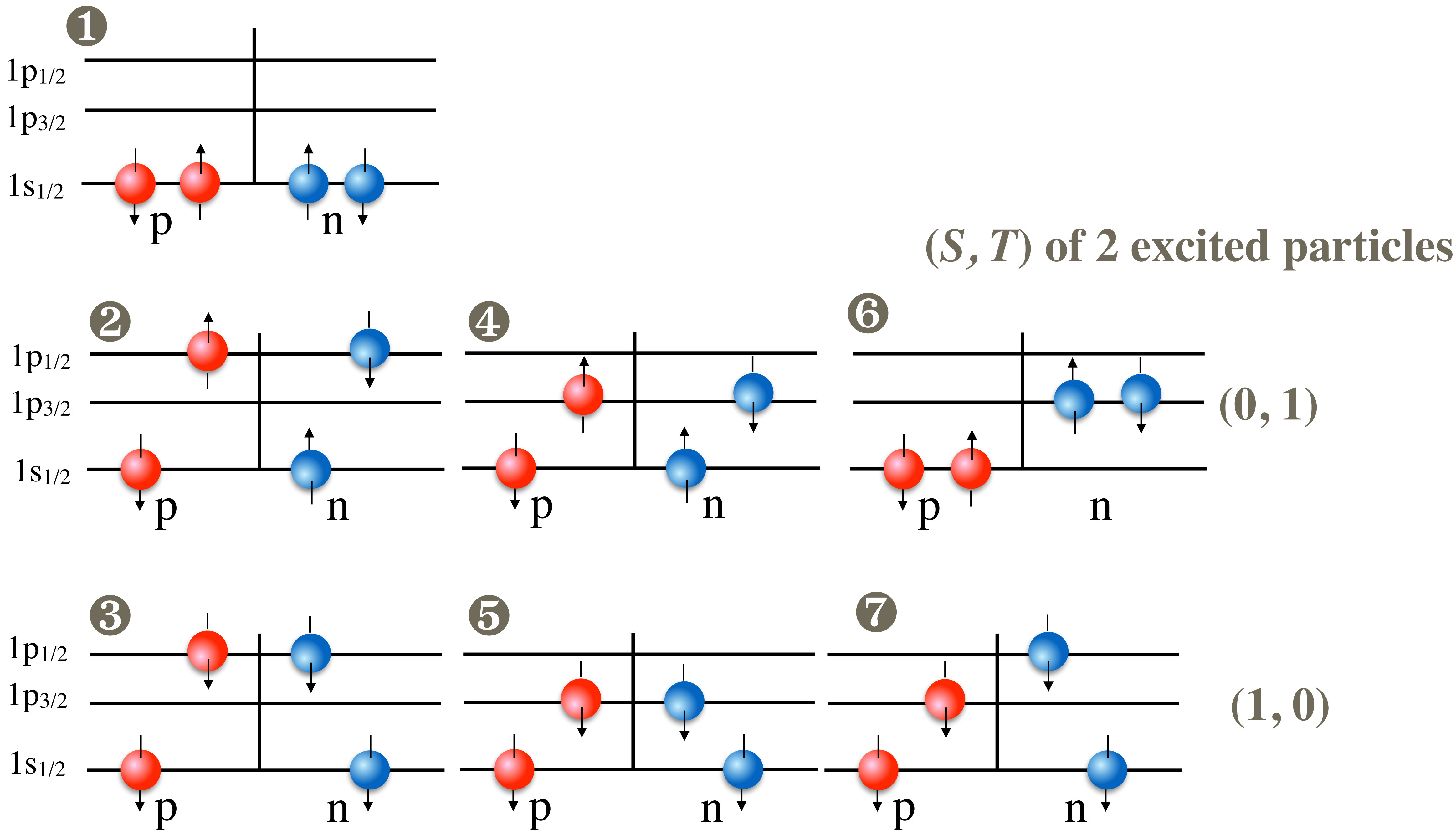
^{4}He:



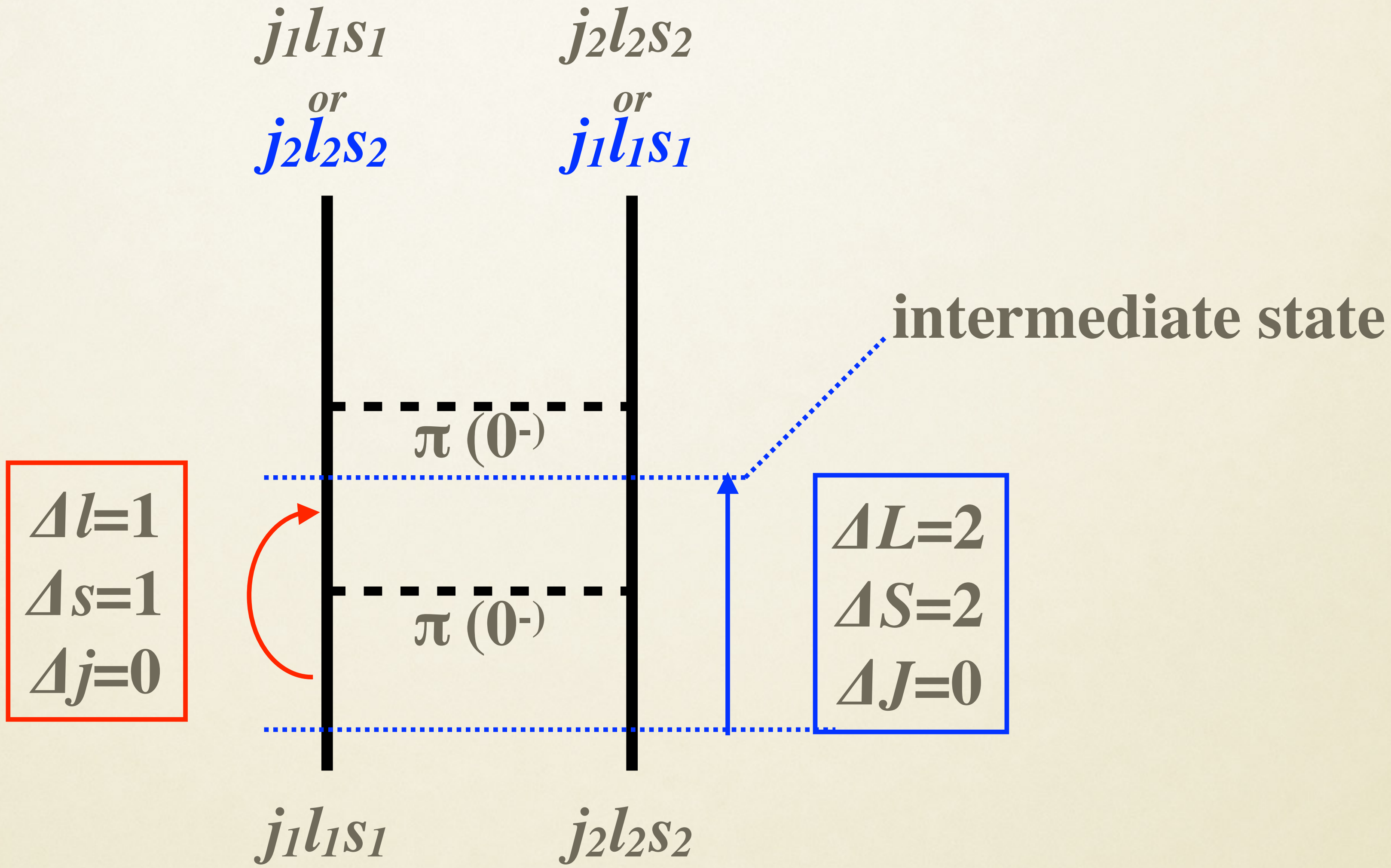
In more general p-n pairs from $(nlj)^2$ configuration to $(n+1,l+1,j)^2$ or $(n+1,l-1,j)^2$

Tensor Optimized Shell Model,

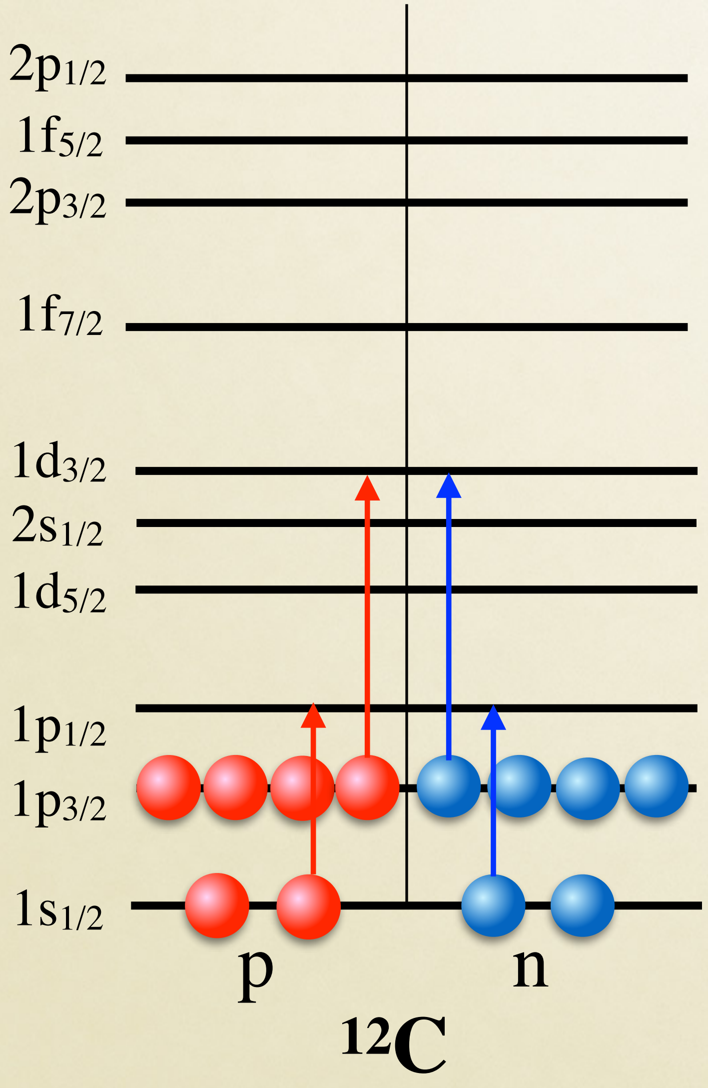
Myo, Toki, Ikeda, Kato, Sugimoto, PTP 117 (2006)



Selection rule of the tensor interaction



Tensor Blocking and Nuclear Saturation



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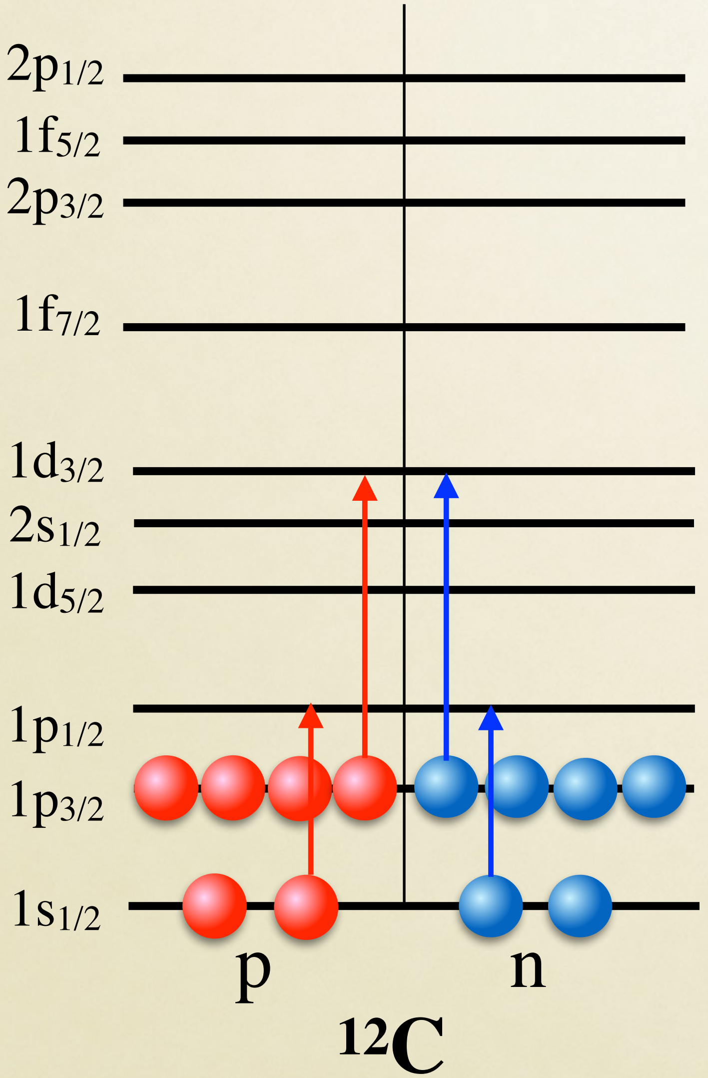
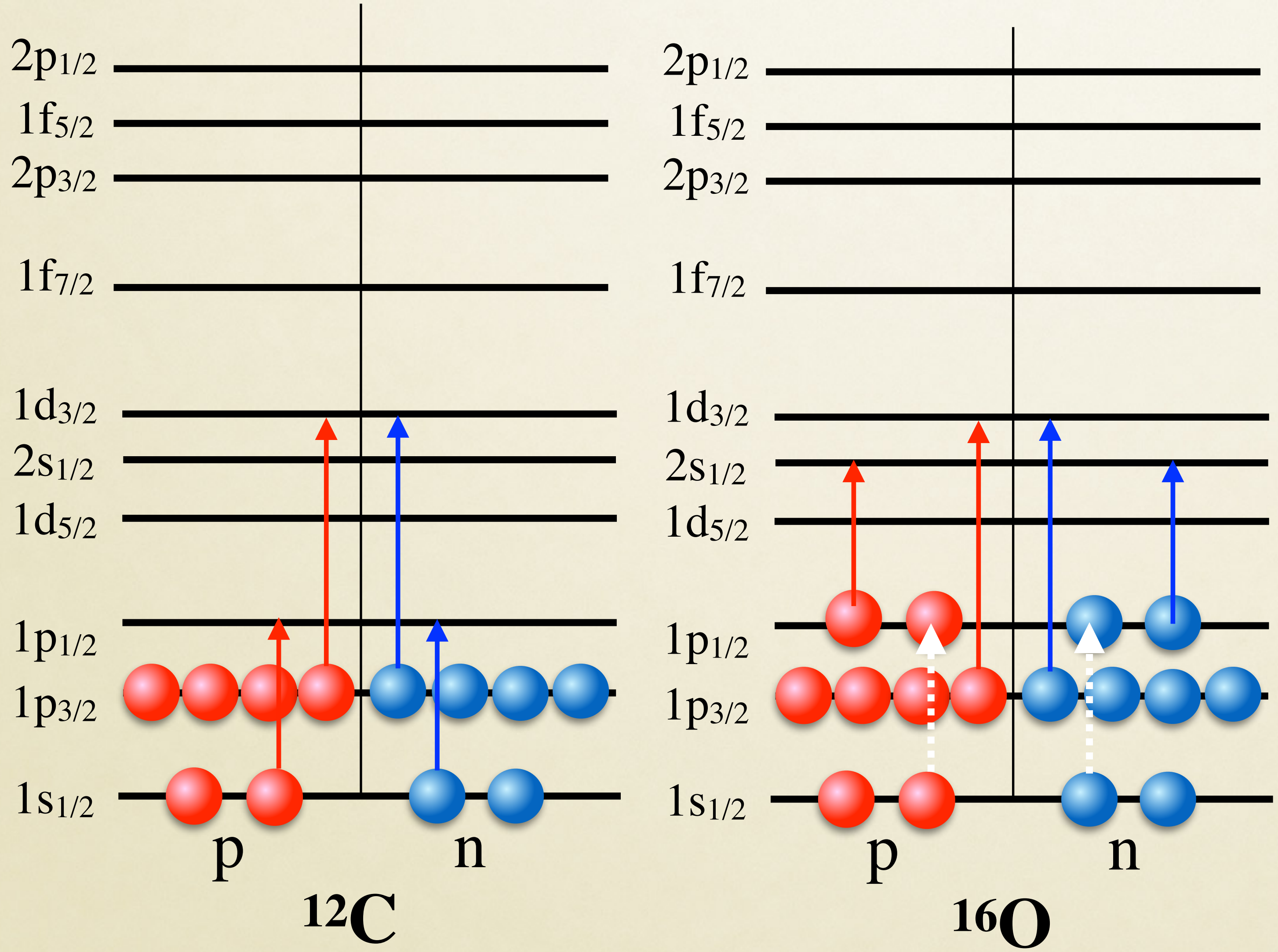


^{12}C do not suffer blocking of tensor!

