Direct Probe of the Tensor Forces in Nuclei

Talk at NUSTAR meeting 2013.2.27

Isao Tanihata
Beihang University and Osaka University

Ab initio calculations of light nuclei tells us that Pion Exchanges are most important for forming nuclei

- **The pion exchange interaction includes the central force and the tensor force with same strength.**

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

R. B. Wiringa

$$\vec{\sigma}_1 \cdot \vec{q}\,\vec{\sigma}_2 \cdot \vec{q} = \frac{1}{3} q^2 S_{12}(\hat{q}) + \frac{1}{3} \vec{\sigma}_1 \cdot \vec{\sigma}_2 q^2 \qquad S_{12}(\hat{q}) = \sqrt{24\pi}\left[Y_2(\hat{q})\left[\sigma_1 \sigma_2\right]_2\right]_0$$

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and three body forces

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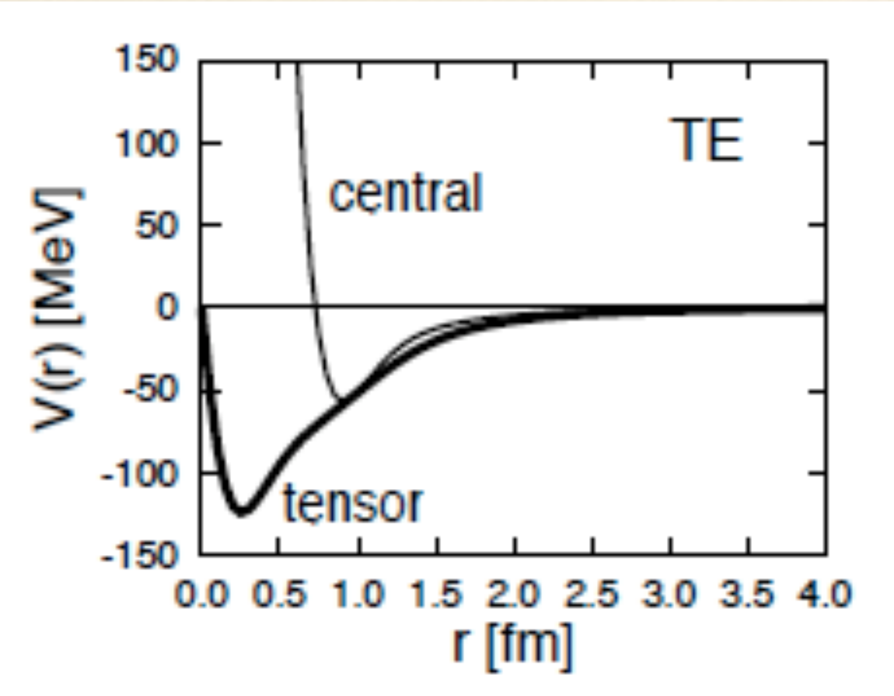
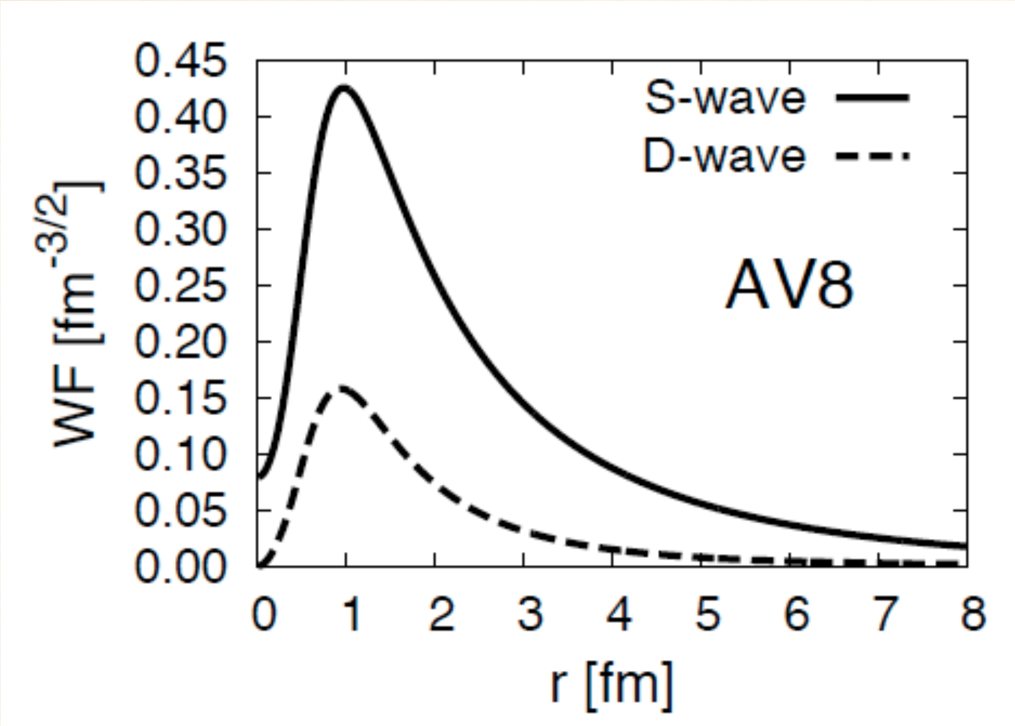
$$S_{12}(\hat{q}) = \sqrt{24\pi} \left[Y_2(\hat{q}) [\sigma_1 \sigma_2]_2 \right]_0$$

The importance of pion is clear in deuteron





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
Tensorc	−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]

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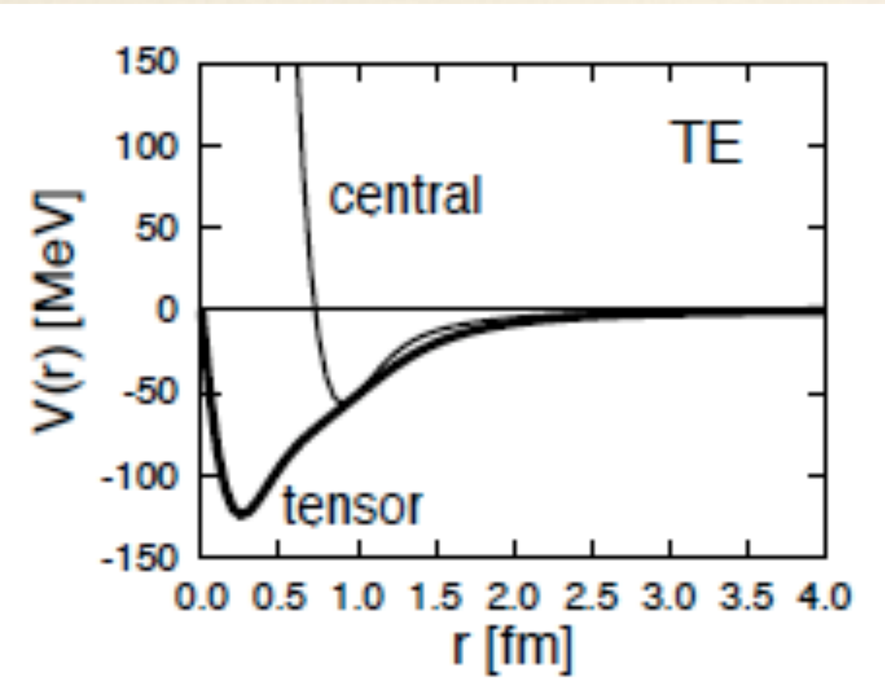

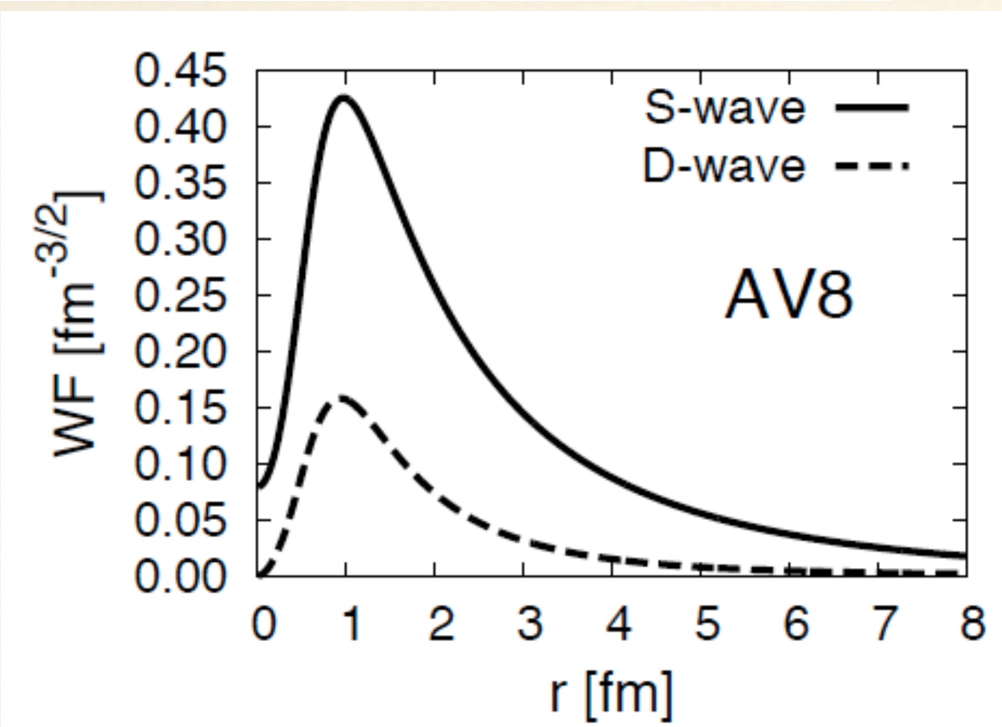

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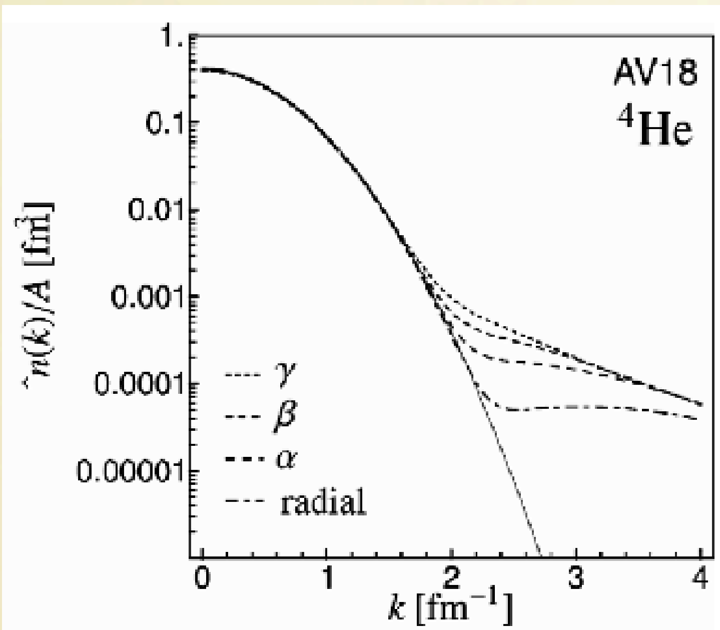
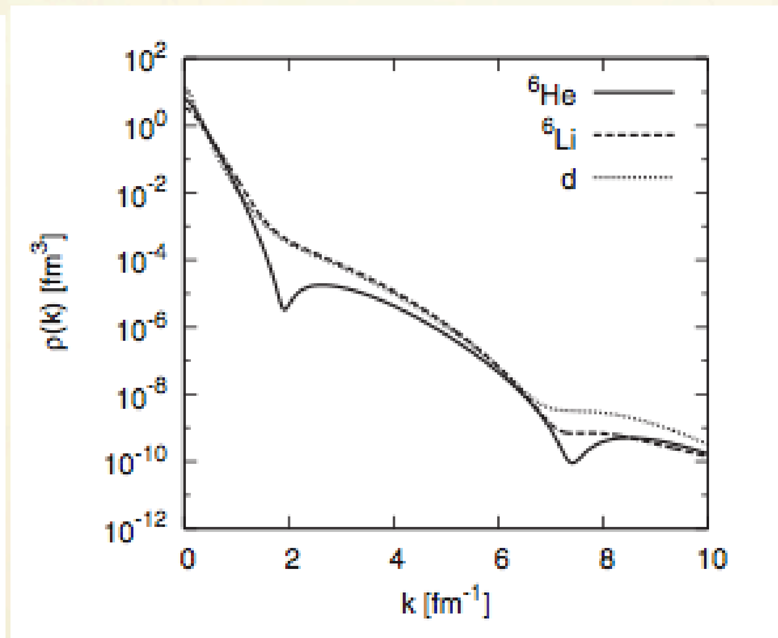
Evidences of tensor forces in nuclei

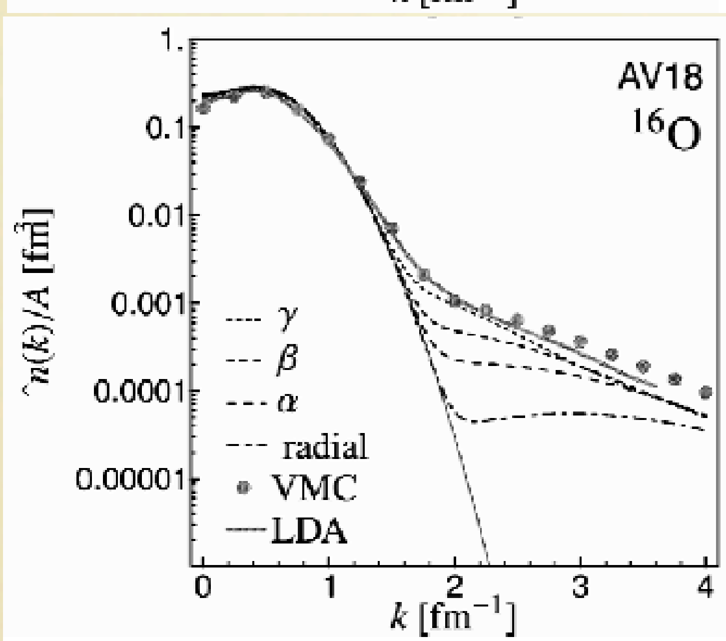
- Change of magic numbers
- Magnetic moments of doubly-magic±1 nuclei
- $(s_{1/2})^2$ and $(p_{1/2})^2$ mixing in ^{11}Li neutron halo
- ...

