Importance of tensor forces in ground state of nuclei through high-momentum nucleons

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  - *pd elastic scattering and fragmentation*
- Nuclear binding and high-momentum nucleons
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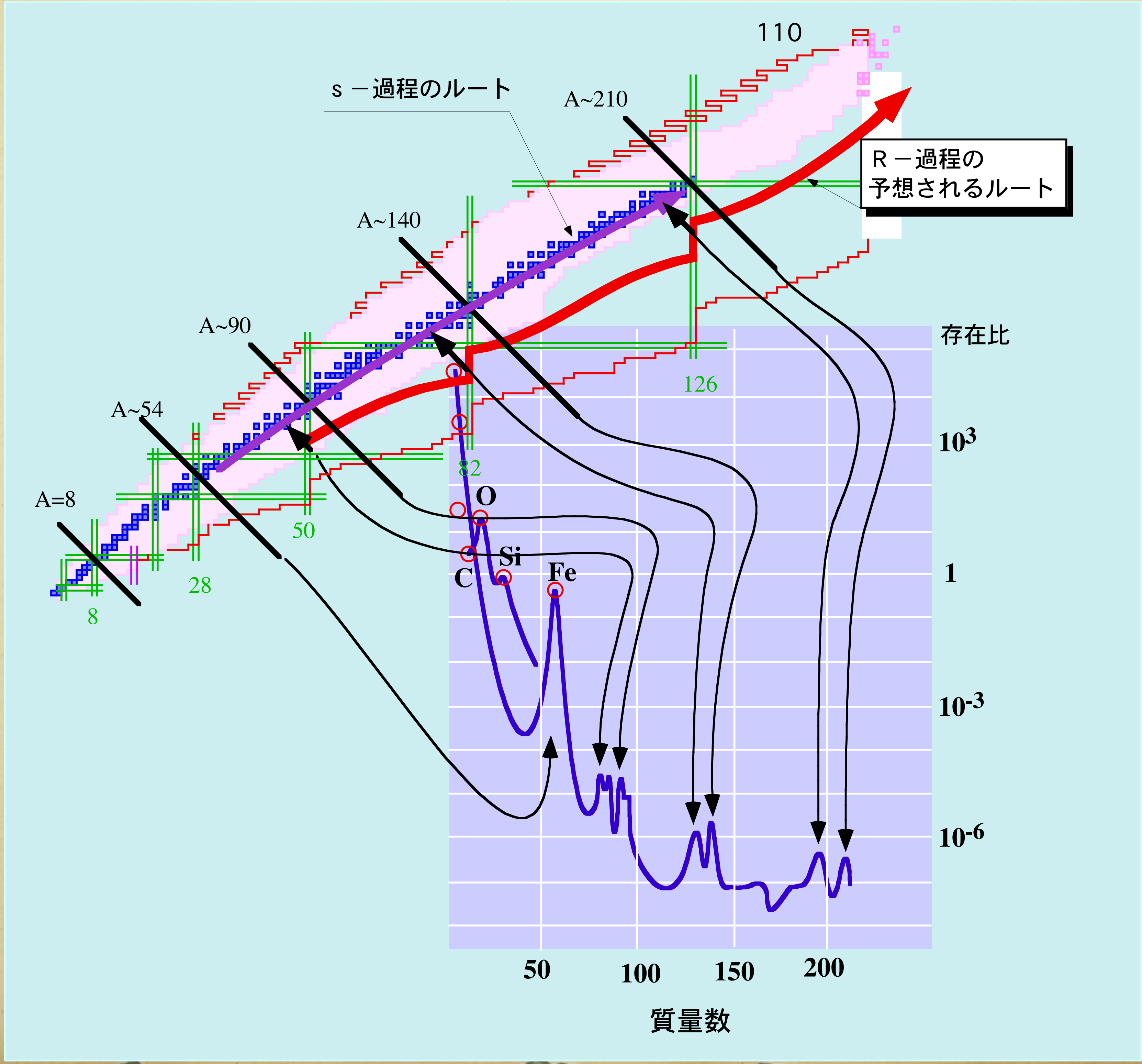
- (p,d) reactions on nuclei
- Summary

Nuclear structure is the most important information for understanding nucleosynthesis



Nuclear structure in more basic view

- We need a model of nuclei which can be extrapolated reasonably well to very-very neutron rich nuclei.
- Shell models and mean field models works very well near the stability line but could not predict properties of extremely neutron rich matter or changes of magic numbers.
- Tensor interactions had not been treated explicitly to explain nuclear biding except for 0s shell nuclei.