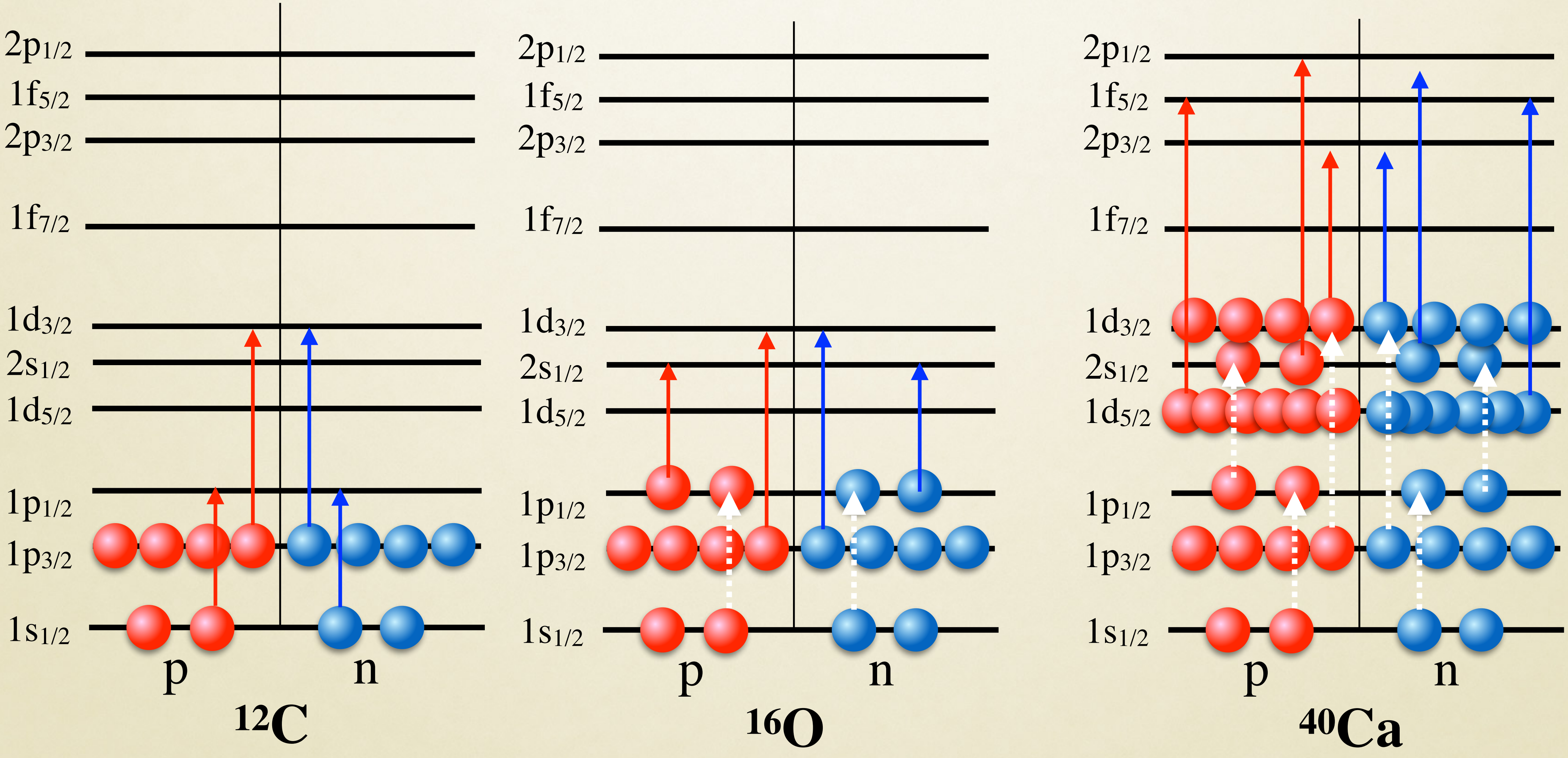
Tensor Blocking and Nuclear Saturation



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

Tensor Blocking and Nuclear Saturation

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



- **Pion exchange produces the Central and the Tensor Forces.**
- **Attraction by the tensor force is gained by a transition of a *pn* pair of to a higher-momentum state under selection rule $\Delta S=2, \Delta L=2$.**
- **Tensor interaction is blocked when nucleon occupy higher orbitals and thus nuclear saturation occurs.**

Experiment to detect high-momentum correlated nucleons

$^{16}O(p,d)^{15}O$ and $^{16}O(p,pd)^{14}N$ studies

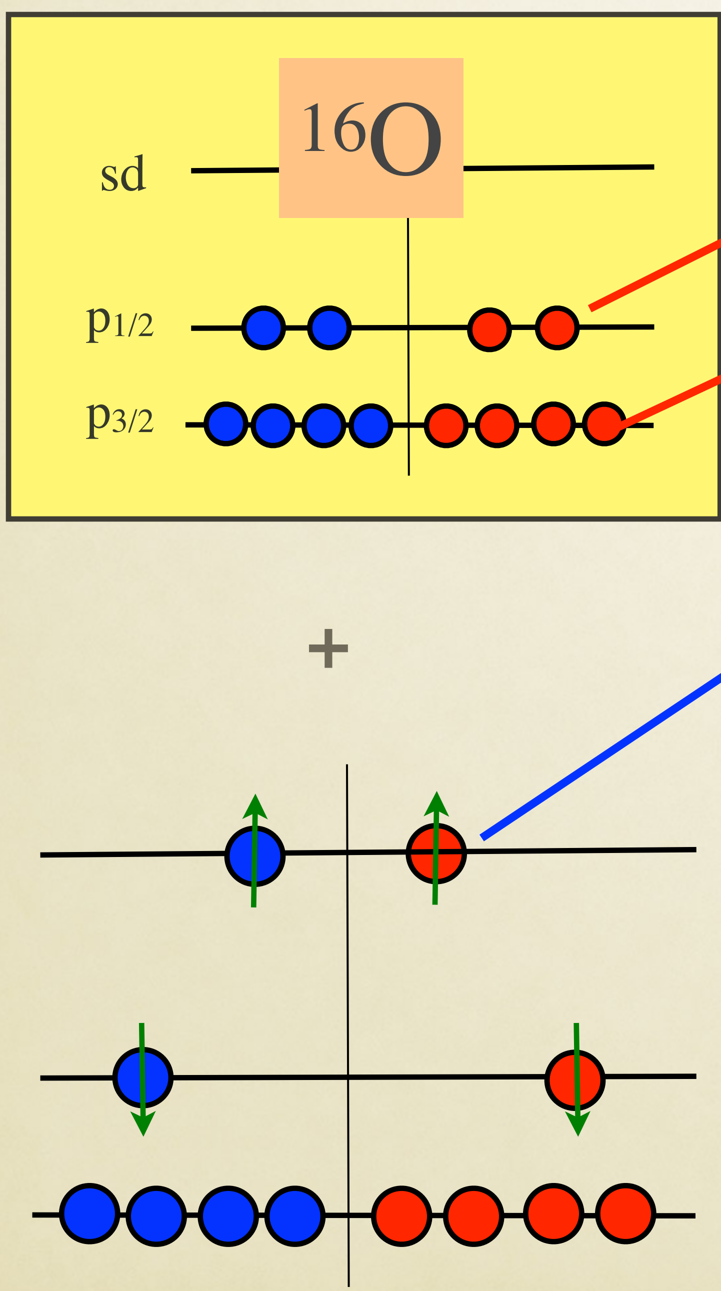
Pick up of high-momentum neutron

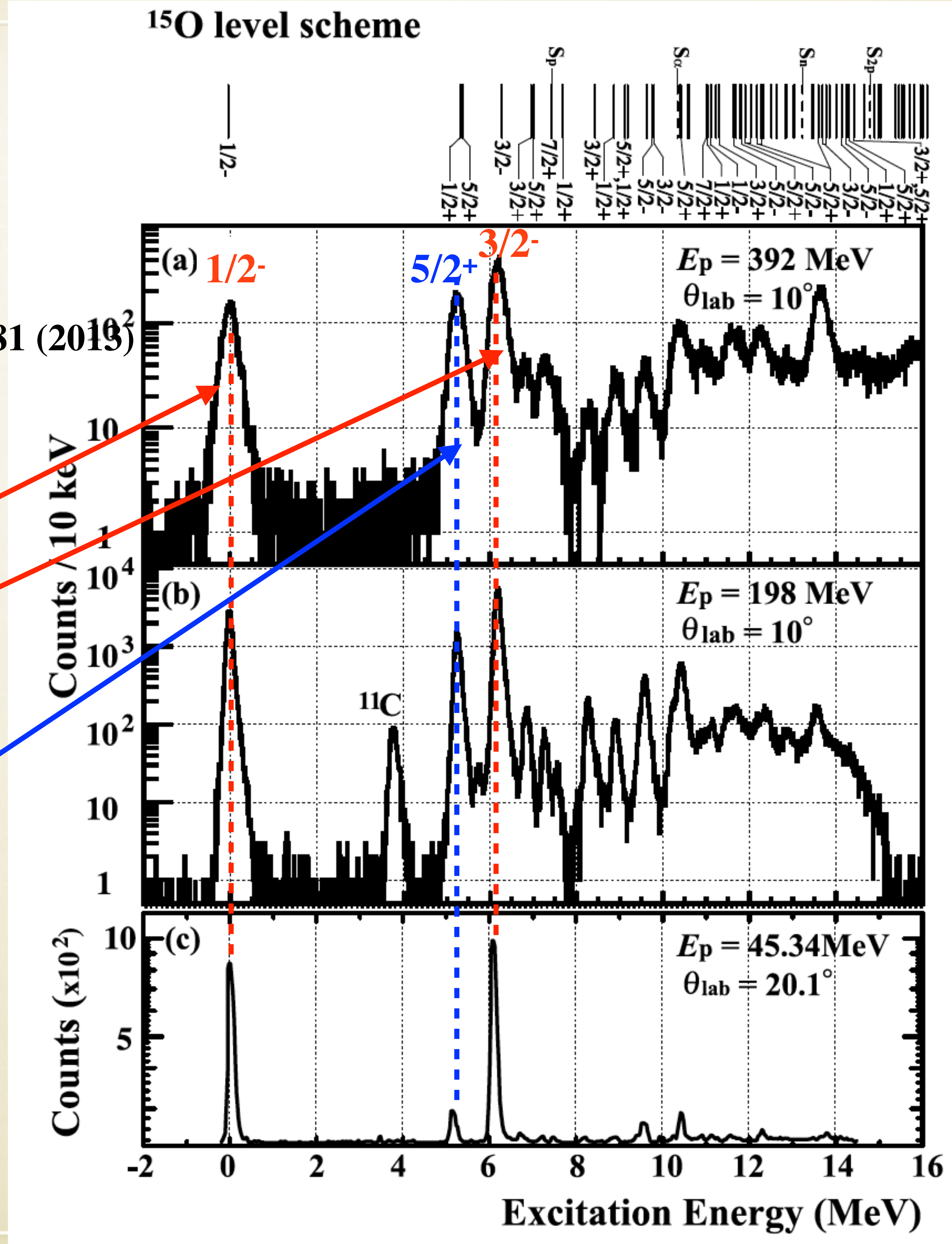
1. **Compare the momentum amplitude of normal shell neutrons and high-momentum neutrons**

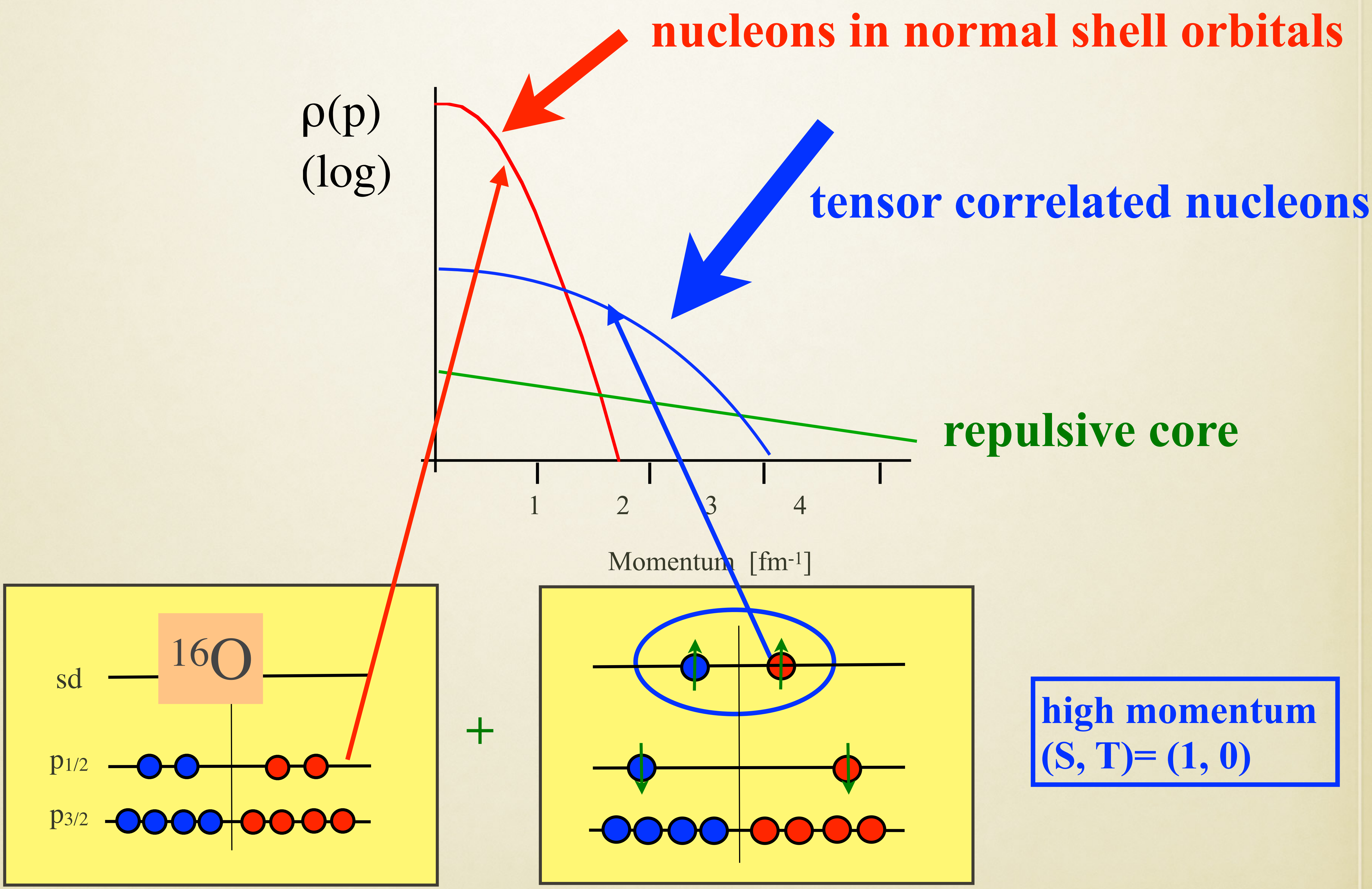
2. **Compare the probability of (*S*, *T*)=(1, 0) and (0, 1) pairs.**