Theoretical Predictions



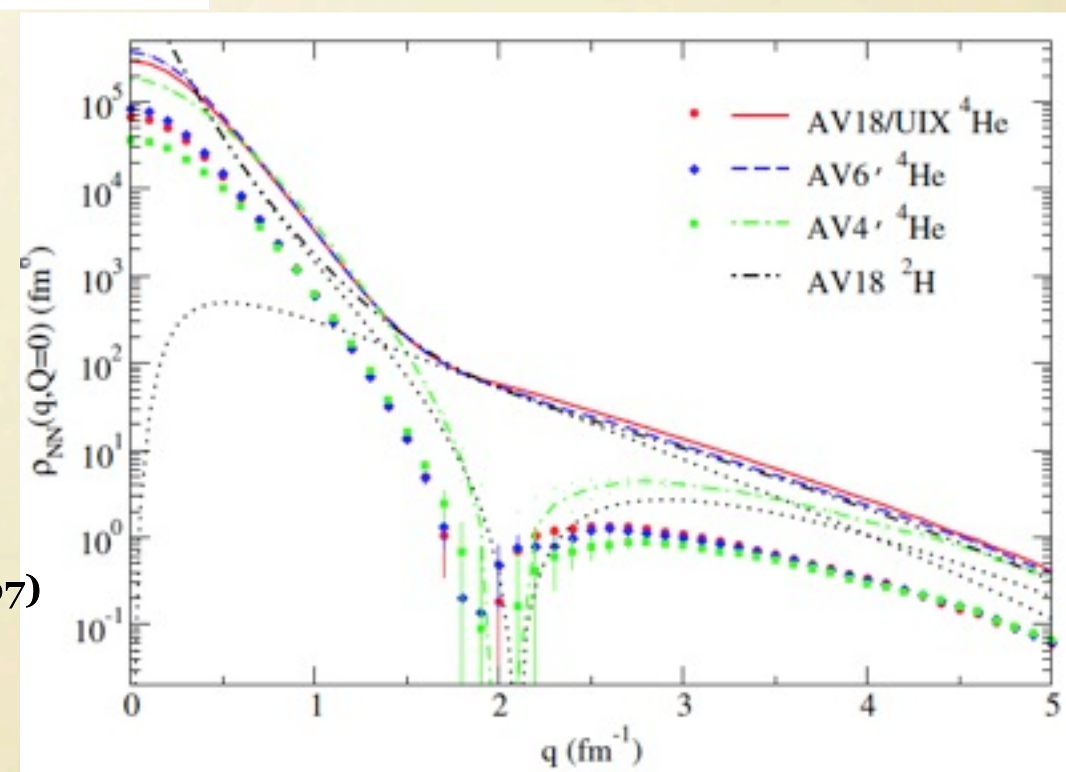


W. Horiuchi and Y. Suzuki,
PRC76, 024311(2007)



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

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



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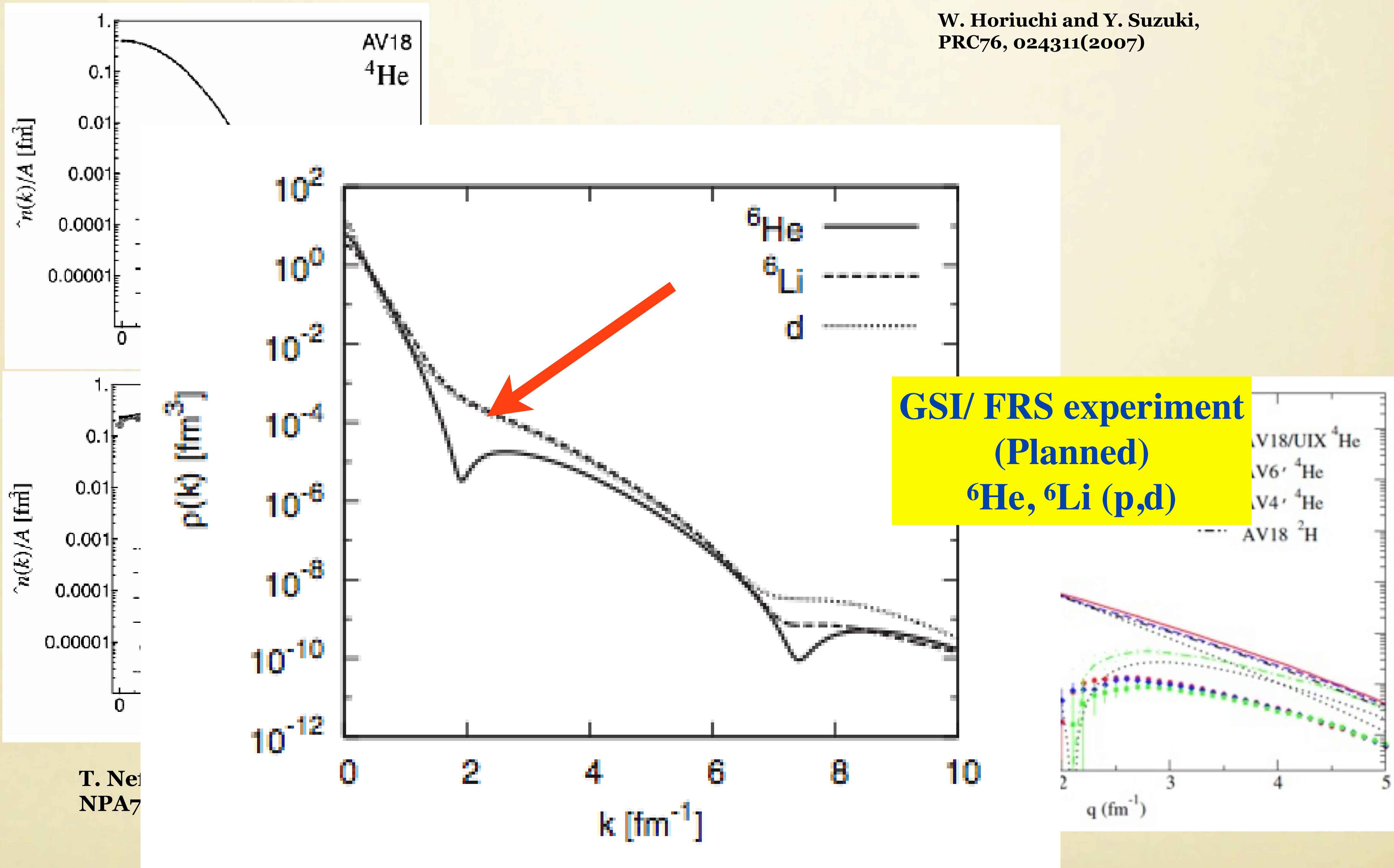

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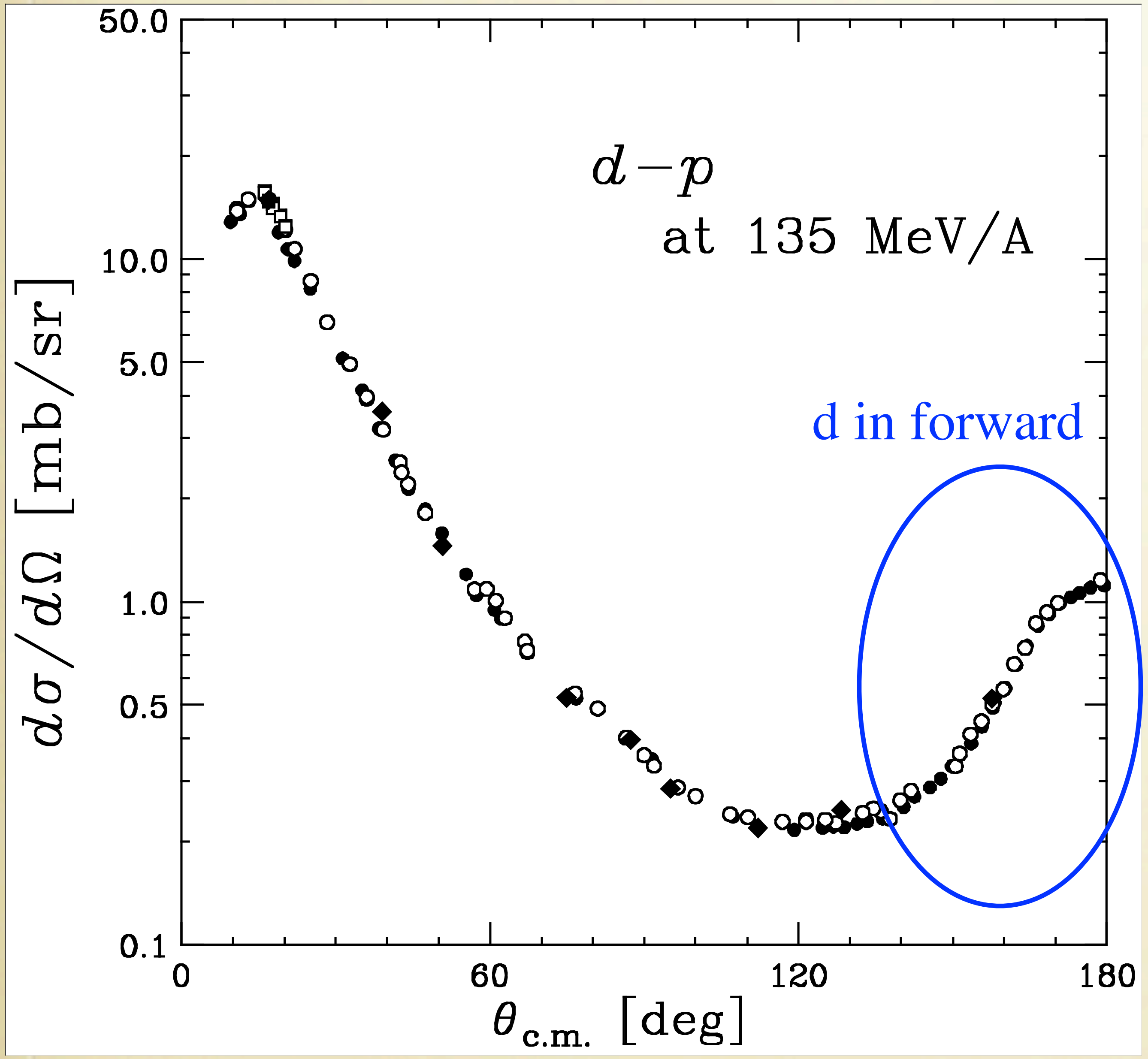
(P,D) SCATTERING

= SUITABLE TO PICK UP HIGH MOMENTUM NEUTRON =



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

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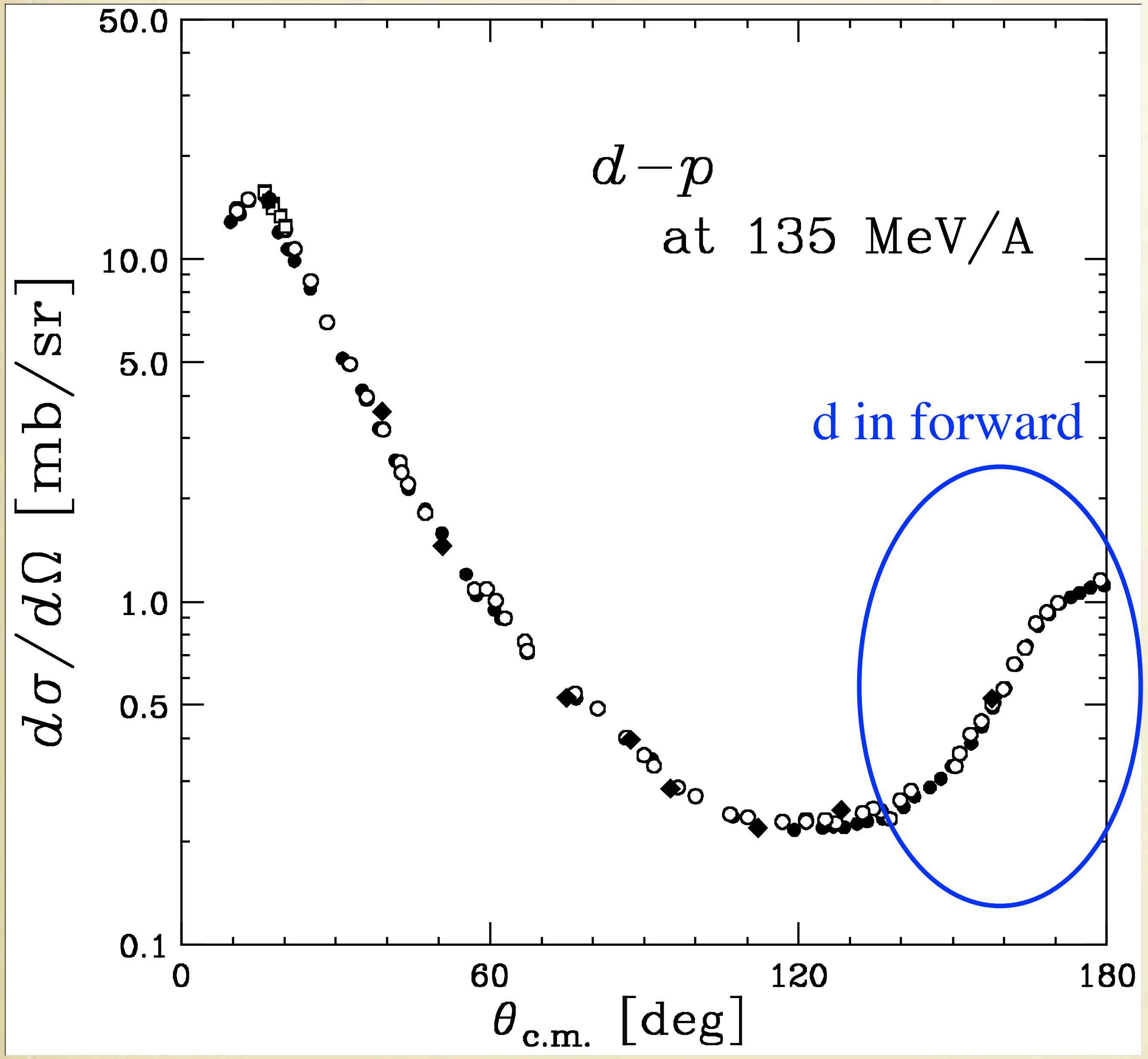