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Nuclear Structure in New Era

Deuteron binding

1. Tensor interactions provides most of the biding energy.
2. It is due to the D-wave mixing through the tensor interactions
3. The binding energy by tensor interactions are not from D^2 term but from SD cross term.
4. D wave has shorter range and thus has high-momentum.
5. High momentum nucleon are necessary to make binding.

The selection rules

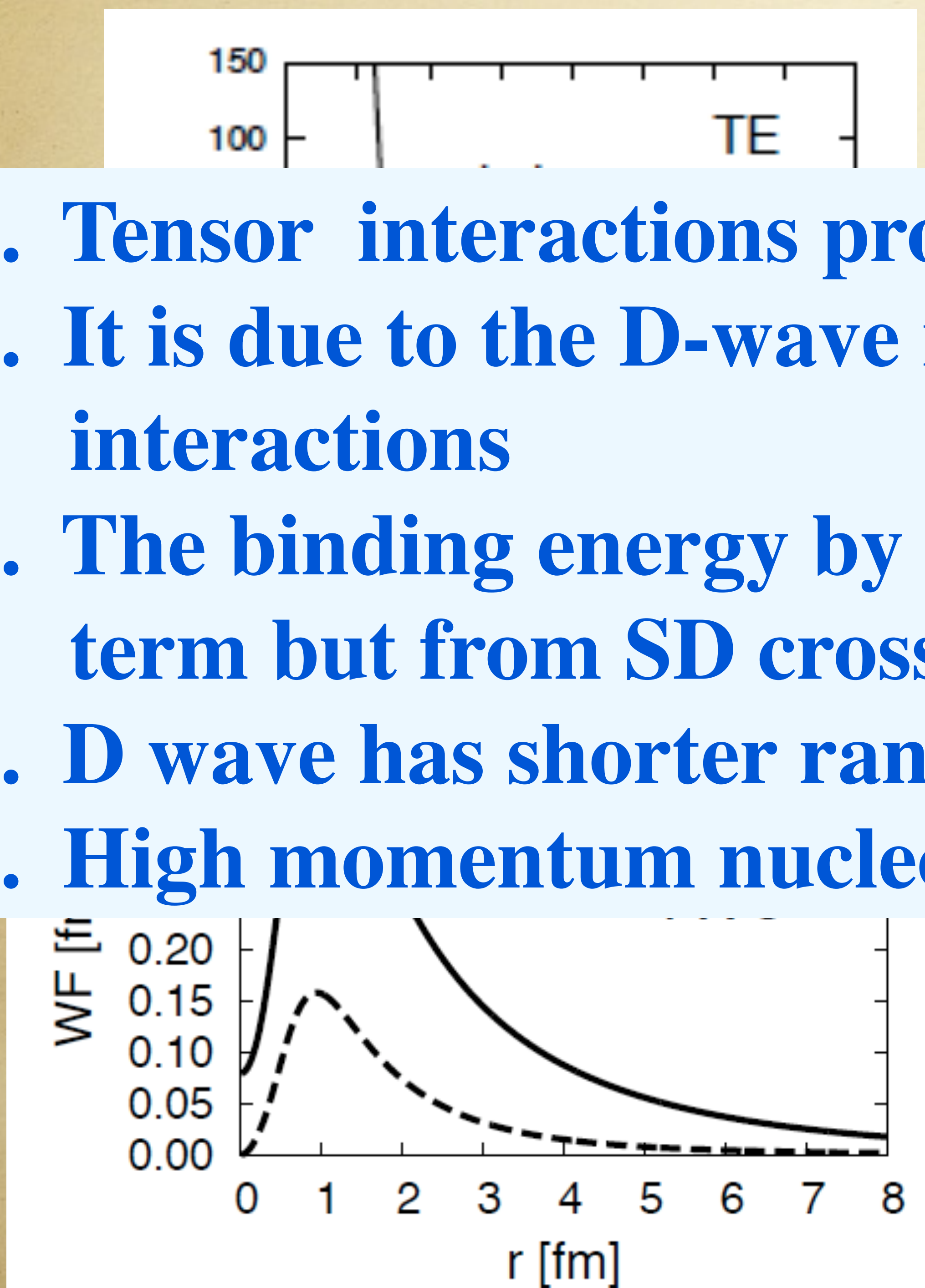
- An important difference is that this D wave is smaller in size and have high-momentum component.
- Another important property of this effect is "It strongly depends on configurations of nucleons."
- It also contribute to some part of spin-orbit term.