$^{16}O(p, d)\,^{15}O$

H.-J. Ong et al., Phys. Lett. B 725, 277-281 (2013)

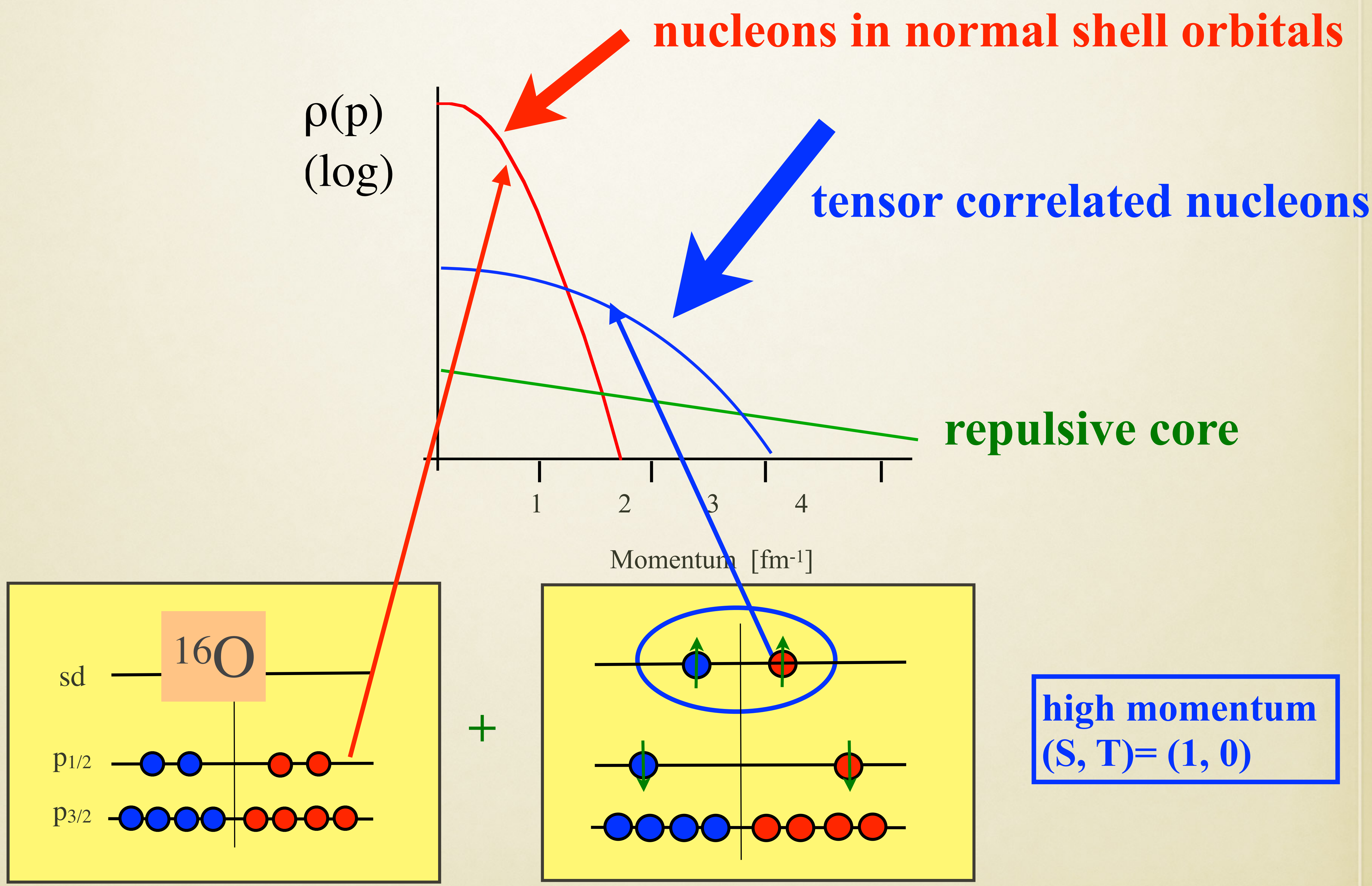






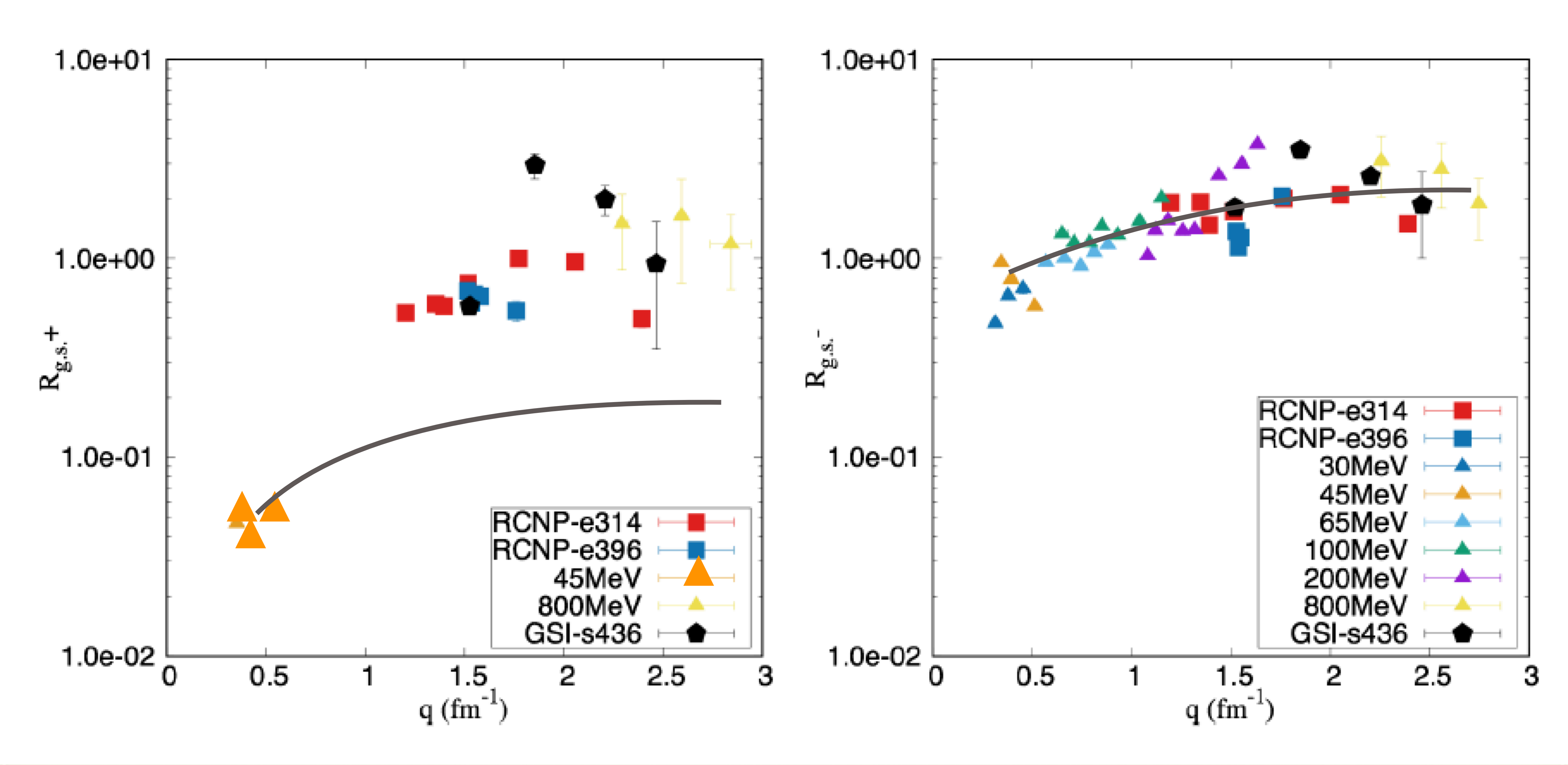
nucleons in normal shell orbitals
ρ(p)
(log)
tensor correlated nucleons
repulsive core
1
2
3
4
Momentum [fm-1]
16O
sd
p1/2
p3/2
+
high momentum
(S, T)= (1, 0)

Momentum distribution of nucleons



Recent Data at FRS at 400, 600, 900, 1200 MeV at 0° scattering angle

Xuan Wang: Talk in this meeting on Friday.



CCBA calculation by Ogata

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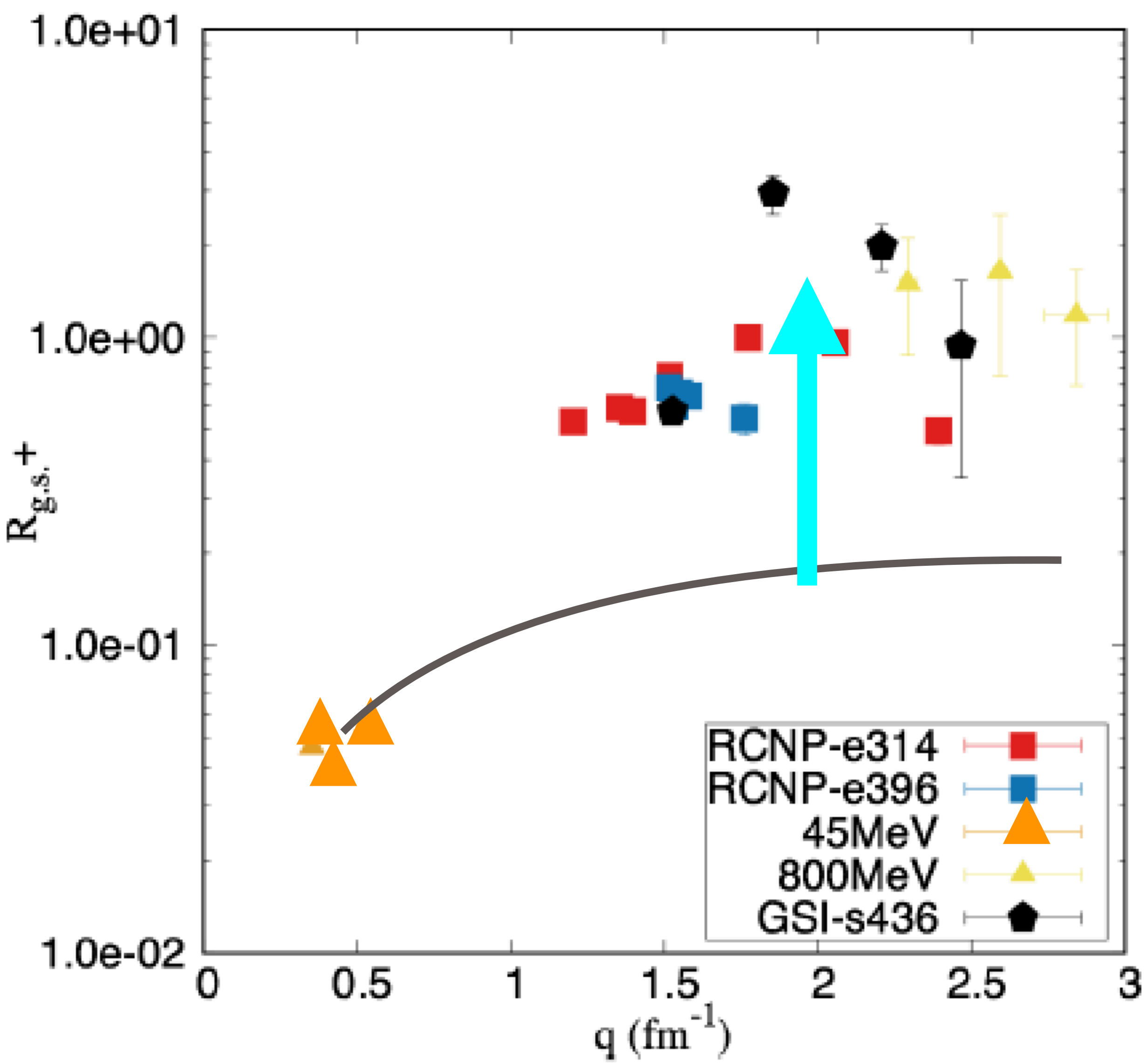
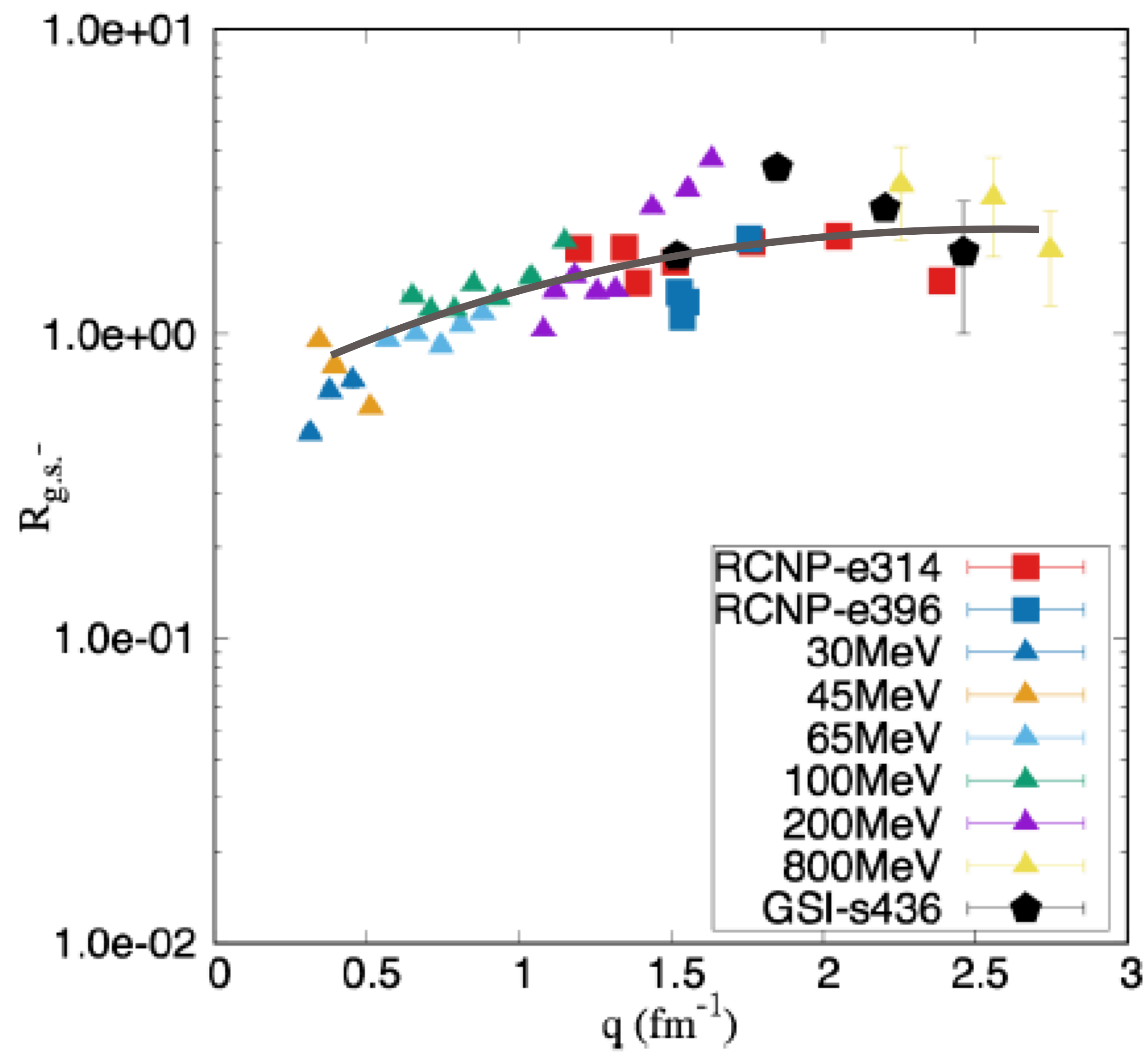