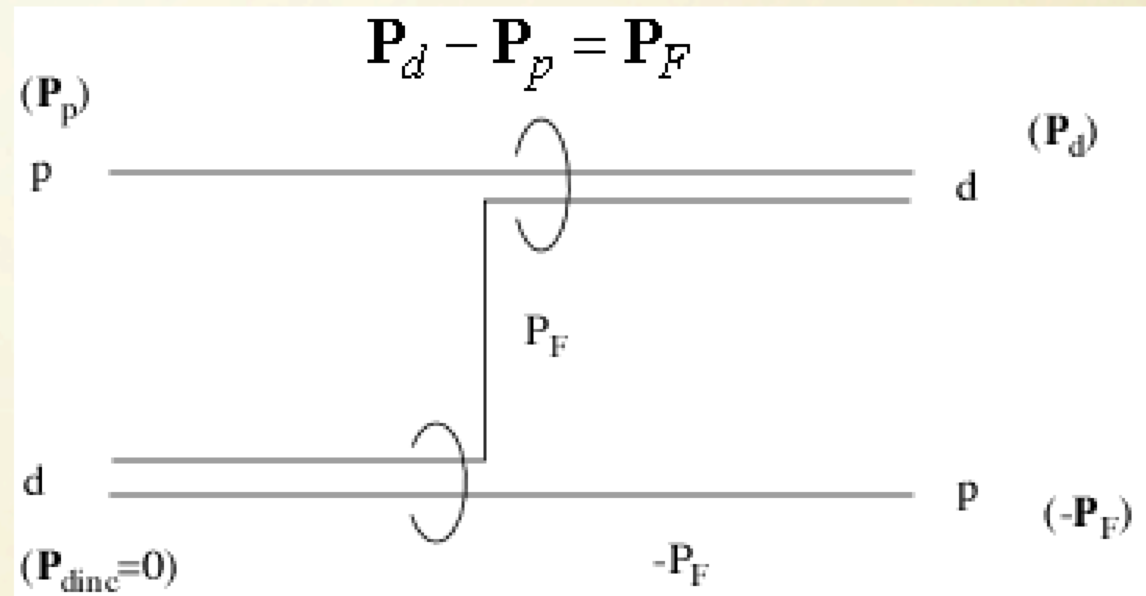

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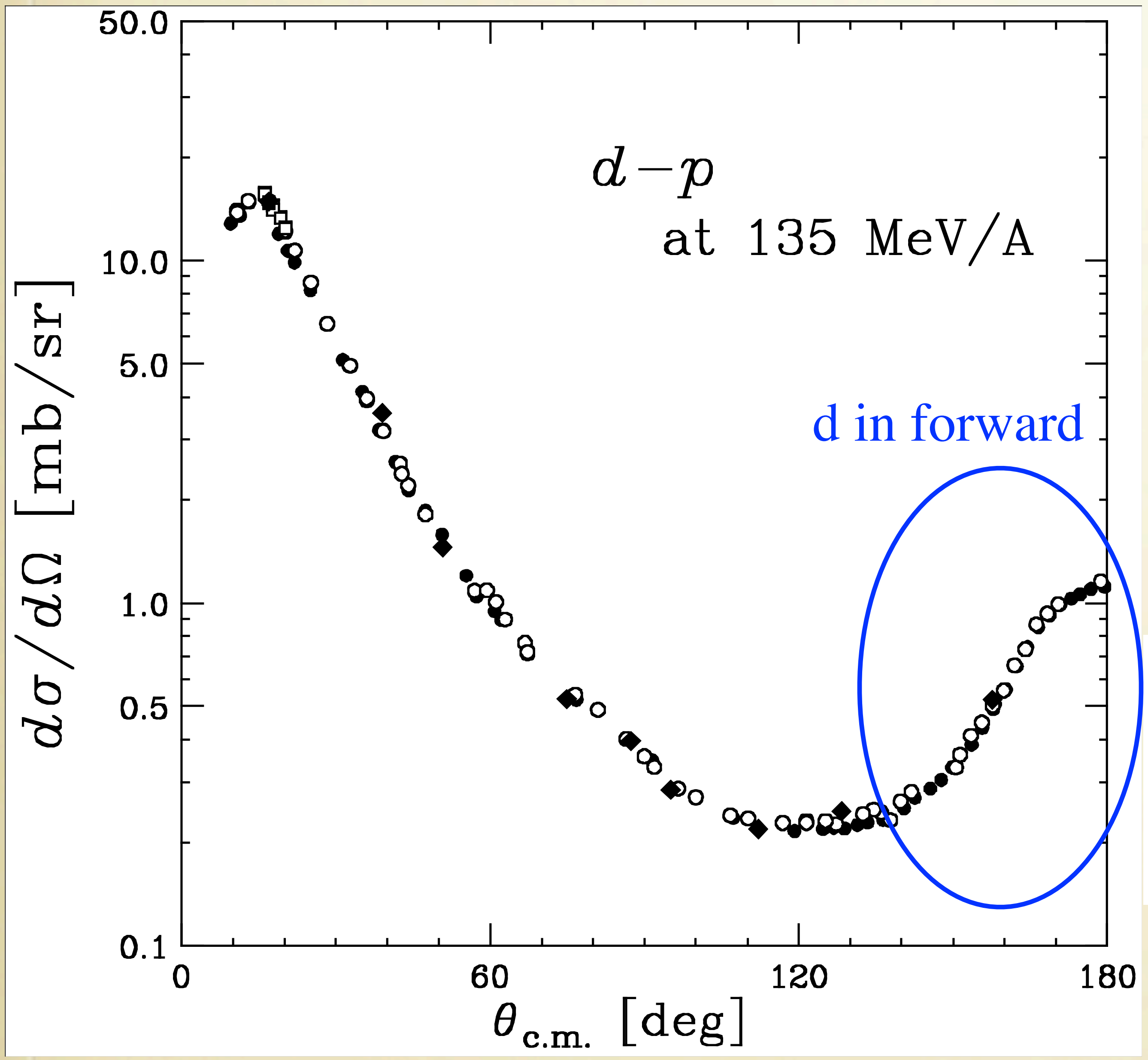
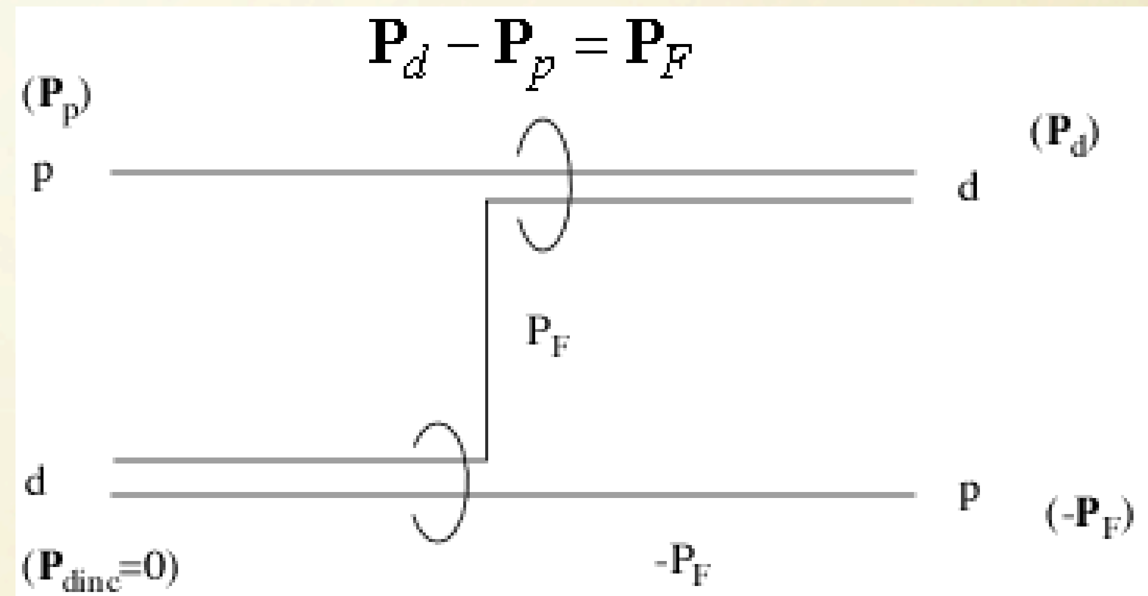




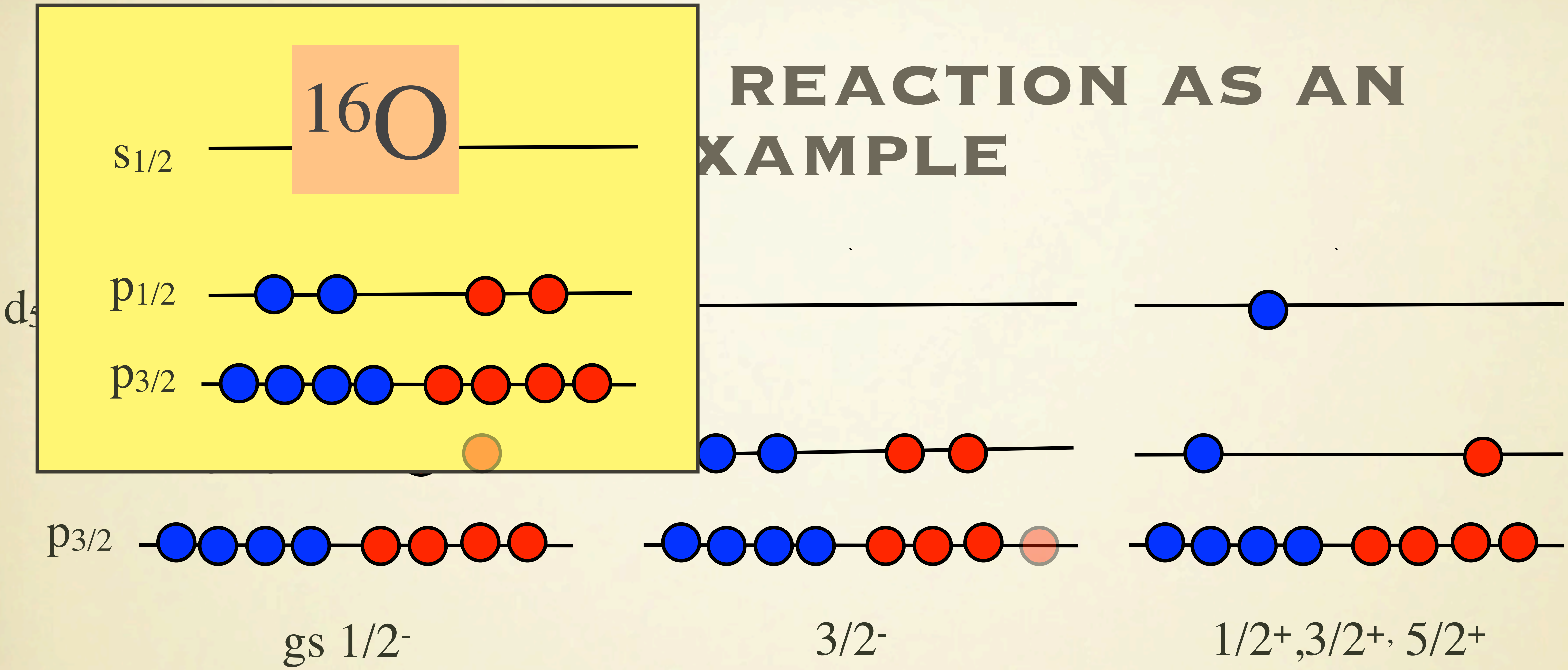
$$\sigma_F = K\frac{P_d}{p}N(P_F)\left[B_D + \frac{\hbar^2}{M}(\mathbf{p}-\mathbf{P}_d/2)^2\right]^2 \left|\left(\varphi(r), e^{i(\mathbf{p}-\mathbf{P}_d\bullet\mathbf{r}/2)}\right)\right|^2$$

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.

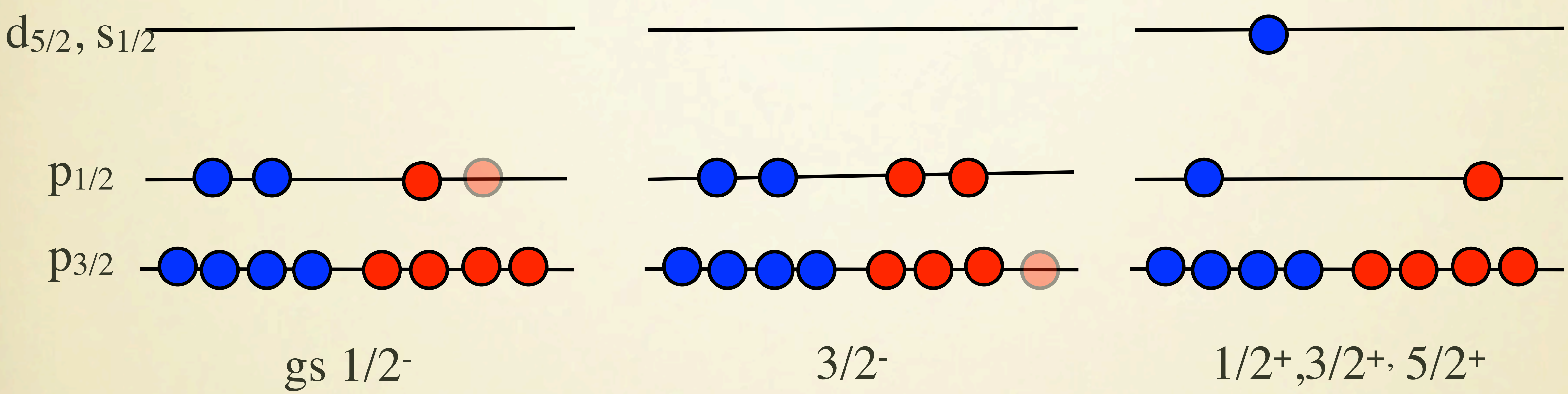
K. Sekiguchi et al.,
PRL **95** (2004) 162301

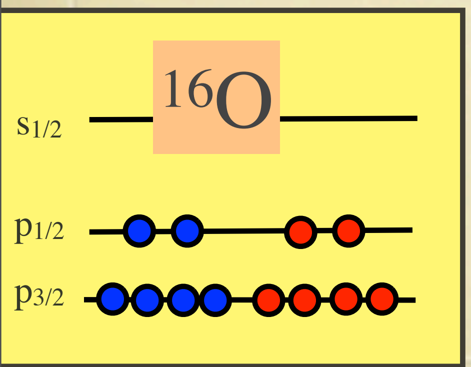
Reaction at backward occurs by the high-momentum component.

REACTION AS AN
XAMPLE



$^{16}O(p,d)^{15}O$ reaction as an example





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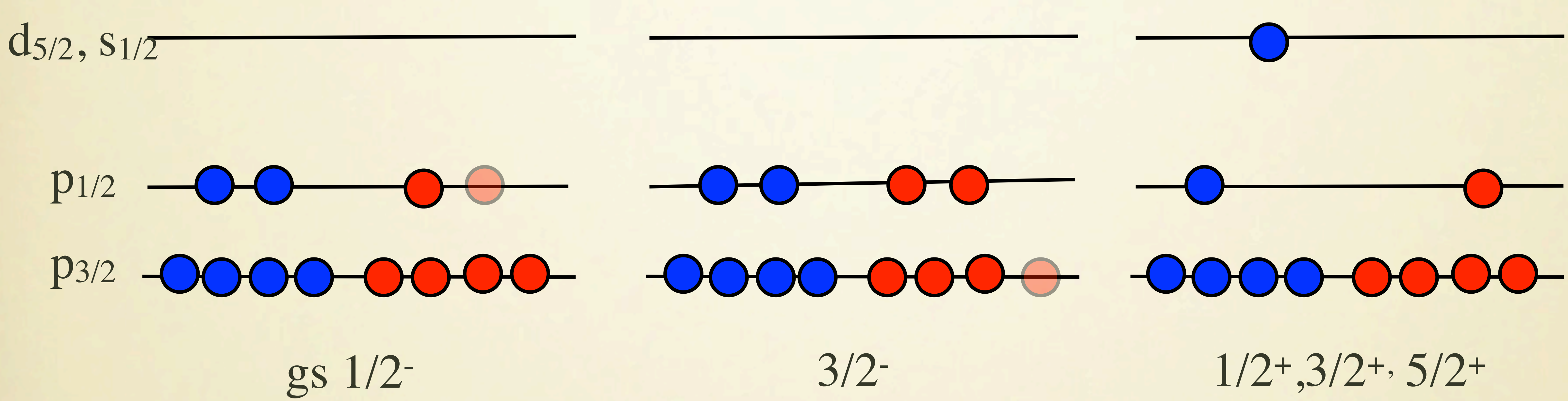
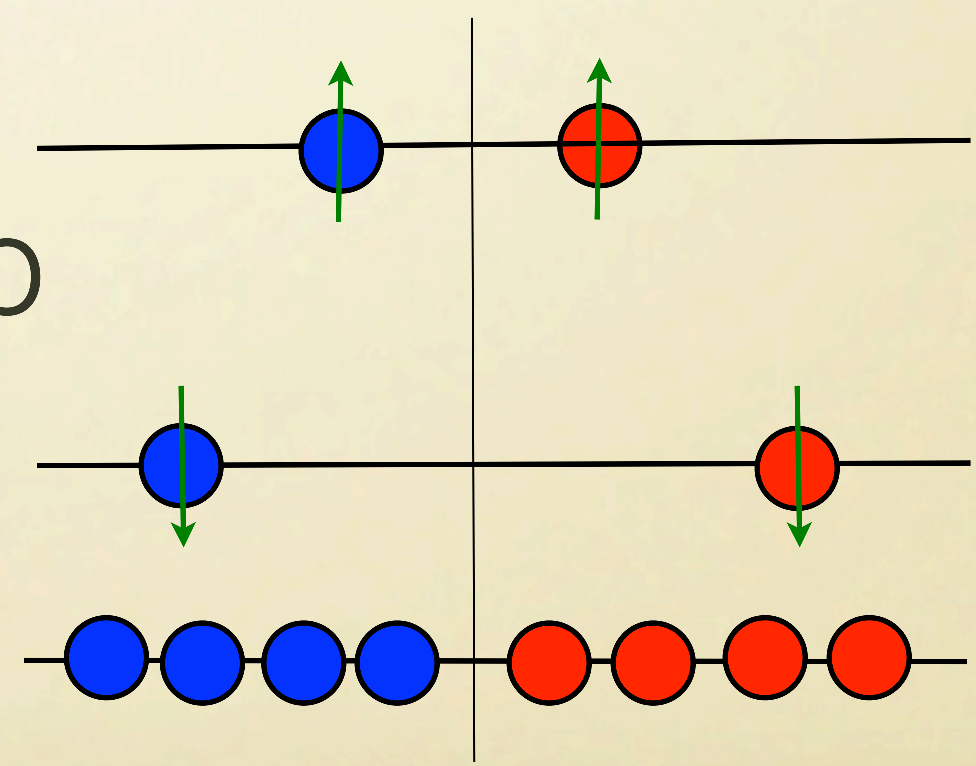
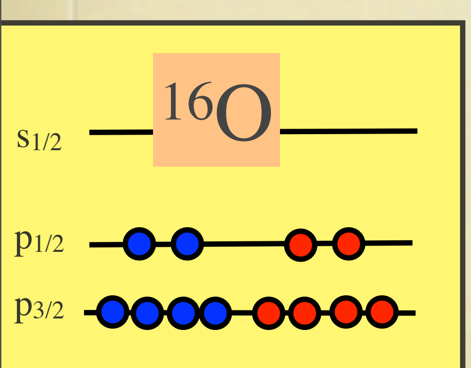