high-momentum nucleons

$^1O+^3O$	-0.4
	9.7
	-0.5
	-3.6
P(D)%	12.8

M. Sakai, I. Shimodaya, Y. Akaishi, J. Hiura, and H. Tanaka, Prog. Theor. Phys. 56(1974)32.

The importance of tensor is clear in deuteron



S=1 and L=0 or 2

Binding of deuteron (1^+)

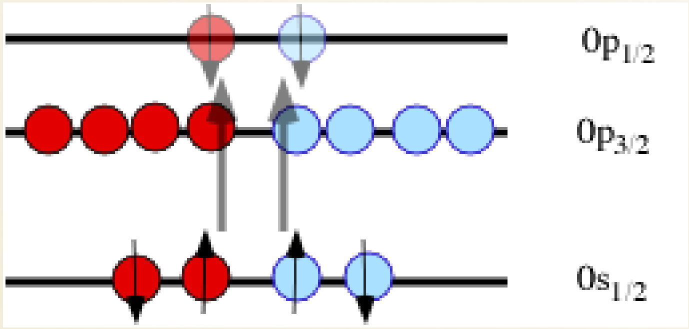
1. **Tensor interactions provides most of the biding energy.**
2. **It is due to the D-wave mixing through the tensor interactions**
3. **The binding energy by tensor interactions are not from D^2 term but from SD cross term.**
4. **D wave has shorter range and thus has high-momentum.**
5. **High momentum nucleon are necessary to make binding.**

P(*D*)	5.78 [%]
Radius	1.96 [fm]
(SS)	2.00 [fm]
(DD)	1.22 [fm]

K.Ikeda, T.Myo, K.Kato,and H.Toki
Lecture Notes in Phys.818(2010) 165.

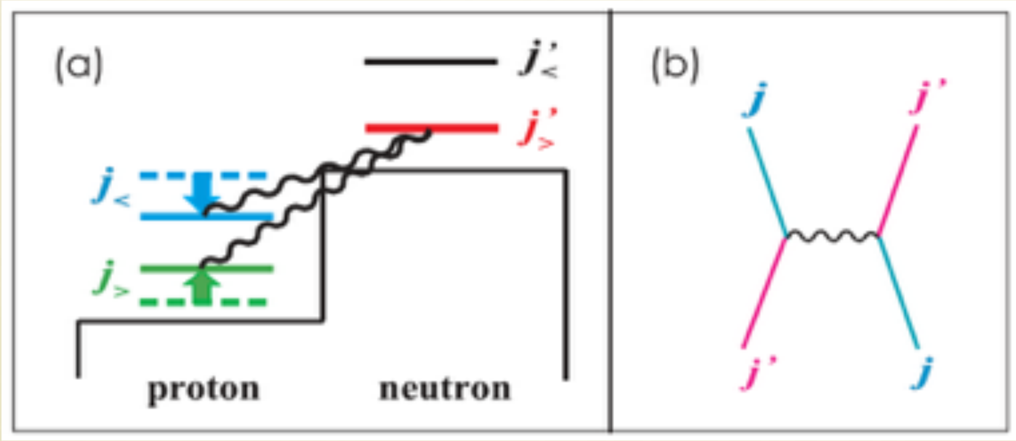
Effects of tensor forces in nuclear structure

- **As major part of the binding energy of nuclei.**
  - *D-wave mixing in d, α… nucleus*



ΔL=2, ΔS=2
p-n pair: yes
n-n, p-p pair: no

- **As changes of single particle orbitals (magic numbers)**
  - *Changes of magic numbers in nuclei far from the stability line.*