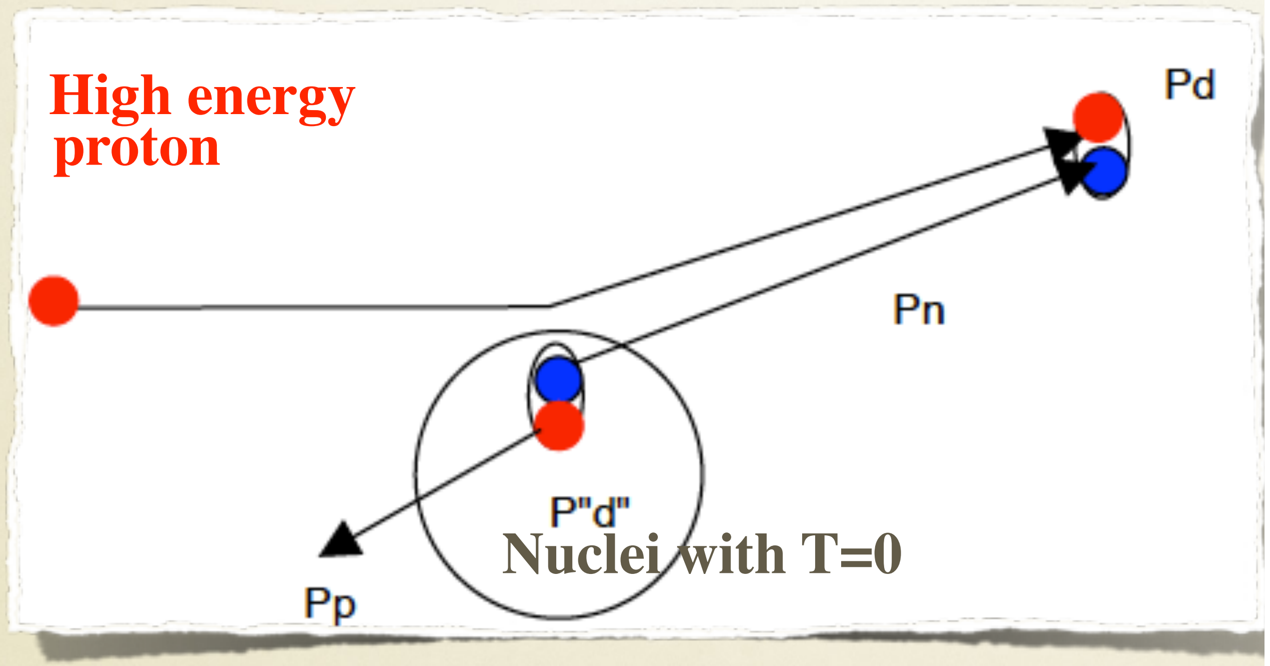


CCBA calculation by Ogata

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

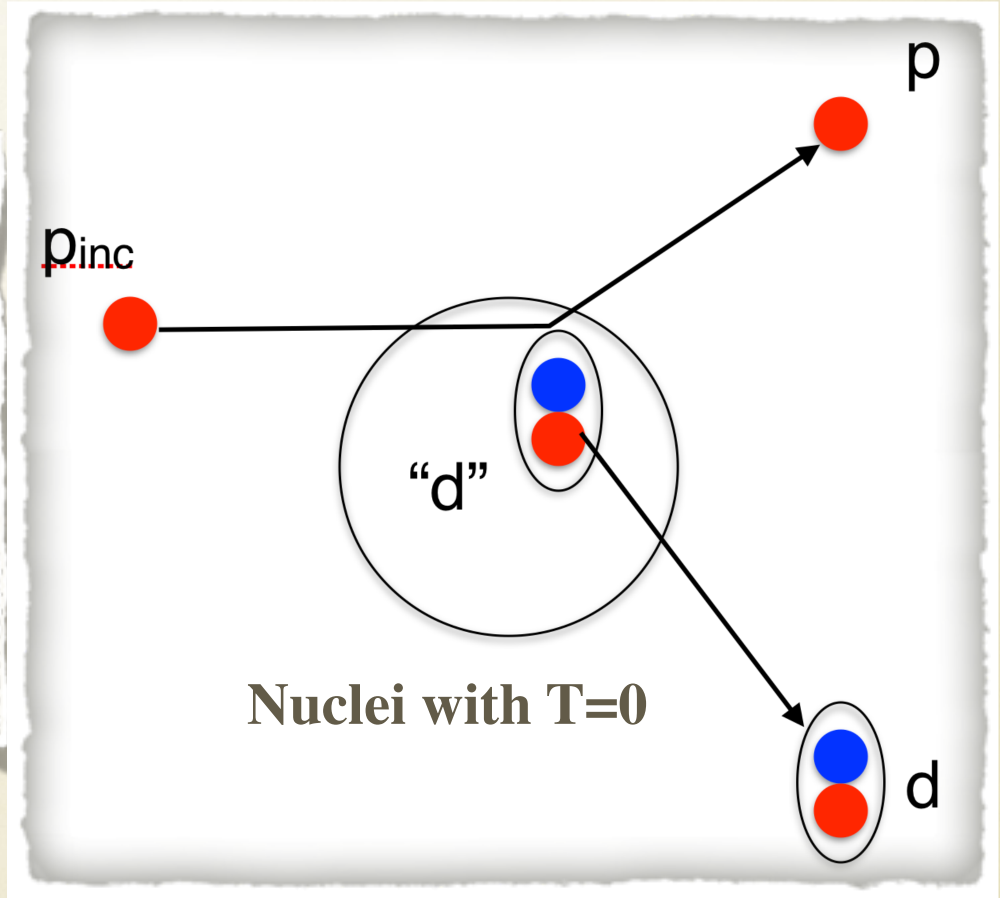
- A measurement of correlated pn pairs in nuclei with large relative momenta.

Pick up



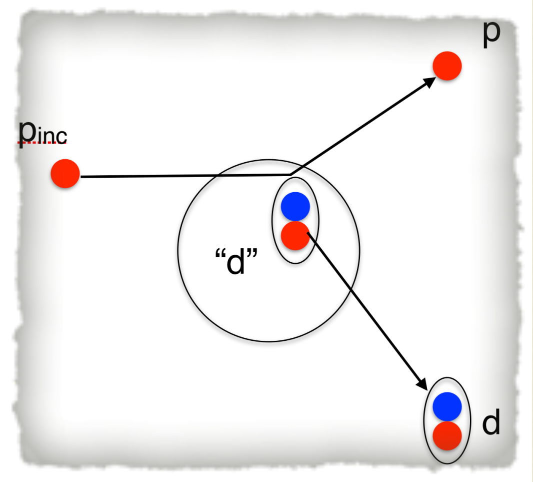
***T* of residual nuclei = *T* of internal "d"**

Knock out

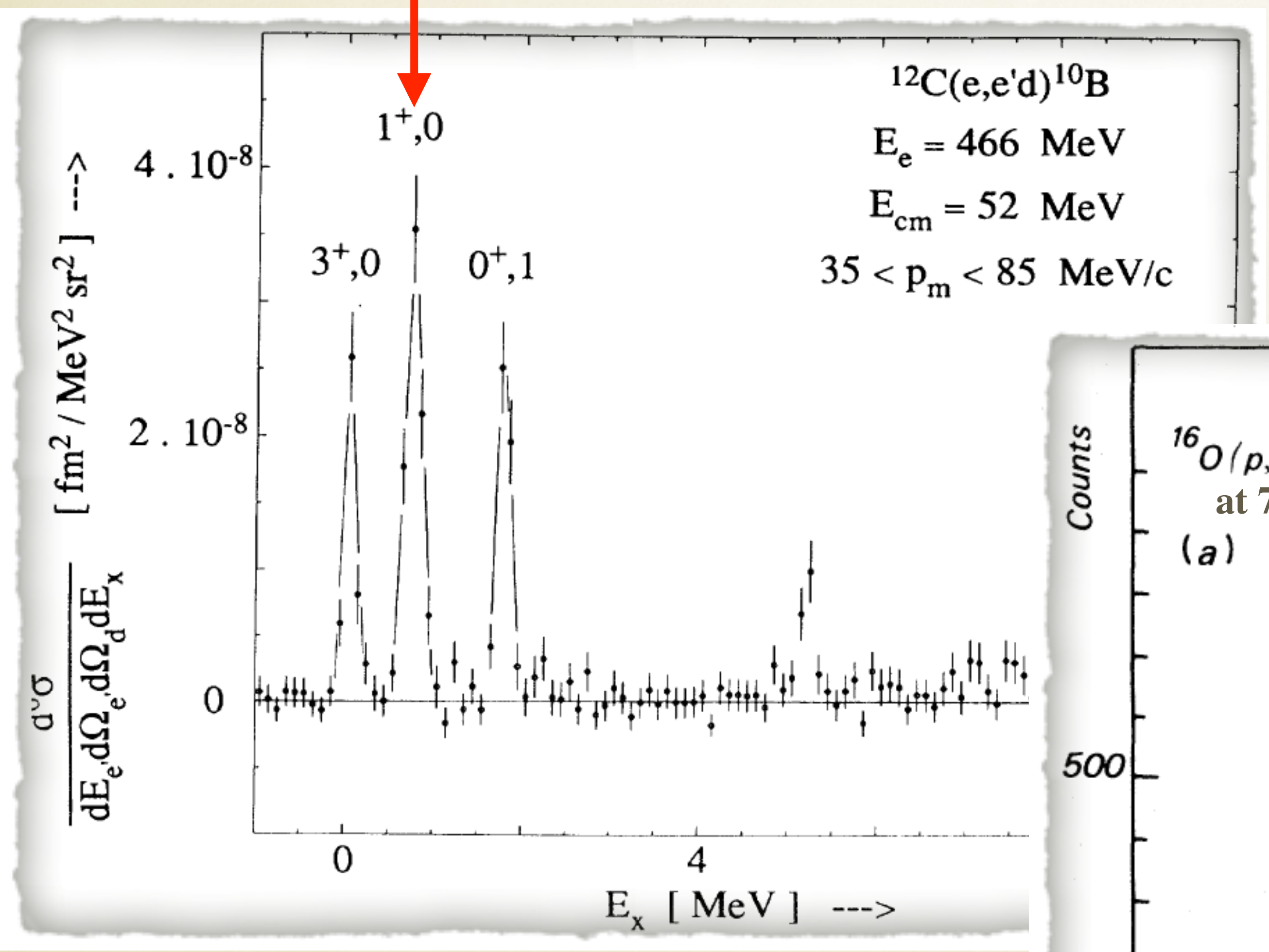


***T* of residual nuclei = 0 or 1**
: independent from *T* of "d"

Knock out data

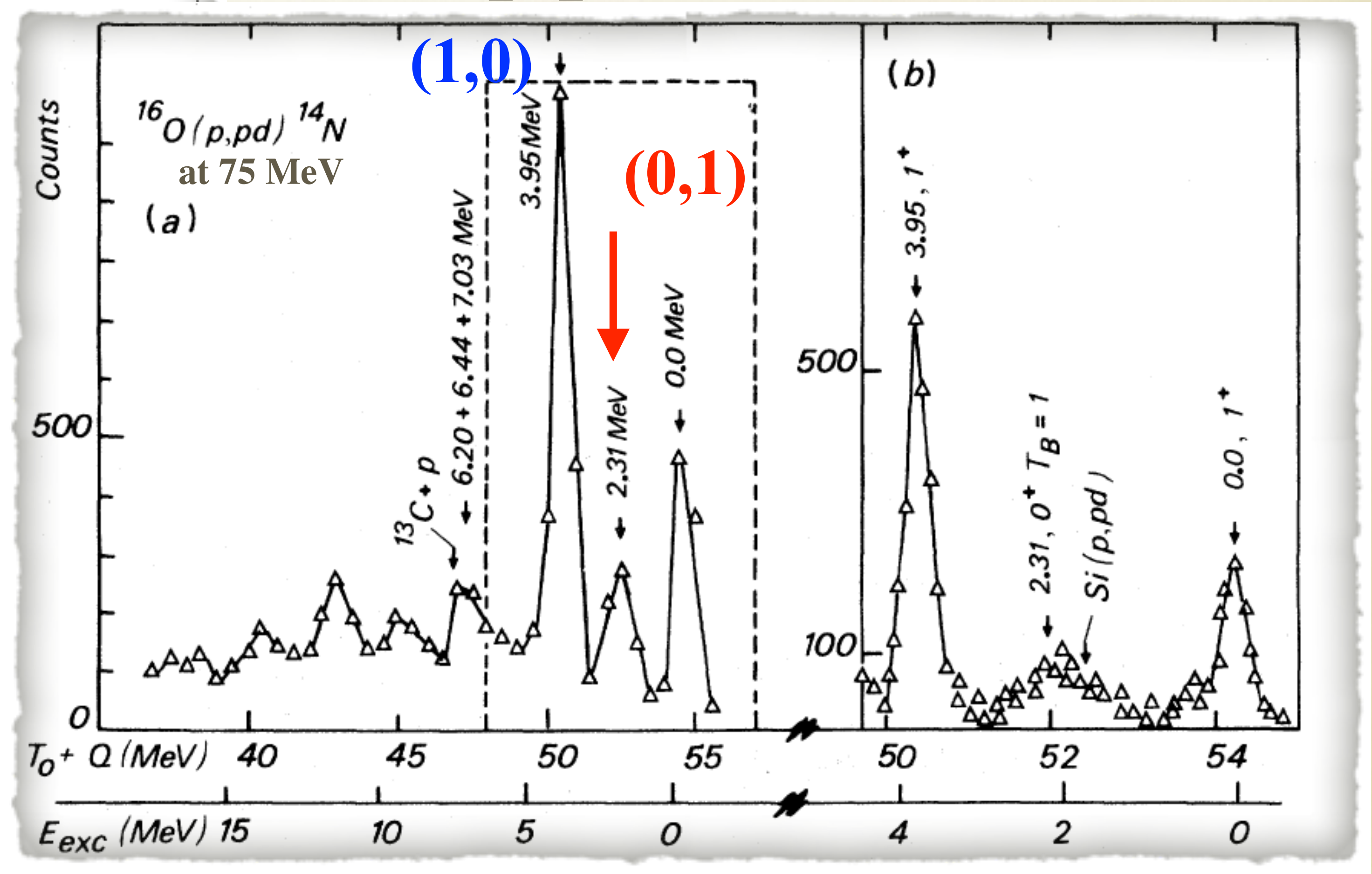


$^{12}C(e,e'd)^{10}B$ @466MeV



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)

