Effects of Tensor Forces in the Ground State of Nuclei

PKU-CUSTIPEN Nuclear Reaction Workshop
2014.3.19

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Based on: I. Tanihata. (2013). "Effect of tensor forces in nuclei." Physics Scripta **2013 T152**:
and new data at RCNP and GSI

The big goal:

- Successful models are based on effective men field that are constructed by central forces
- We know that the nucleon-nucleon interaction, in particular, the important pion exchange includes tensor forces in a same amplitude. $\vec{\sigma}_1 \cdot \vec{q}\vec{\sigma}_2 \cdot \vec{q} = \frac{1}{3}q^2 S_{12}(\hat{q}) + \frac{1}{3}\vec{\sigma}_1 \cdot \vec{\sigma}_2 q^2$ $\quad S_{12}(\hat{q}) = \sqrt{24\pi}\left[Y_2(\hat{q})\left[\sigma_1\sigma_2\right]_2\right]_0$

R. B. Wiringa:

- 80% of attraction is due to pion
- Tensor interaction is particularly important

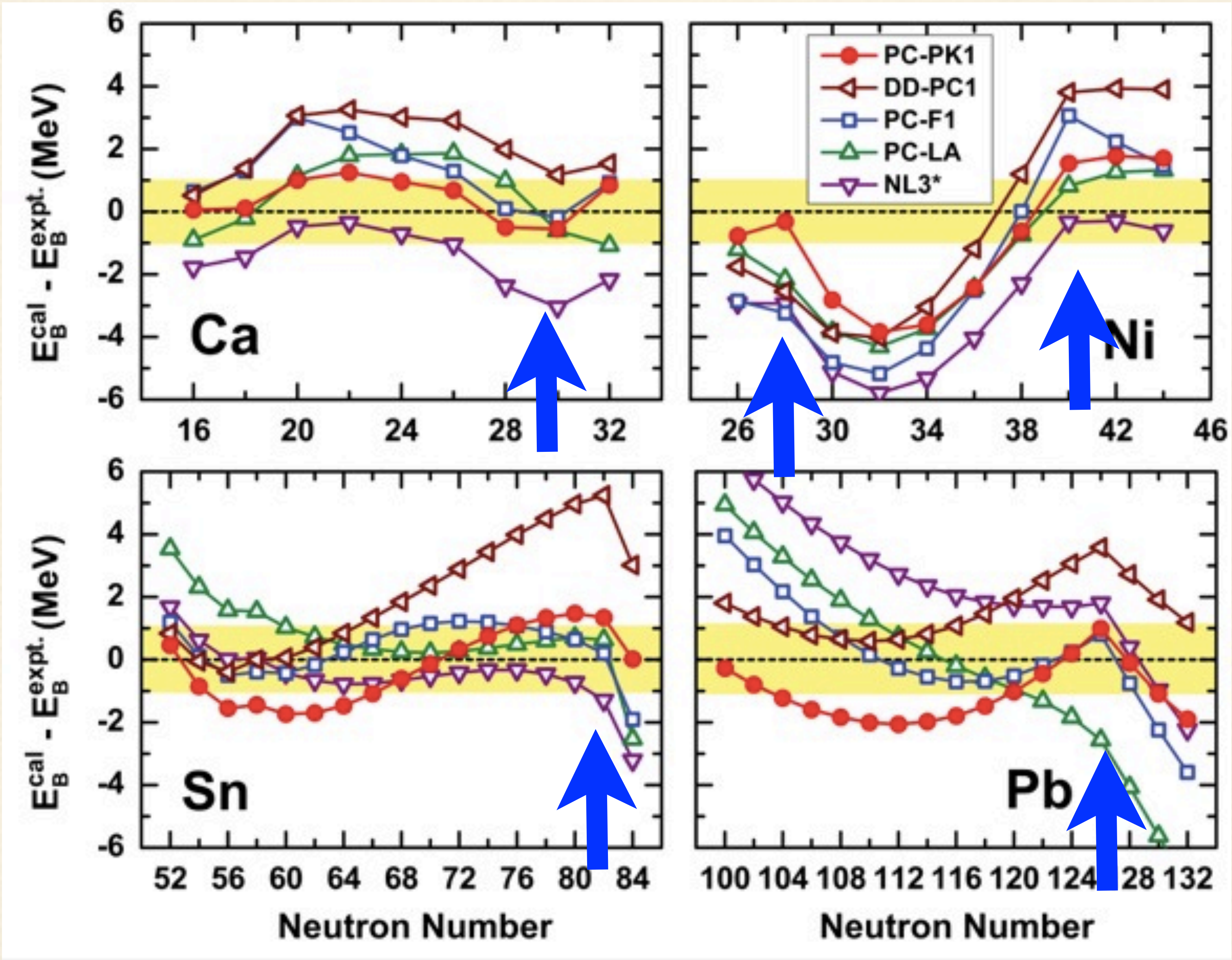
- Don't tensor forces introduce abrupt change of an effective mean field?

A State of the art Mean Field model

the nuclear covariant energy density functional

Nuclear mass : Difference between the model and the experimental values.

P. W. Zhao et al., Phys. Rev. C **82**, 054319 (2010)



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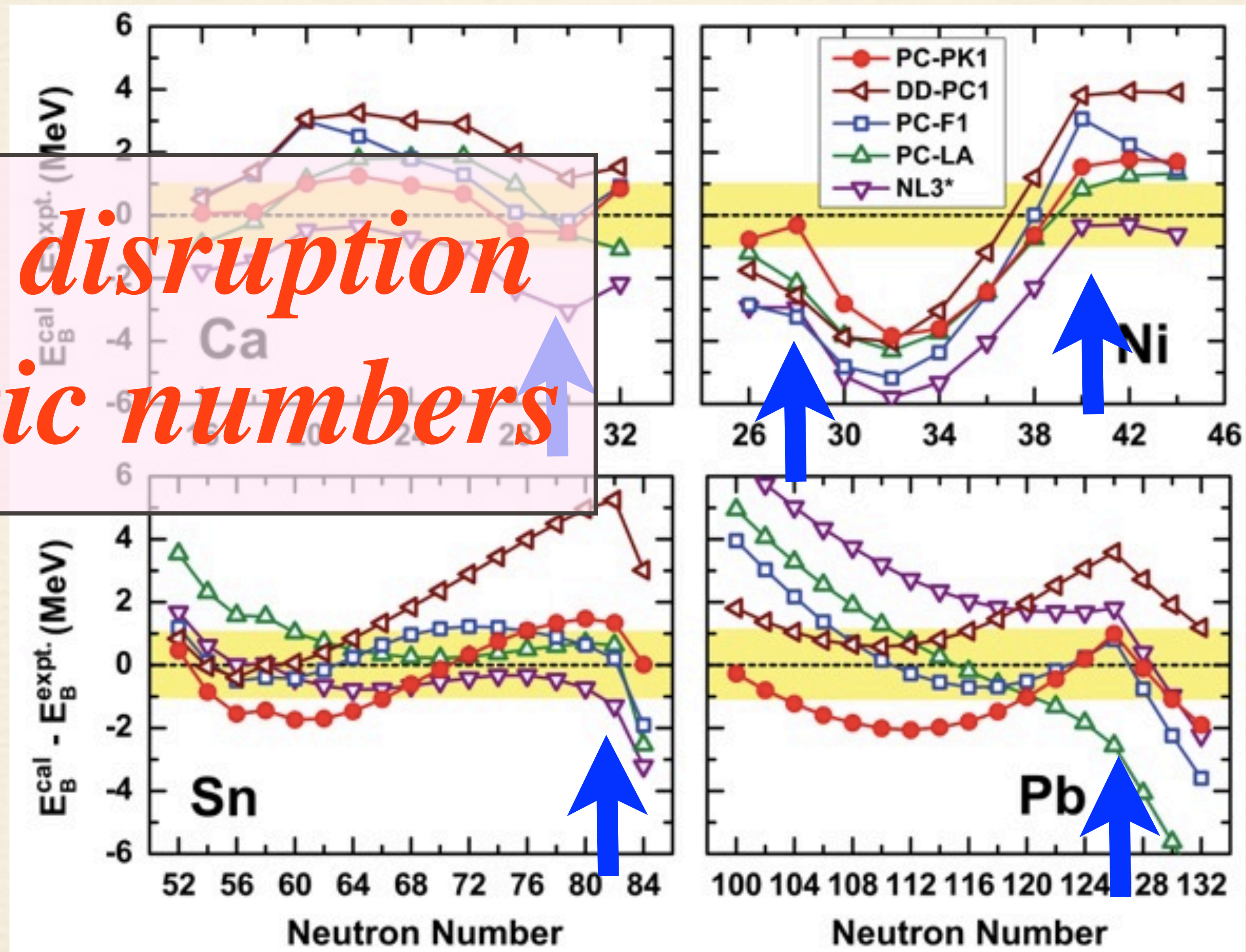
Sharp disruption at magic numbers



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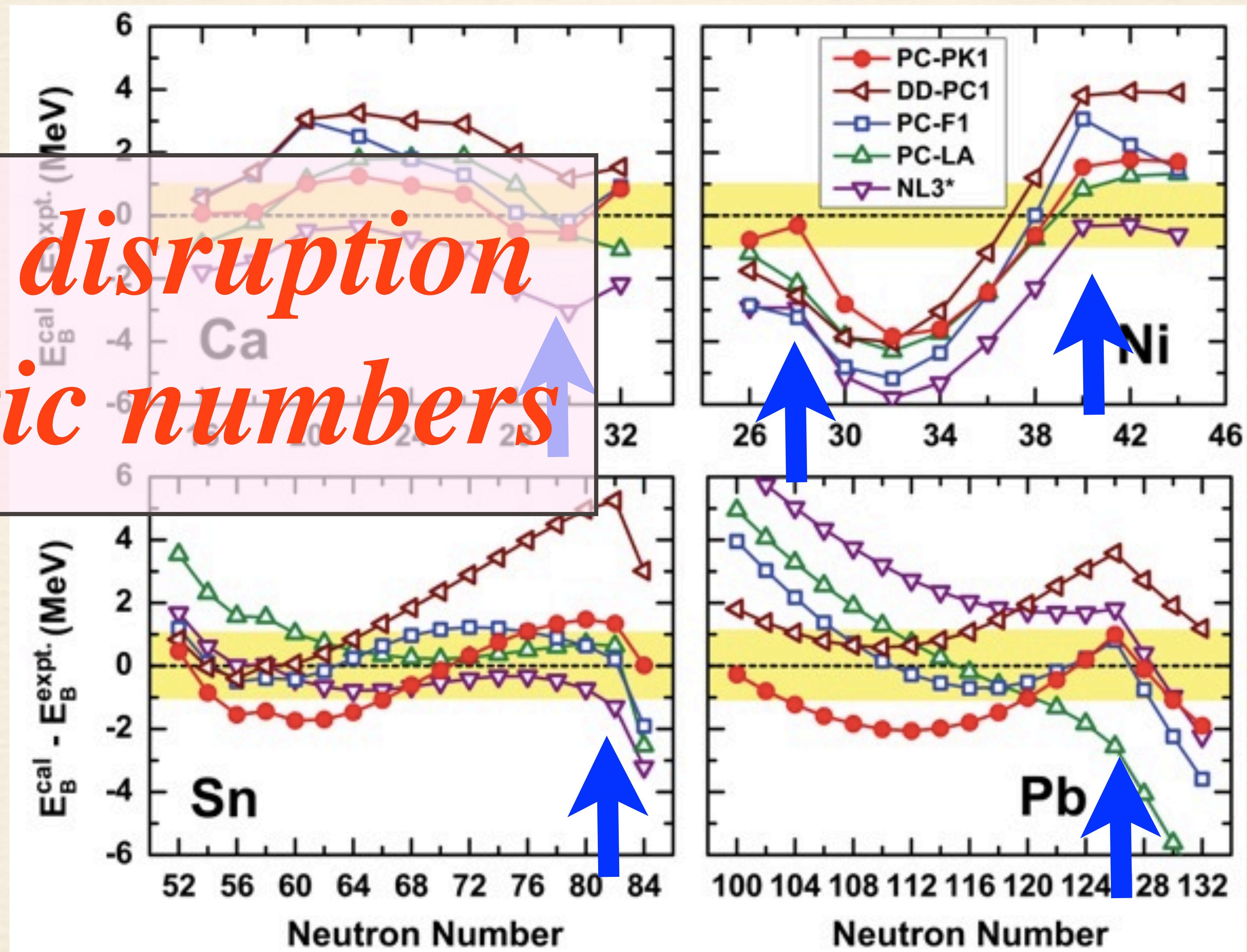

With effective central forces!

The importance of pion is clear for d, ^{4}He

Contributions of various energies to the binding energy of ^{4}He nucleus.

M. Sakai, et al., Prog. Theor. Phys. 56(1974)32.

		H-J
Energy		-20.6
Kin. E		131.1
Pot. E		-151.7
C	^{1}E	-51.3
C	^{3}E	-26.2
C	^{1}O+^{3}O	-0.4
T	^{3}E	-69.7
T	^{3}O	-0.5
LS+QLS		-3.6
P(D)%		12.8

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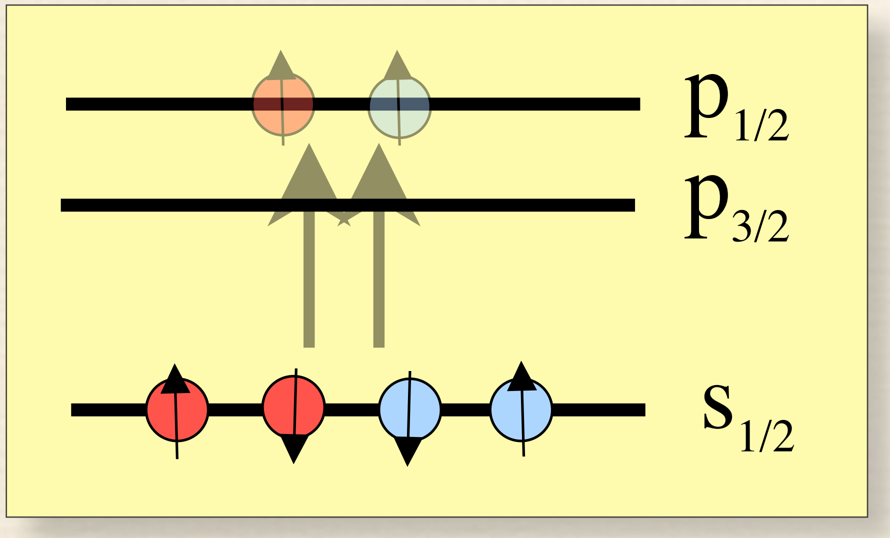

$\Delta L=2$, $\Delta S=2$
p-n pair: yes
n-n, p-p pair: no

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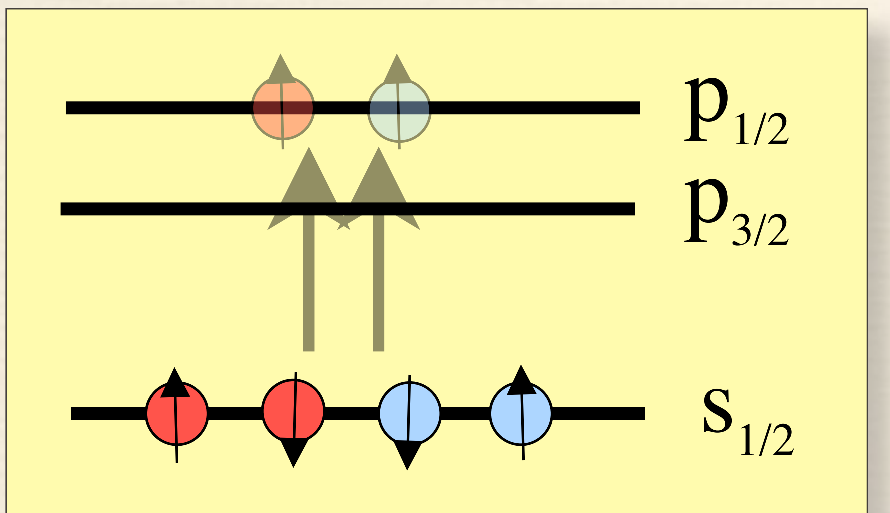

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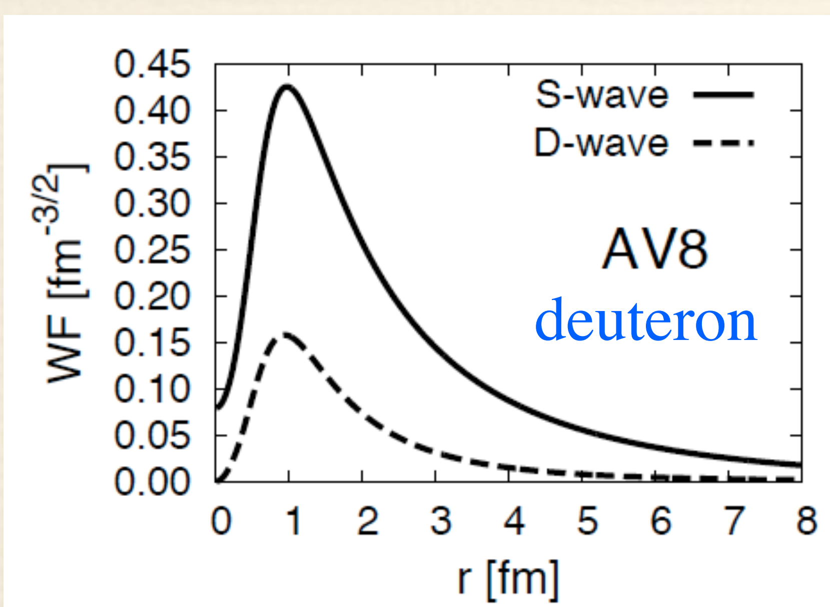