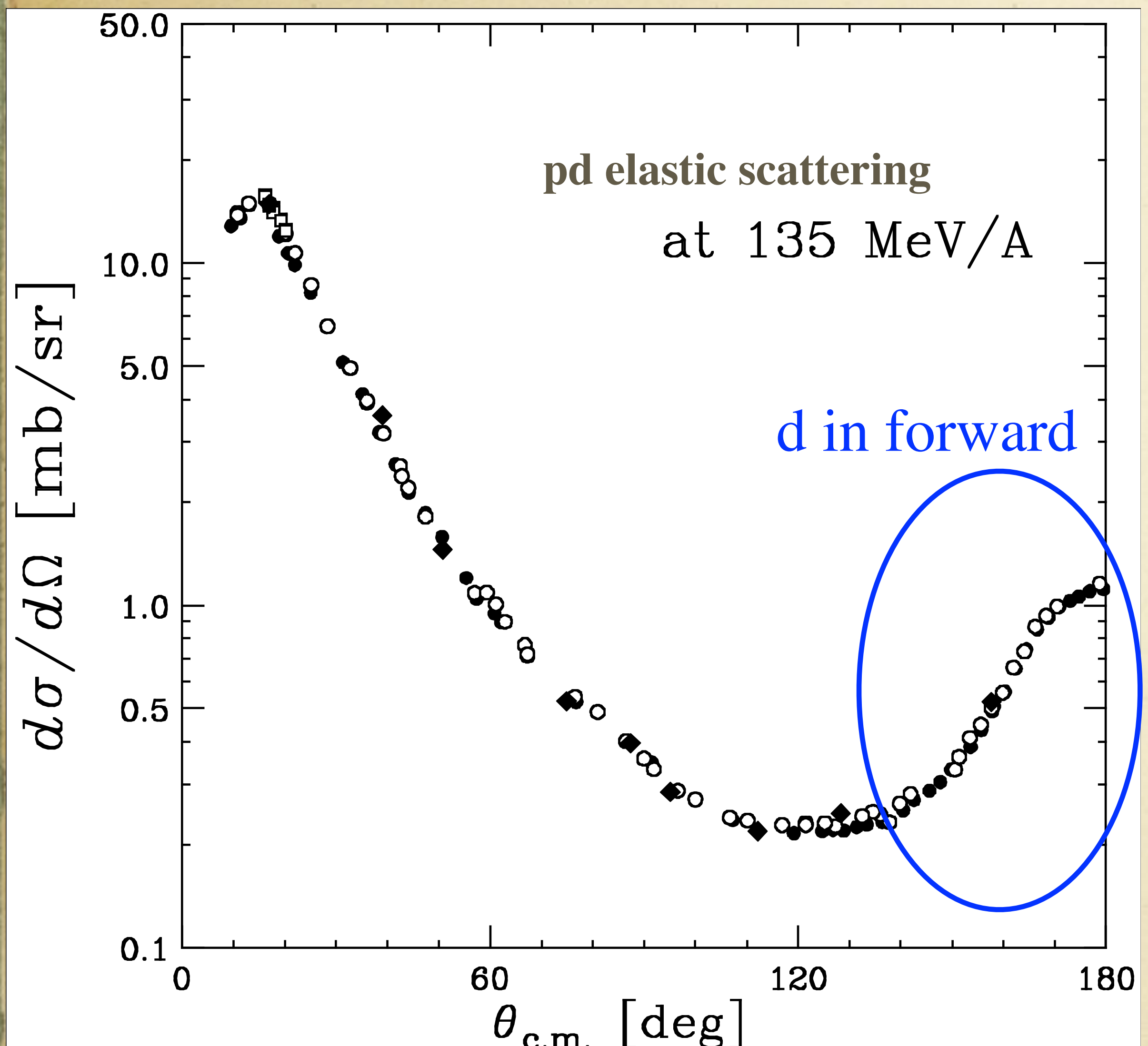
Known effects related to 2p-2h configuration by tensor forces