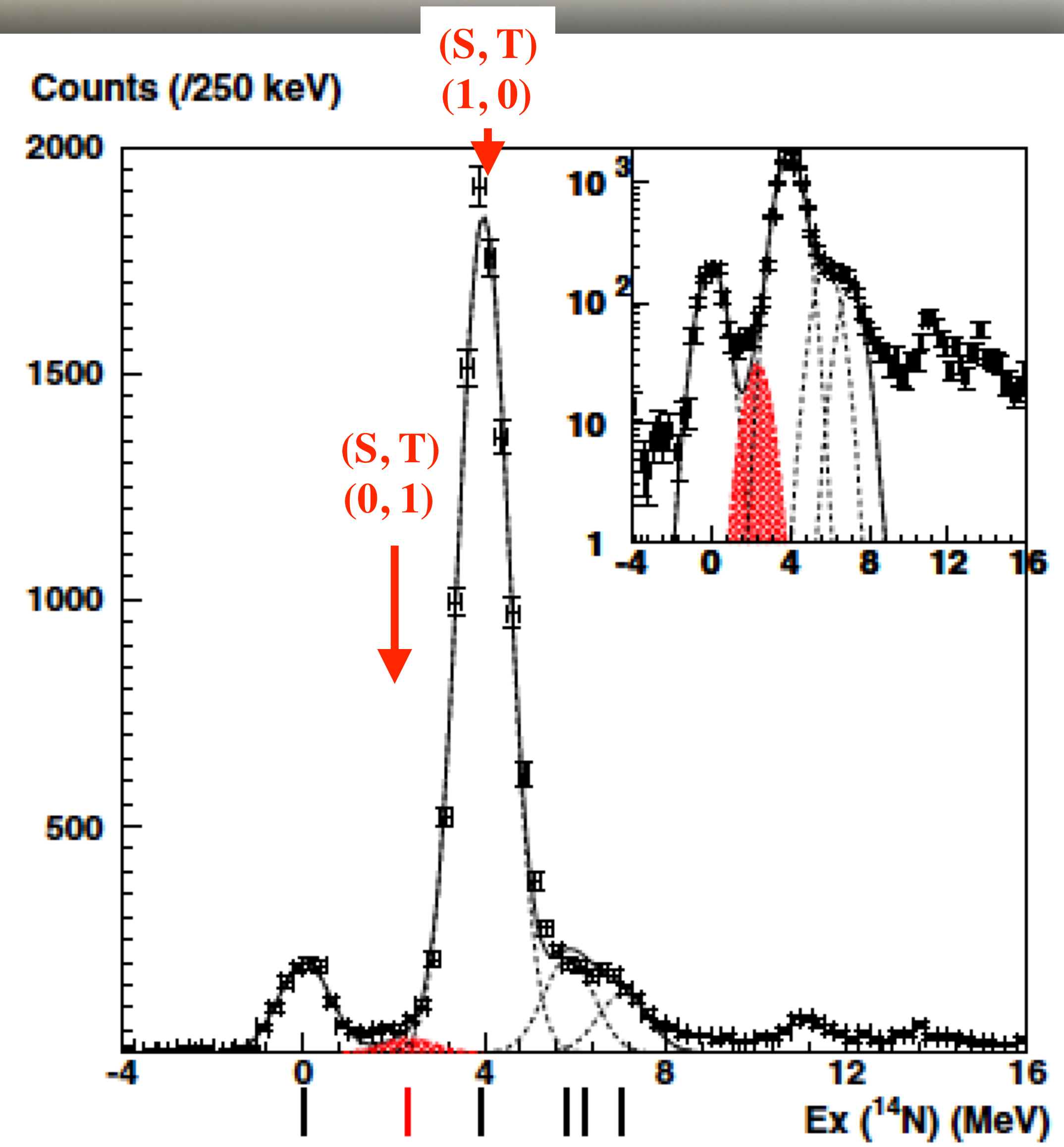
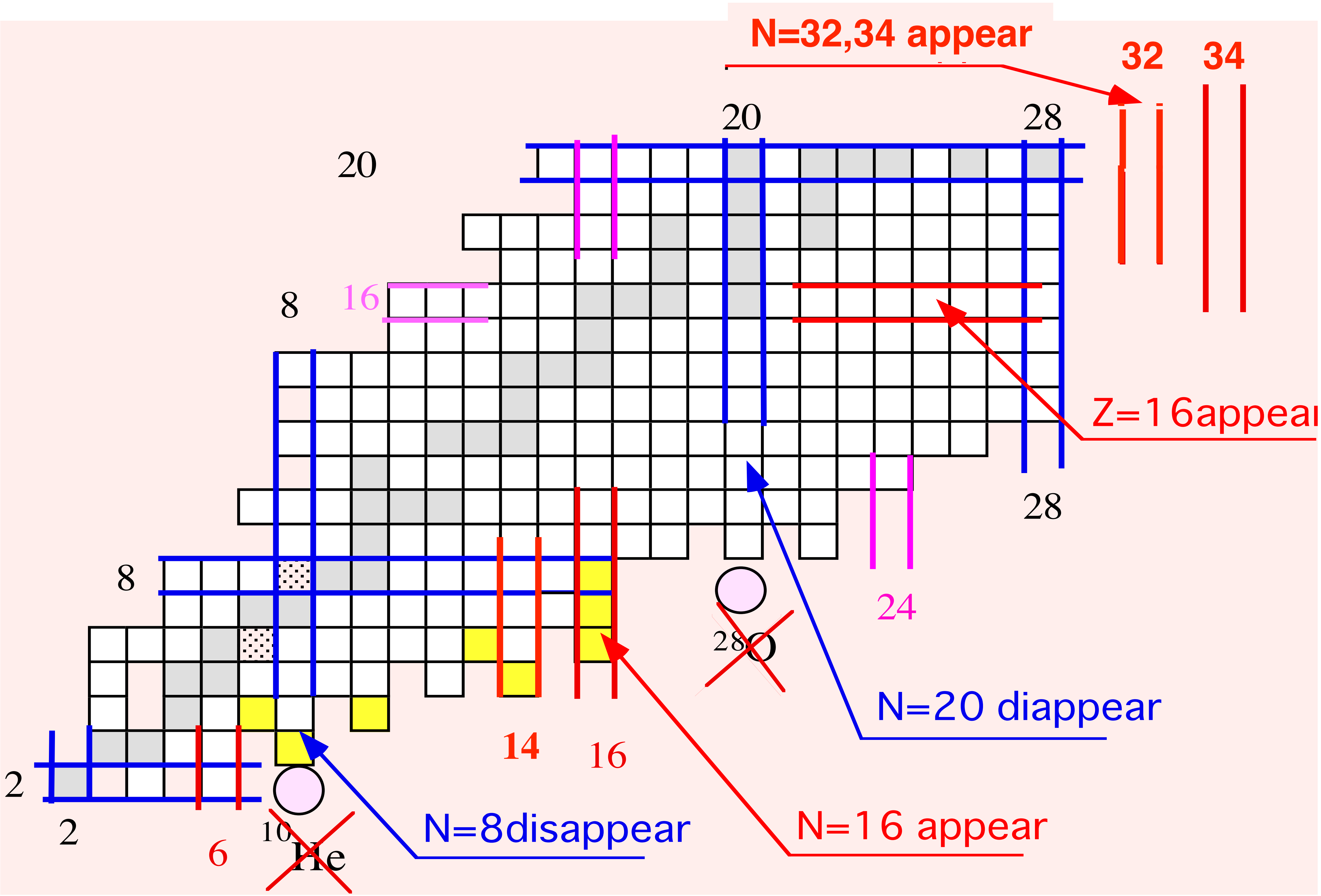


FIG. 2. The excitation energy spectrum of $^{16}O(p, pd)$ for $\theta_d = 8.6°/\theta_p = 138.4°$ with the total and individual fitting results shown by the solid and dashed lines, respectively.

When high-momentum neutron is picked up, most of the "d" was *S*=1 and *T*=0 pair consistent with tensor correlated pair.

Change of magic numbers

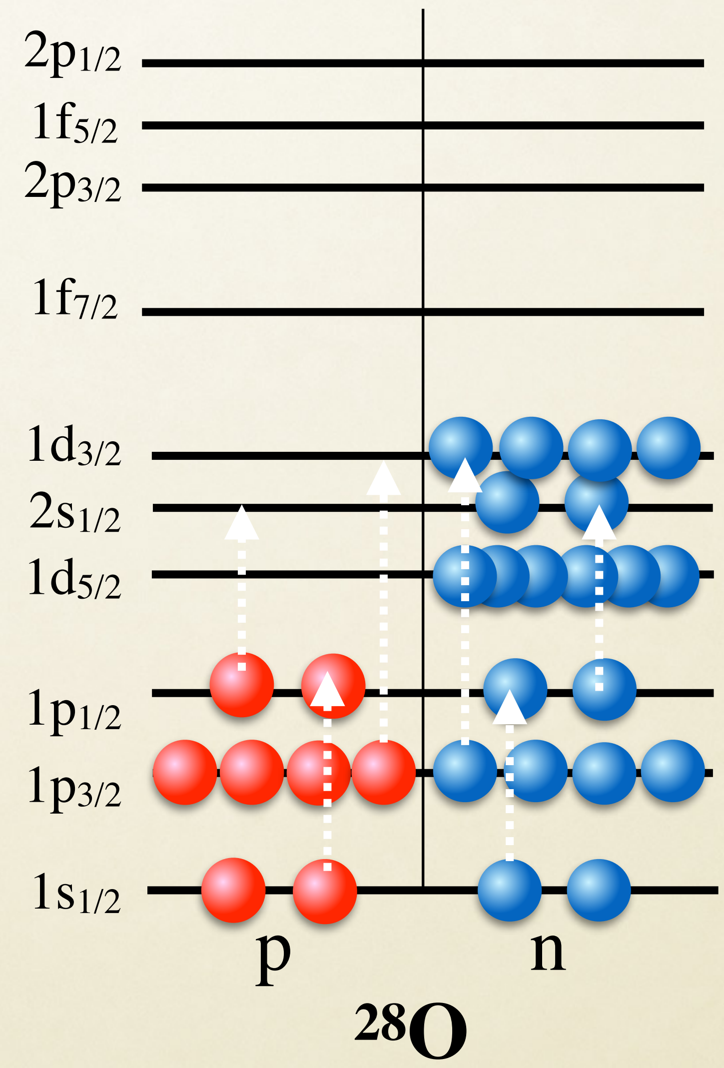
Studies with RIB changed the Map of Nuclei



What is the difference between stable and neutron rich nuclei?

Symmetric nuclei

Neutron rich nuclei



Blocking and Opening occur simultaneously.

Only tensor blocking occurs.

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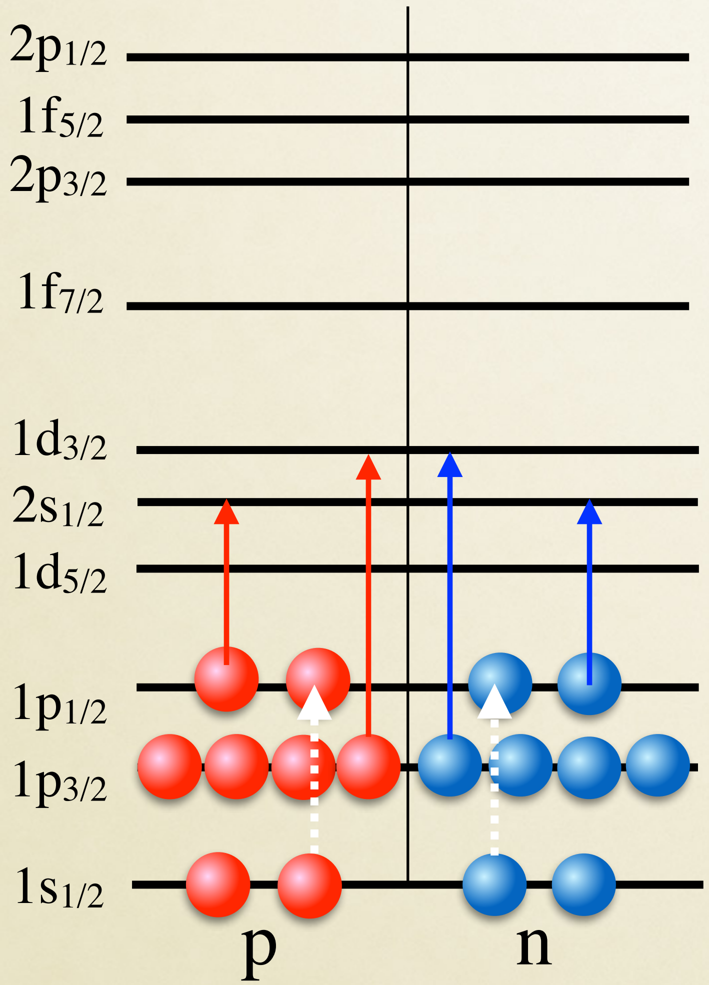