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Importance of Tensor force in Nuclei

Selected subjects

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- Mixing of s- and p-waves in ^{11}Li halo
- Magnetic moment of single particle state
  - *Deviation of the magnetic moments of (doubly-closed ±1) nuclei*

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- Mixing of s- and p-waves in ^{11}Li halo
- Magnetic moment of single particle state
  - *Deviation of the magnetic moments of (doubly-closed ±1) nuclei*
- High momentum component of nucleon

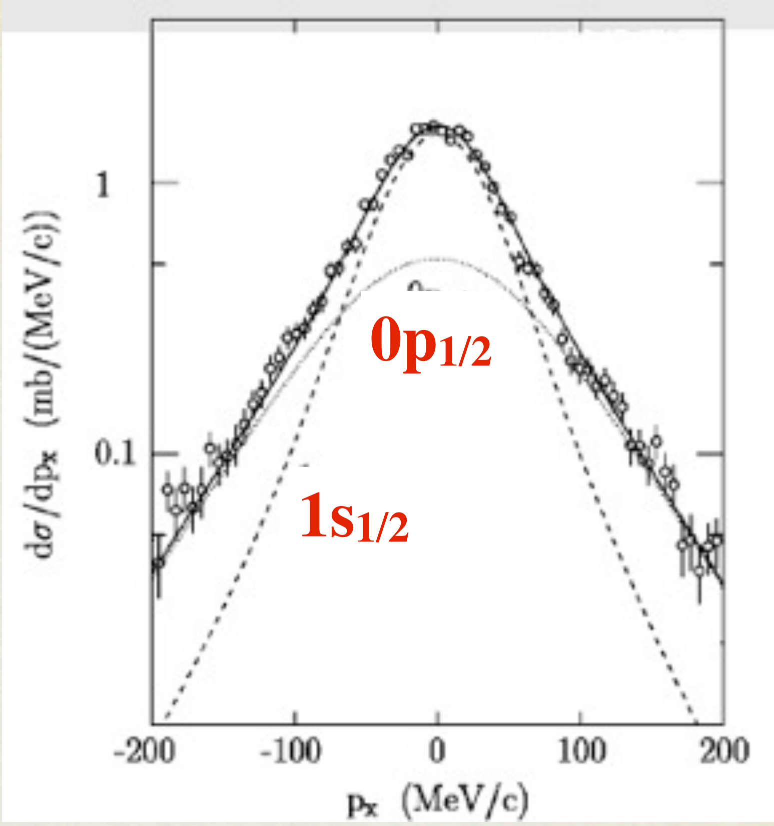
s- and p- waves mixing in ^{11}Li

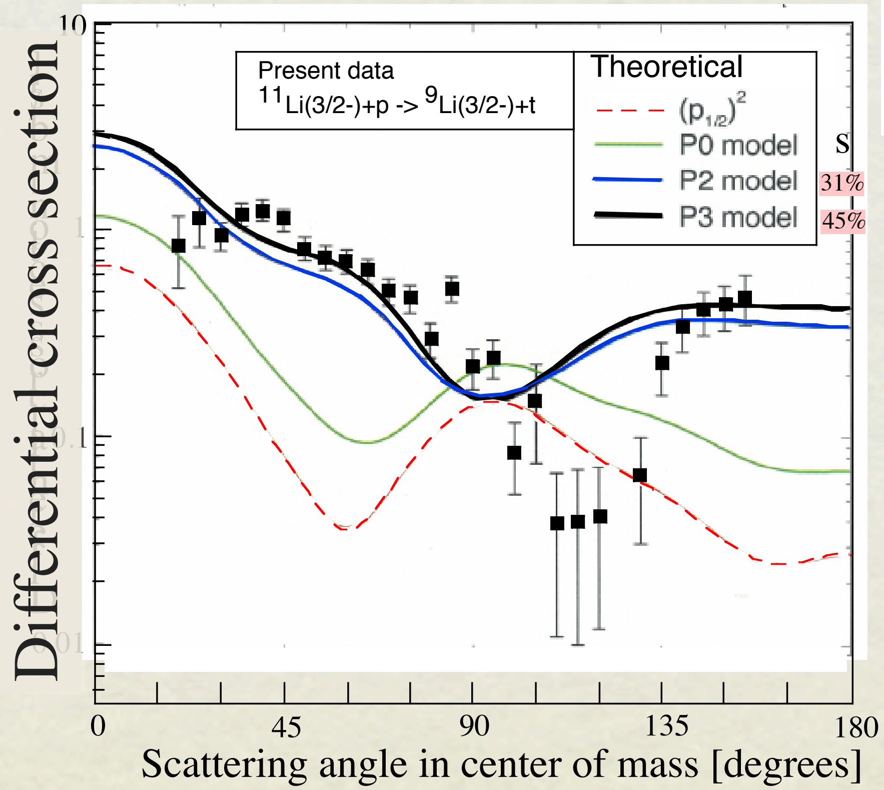
$0p_{1/2}$

$1s_{1/2}$

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

- **Momentum distribution of fragments ^{10}Li**
  - *Equal amount of $p_{1/2}$ and $s_{1/2}$. (Simon 1999)*
- **Beta-decay**
  - *30-40% $s_{1/2}$ wave and small amount of $p_{1/2}$ (Borge 1997)*
- **two-neutron transfer reaction**
  - *(^{11}Li+p --> ^{9}Li+t)*
  - *31-45% $s_{1/2}$ and $p_{1/2}$*
  - *(Tanihata 2008)*





41% s

35% s

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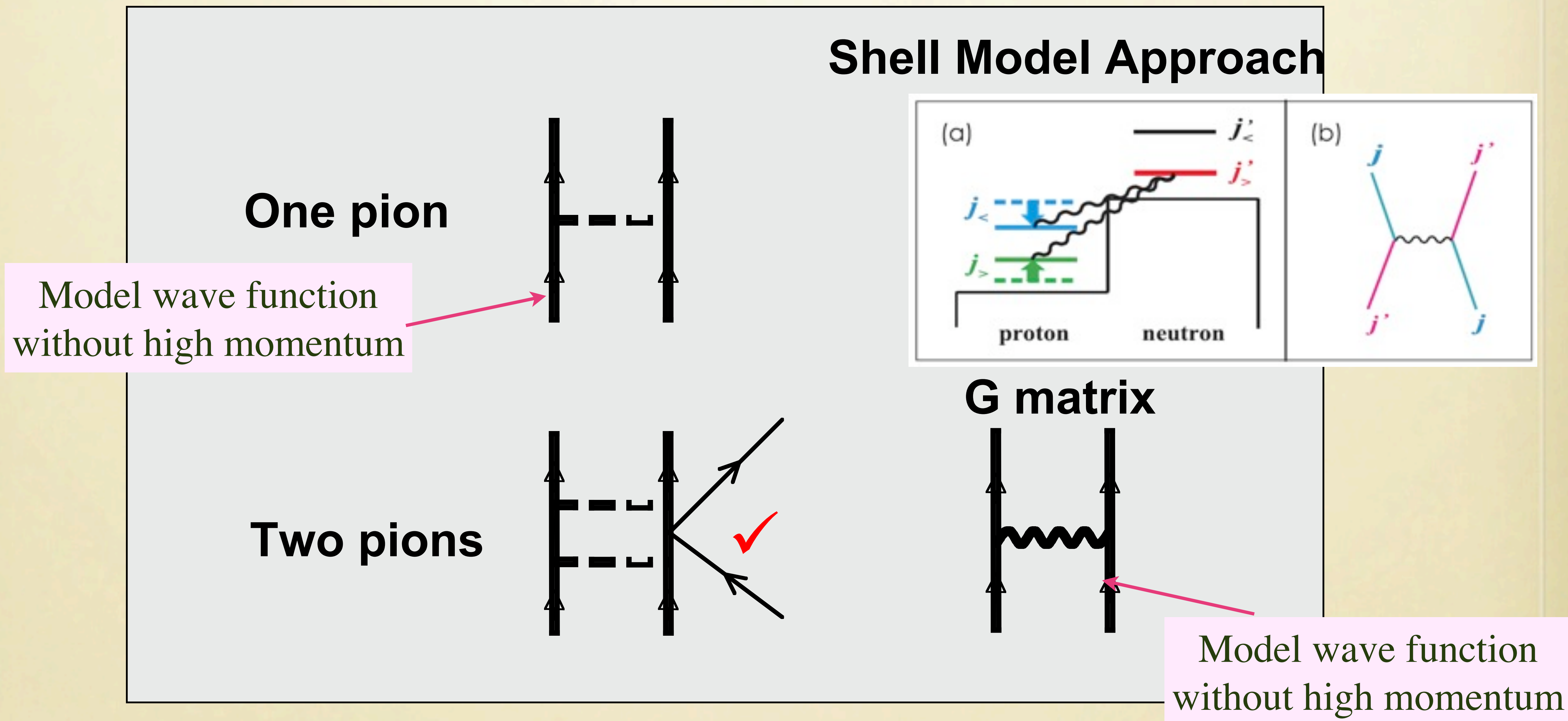
Difference between Shell model treatment and reality

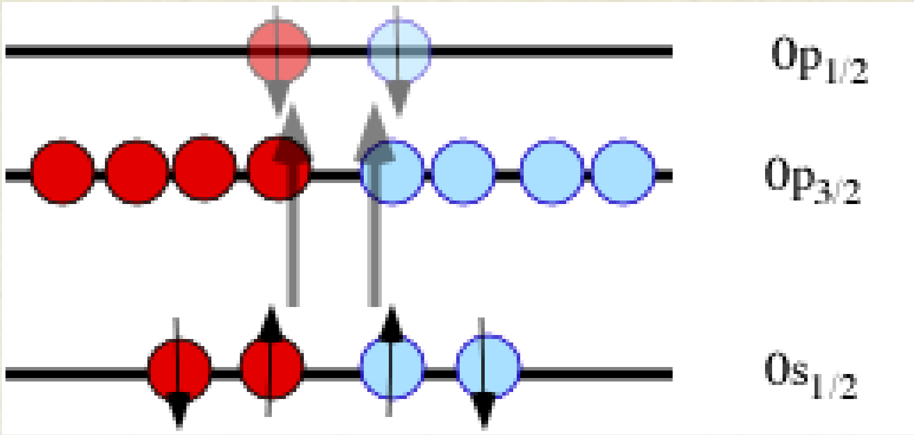
pion exchange: $\propto S_{12} \frac{q^2}{m^2 + q^2}$



✓ **High Momentum Component**

Tensor Optimized Shell Model (TOSM)

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



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p-n pair: yes
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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: $b_{0s} \neq b_{\overline{0p}}$

Energy variation

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

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

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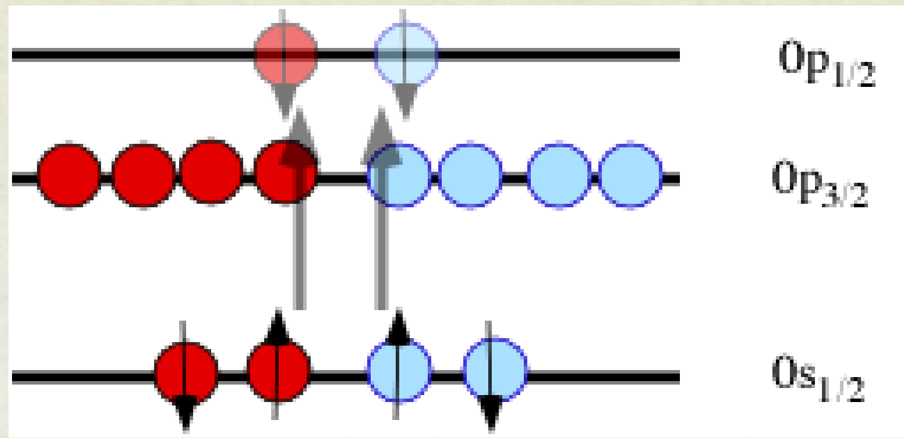

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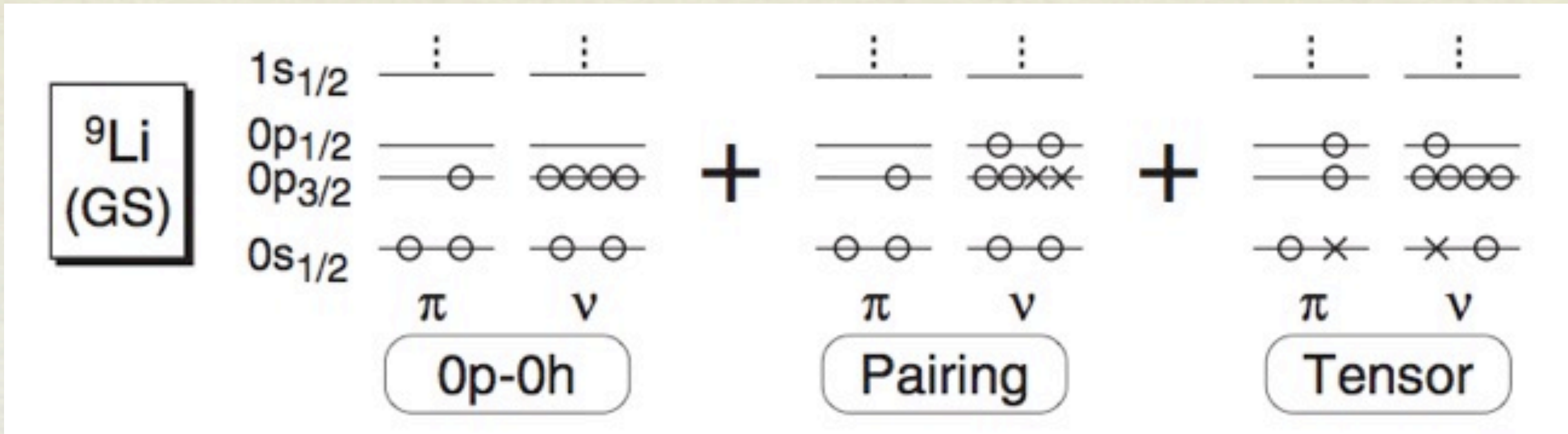
1. Explicitly include 2p-2h excitation due to the tensor forces.

2. Size of the each orbitals are variational parameters.

E

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

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.

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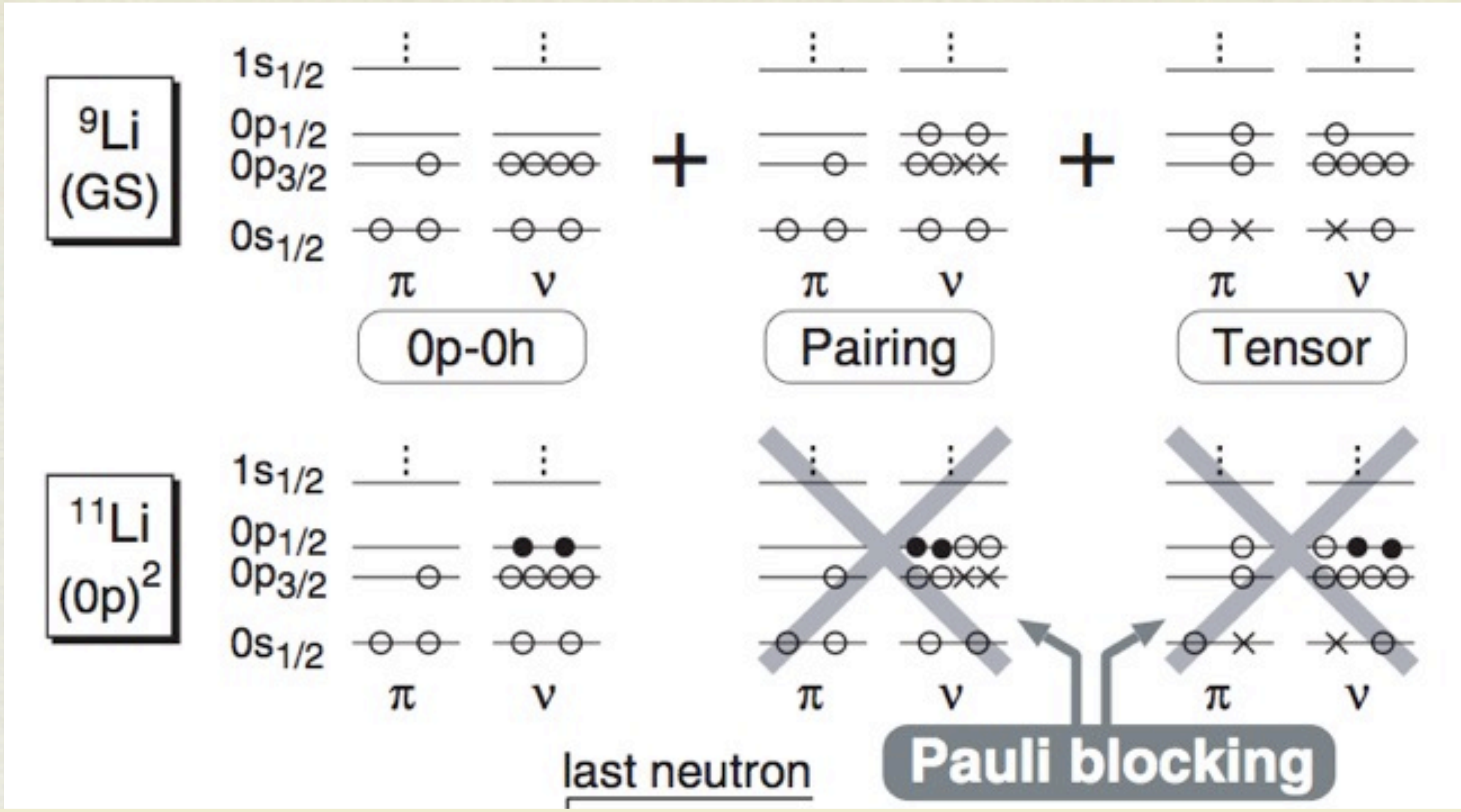