Tensor interaction in ^{16}O



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



At 45 MeV

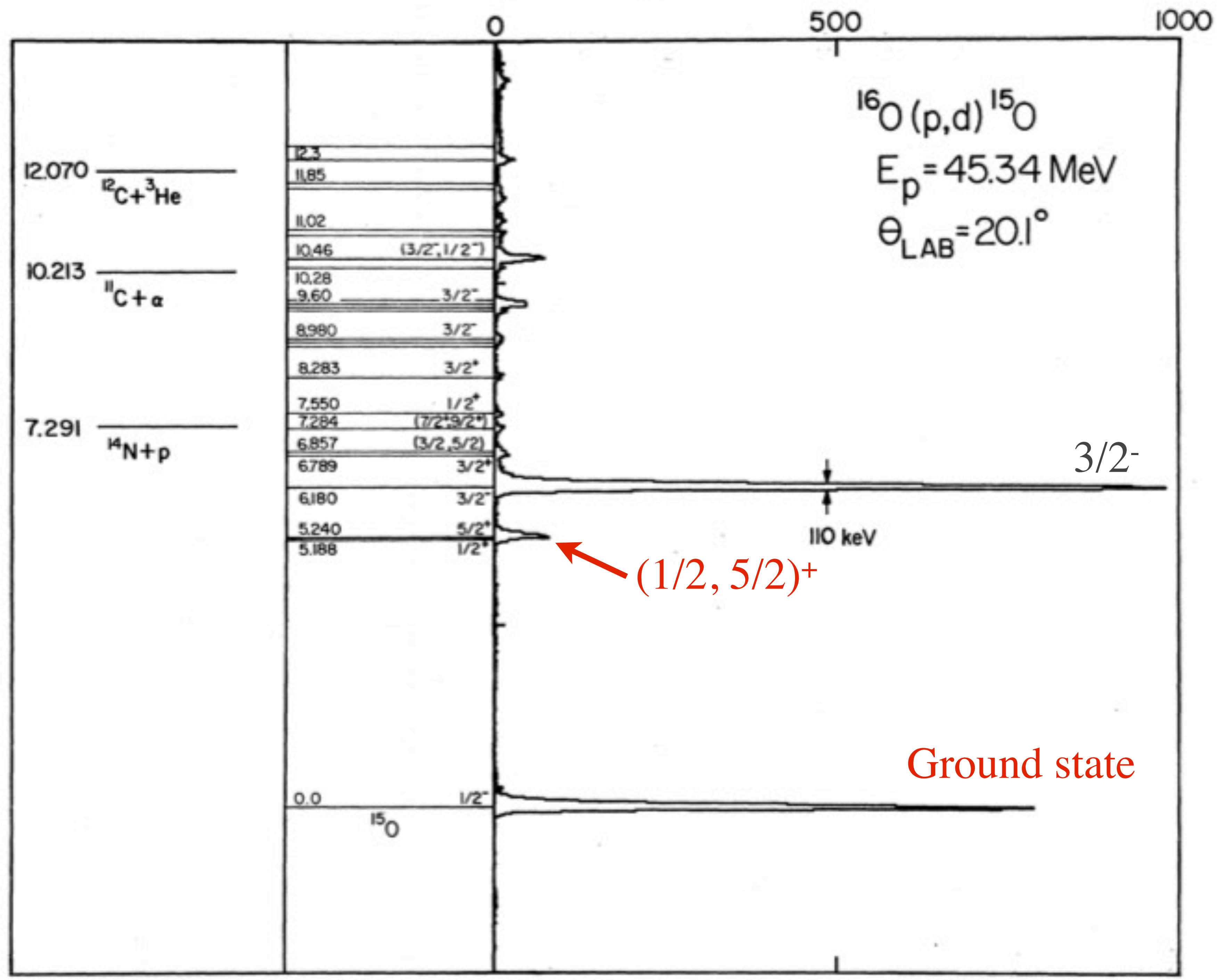
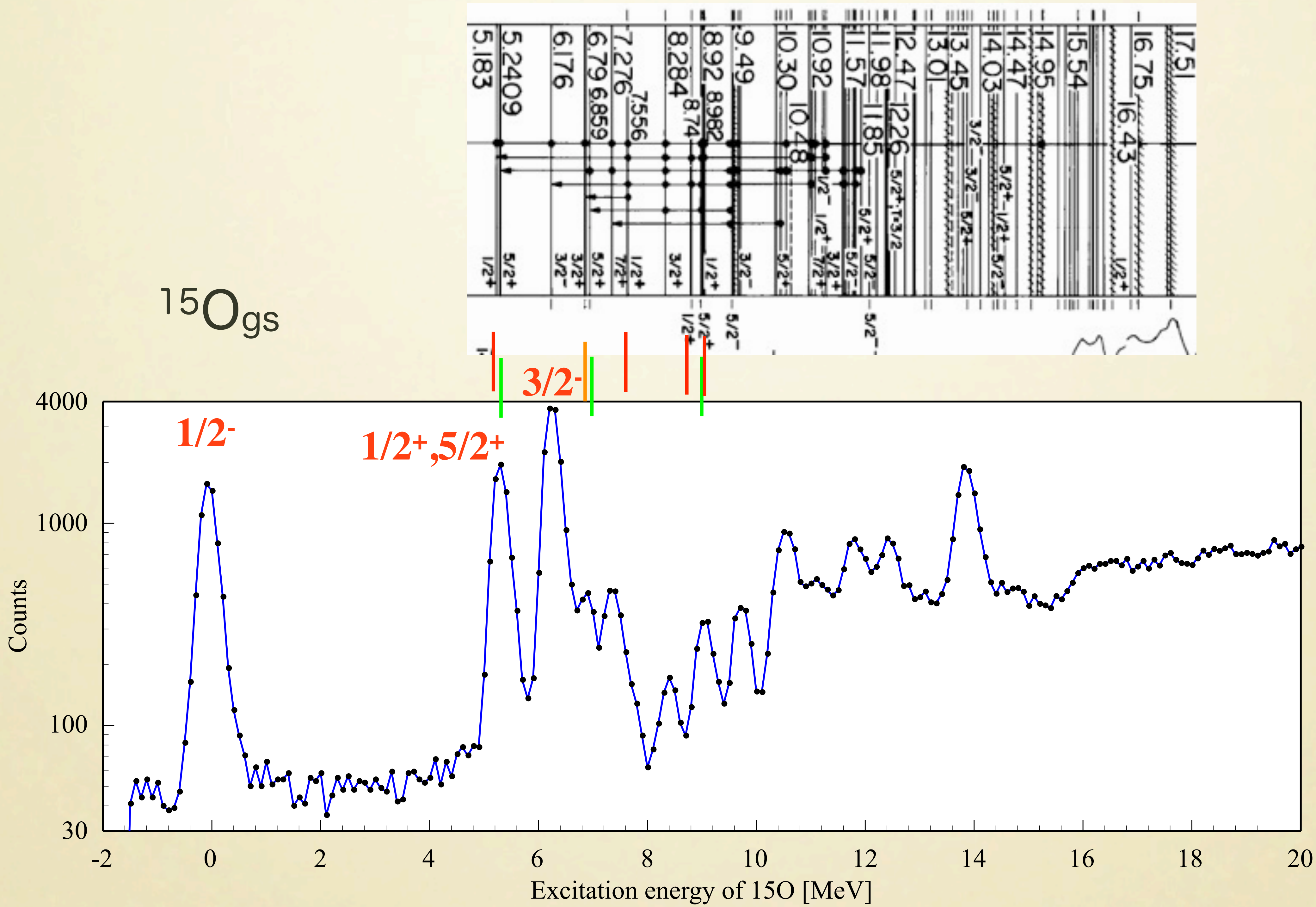


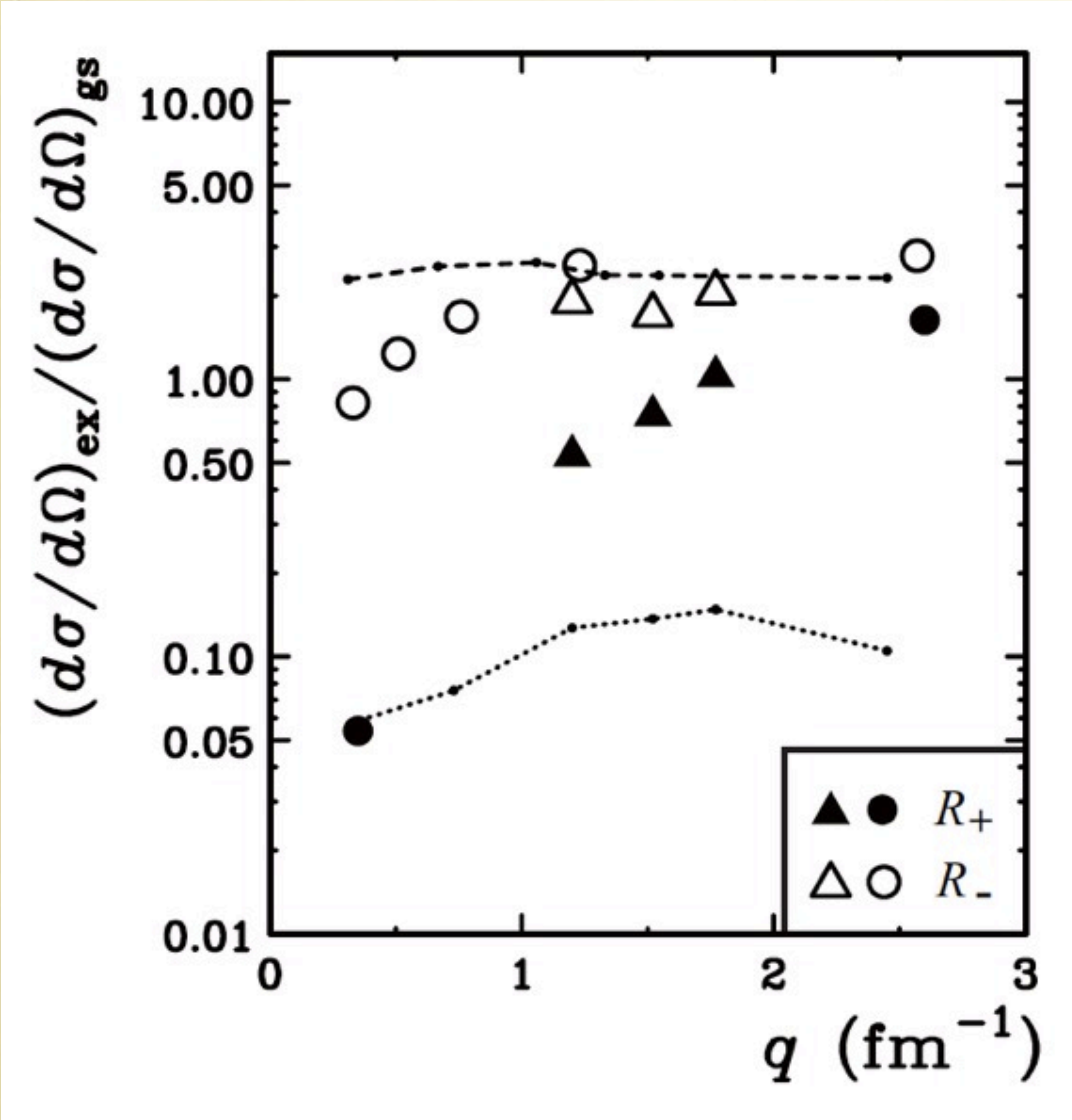
FIG. 2. Energy-level diagram of ^{15}O displayed beside a deuteron energy spectrum from the $^{16}O(p, d)^{15}O$ reaction for E_p=45.34 MeV and θ_{lab}=20.1°.