- **Spin-orbit Splitting and Tensor Force.**
  - ***T. Terasawa, PTP 23 (1960) 87.***
  - ***A. Arima and T. Terasawa, PTP 23 (1960) 115.***
- **Deviation of scaler magnetic moments (or <σ_Z>) of doubly closed shell±1 from Schmidt values.**
  - ***H. Hyuga, A. Arima, and K. Shimizu, Null. Phys. A 336 (1980) 363.***
- **Mixing of $(s_{1/2})^2$ and $(p_{1/2})^2$ in ^{11}Li halo**
  - ***T. Myo, K. Kato, H. Toki, K. Ikeda, Phys. Rev. 76 (2007) 024305.***

Momentum distribution of nucleons in deuteron

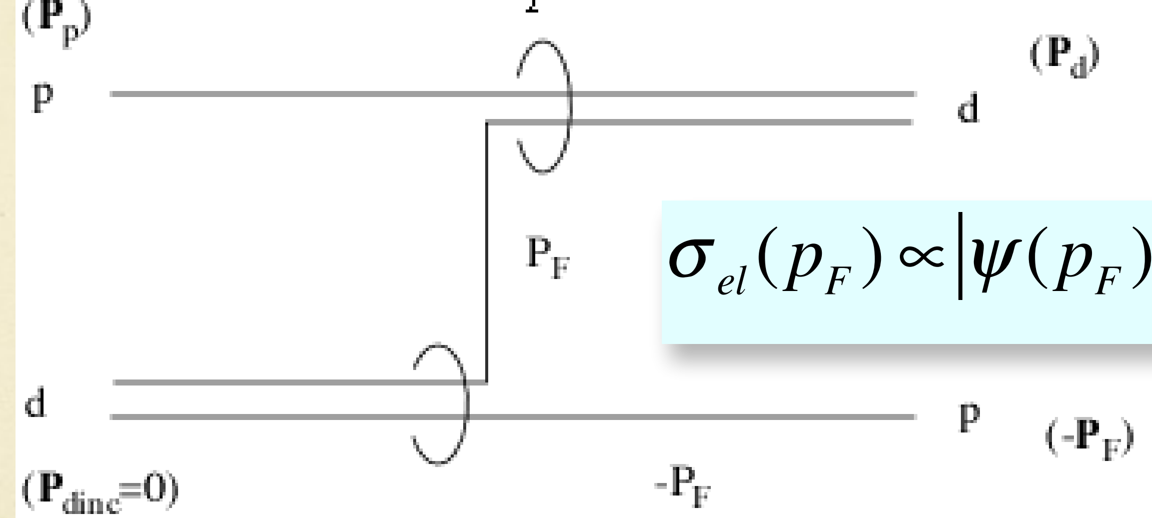
- pd elastic scattering
- projectile fragmentation of deuteron