^{16}O

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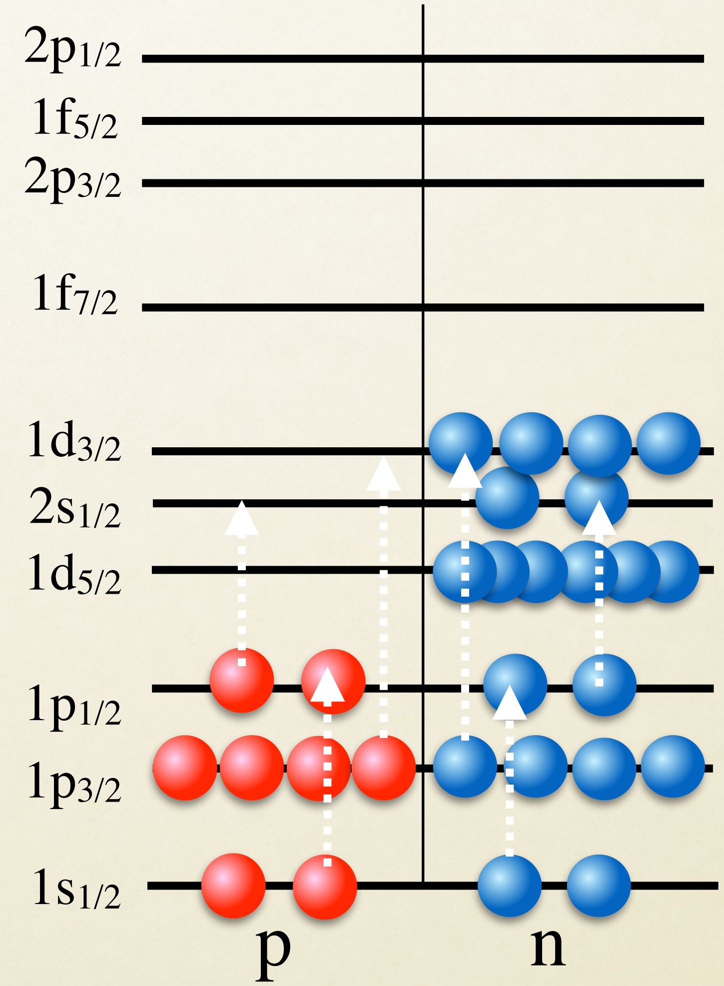
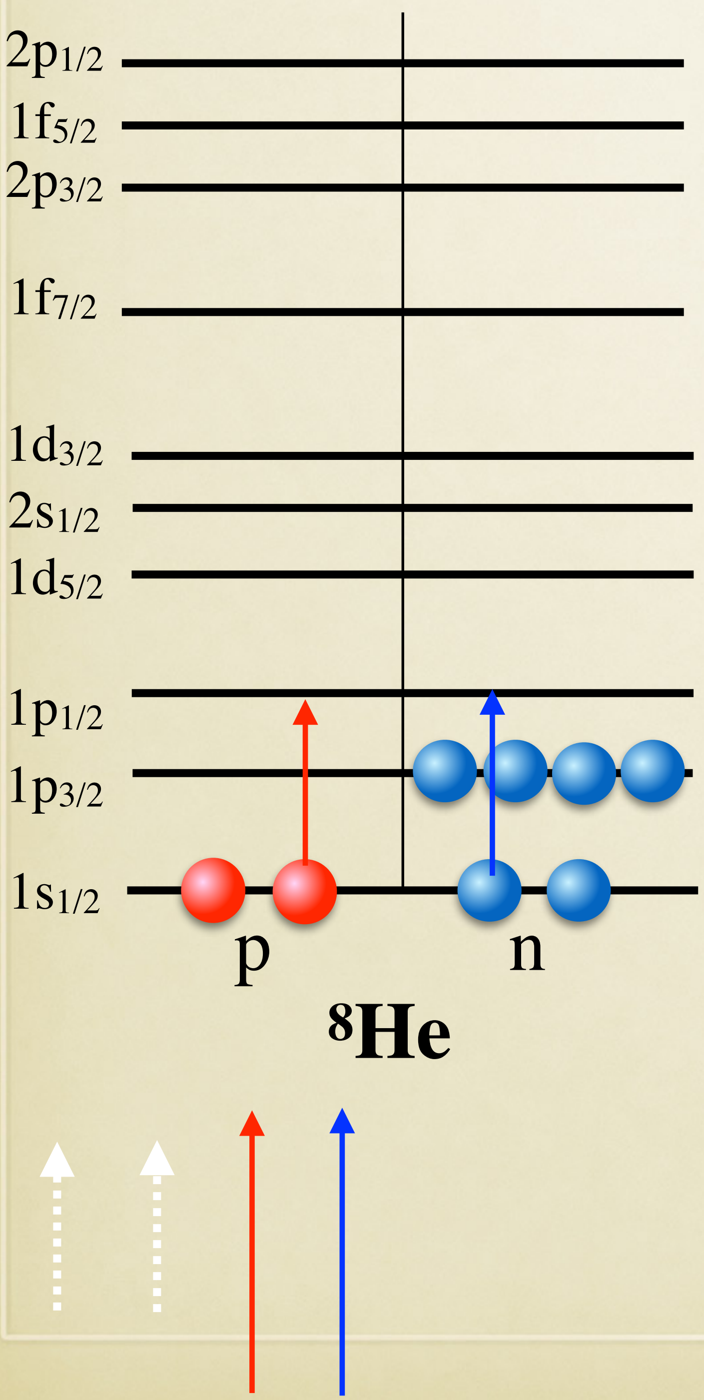
Neutron rich nuclei

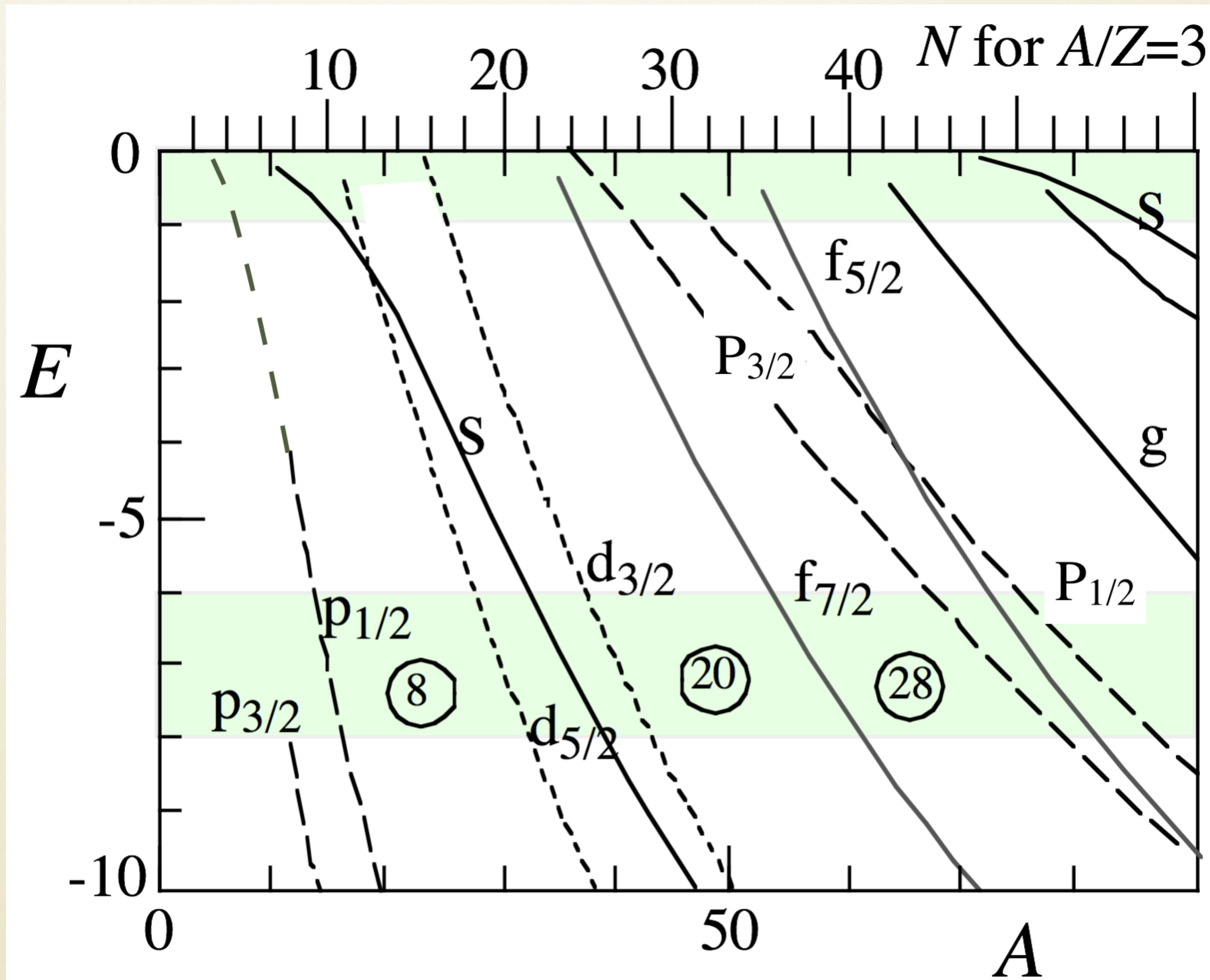


^{28}O

Only tensor blocking occurs.

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





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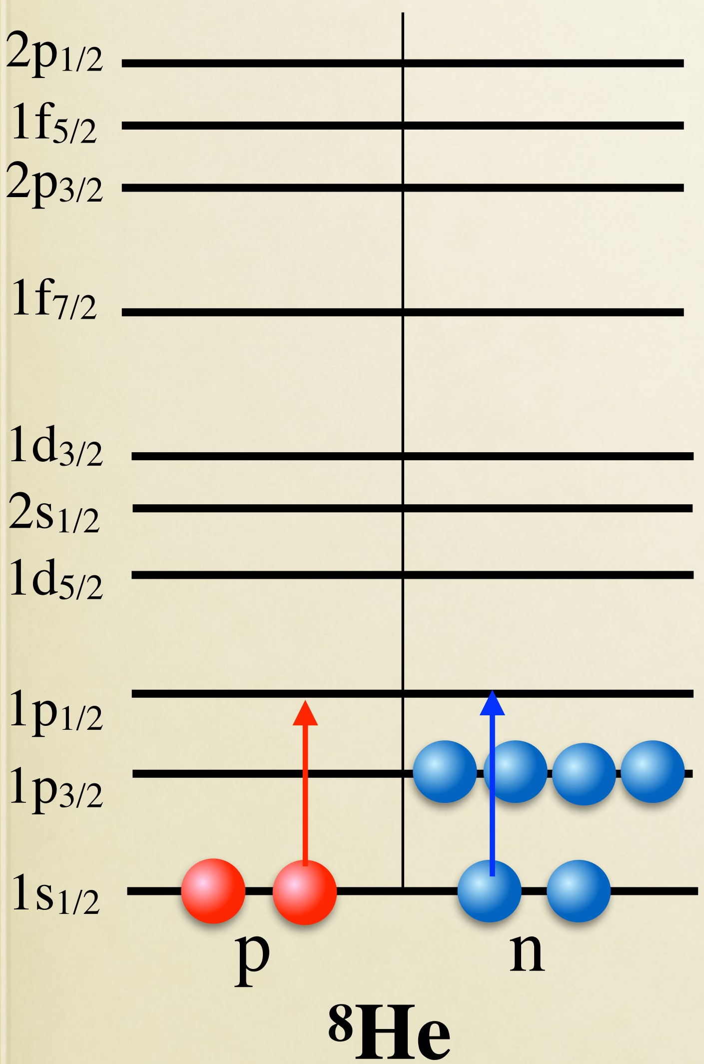

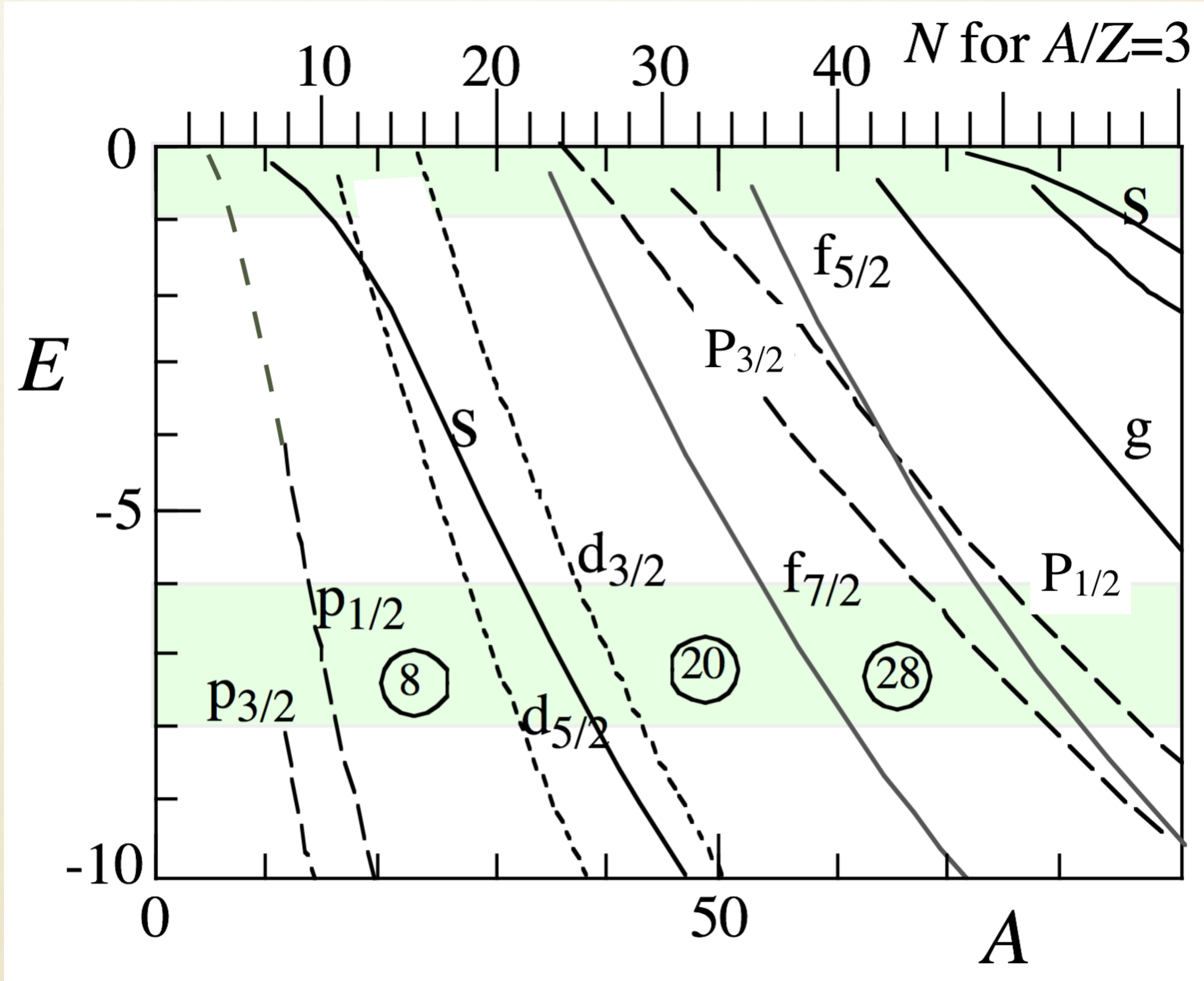

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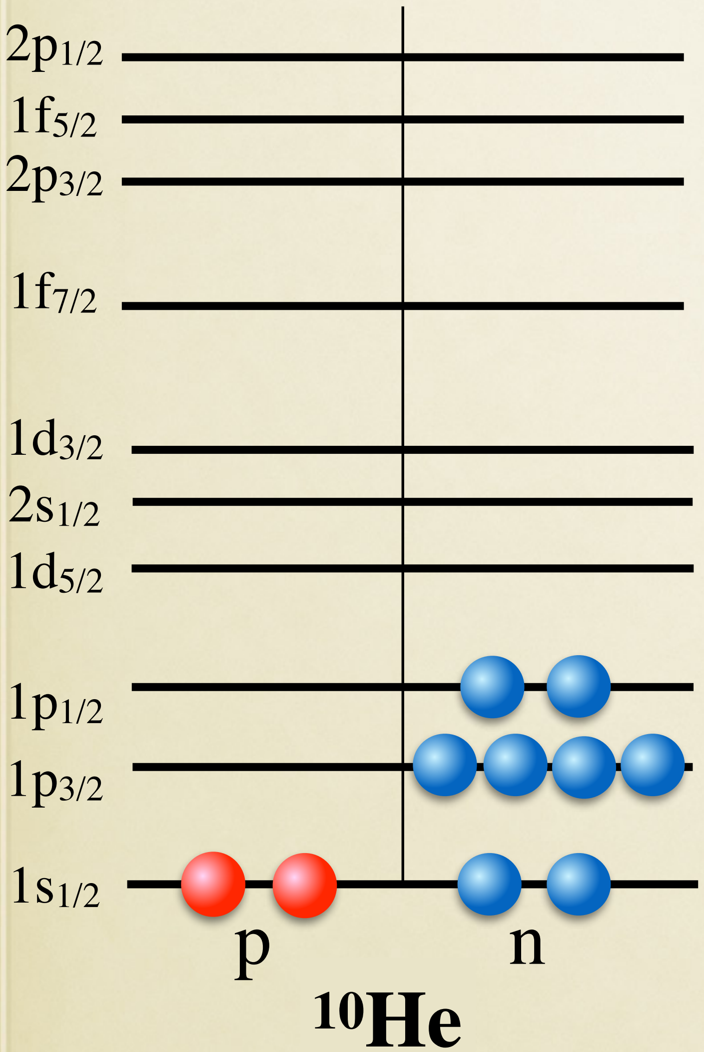