Data at RCNP

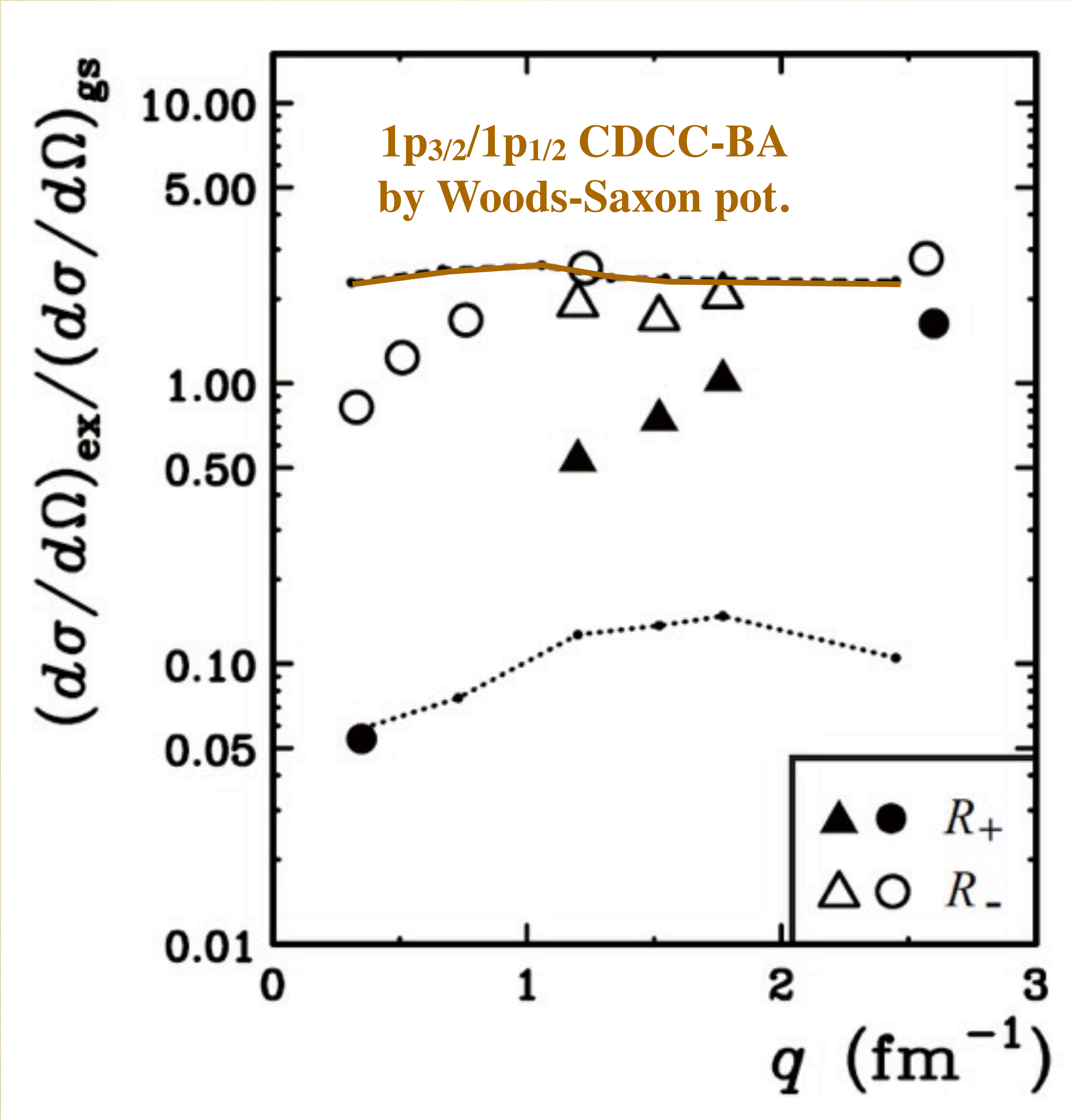
H.J. Ong et al arXiv:1205.4296



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



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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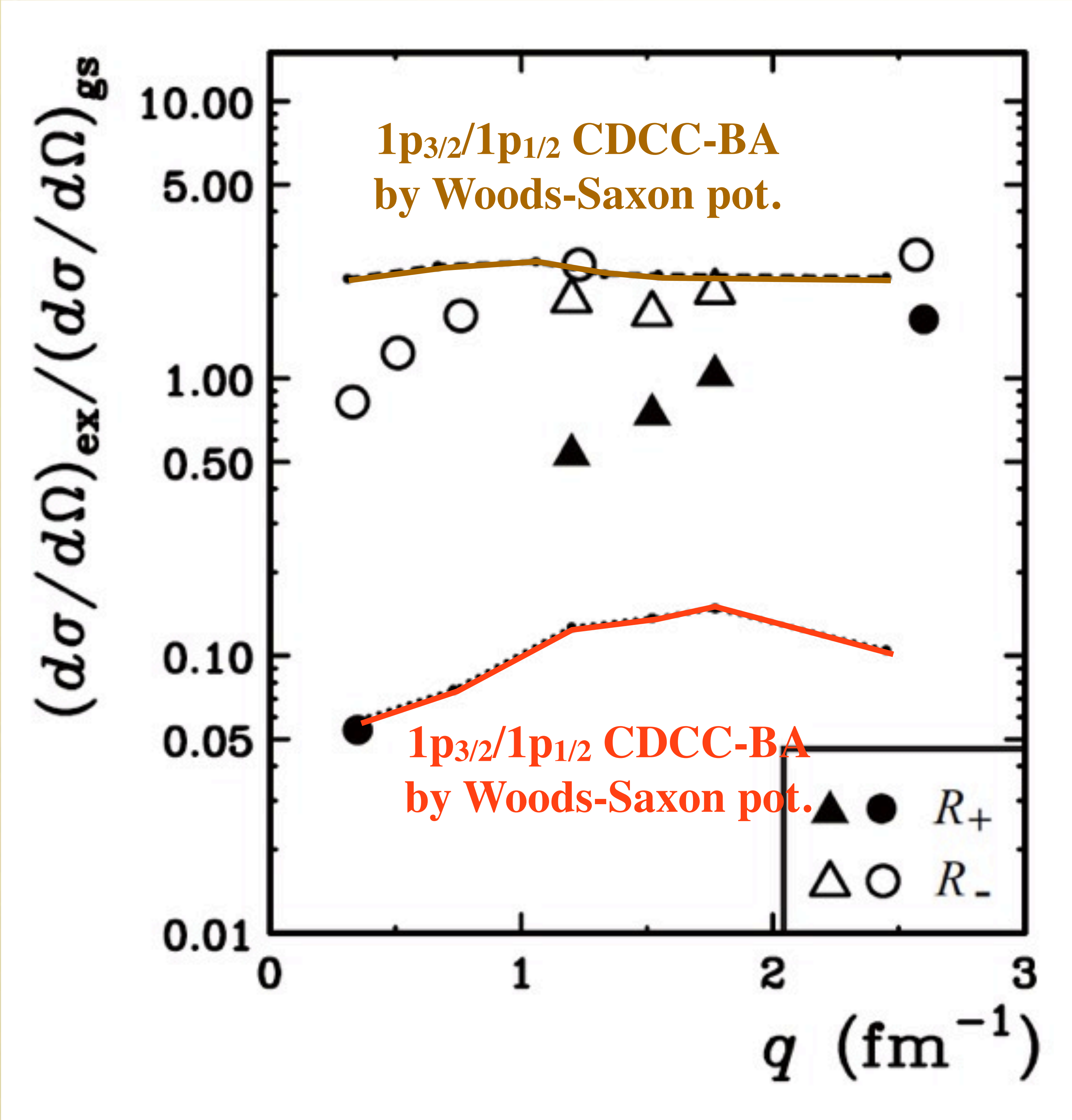

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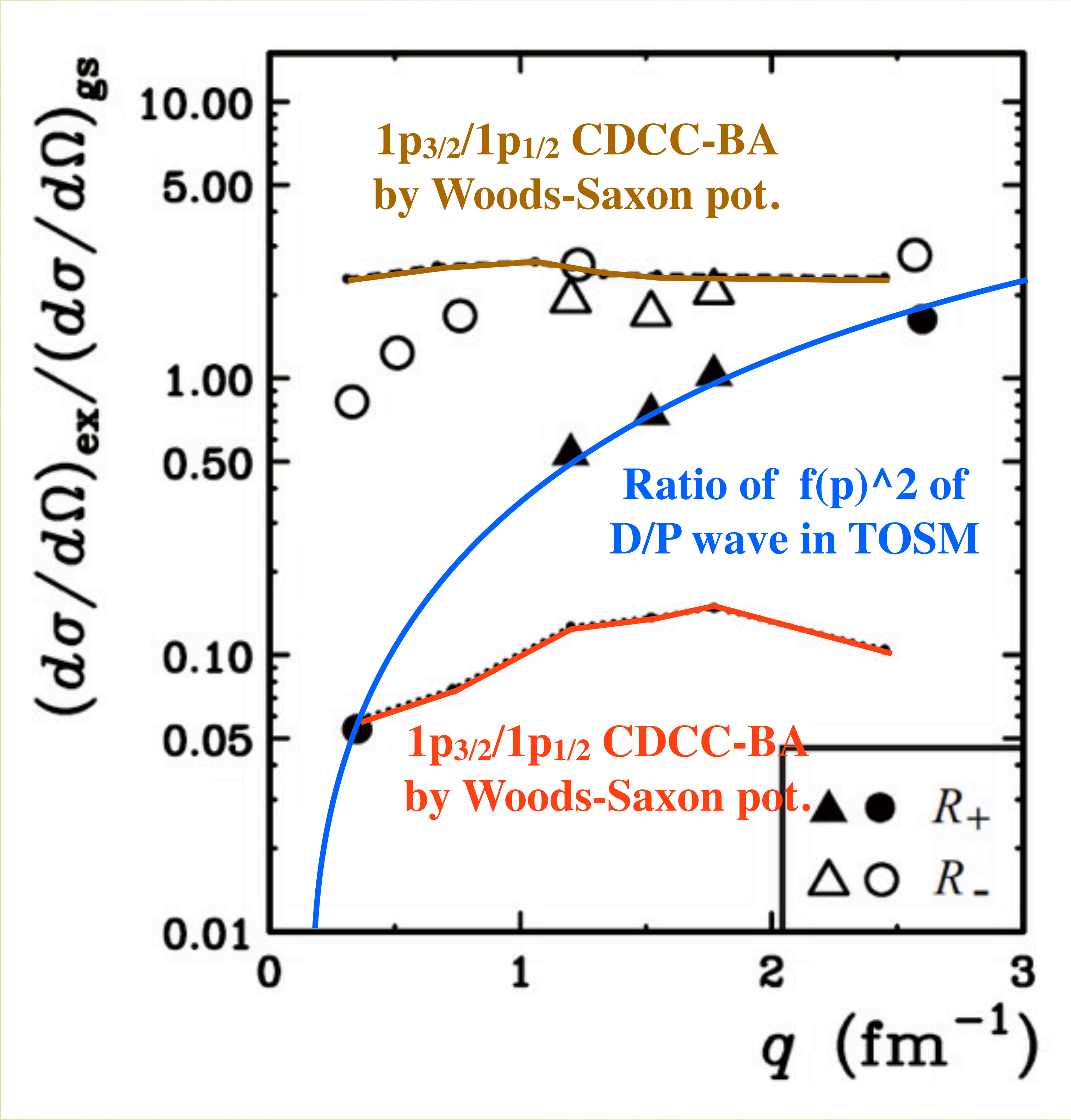

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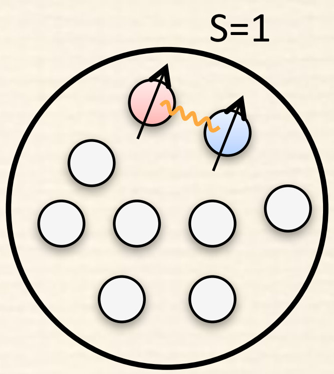
Tensor forces and Spin correlation

$$V_T = V_T(r)\left\{3\frac{(\vec{\sigma}_p\cdot\vec{r})(\vec{\sigma}_n\cdot\vec{r})}{r^2} - \vec{\sigma}_p\cdot\vec{\sigma}_n\right\}$$

Act only on S=1 pair of a proton and a neutron



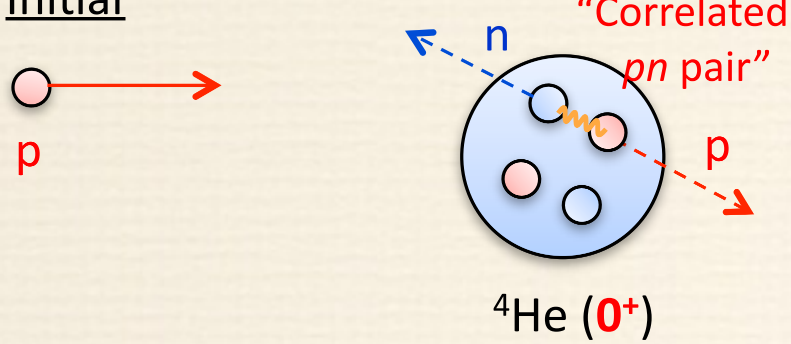
Study of channel **spin *S*** of **correlated *pn* pair**
at high relative momentum (P_{rel})

Start from ^{4}**He**, because of its simplicity.

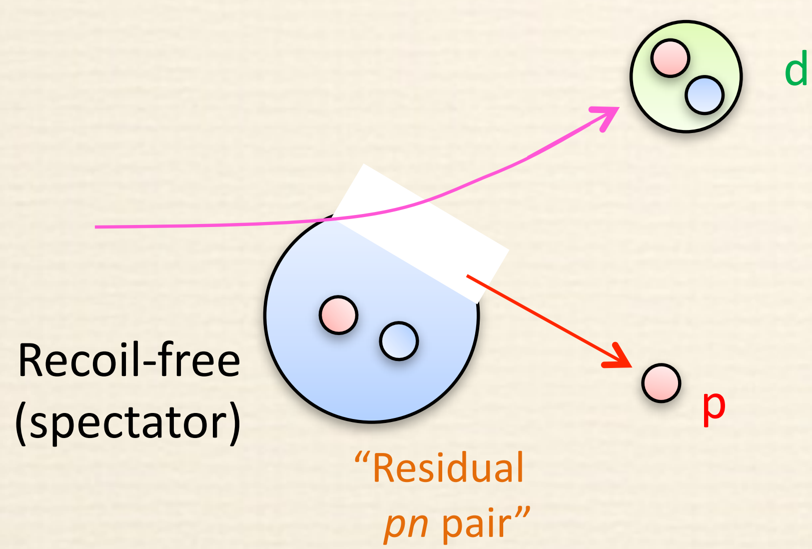
Study of tensor correlations in ^{4}He via the ^{4}He(p,dp) reaction

- Method : **(p,dp)** measurement

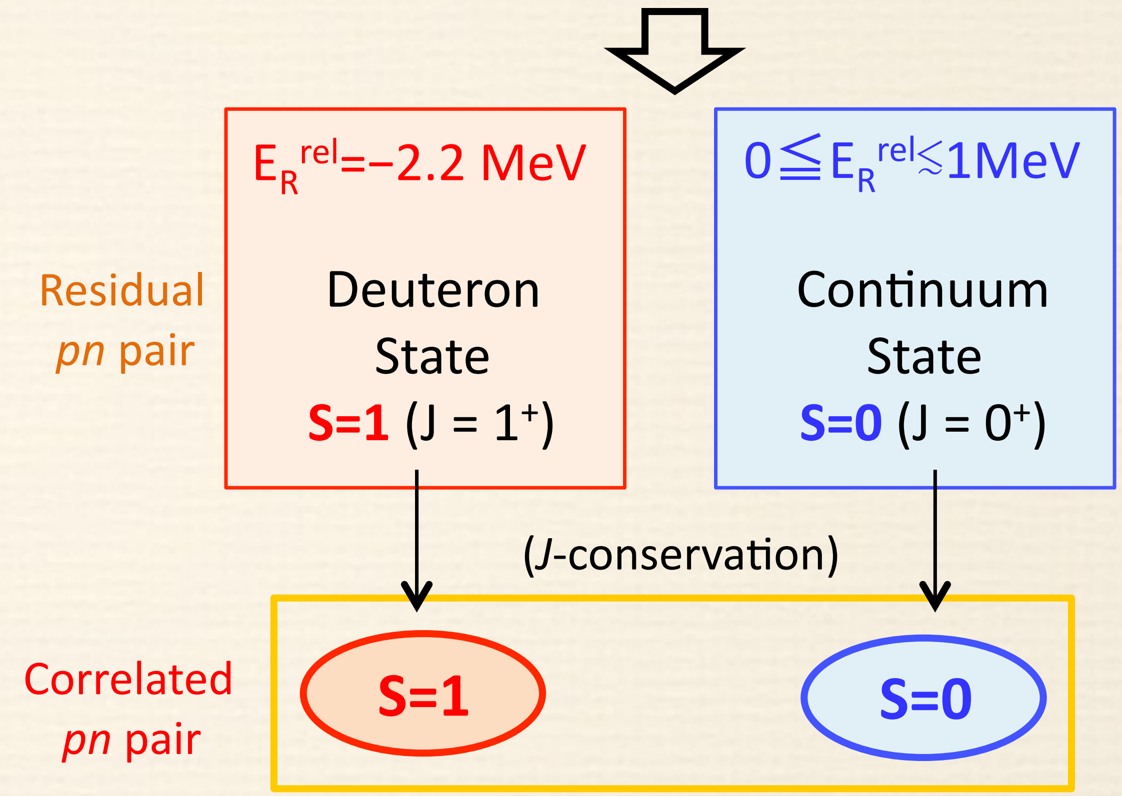
Initial



Final



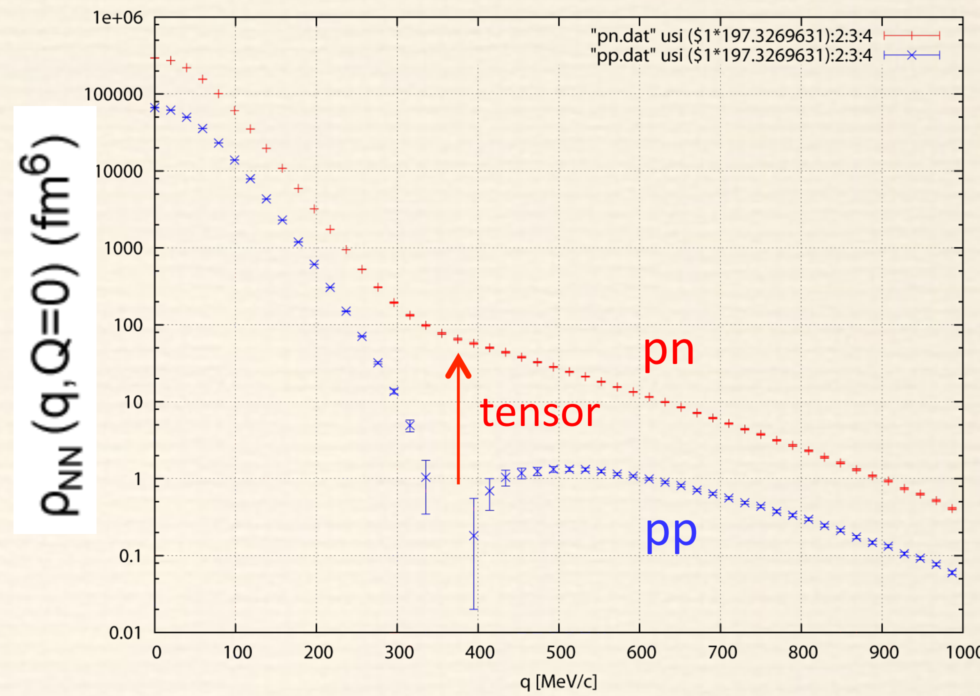
The excitation energy of residual nuclei (E_R^{rel}) can be determined by missing mass method.