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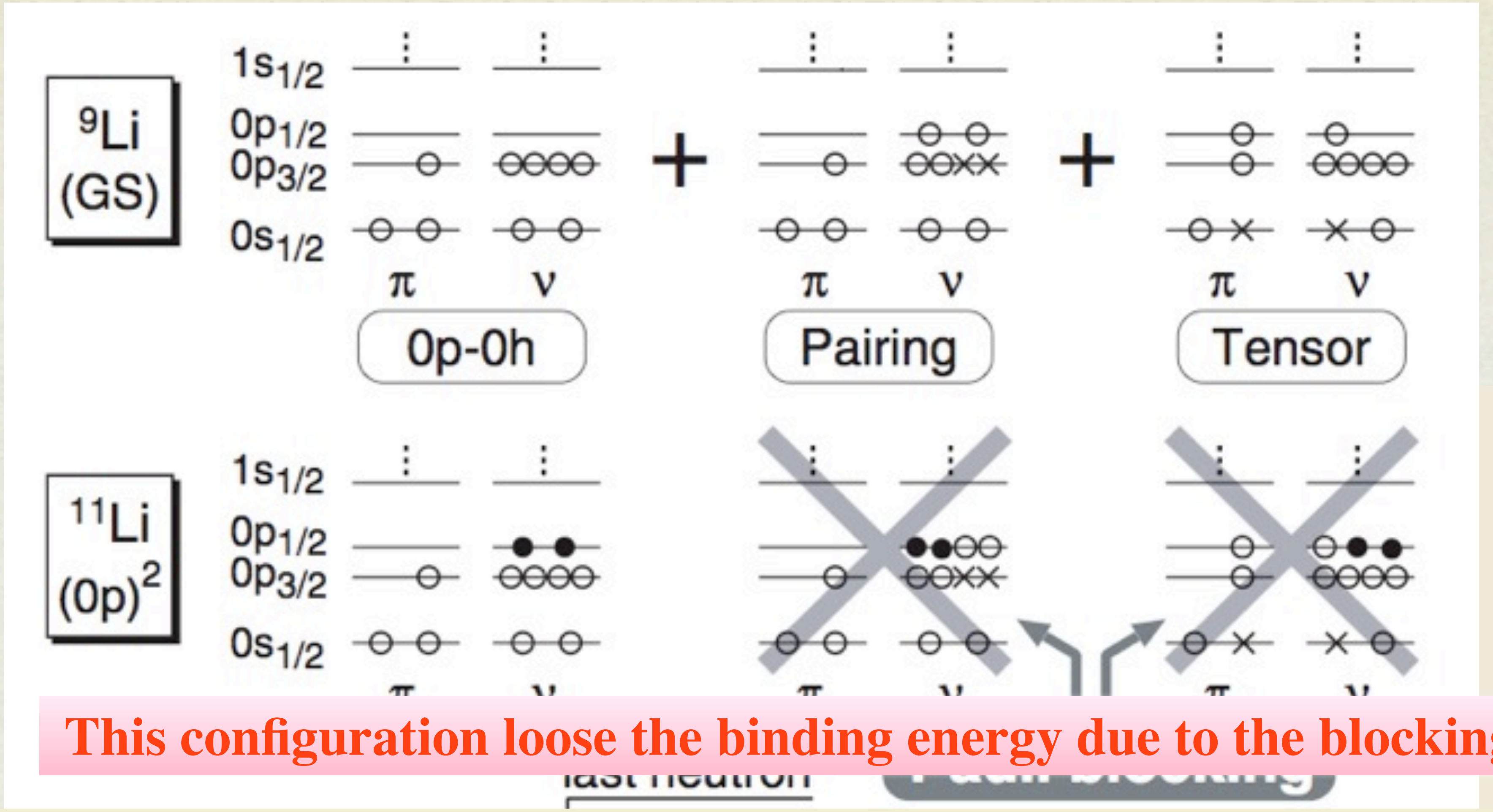

This configuration loose the binding energy due to the blocking

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

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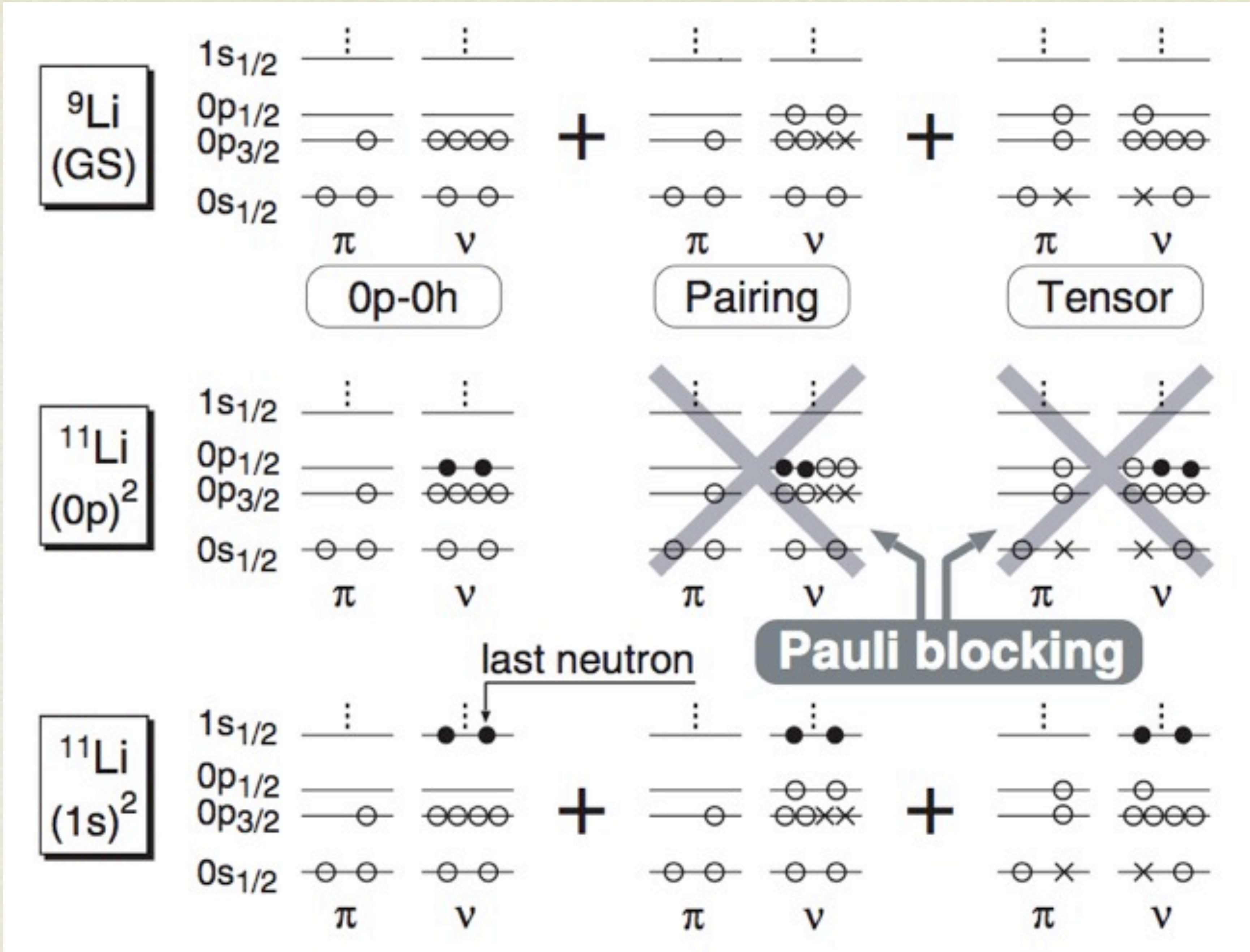

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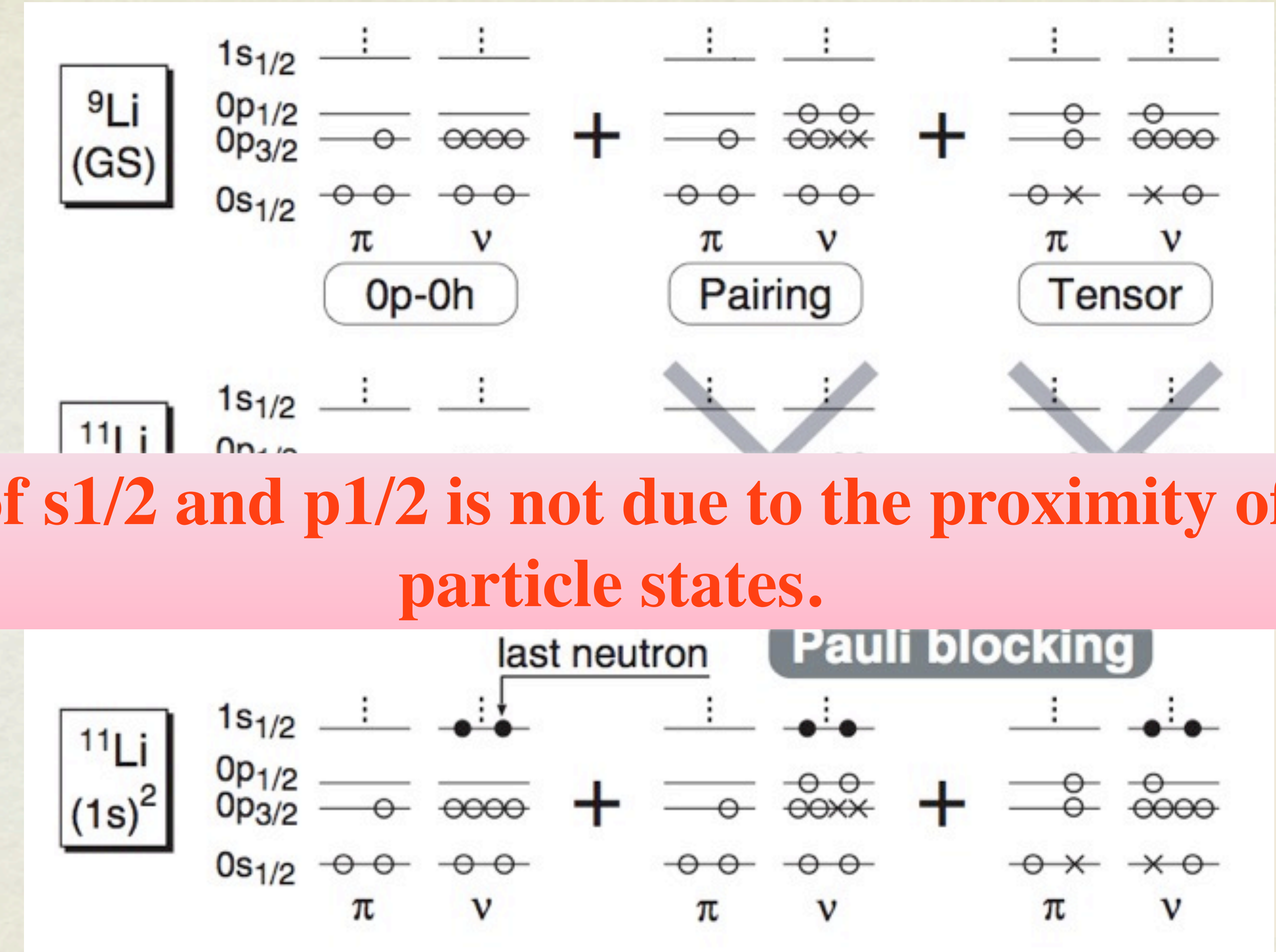
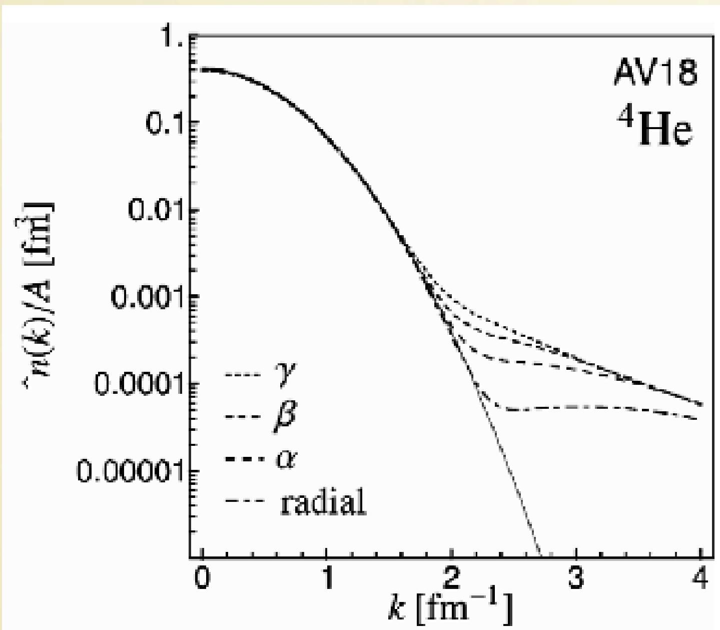


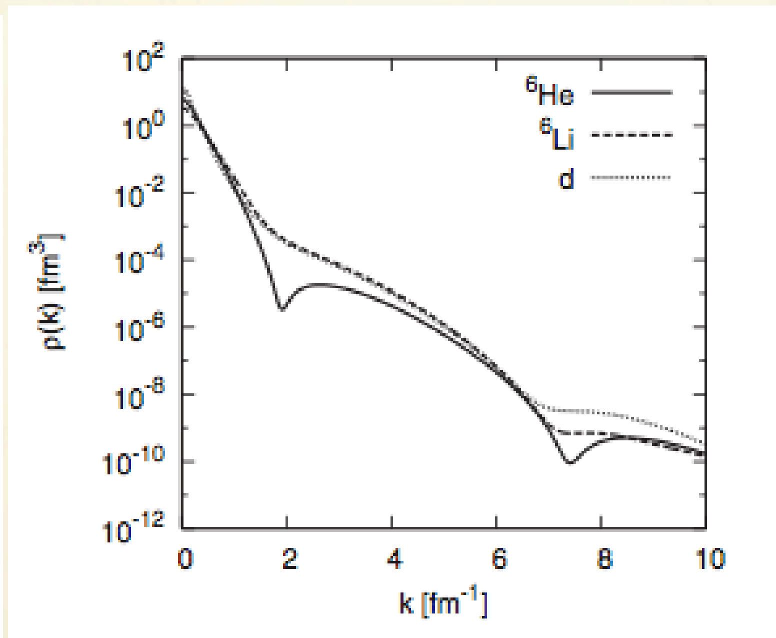
Mixing of s1/2 and p1/2 is not due to the proximity of single particle states.

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

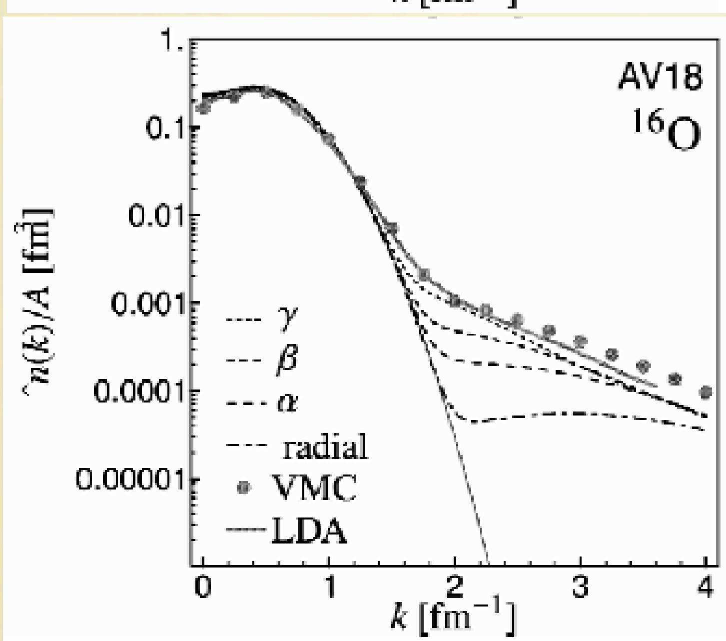
- **Mixings of waves occur due to the Pauli blocking of mixed states.**
- **Tensor forces introduce mixing of 2p-2h ($\Delta L=2, \Delta S=2$) *states with high momentum component.***
- ***Can we observe such high-momentum component?***