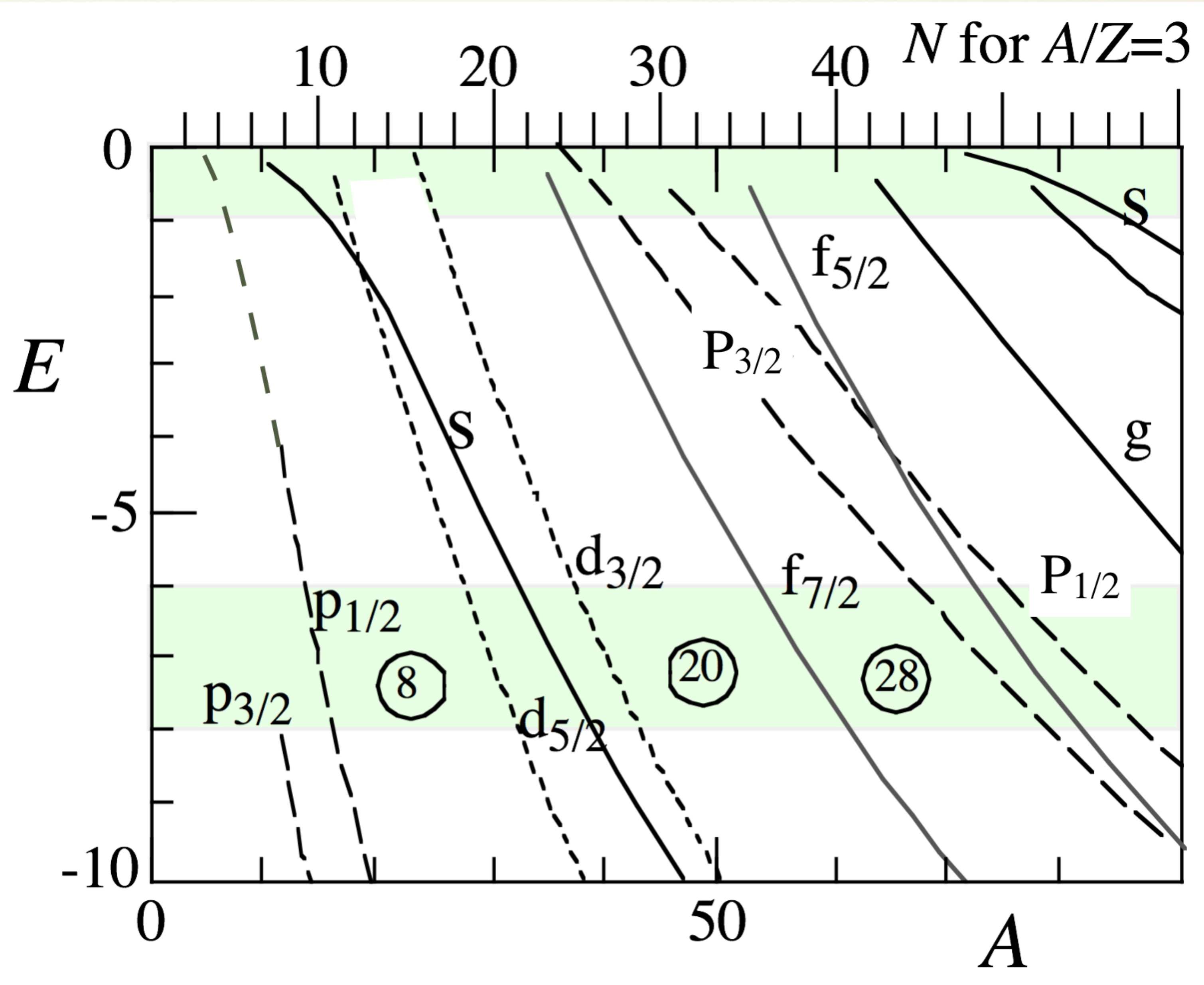

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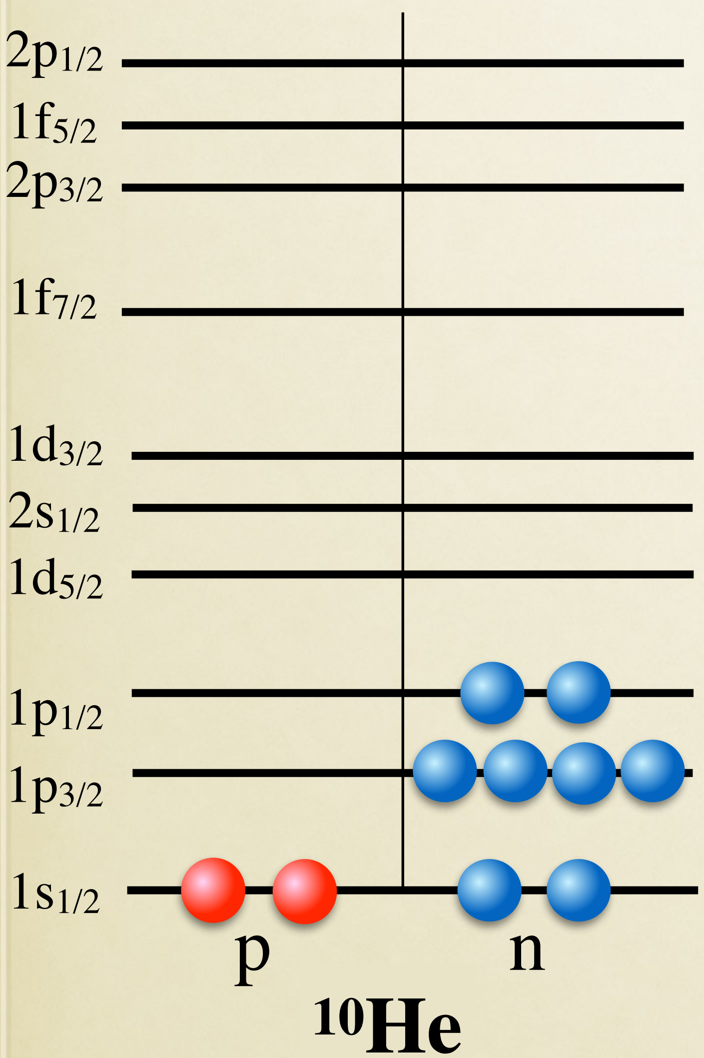

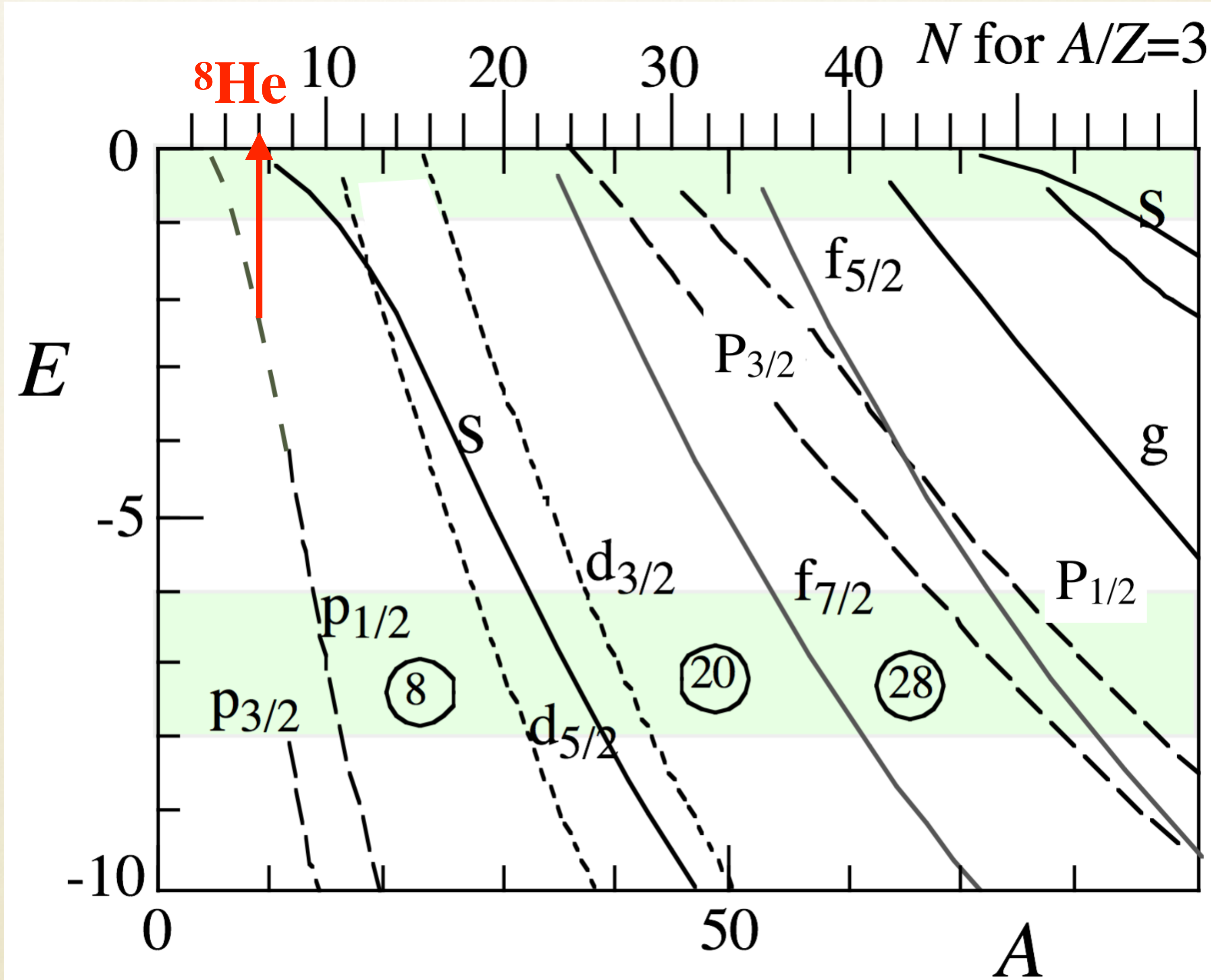

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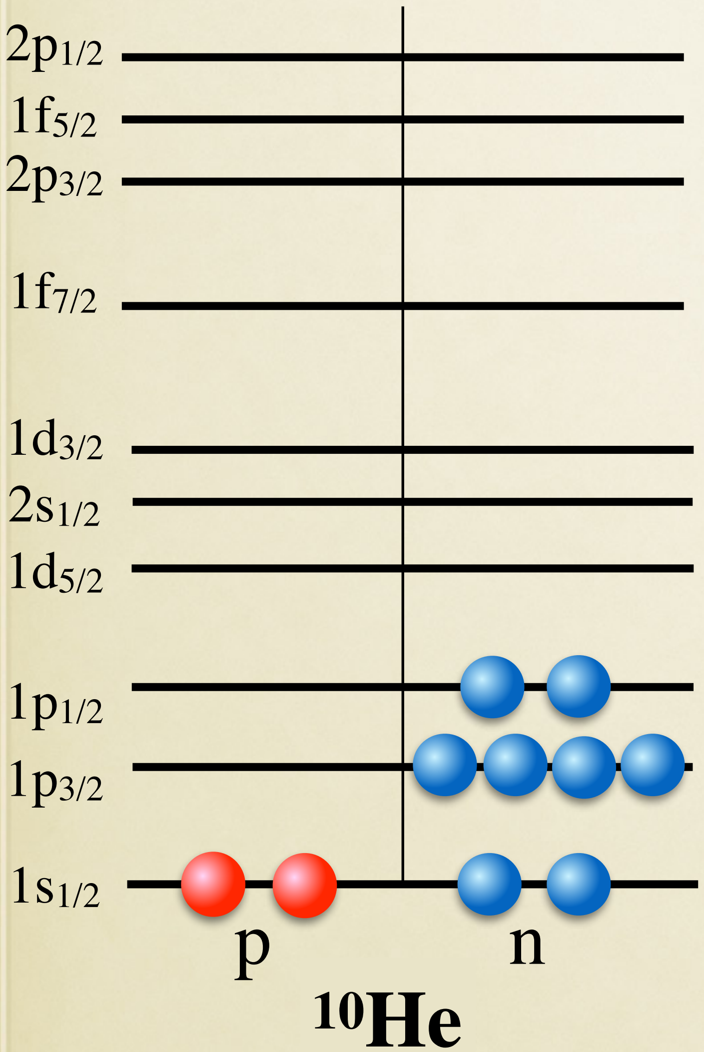