" We can identify the spin of correlated *pn* pair ! "

Expected observation

- ^{4}He momentum distribution
  - Variational Monte Carlo
    Schiavilla et al., PRL 98, 132501 (2007)



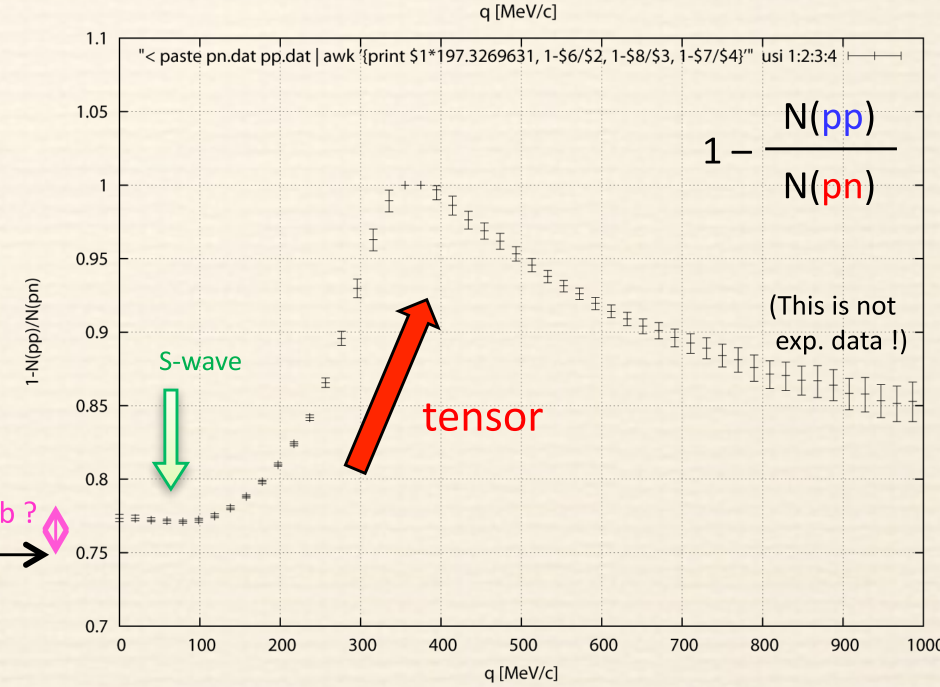
- S=1 fraction in pn pairs

$$\frac{N(pn;\,S=1)}{N(pn;\,S=1)+N(pn;\,S=0)} \sim 1-\frac{N(pp)}{N(pn)}$$

if L=0
pn : (S=1, S_z=+1, T=0)
(S=1, S_z= 0 , T=0)
(S=1, S_z=-1 , T=0)
(S=0, S_z= 0 , T=1)
pp : (S=0, S_z= 0 , T=1)

maybe Coulomb ?

75% : Spin d.o.f. →



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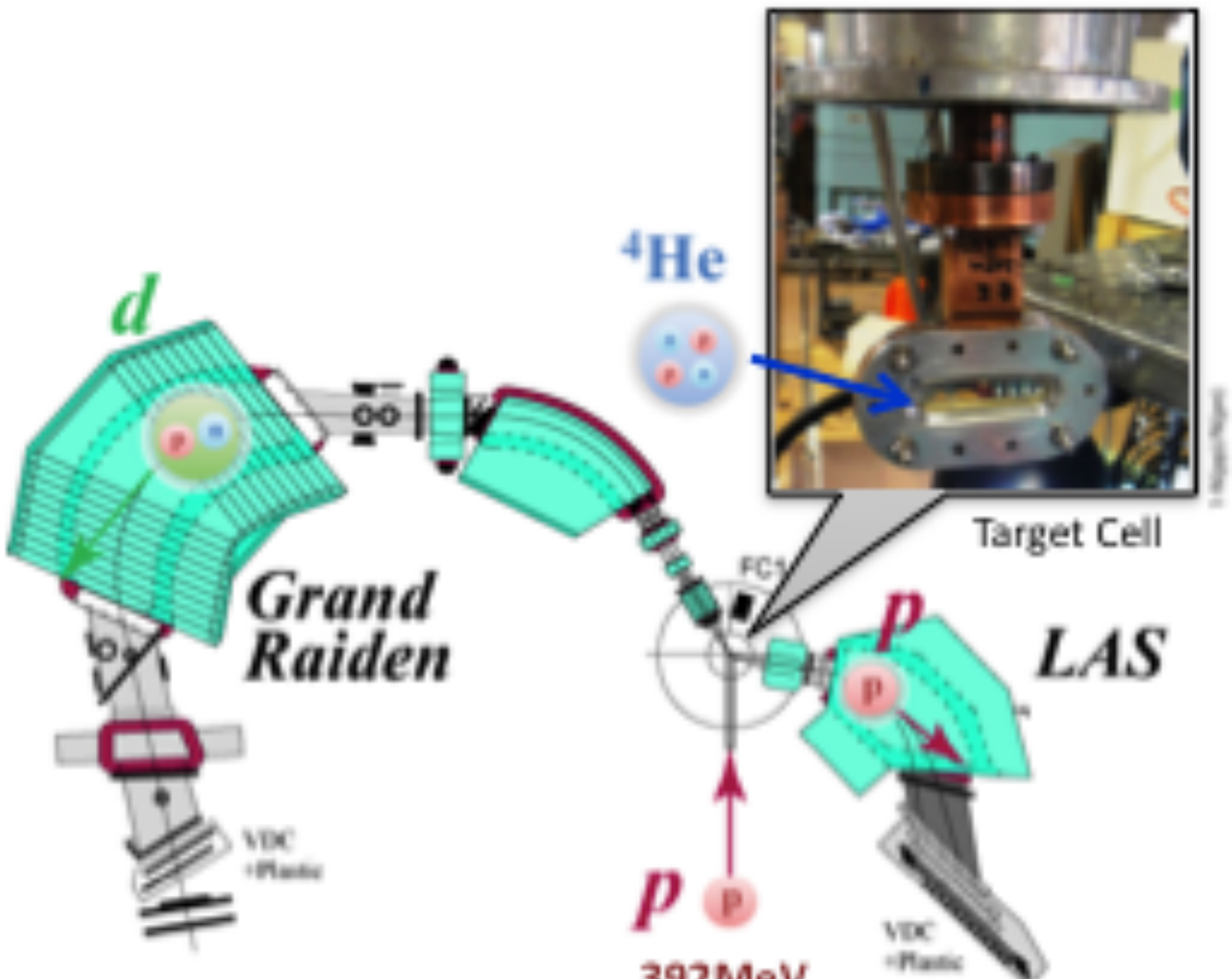
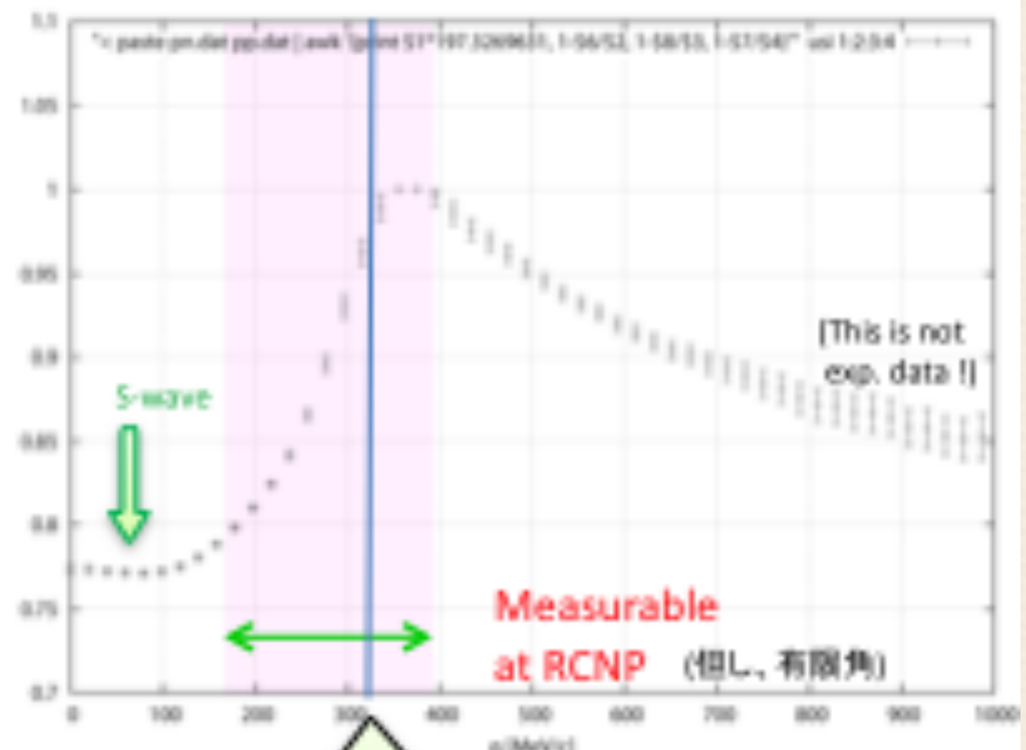
Experimental Setup

- WS course in RCNP
  - Beam : proton 392MeV 10nA
  - Cryogenic Target (by Sagara Gr.) :
    ^{4}He gas at 2atm & 10K
    [Aramid window 12.5mm x2]



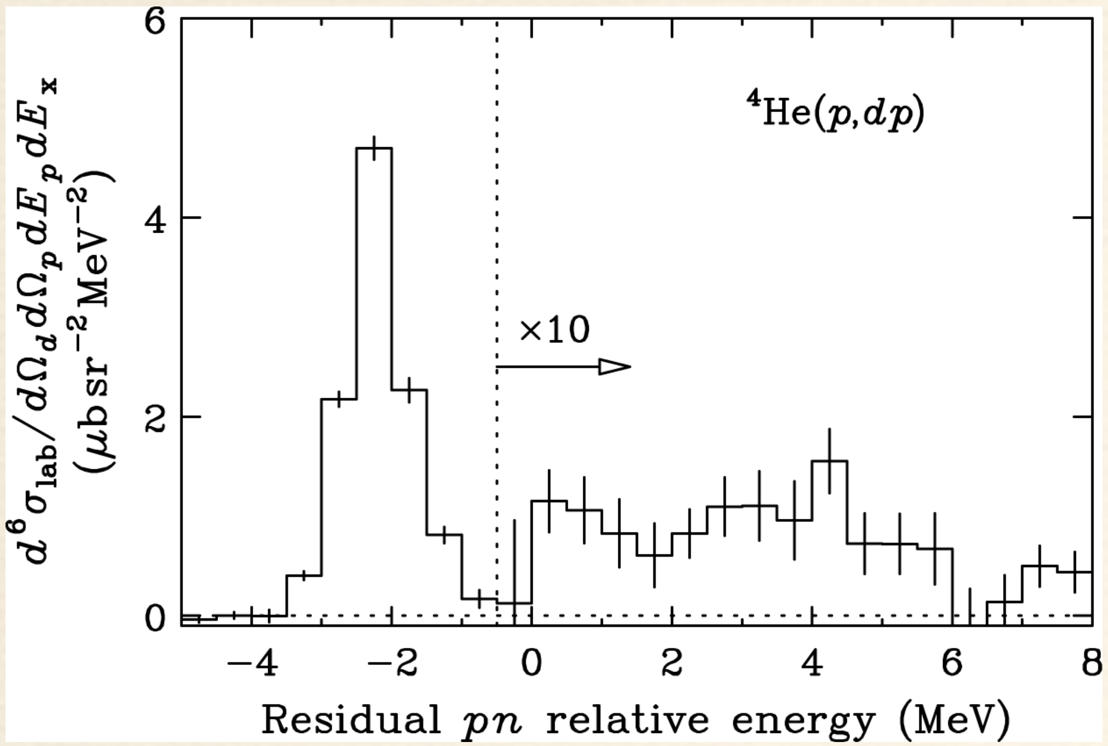
"Tensor region" can be covered.



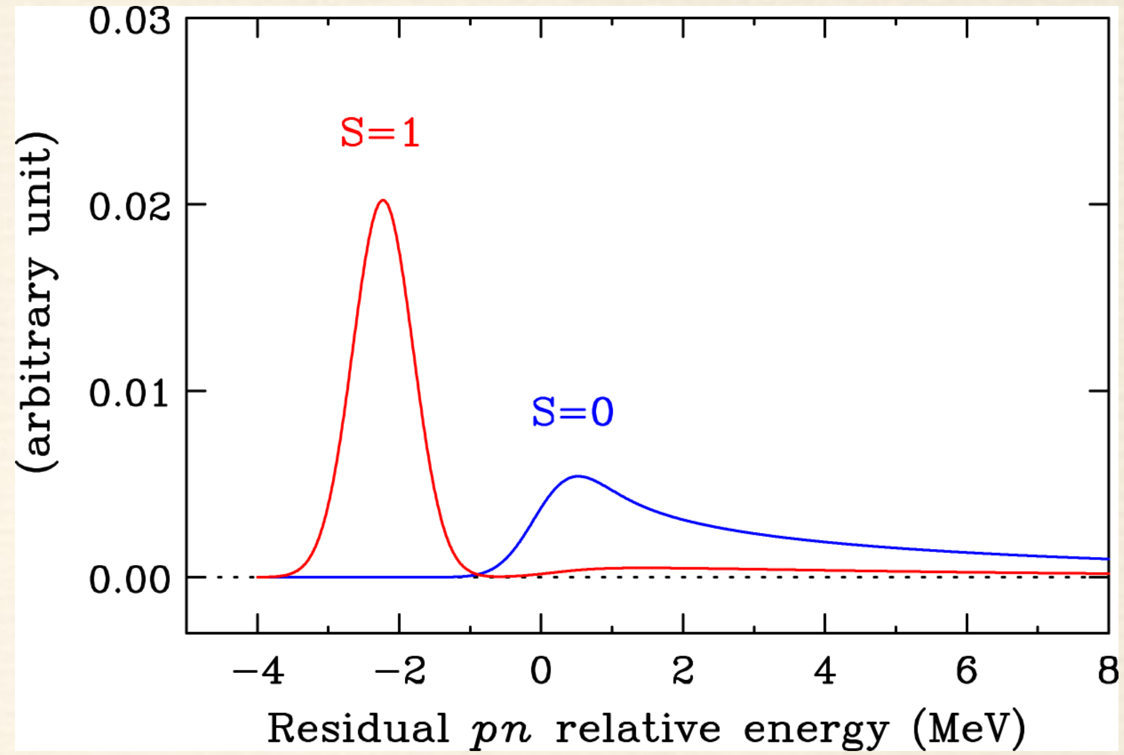
1-day Test Exp. last June
for 315MeV/c.