Theoretical Predictions



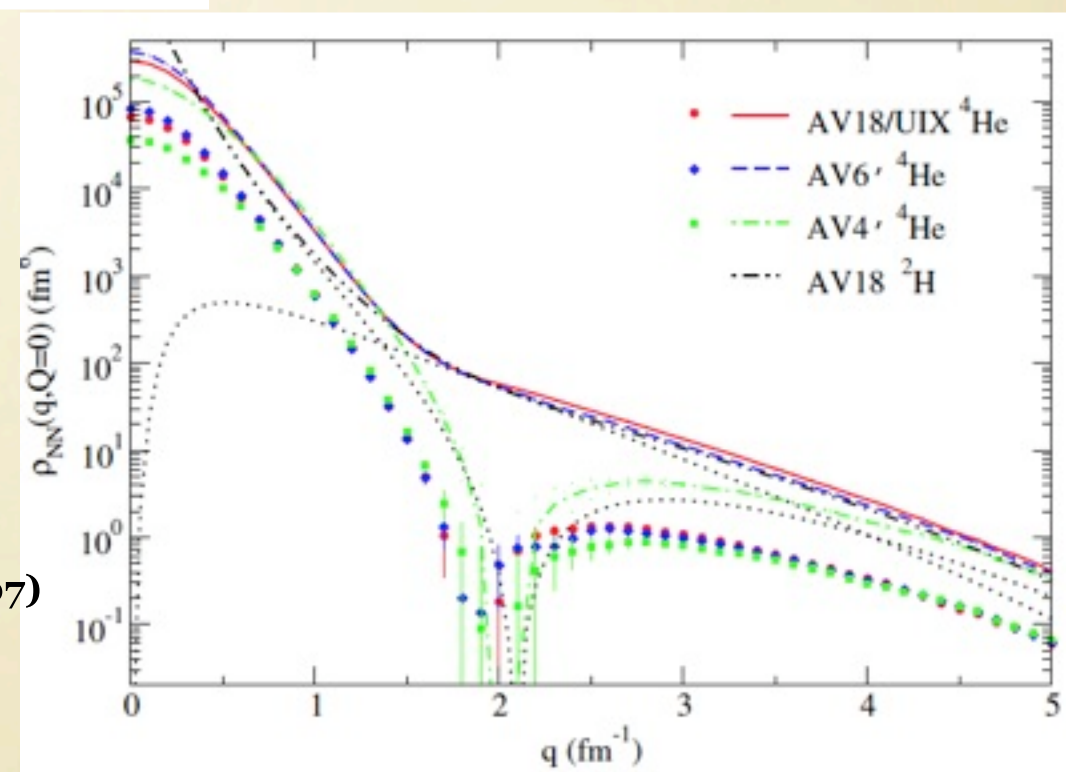


W. Horiuchi and Y. Suzuki,
PRC76, 024311(2007)



T. Neff and H. Feldmeier,
NPA713, 311(2003)

R. Schiavilla et al.,
PRL 98 132501 (2007)



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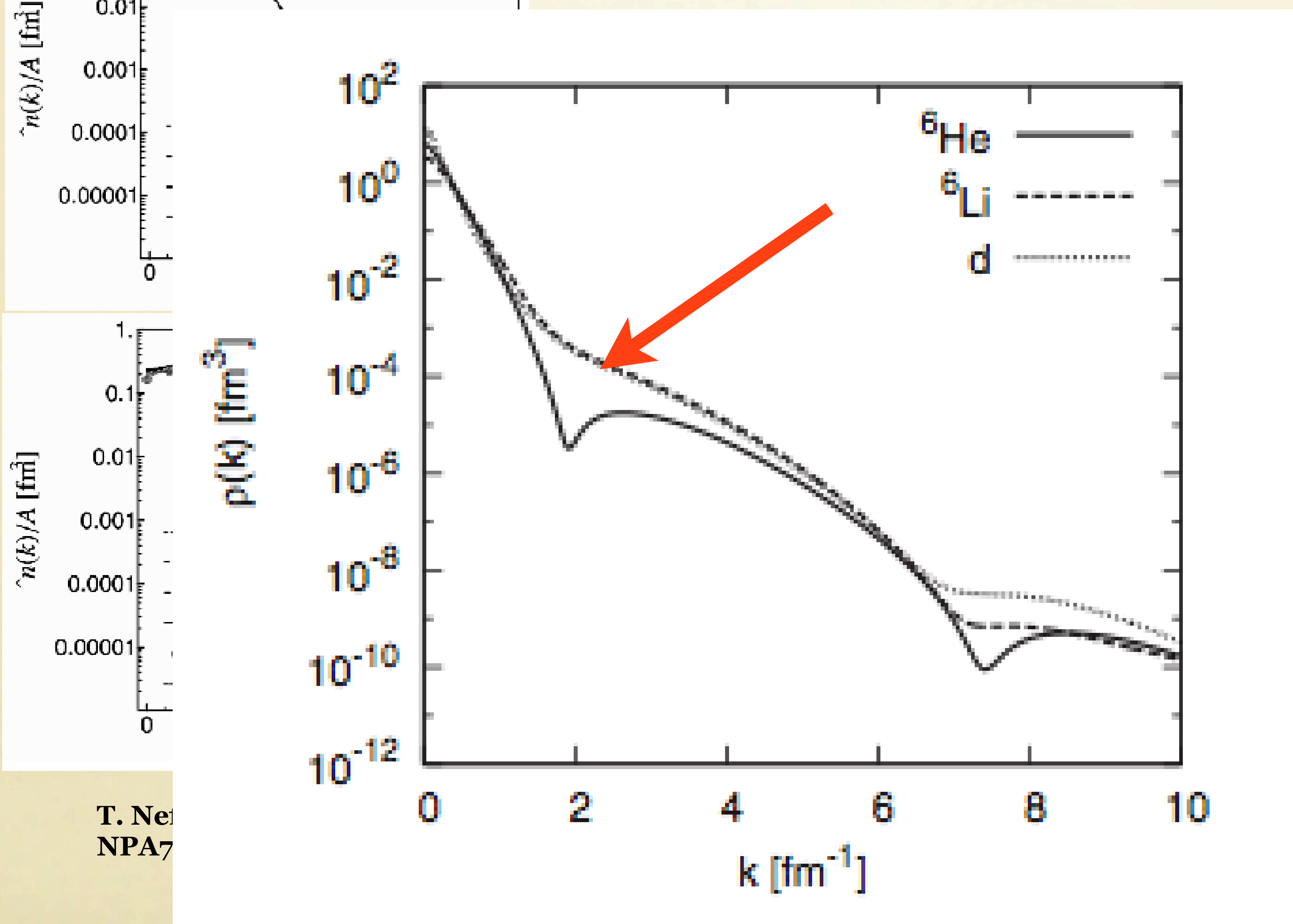
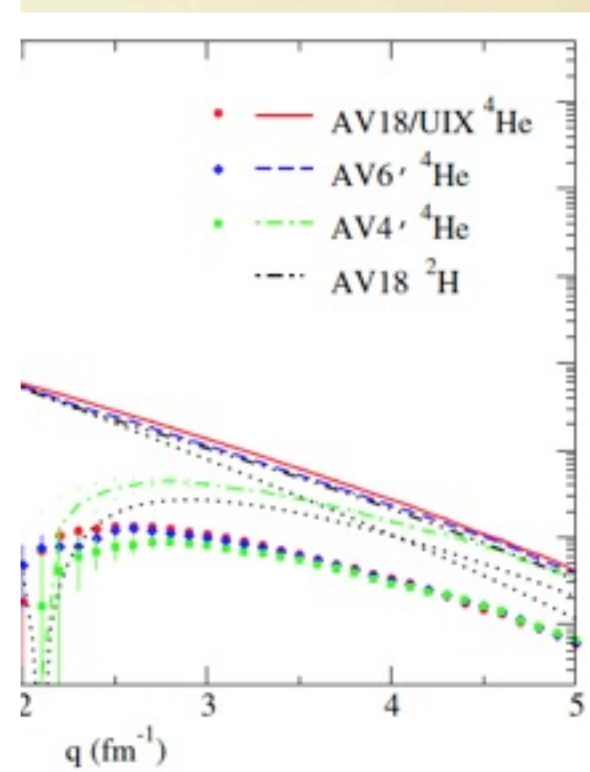
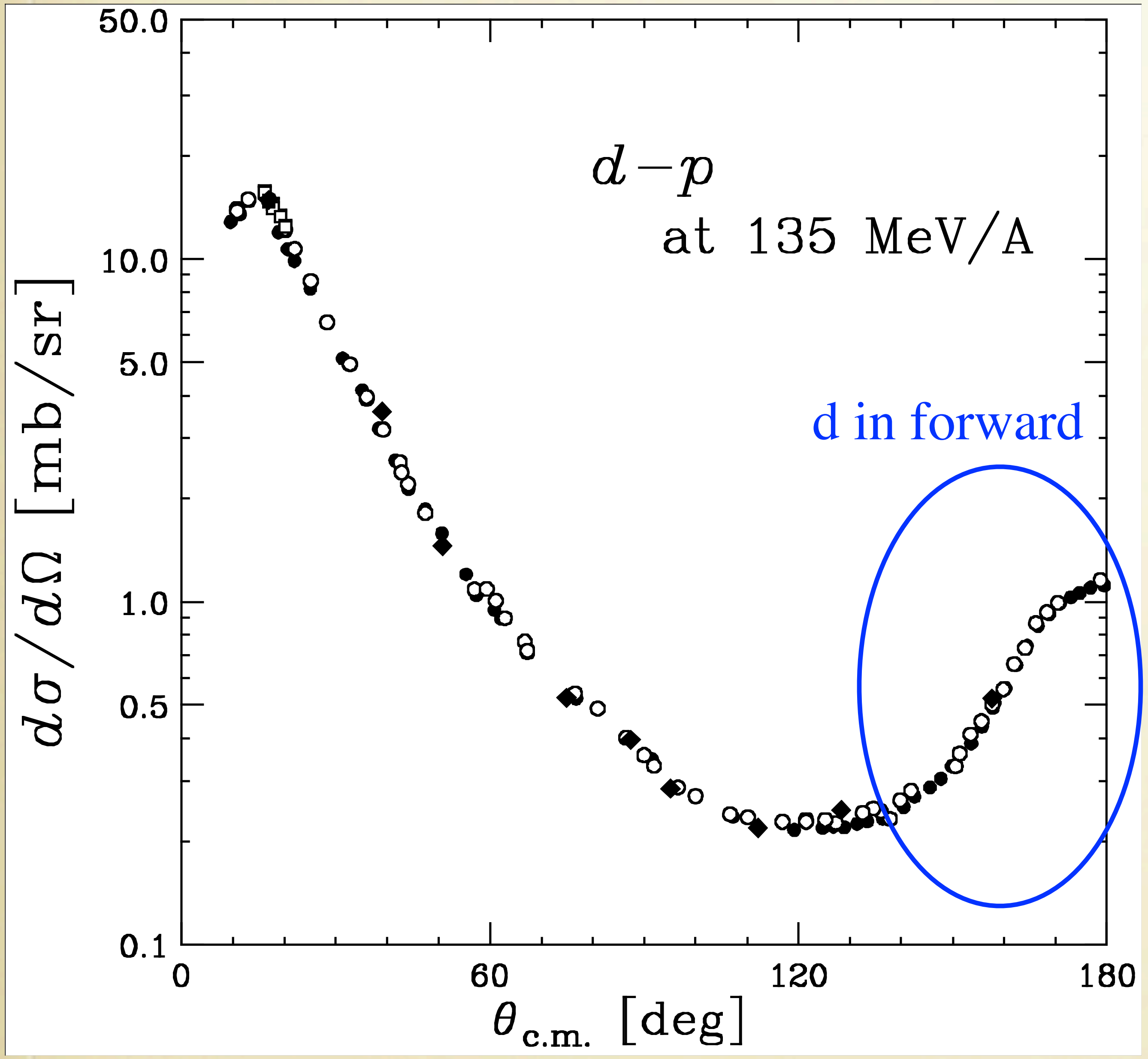




T. Nef
NPA7

(P,D) SCATTERING

= SUITABLE TO PICK UP HIGH MOMENTUM NEUTRON =



K. Sekiguchi et al.,
PRL **95** (2004) 162301

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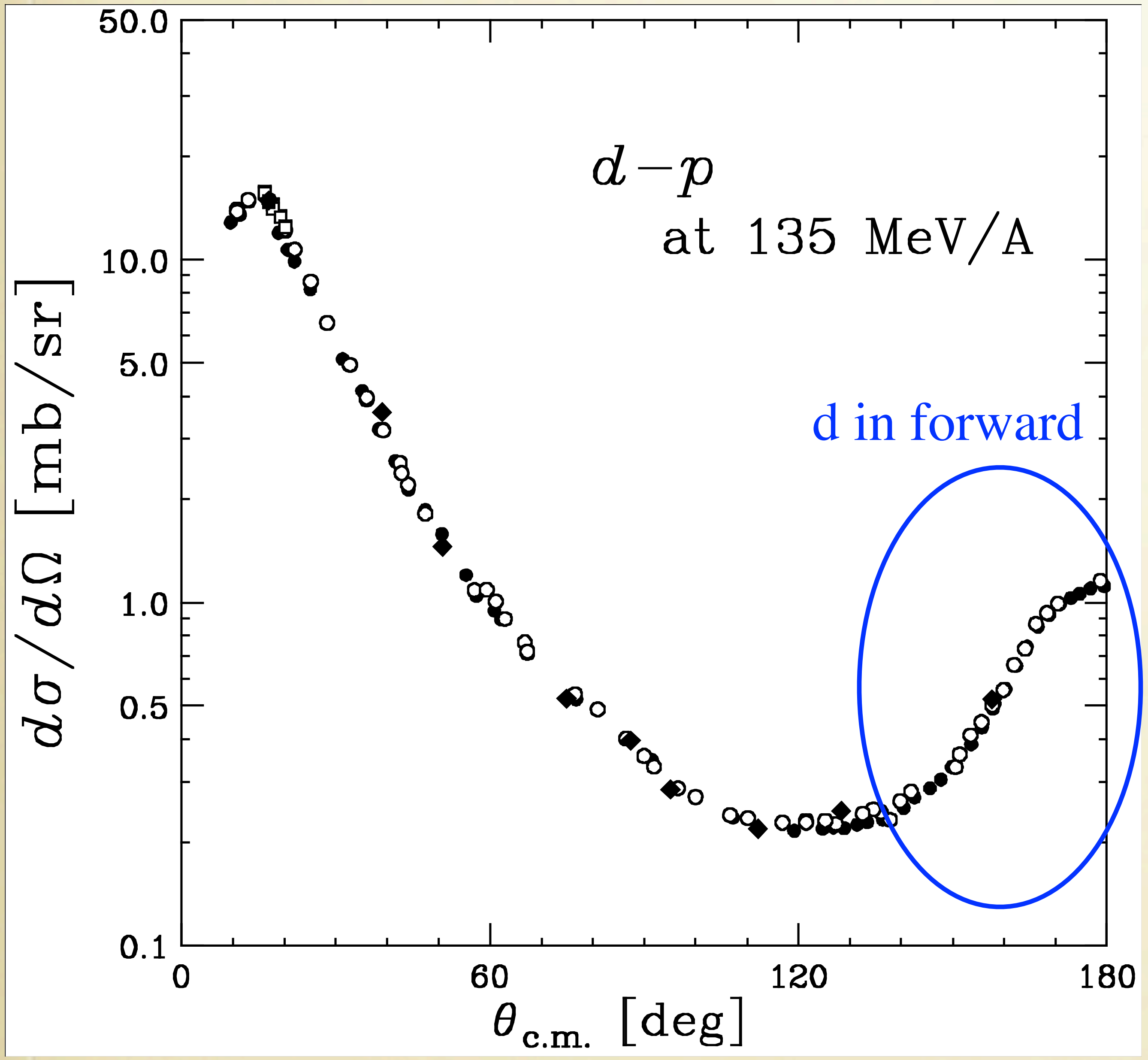