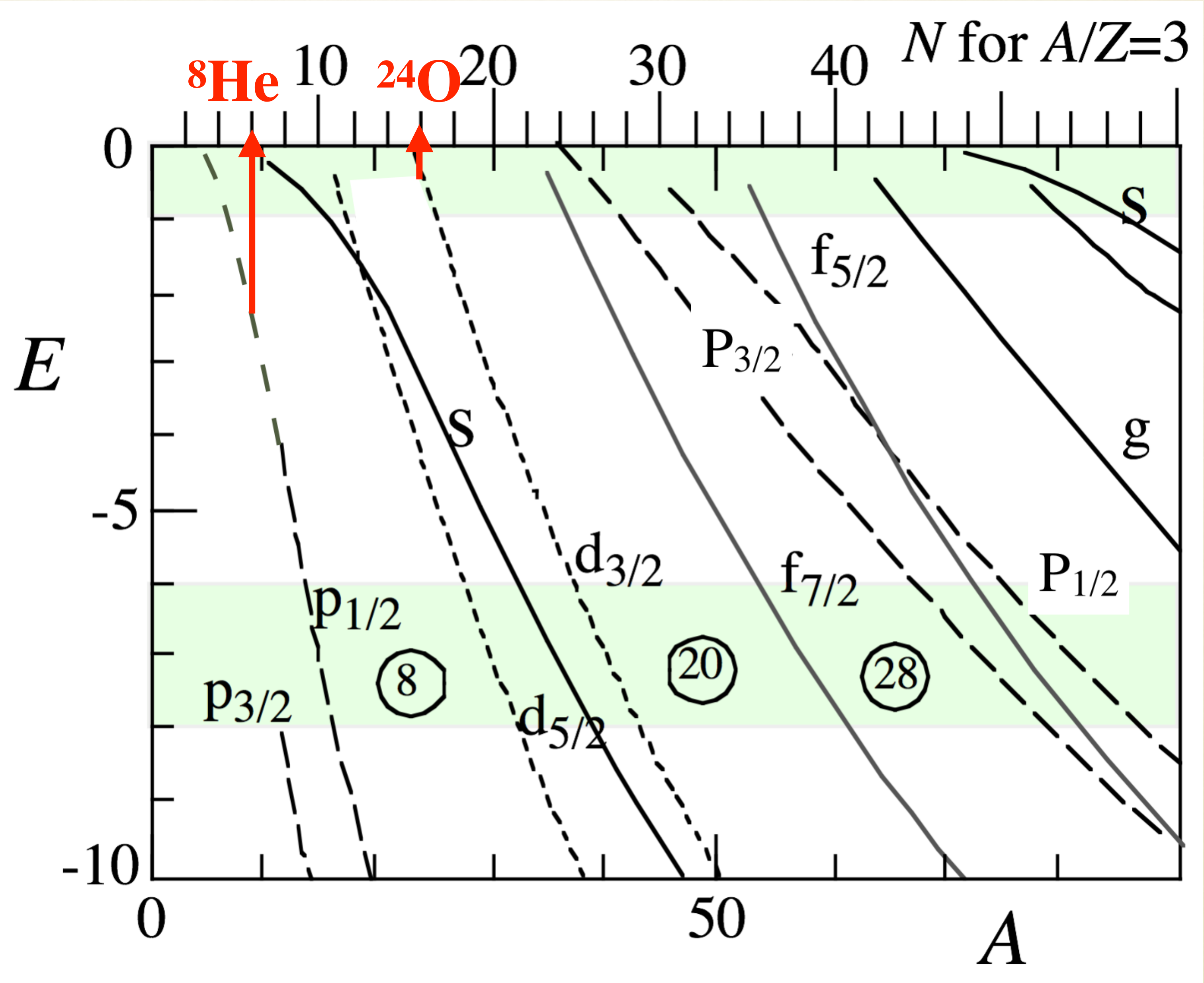

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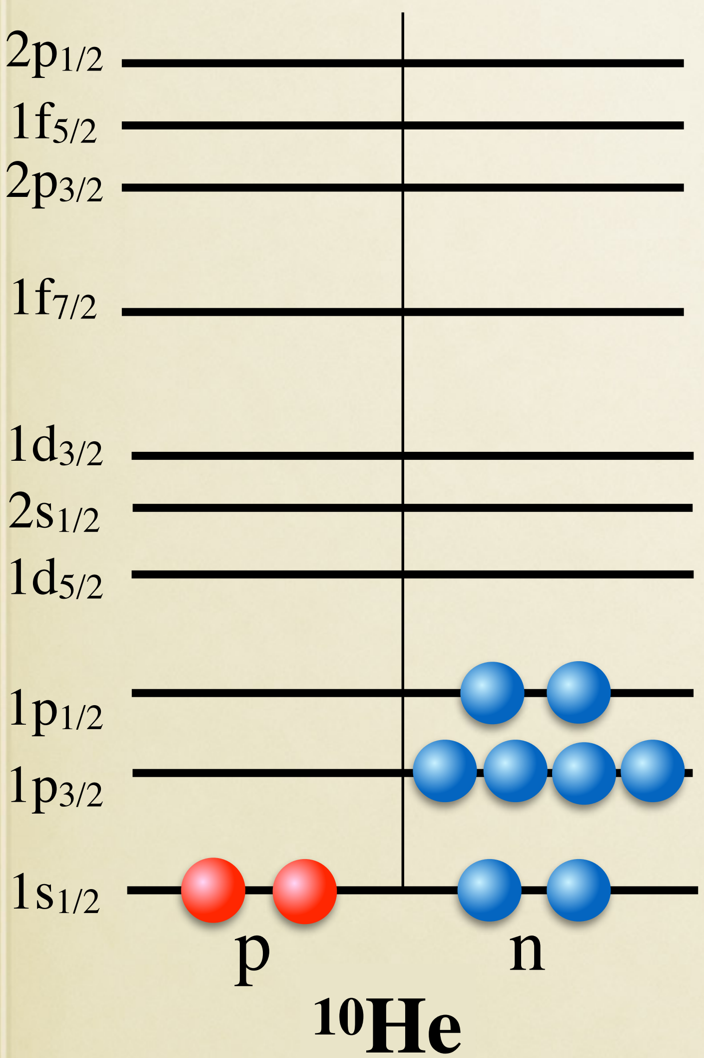
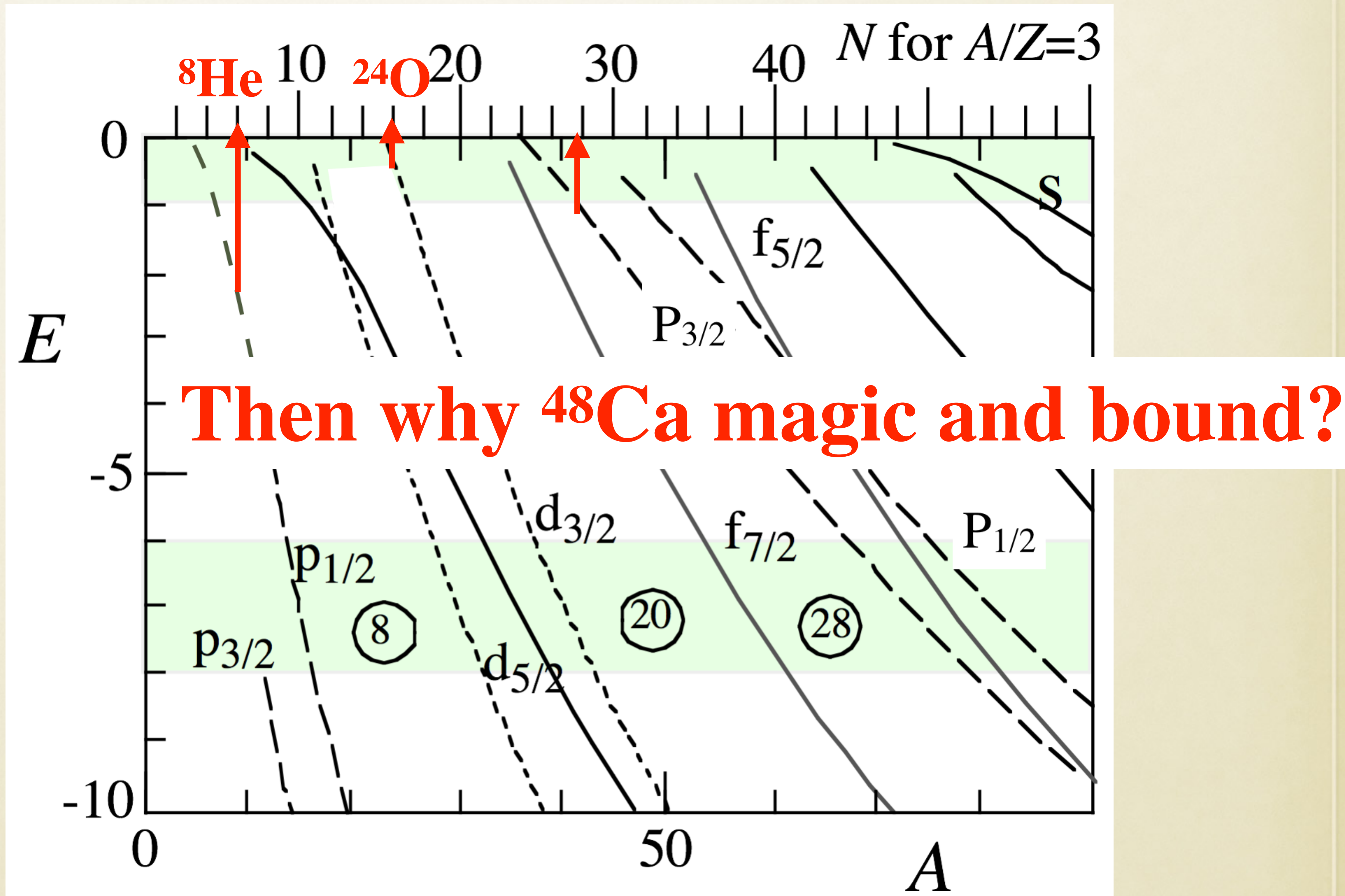
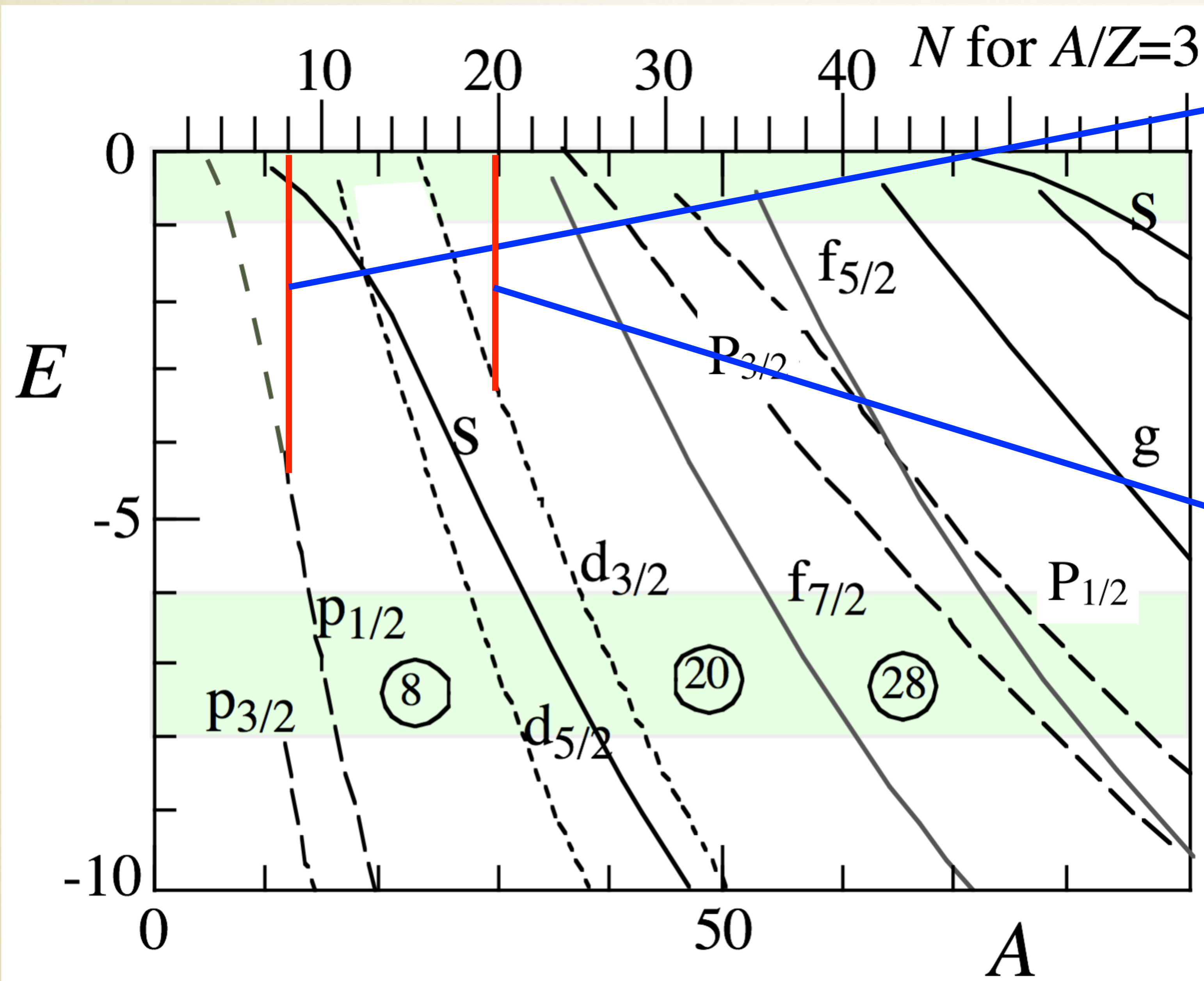




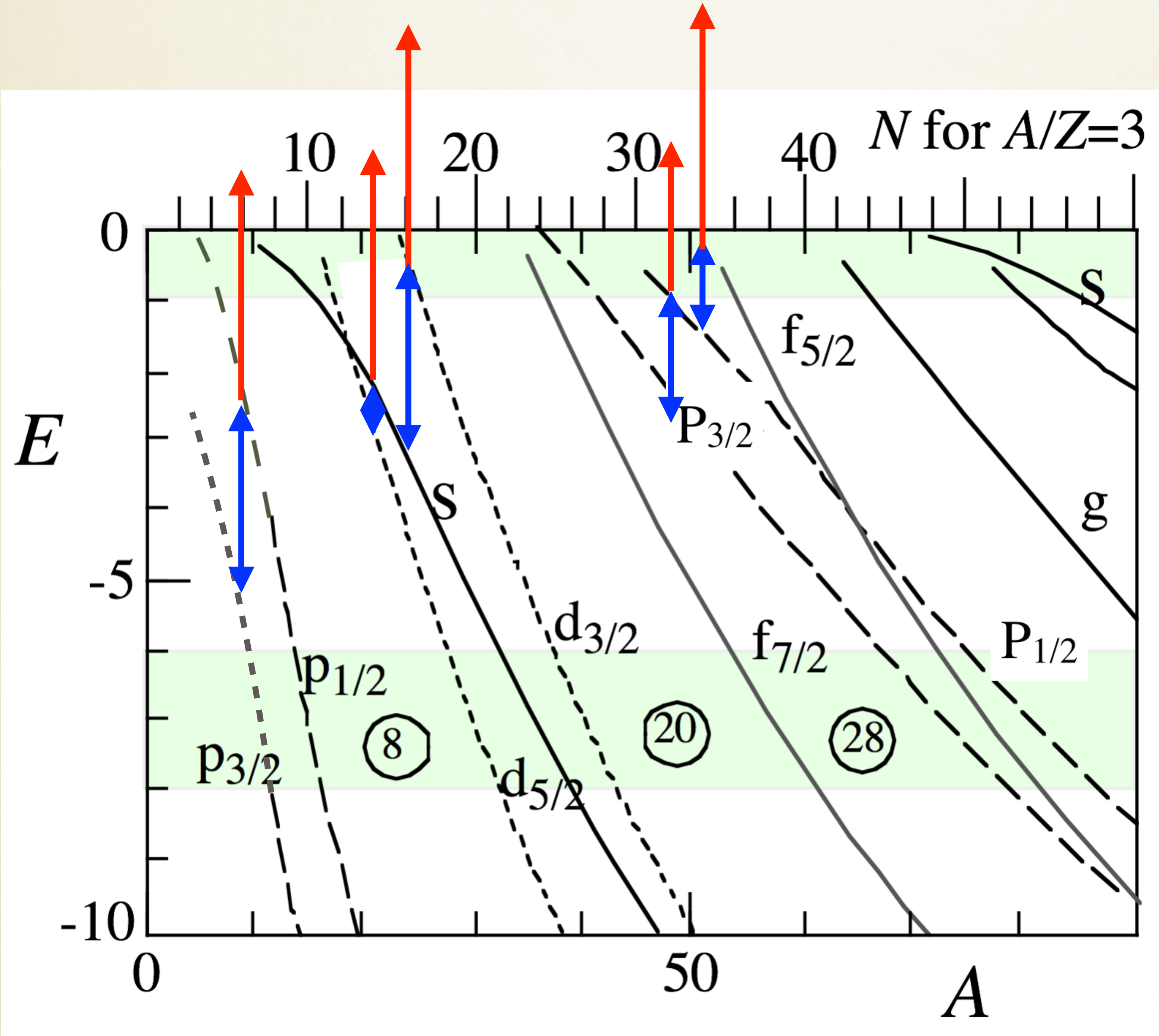
Why magic numbers *N*=8 and *N*=20 disappear in neutron-rich nuclei?



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 $p_{3/2}$ does not until proton fills $d_{3/2}$.

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.

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.**

Summary

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Conclusion

- All new magic numbers appeared in neutron rich nuclei are strongly affected by the tensor blocking.
- Disappearance of traditional magic numbers and non binding of ^{8}He and ^{28}O are consistent with the tensor blocking.
- Sudden extension of dripline in F is understood.
- A peculiar change of GS configurations is understood.

Collaborators

- H. Toki, RCNP Osaka Univ., Osaka, Japan
- S. Terashima, IRCNPC Beihang Univ., Beijing, China
- H.-J. Ong, RCNP Osaka Univ., Osaka Japan

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Thank you for your attention