An observed spectrum

A spectrum at P_{rel}=315 MeV/c



Fit

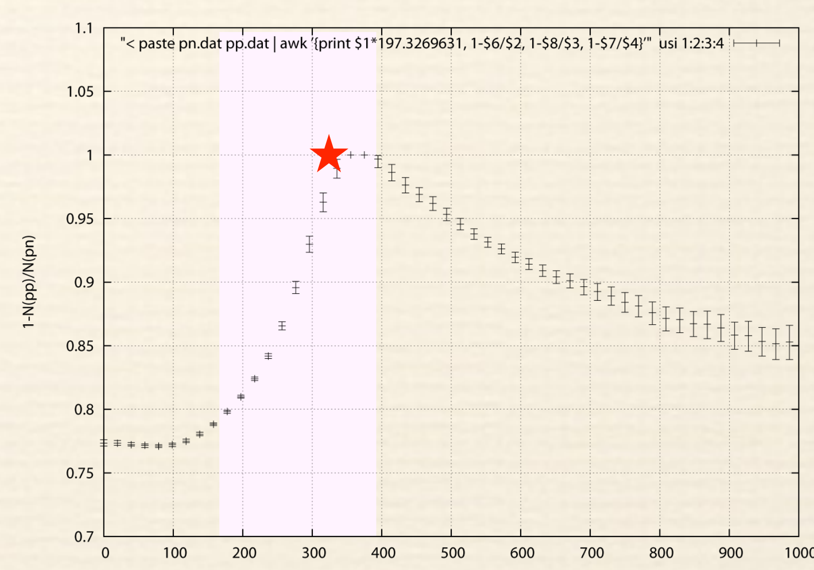


RESULT

- S=1 : **100** (+0/−2) %
- S=0 : **0** (+2/−0) %

c^2/ndf=4.2 [prelim.]

" Dominance of S=1 suggests strong tensor correlation at P_{rel}=315MeV/c. "

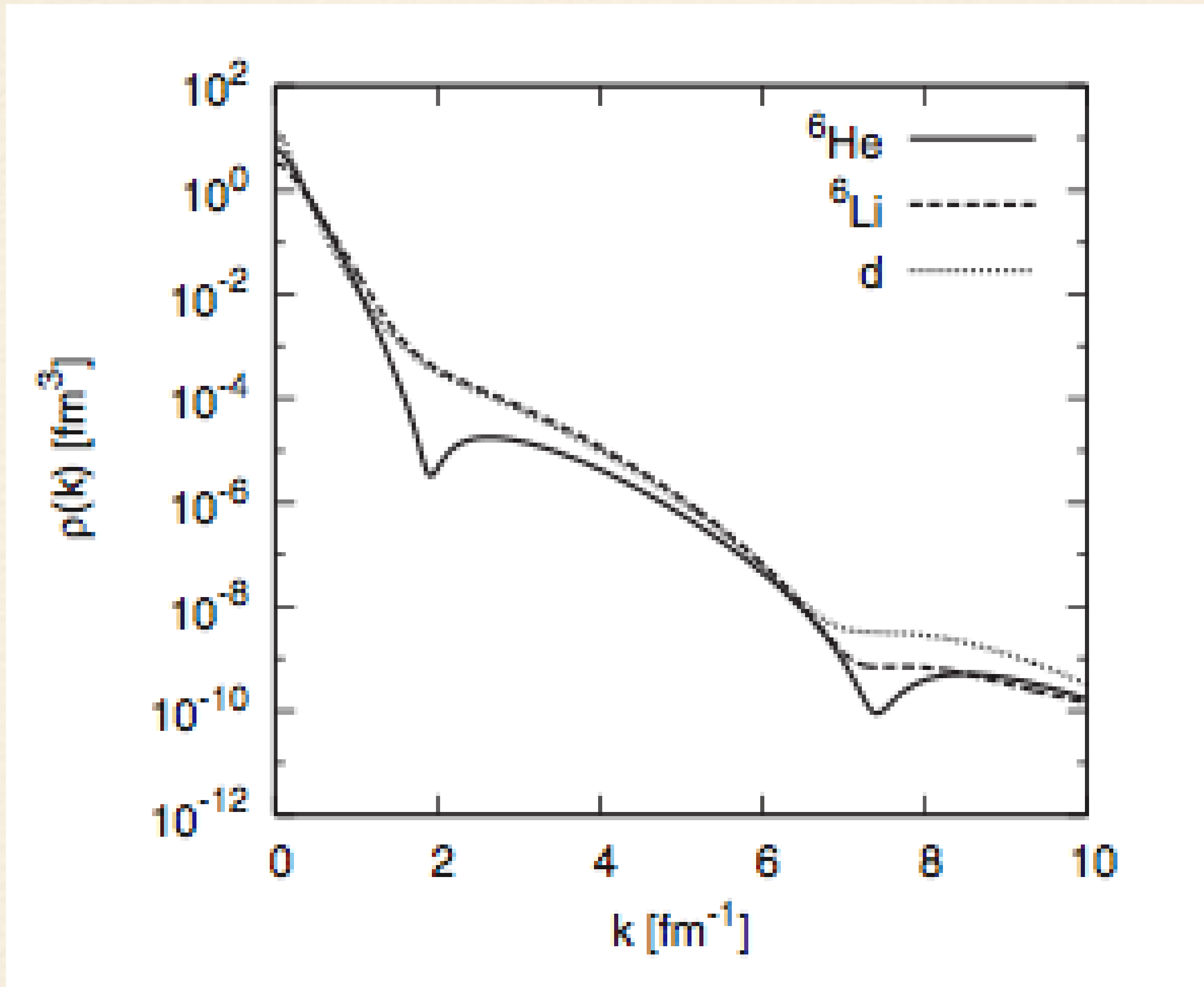


Needs momentum dependence

Experiments at GSI

- $p(^6He, d)^5He$ and $p(^6Li, d)^5Li$ reactions at 0 degree scattering angle.
  - *at 200A, 500A and 800A MeV*
- $^{16}O+p$ -> $^{15}O+d$ at 0 degree scattering angle
  - *at 800A and 1200A MeV*
- **GSI is only the place where such beams and high resolution spectrometer are available!**

Momentum distribution in ^{6}He and ^{6}Li



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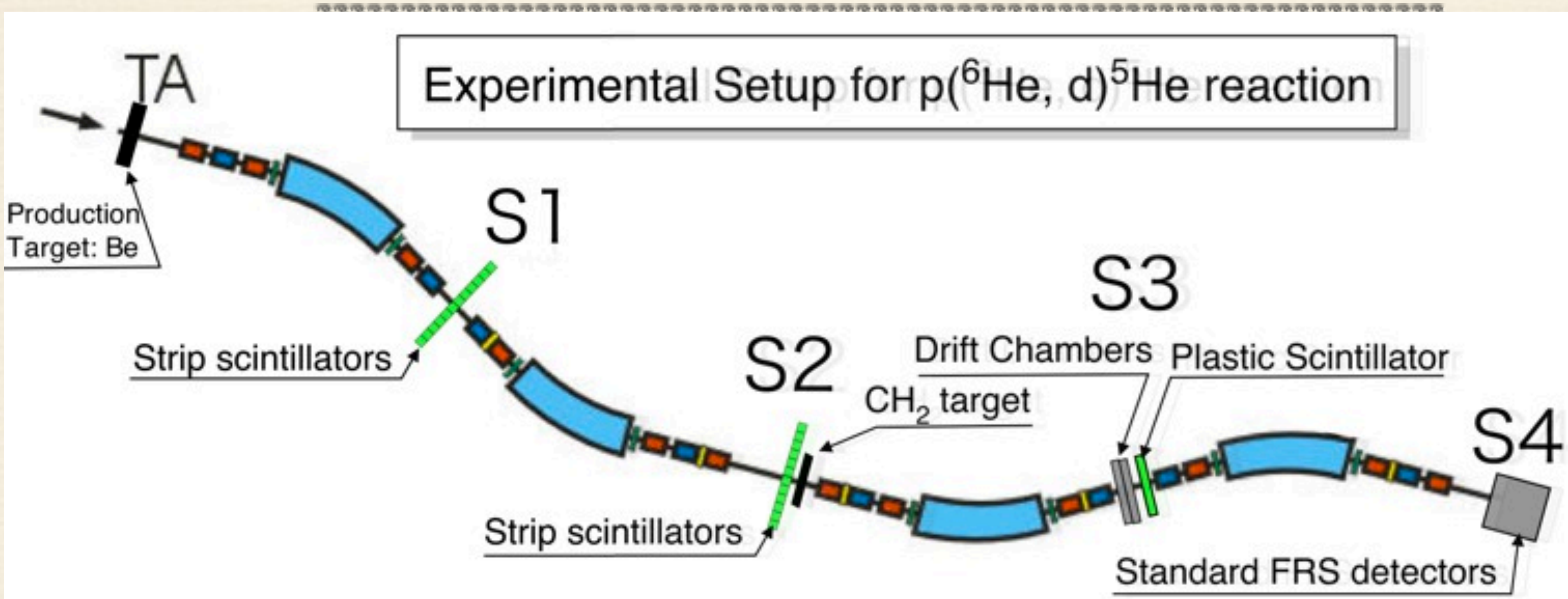
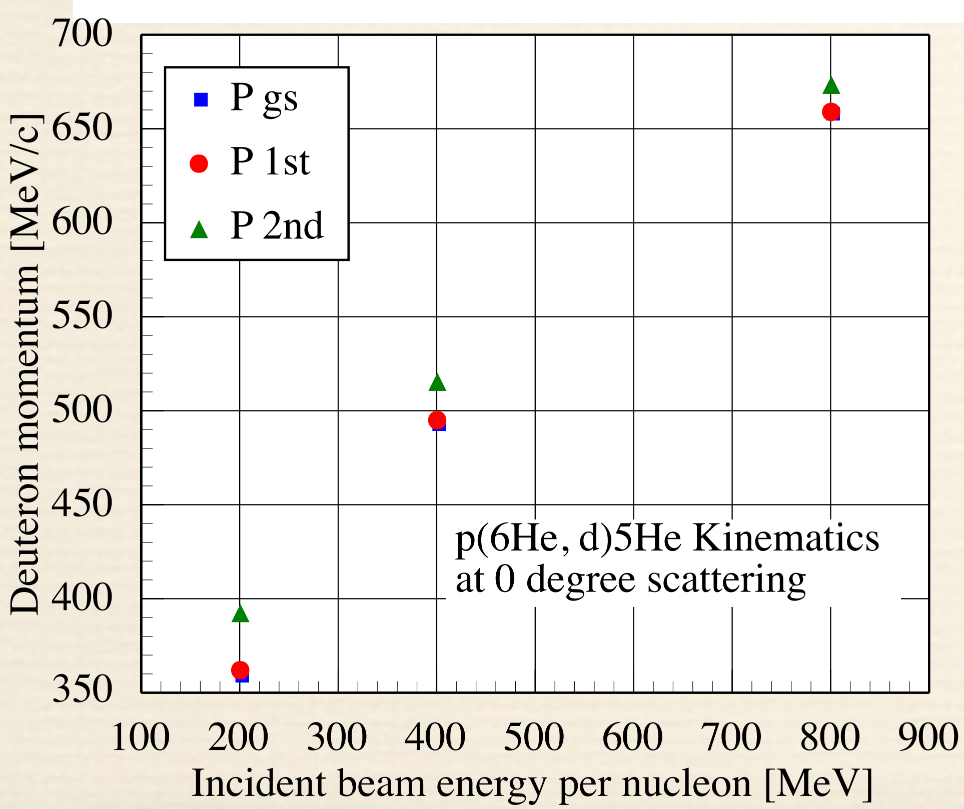
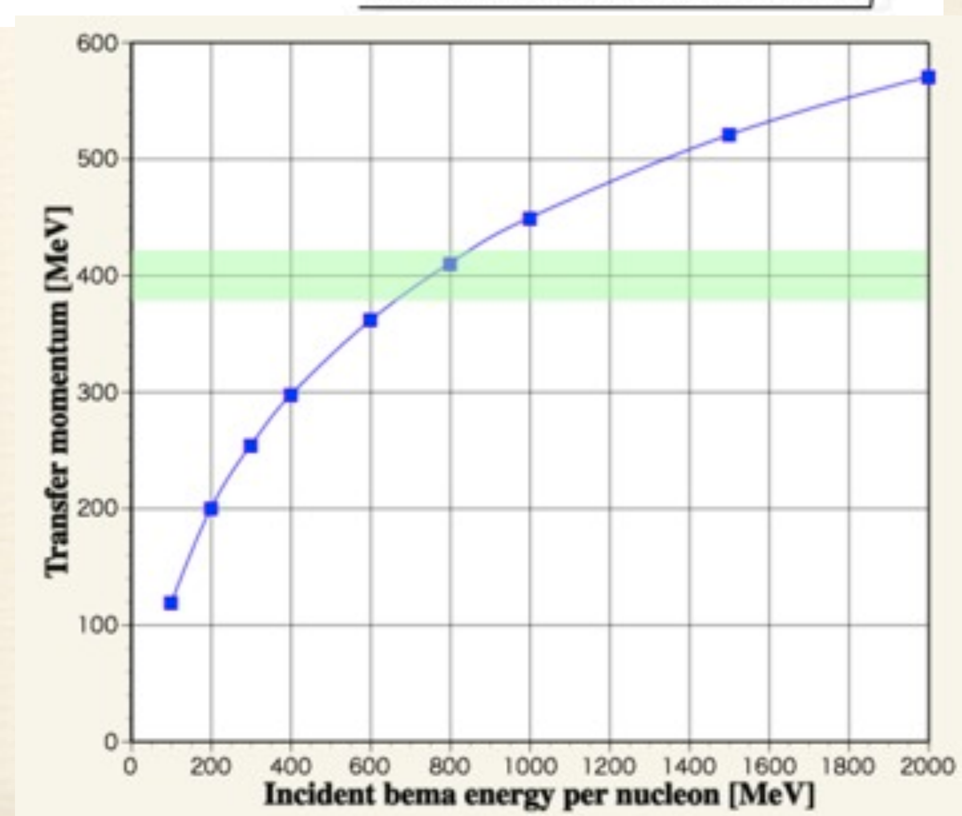
Experimental Set up