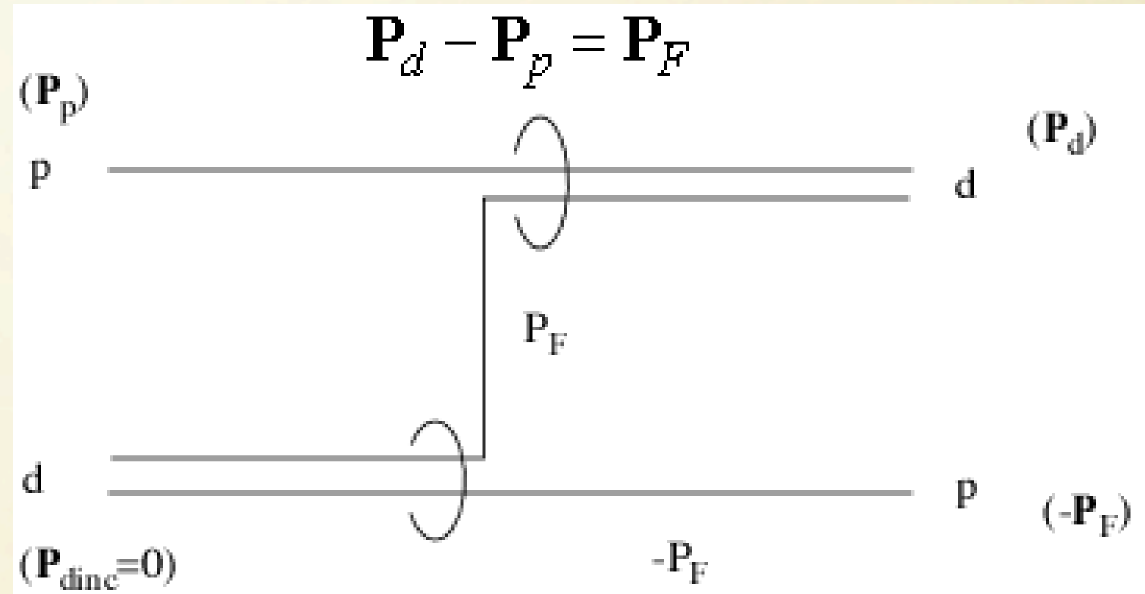

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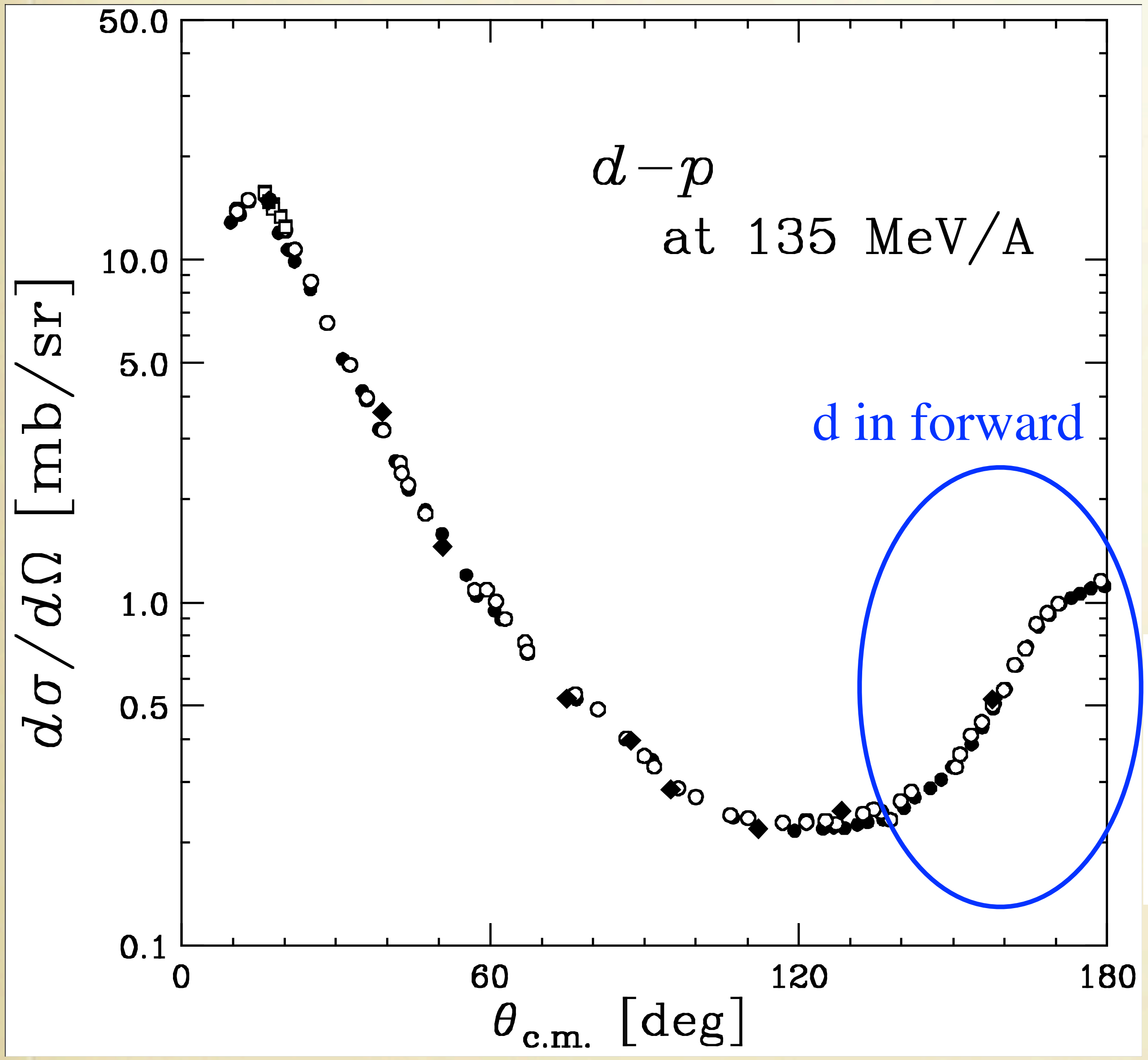

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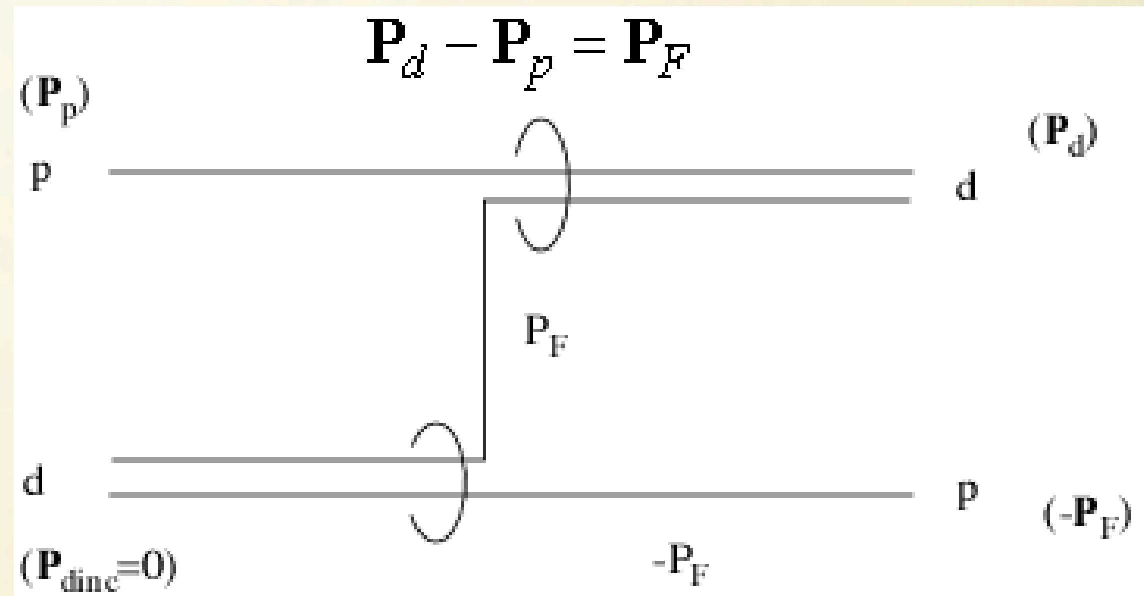
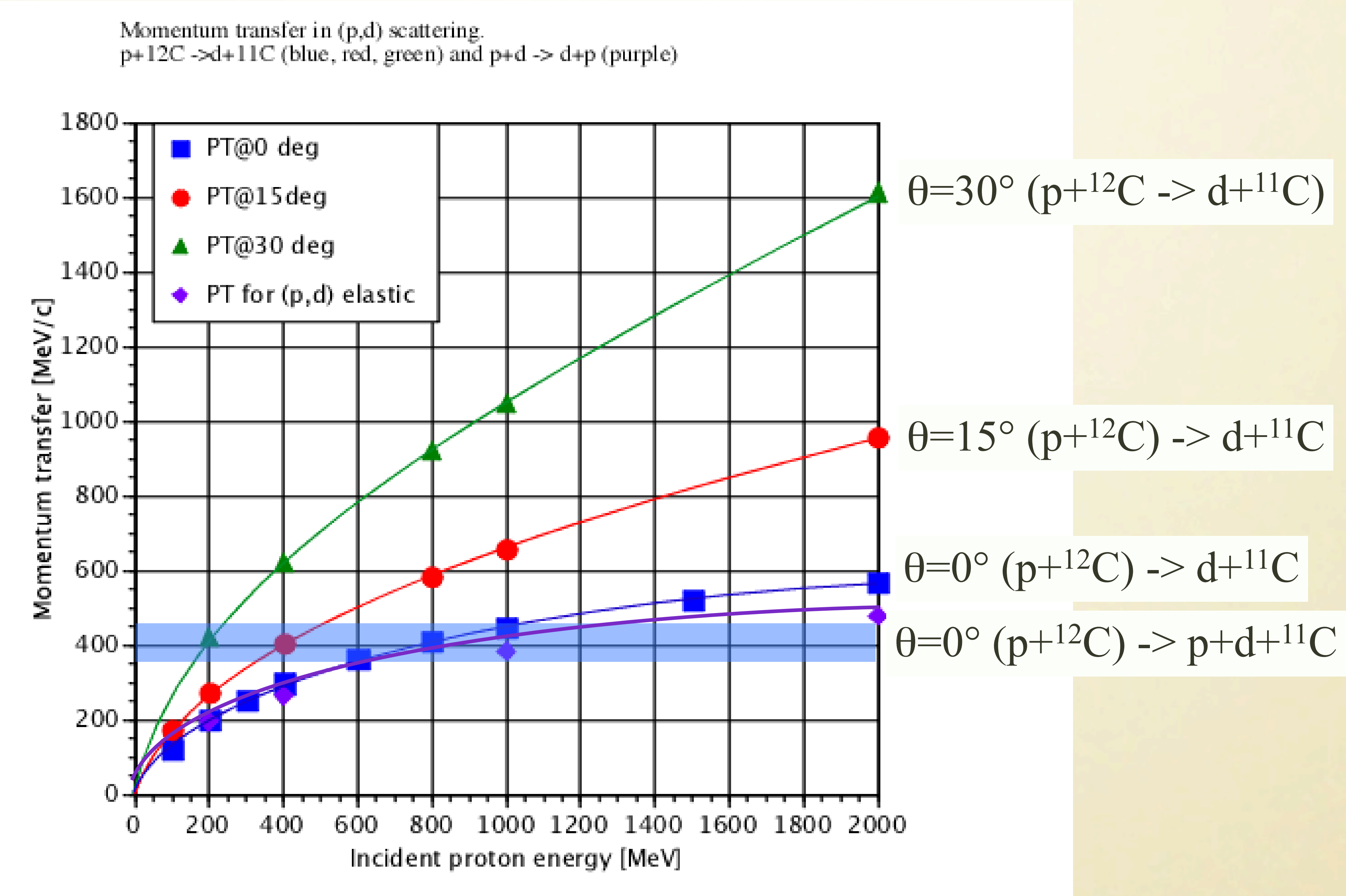


$$\sigma_F = K\frac{P_d}{p}N(P_F)\left[B_D + \frac{\hbar^2}{M}(\mathbf{p}-\mathbf{P}_d/2)^2\right]^2 \left|(\varphi(r), e^{i(\mathbf{p}-\mathbf{P}_d\cdot\mathbf{r}/2)})\right|^2$$

K: phase space constant, B_D: deutron binding energy, M: nucleon mass
by G. F Chew and M.L. Goldberger Phys. Rev. **77** (1950) 470.

Reaction at backward occurs by the high-momentum component.

Necessary beam energies



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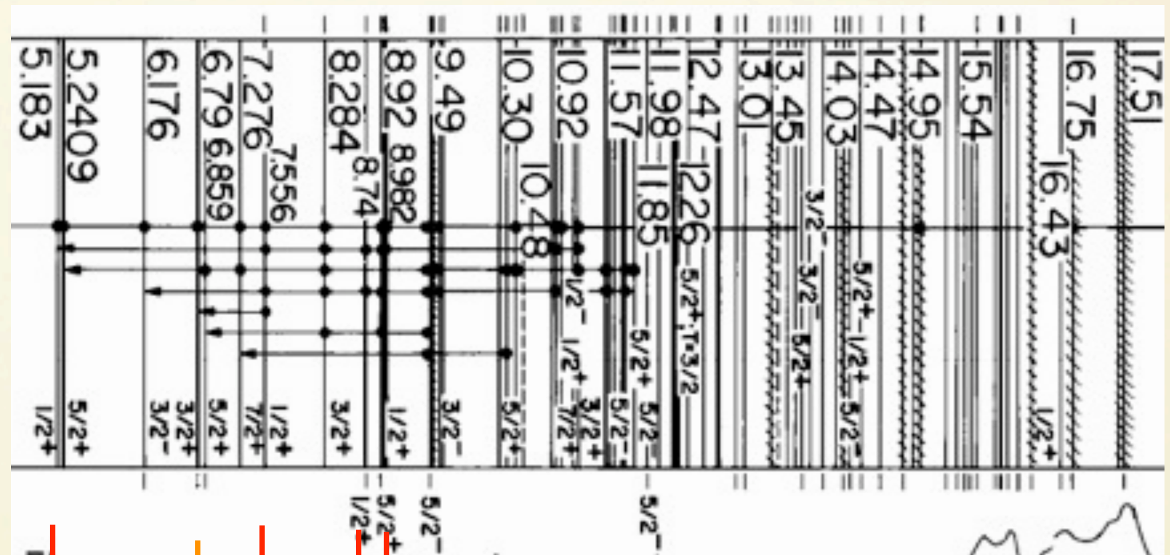
Experiment at RCNP

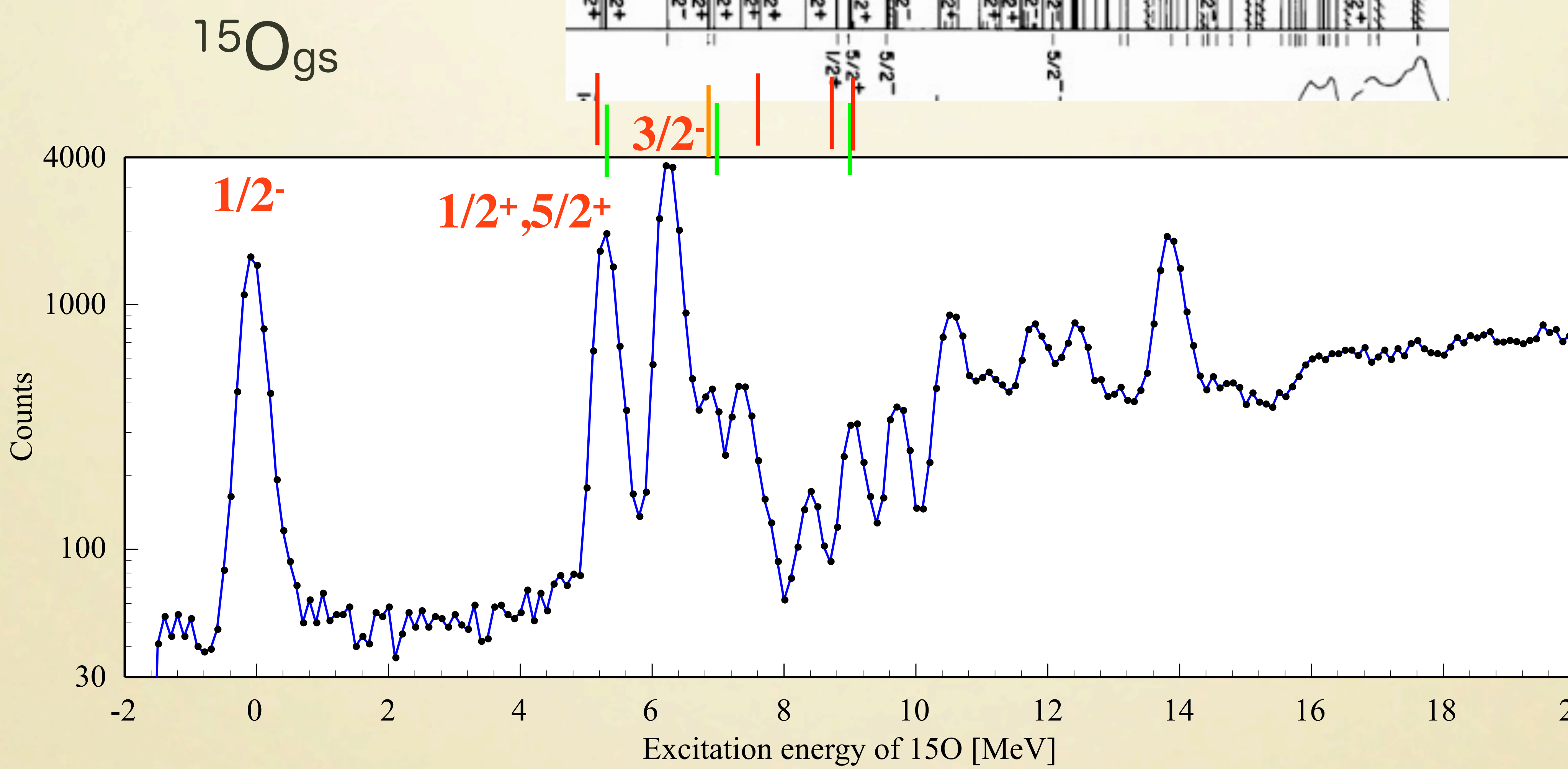
$^{16}O(p,d)^{15}O$ at E_p=200 - 400 MeV at θ_s=10°

Data at RCNP

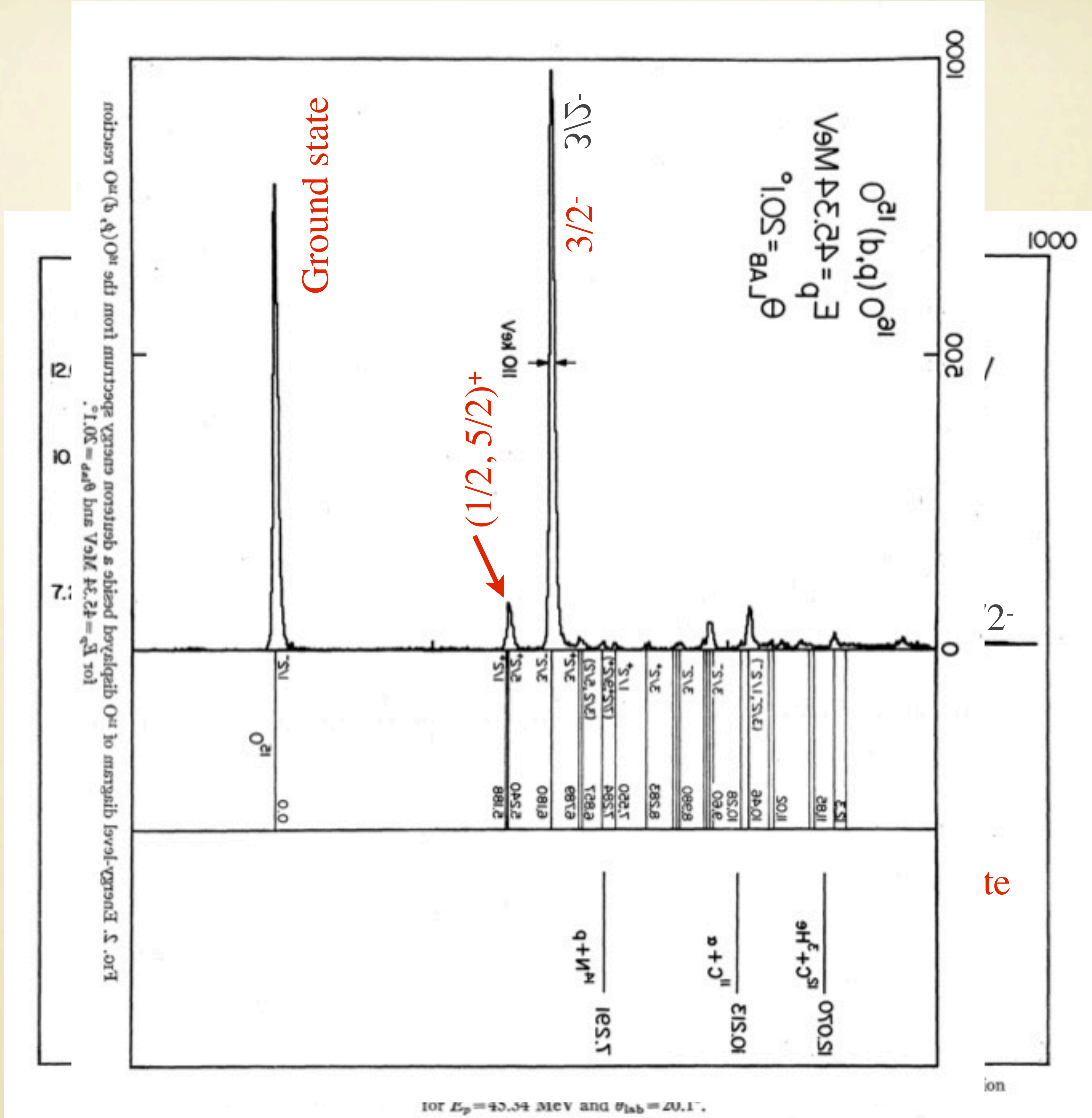
H.J. Ong et al. Phys. Lett. B 725, 277 (2013)

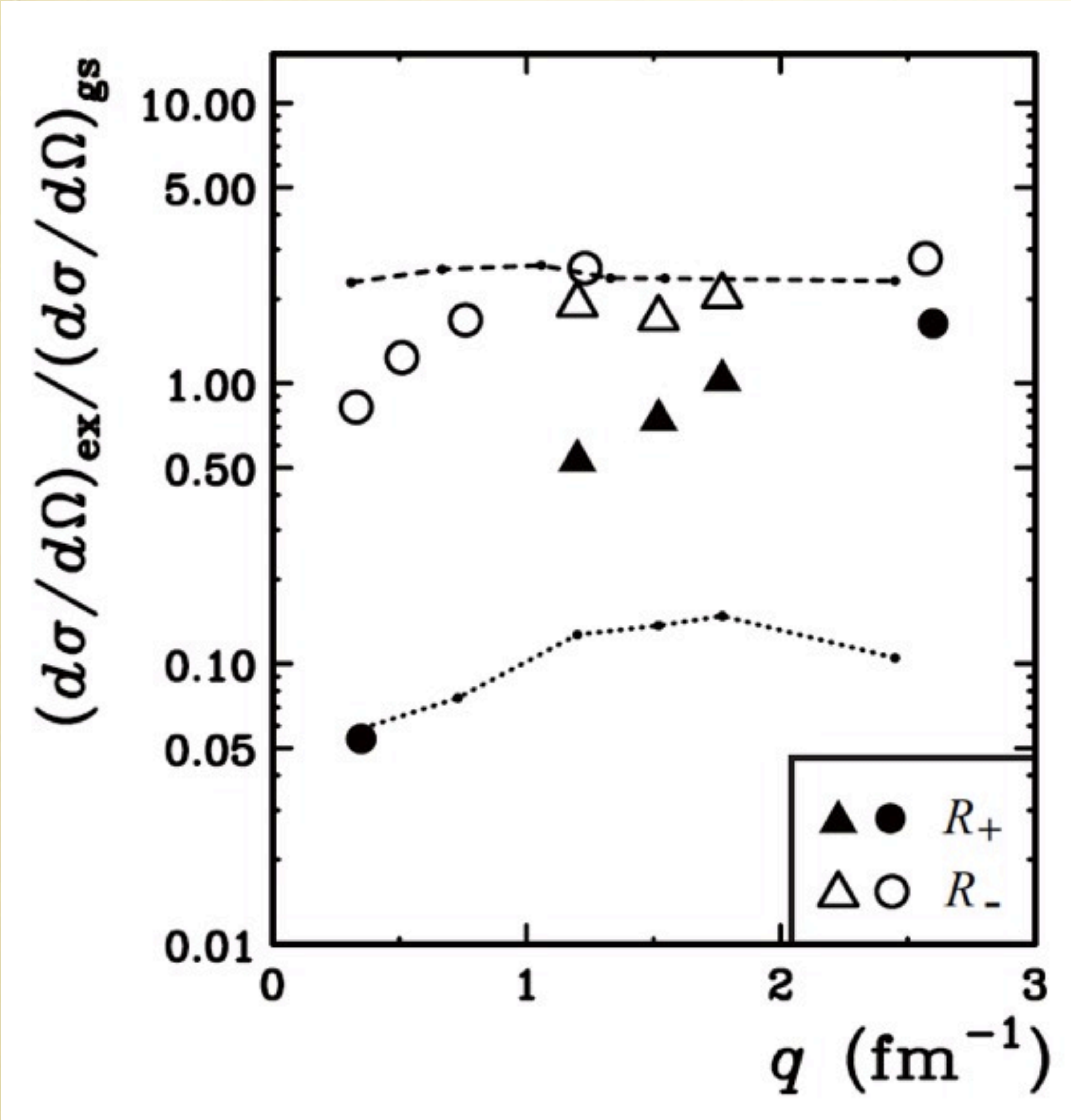
$^{16}O(p,d)^{15}O$
at θ_s=10°



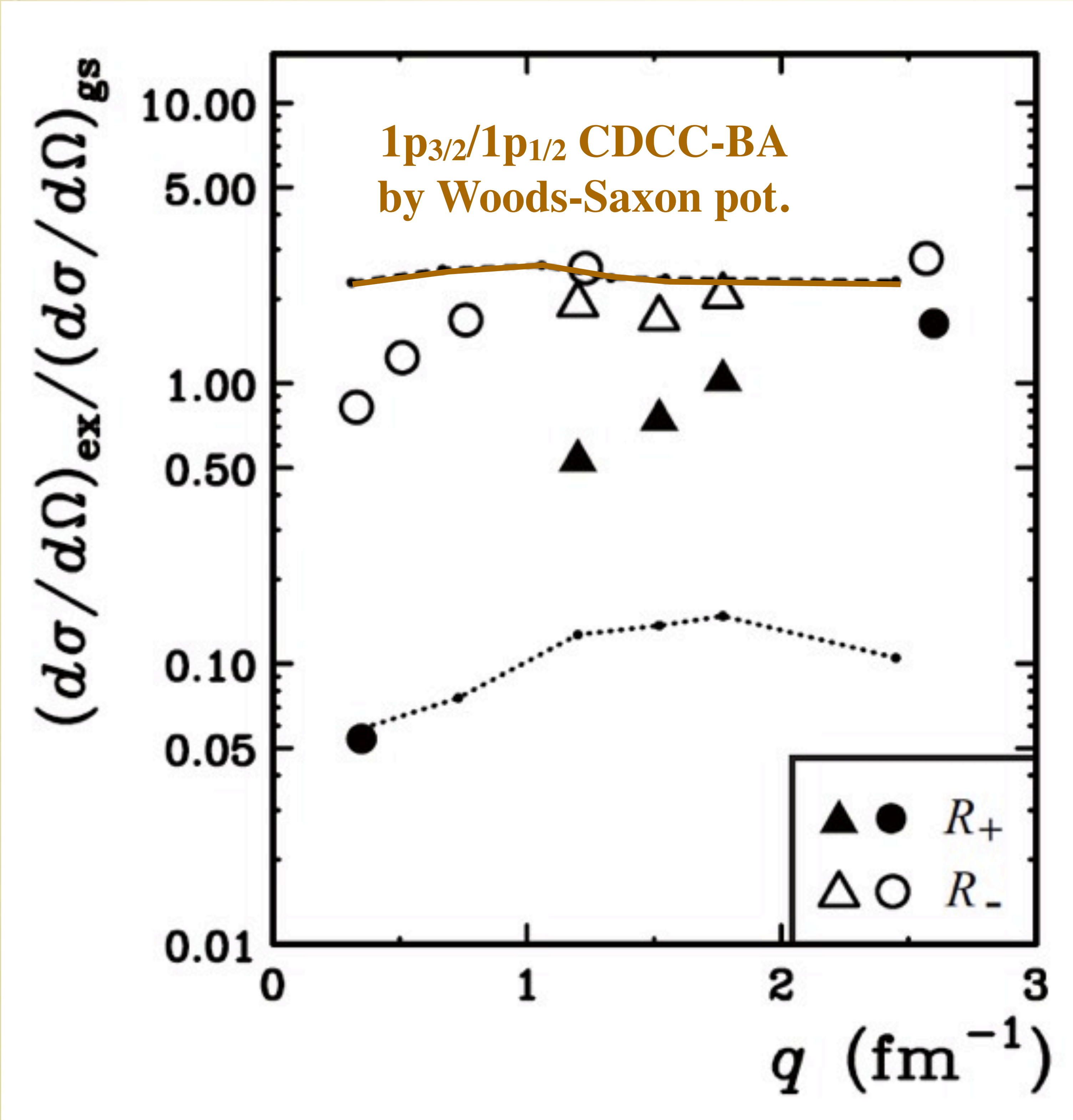


Transition to $1/2^+$ is as strong as the transition to the ground state.


Ground state
3/2-
(1/2, 5/2)+
110 KeV



The dashed (dotted) curve represents the ratios of the 1p3/2 (1d5/2) and 1p1/2, obtained by zero-range CDCC-BA calculations with finite-range correction using the Dirac phenomenological potentials. (by K. Ogata)
Wavefuncions are from Wood-Saxon potential.



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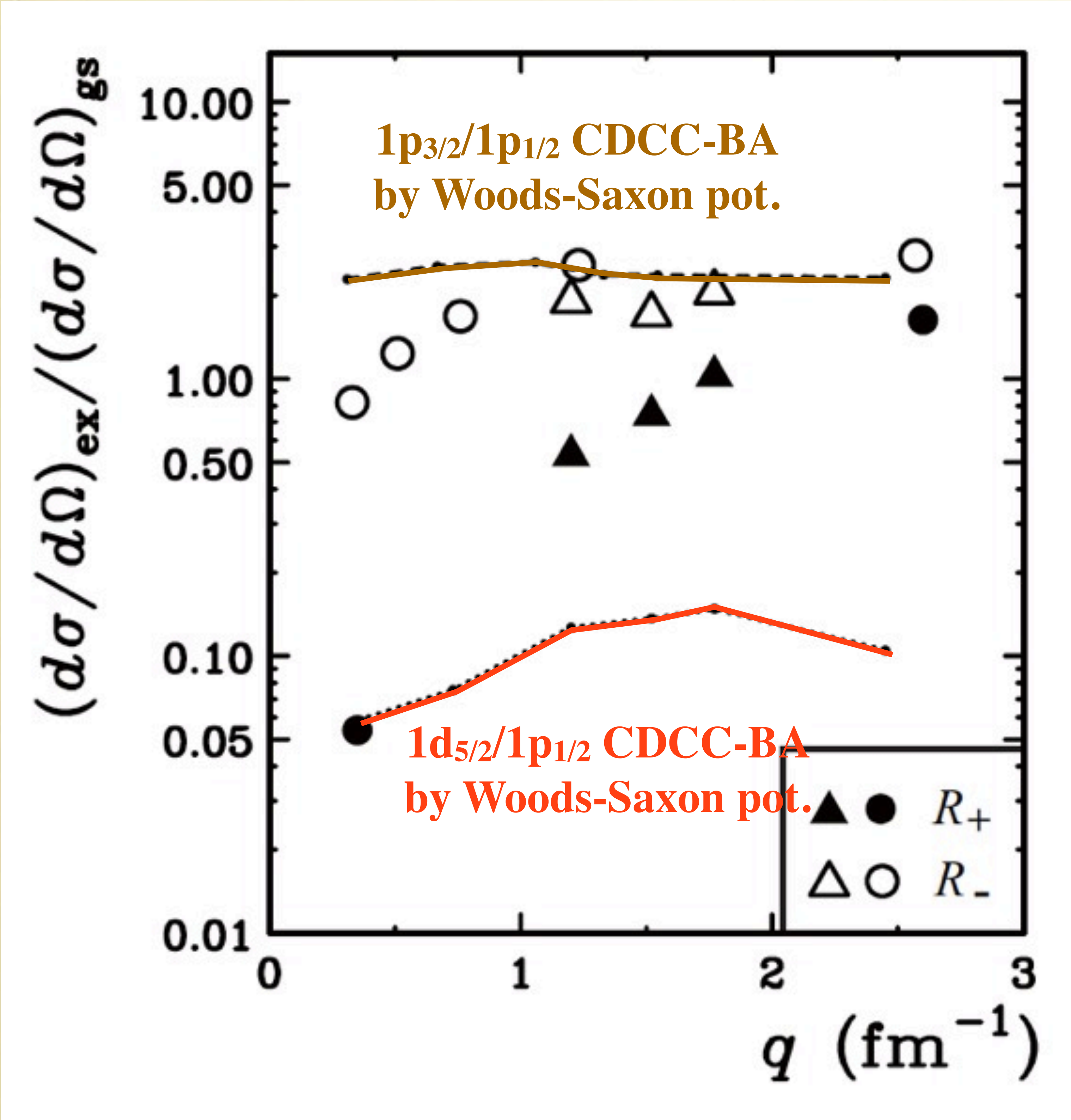

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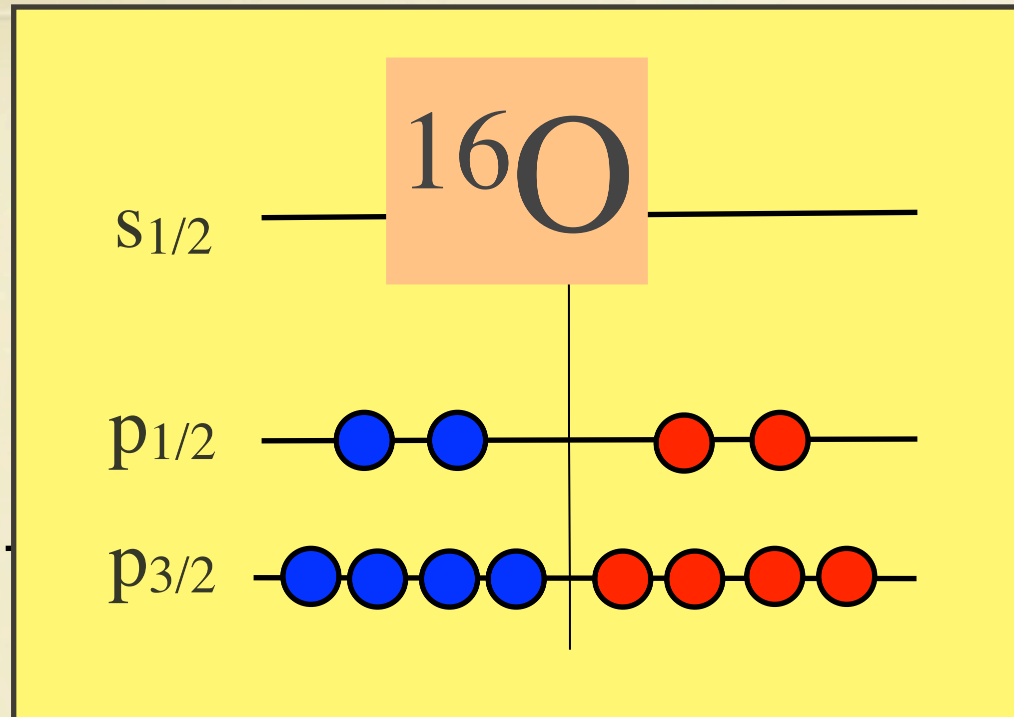
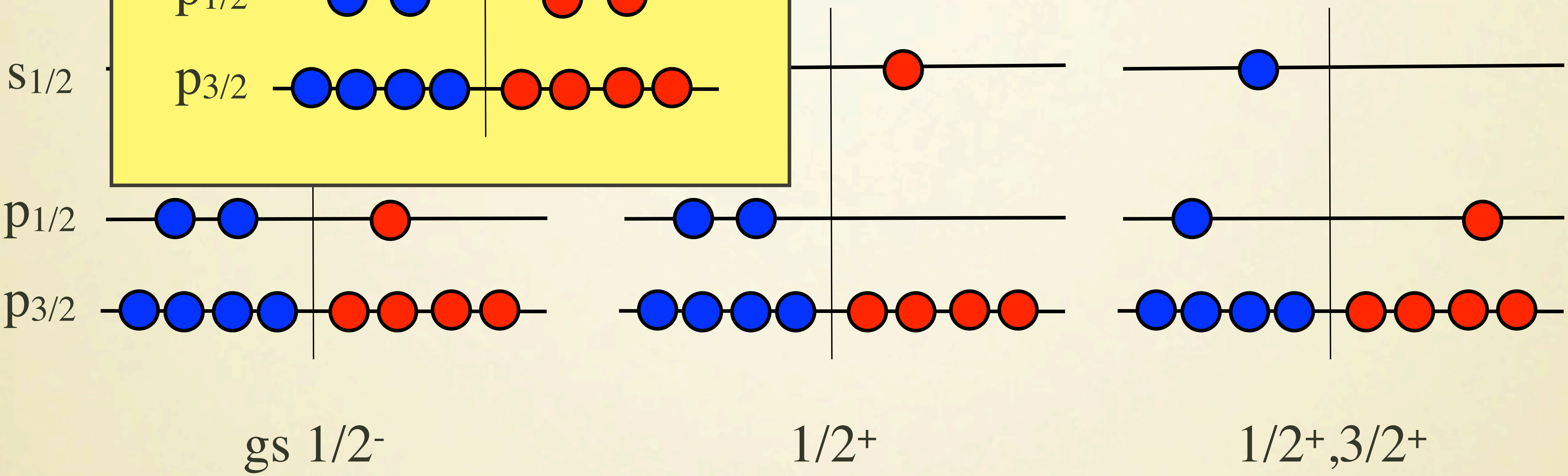
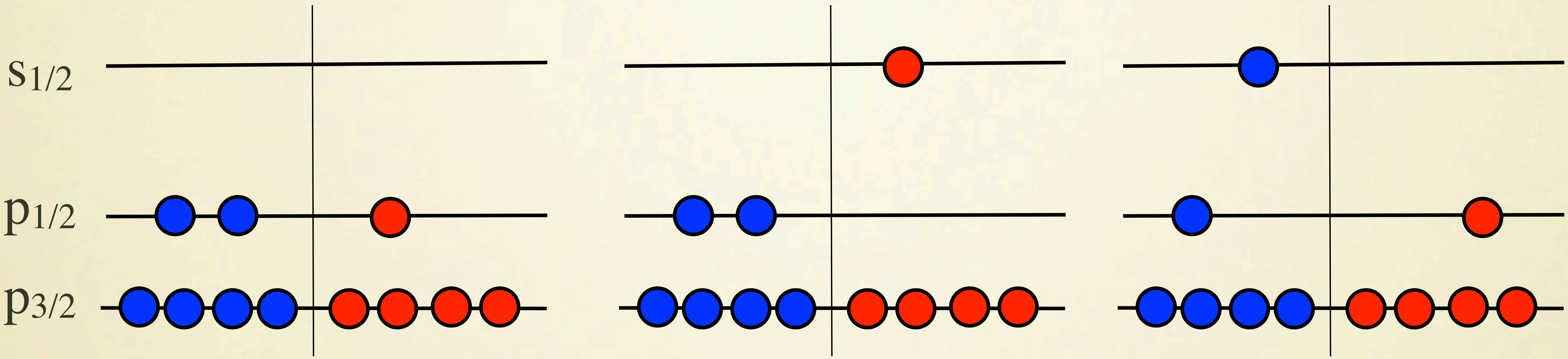
ES IN ^{15}O AS AN MPLE