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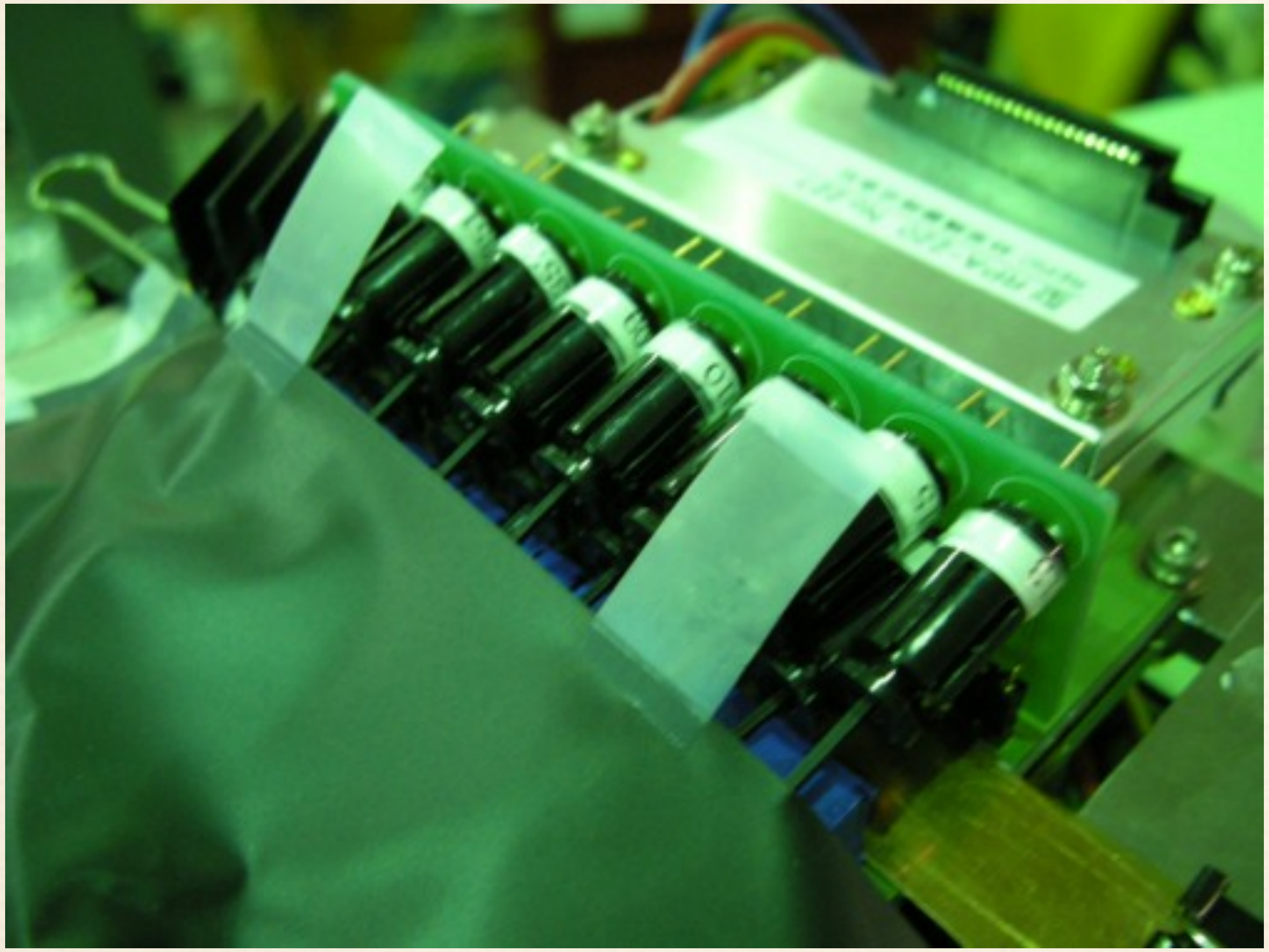
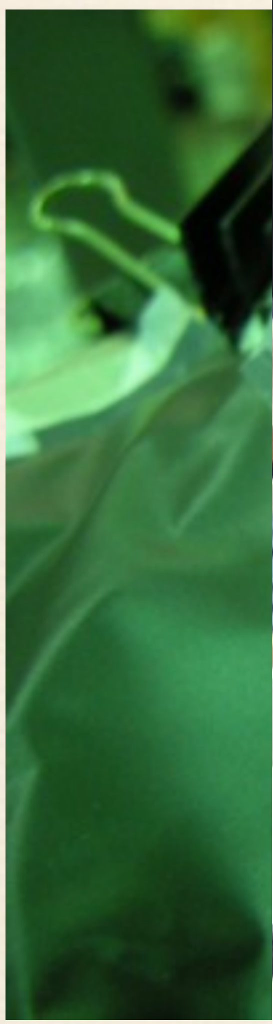
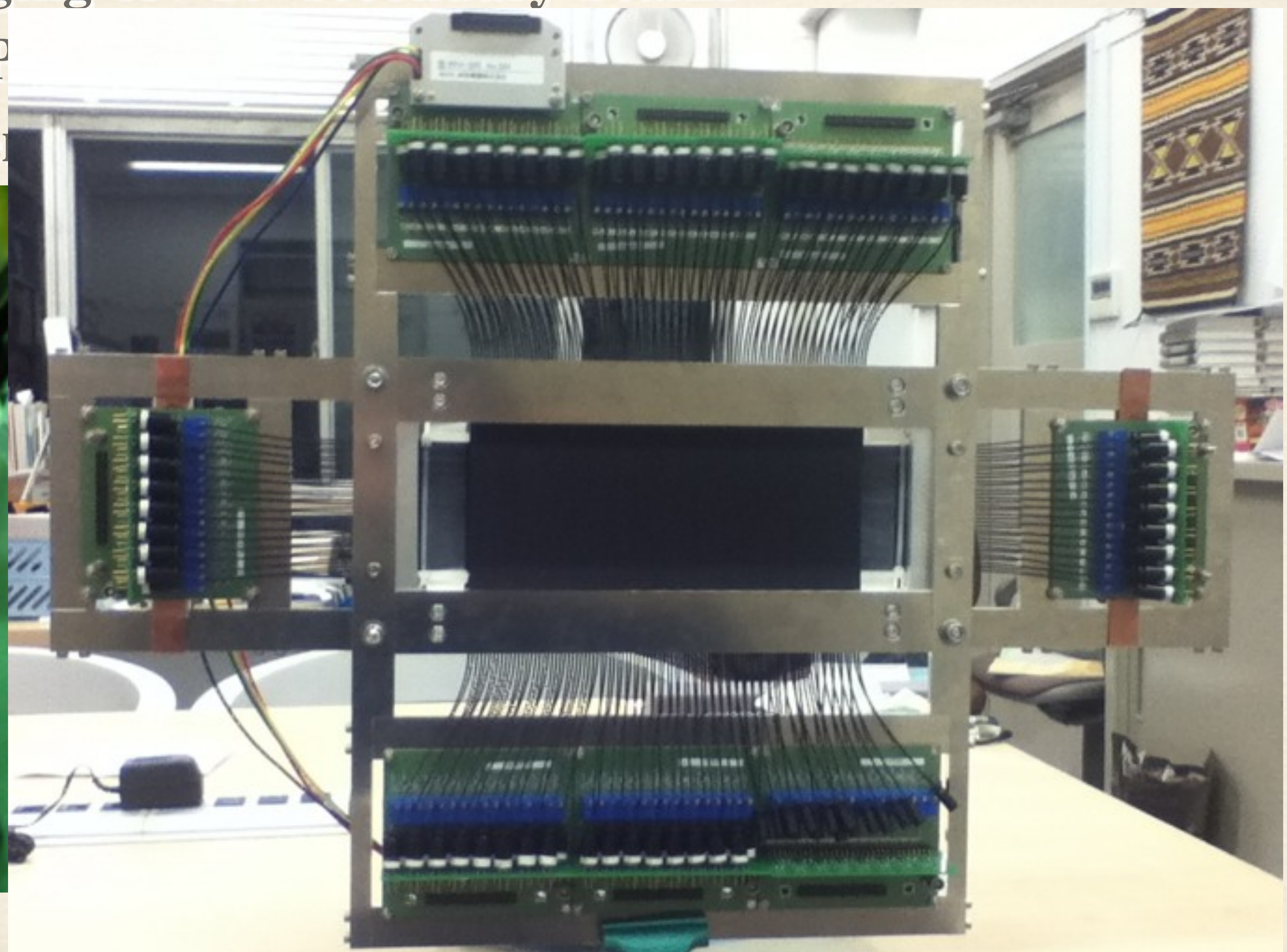
- Fiber scintillators



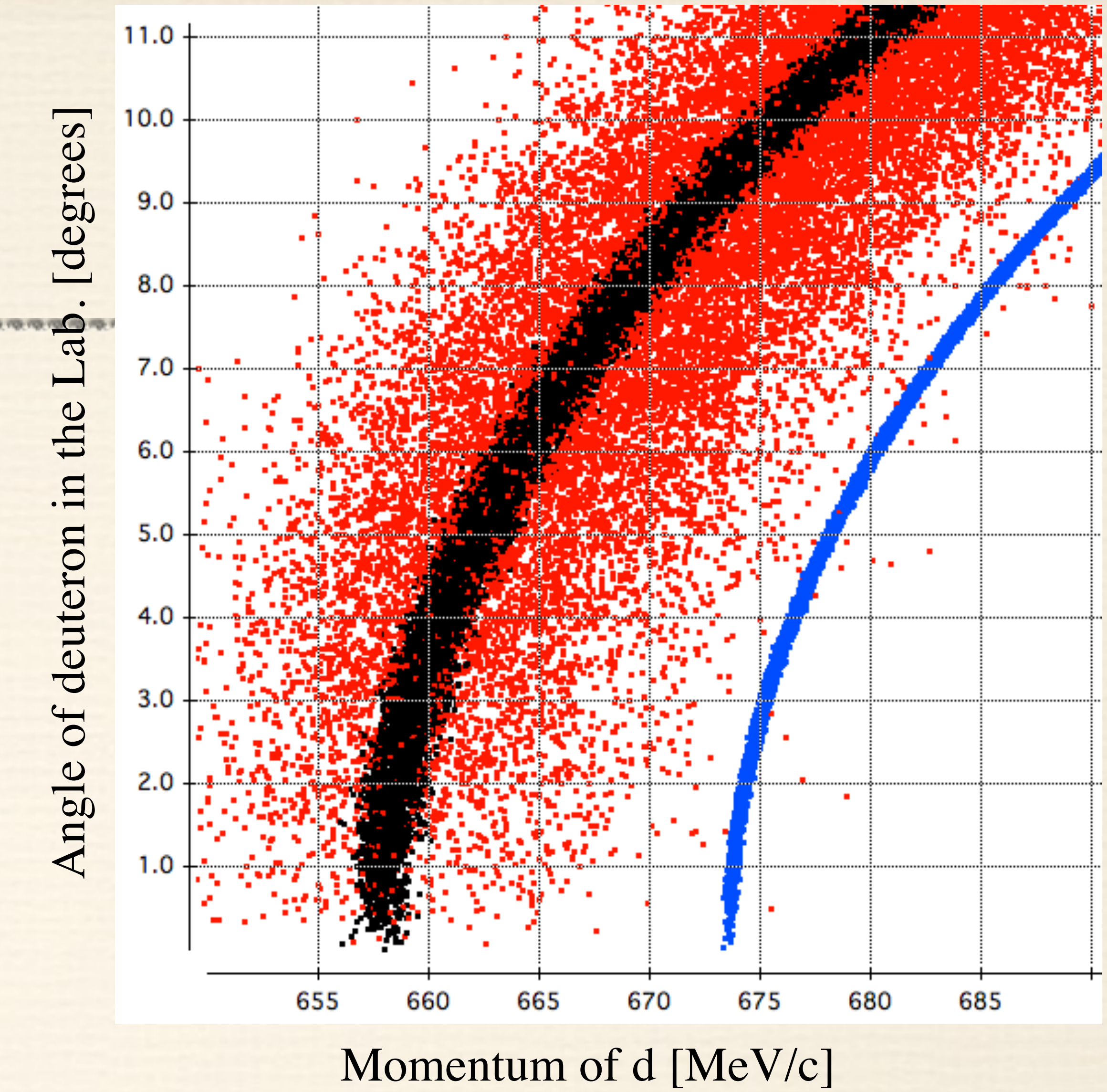
An important development for future

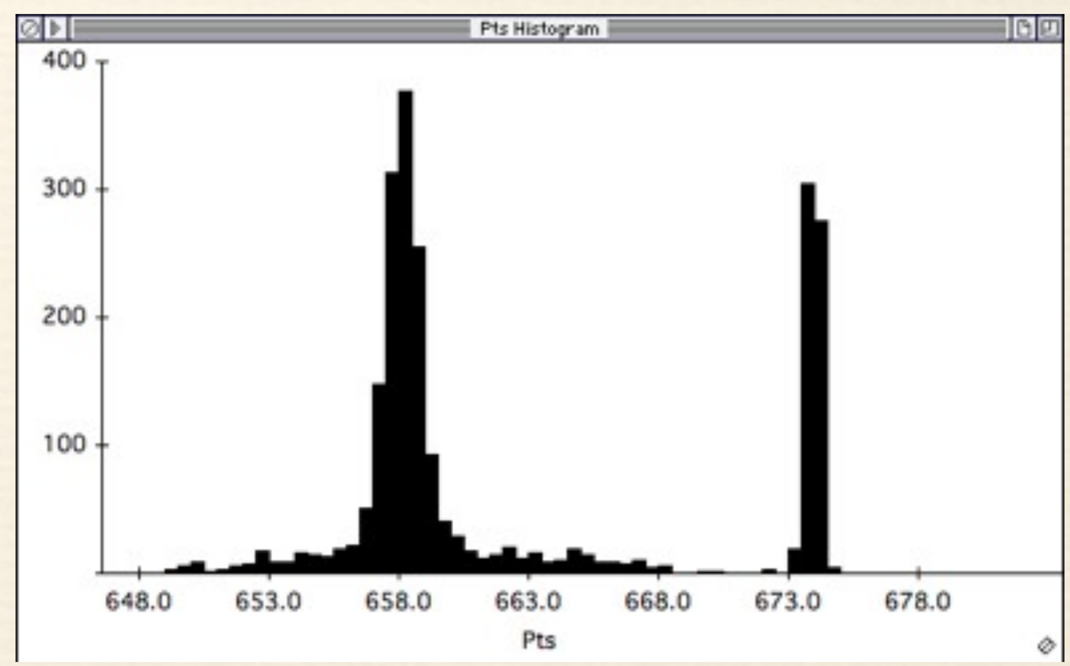
- Tagging of $>10^7$ secondary beams
- MPP
- Fibe





Kinematics of p(^{6}He, d)^{5}He reaction near 0 degrees with 800A MeV incident





Yield estimation

Under the assumptions;

1. The incident secondary beam: 10^7 /s
2. The target thickness: 12 x 10^{22} /cm^2 (15 mm thick)
3. Cross section: 10 μb/sr
4. The solid angle: 1 msr (assuming the opening FWHM=32 mrad from Terashima's calculation

The detection rate of deuterons is ~0.7 /min or 1000 /day

Beam time request

Primary beam [MeV/nucleon]	*Secondary Beam*	*Time necessary for setup [days]*	*Measurement time [days]*	*sub-Total*
^{7}Li 250	^{6}He, ^{6}Li	1	4	5
^{7}Li 524	^{6}He, ^{6}Li	1	4	5
^{7}Li 810	^{6}He, ^{6}Li	1	4	5
^{6}Li 200	-	0.5	0.5	1
^{6}Li 500	-	0.5	0.5	1
^{6}Li 800	-	0.5	0.5	1
Contingency				3
Total Requested				21 days

For proton beam experiment $^{16}O(p,d)^{15}O$ at 0 degree

- Estimated yield of relevant deuteron with ~0.5 g/cm ice target is ~0.5 /s for 10^8 /s incident beam. 10h of measurement gives enough statistics for all states ($3/2^-$, $1/2^-$, and $5/2^+$)

- In total a few days of beam on target is enough.

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.

- The experiment at GSI will provide essential information on the importance of tensor forces in nuclei