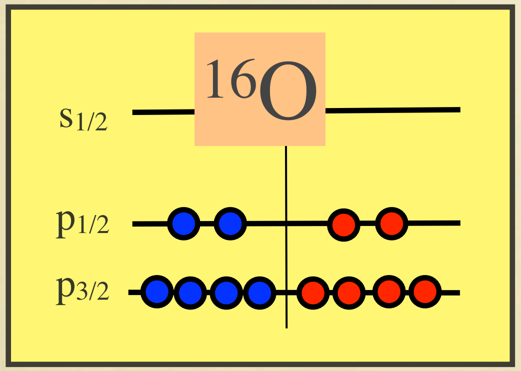
1/2+, 3/2+ states in ^{15}O as an example



gs 1/2-

1/2+

1/2+,3/2+



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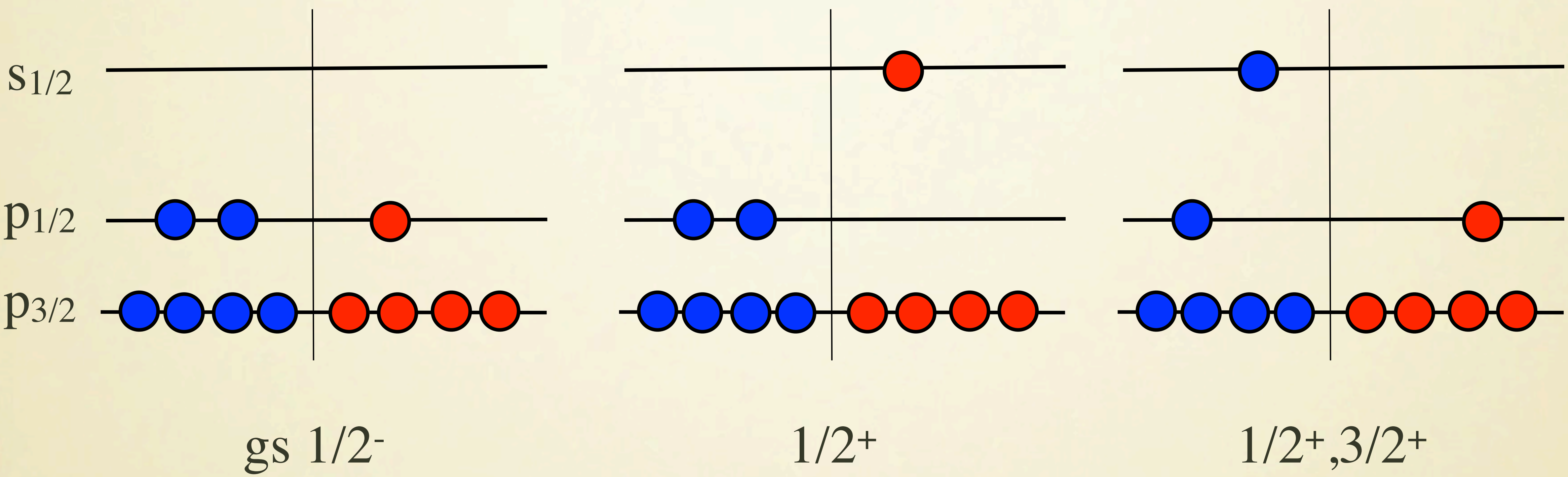
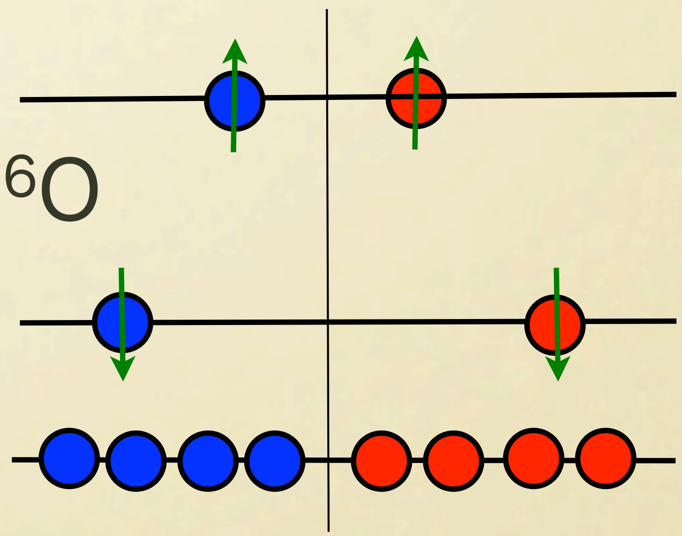
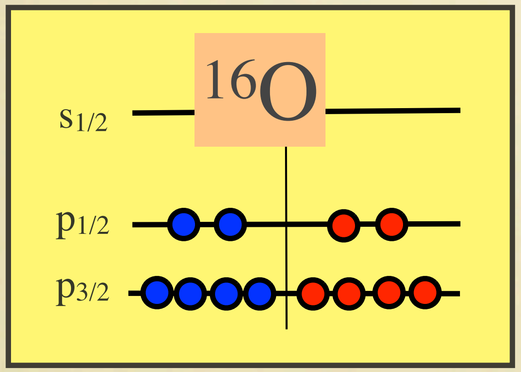
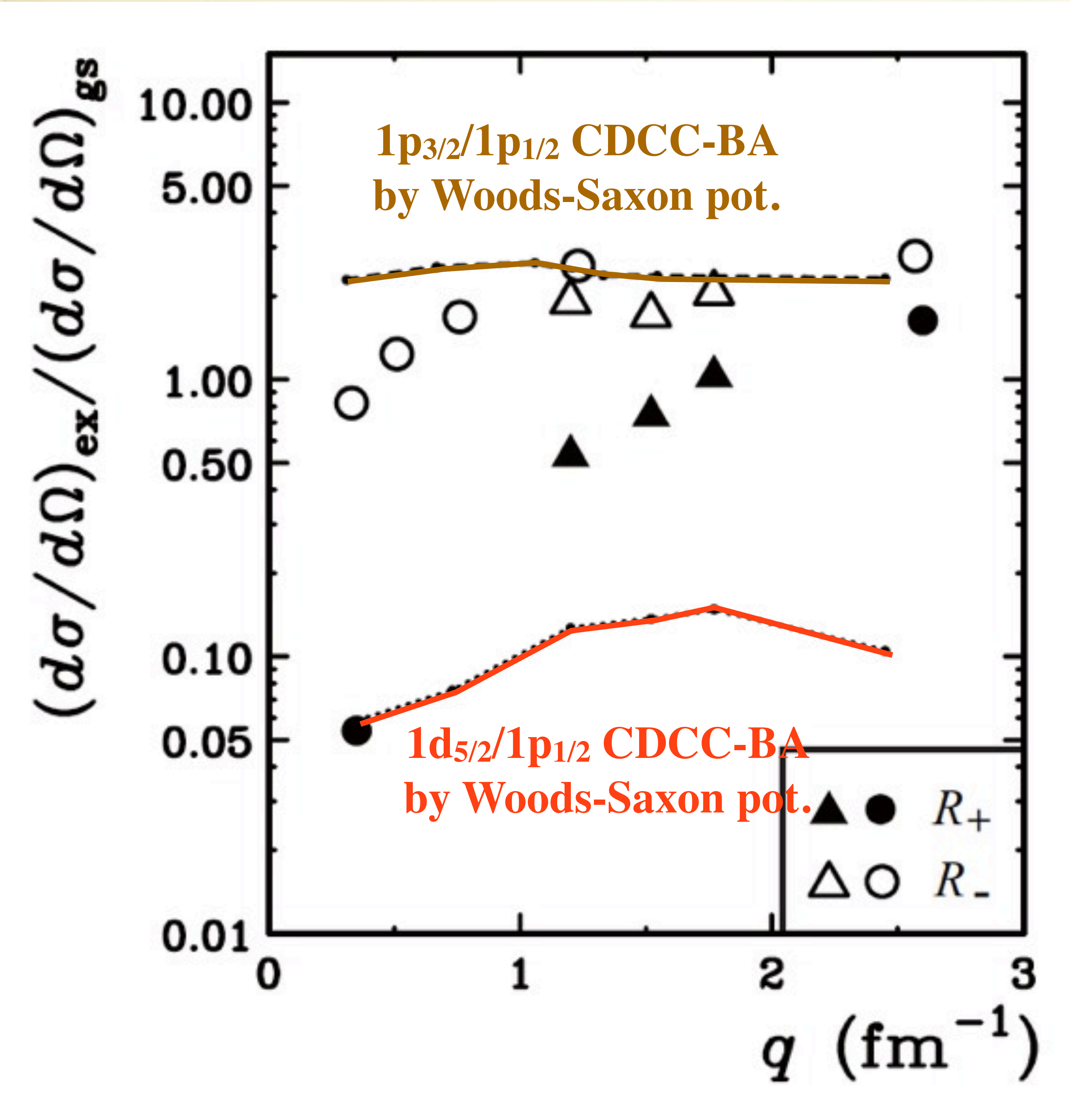


Tensor interaction in ^{16}O







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

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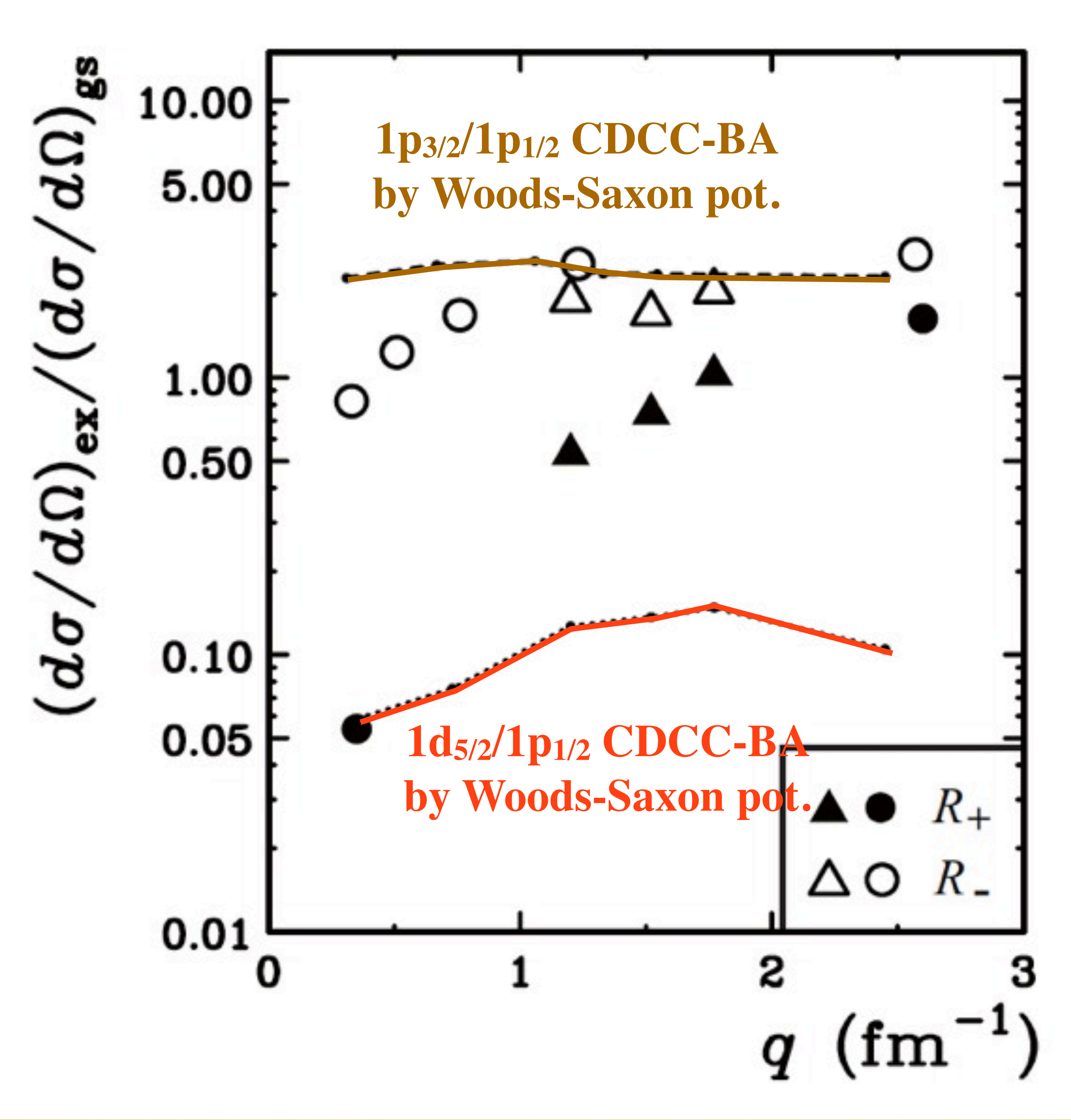

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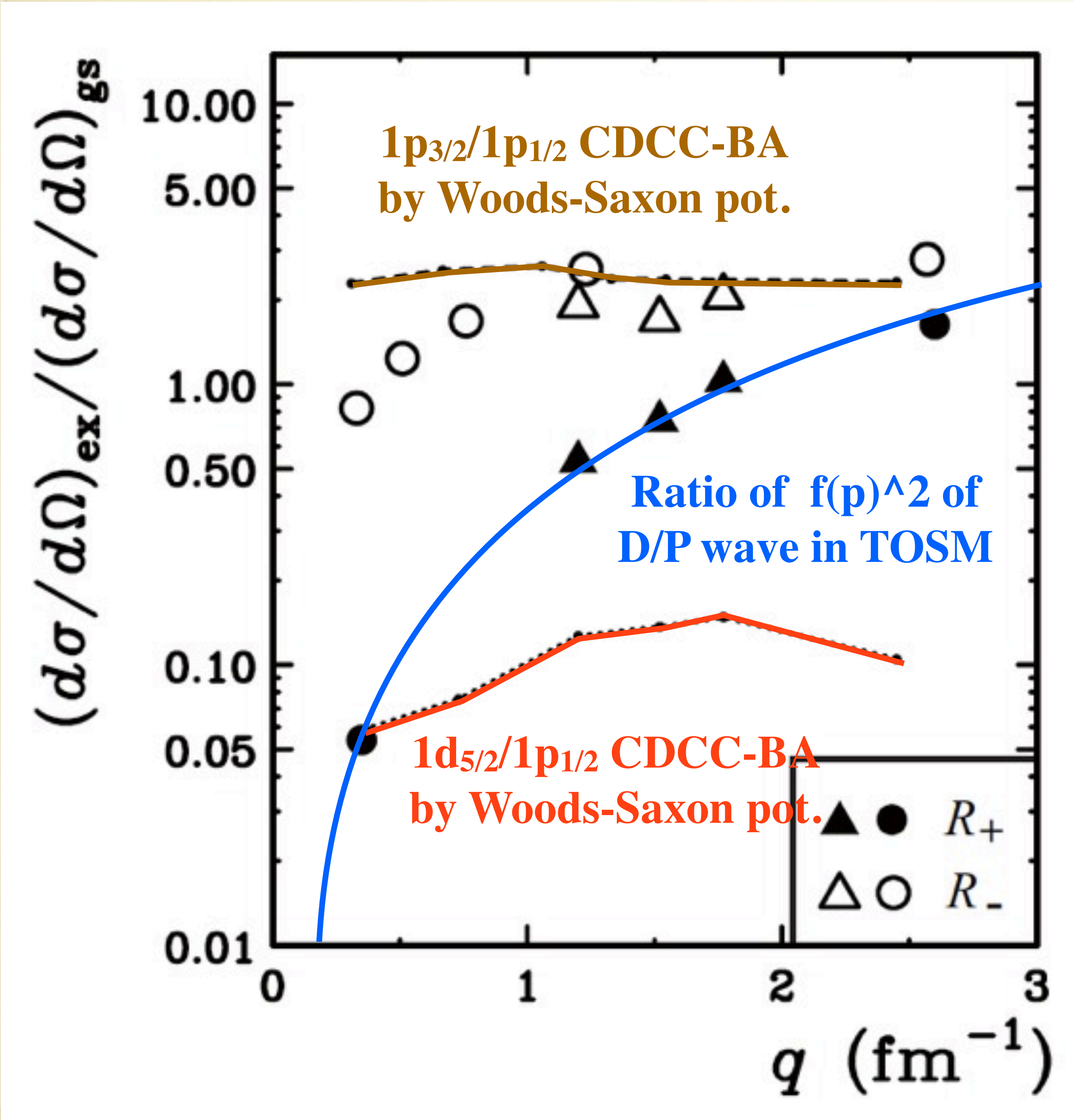
H.J. Ong et al. Phys. Lett. B 725, 277 (2013)

$$\sigma_F = K\frac{P_d}{p}N(P_F)\left[B_D + \frac{\hbar^2}{M}(\mathbf{p}-\mathbf{P}_d/2)^2\right]^2 \left|\left(\varphi(r), e^{i(\mathbf{p}-\mathbf{P}_d \cdot \mathbf{r}/2)}\right)\right|^2$$

K: phase space constant, B_D: deutron binding nergy, M: nucleon mass
by G. F Chew and M.L. Goldberger Phys. Rev. **77** (1950) 470.



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Reaction mechanism?

- **Measurement at θ_s=0° is least sensitive to the reaction mechanism.**

- **New measurement at RCNP @ 400 MeV**
  - ***θ_s=0 - 10°***
- **New measurement at GSI @400, 600, 900, 1200 MeV**
  - ***θ_s=0° : covers up to 2.5 fm^{-1}***

Beihang-RCNP-GSI-.. Collaboration

$$\sigma_F = K \frac{P_d}{p} N(P_F) \left[B_D + \frac{\hbar^2}{M} (\mathbf{p} - \mathbf{P}_d/2)^2 \right]^2 \left| \left(\varphi(r), e^{i(\mathbf{p}-\mathbf{P}_d \cdot \mathbf{r}/2)} \right) \right|^2$$

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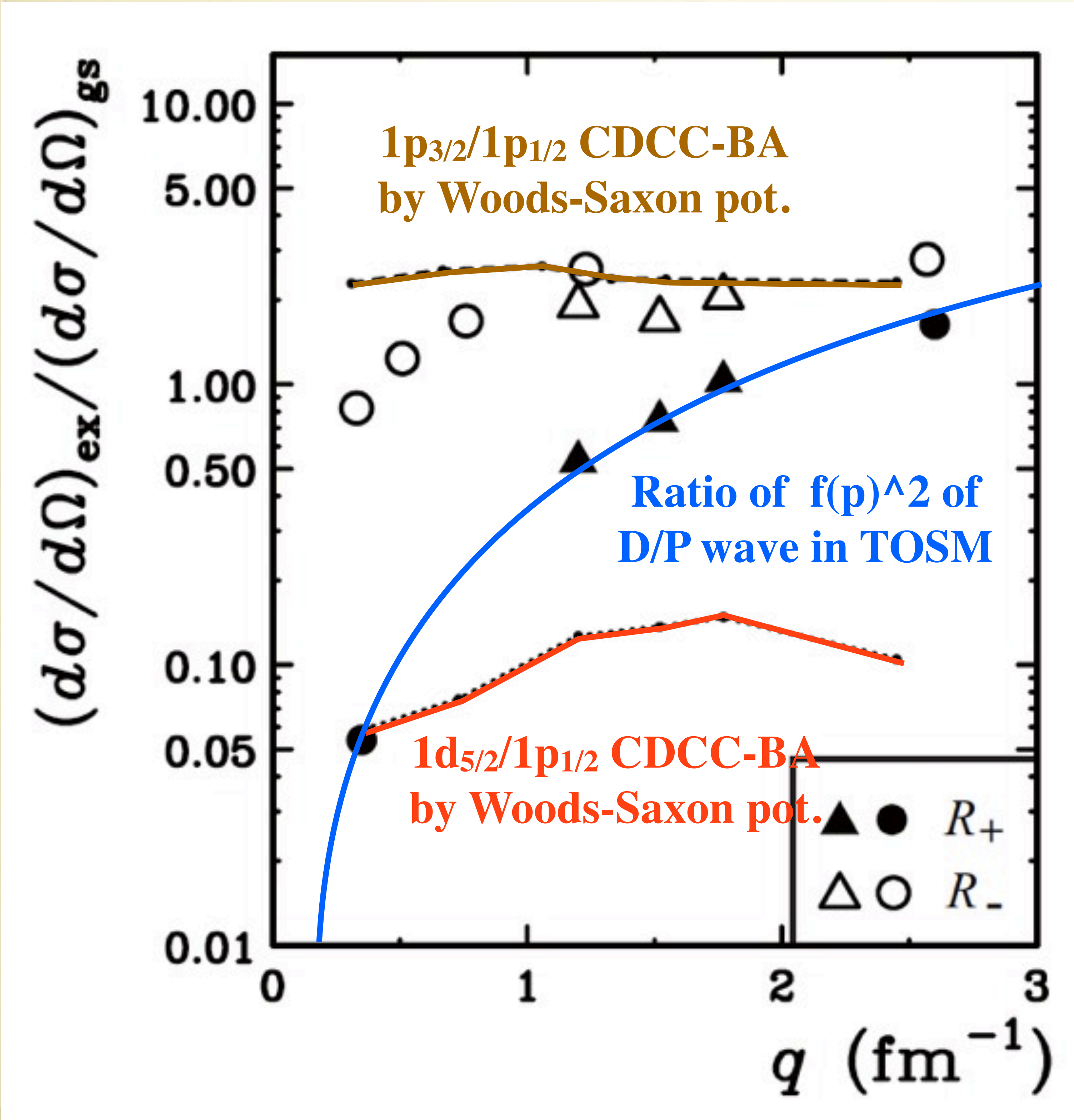

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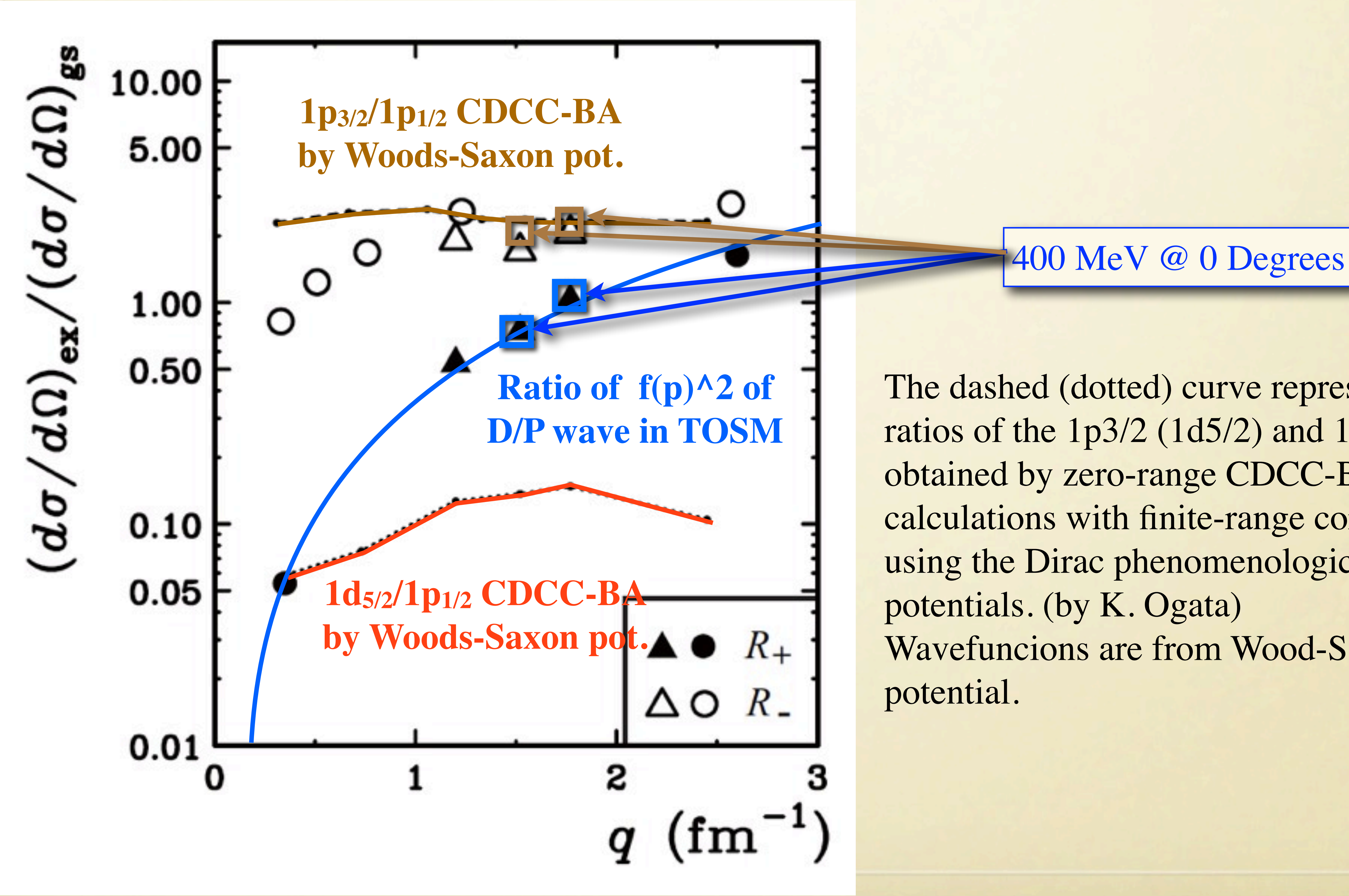

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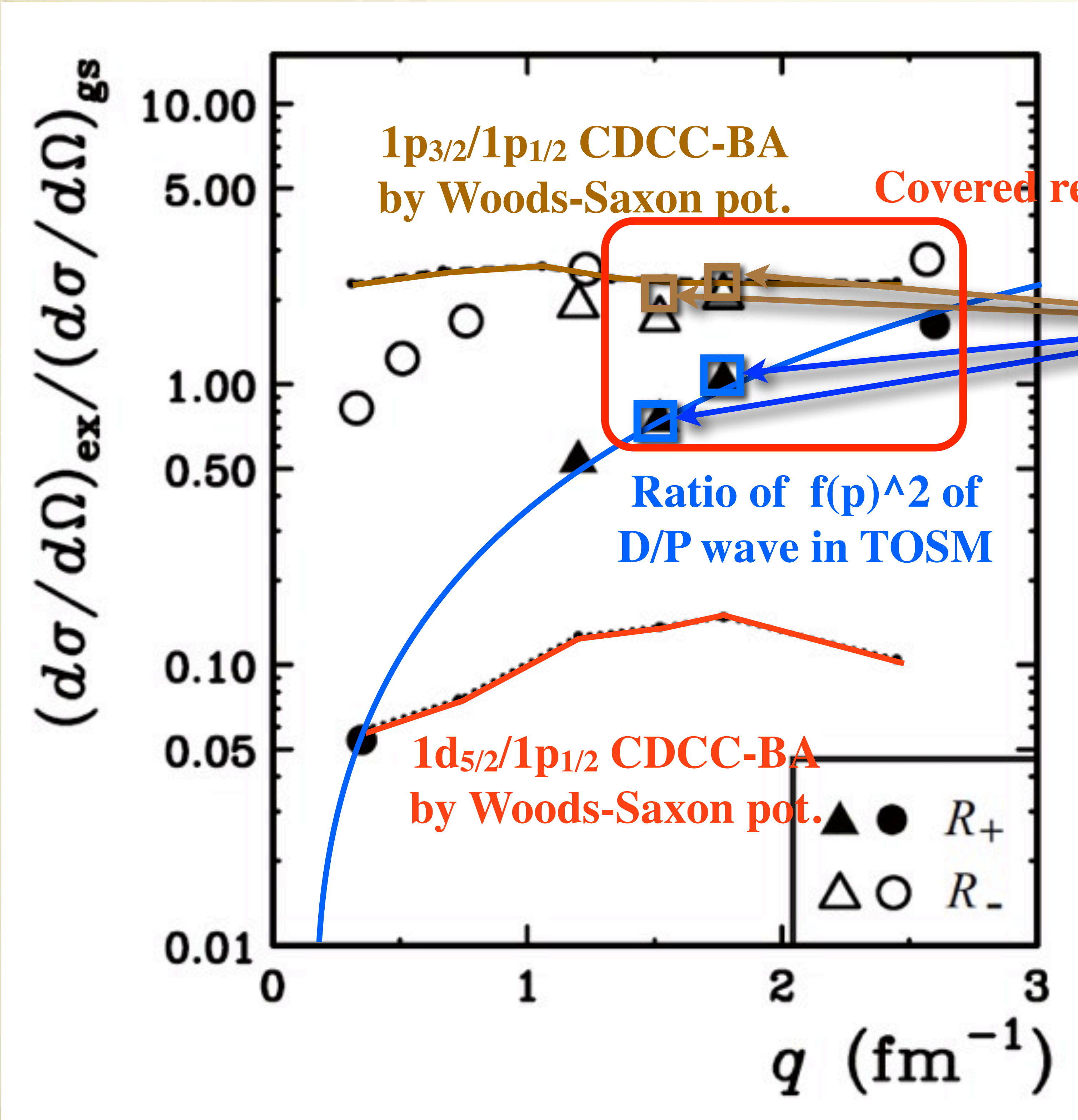

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Summary

- Tensor forces plays important roles for binding nuclei.
- It also contribute to changes of orbitals in new ways.
- Tensor forces can not be included in a mean field model in a explicit way.
- Effects of tensor forces depend strongly on configurations of nucleons.

- One of the direct method to see tensor forces effect is to observe high-momentum components of nucleons in nuclei.

- We need a model that treat the tensor force explicitly in the base wave function for heavier nuclei. The effect of high-momentum nucleons should not be forgotten.

Collaborators

(p,d) (p,pd) reaction

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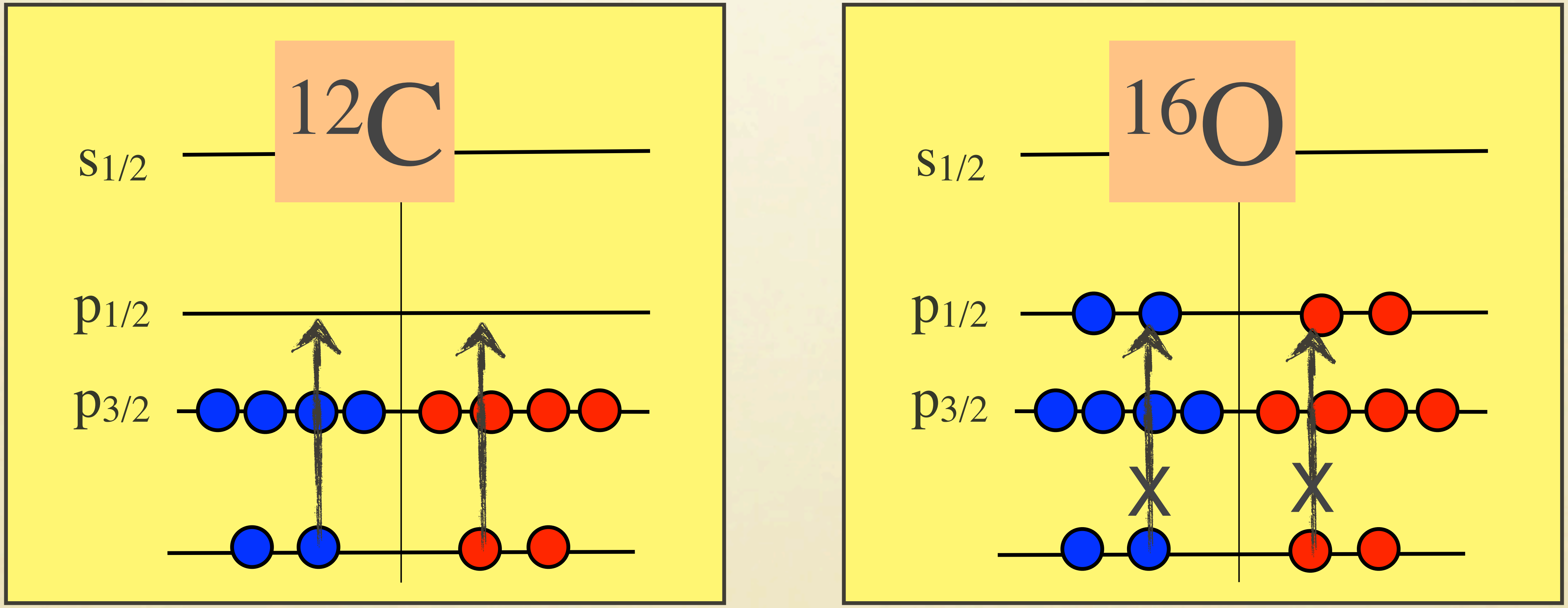
Answer to the question:

Do tensor forces introduce abrupt change of an effective mean field?

- Yes,
- For example: ^{12}C and ^{16}O



14年8月12日火曜日