pd elastic scattering



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

$$\mathbf{P}_d - \mathbf{P}_p = \mathbf{P}_F$$



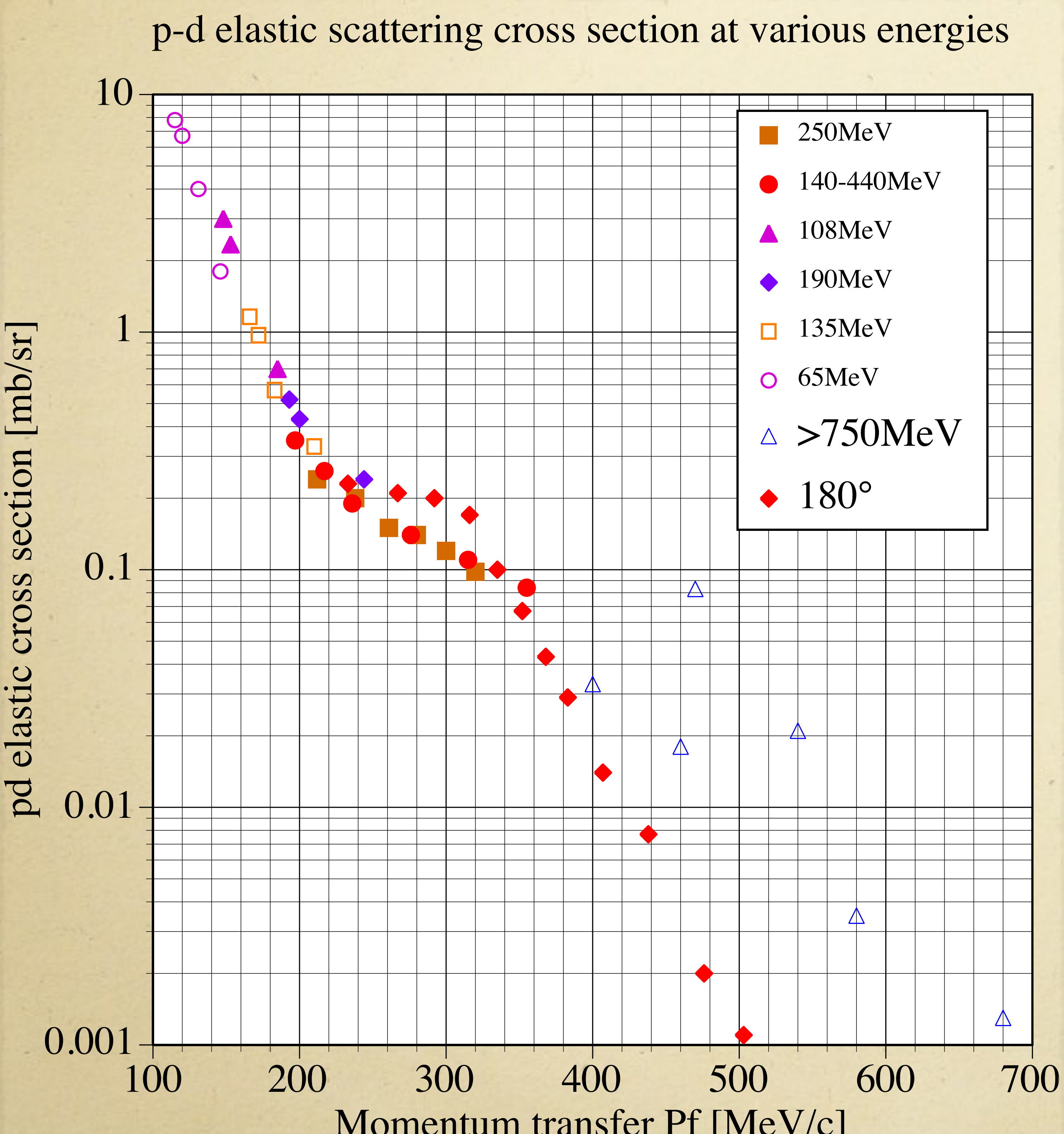
$$\sigma_{el}(p_F) \propto |\psi(p_F)|^4$$

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

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.

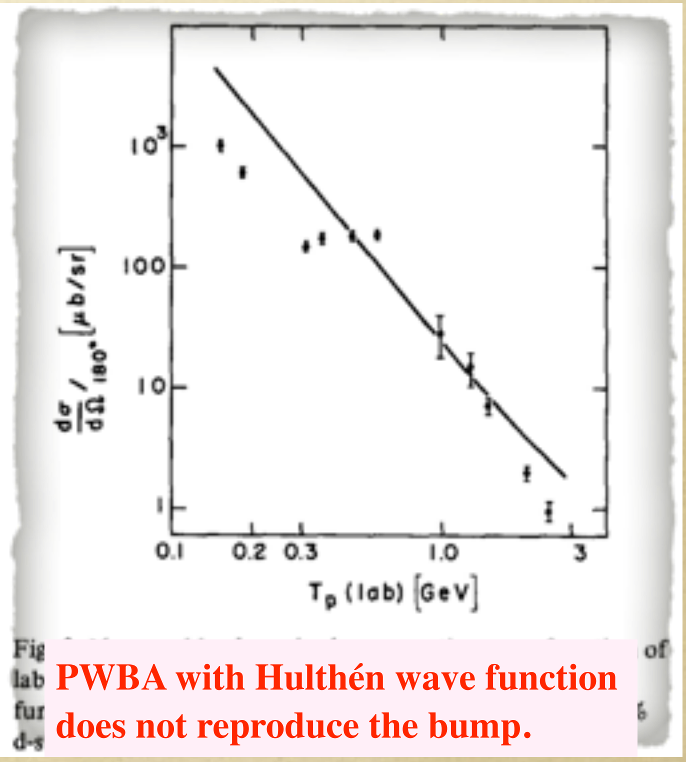
Reaction at backward occurs by the high-momentum component.

pd elastic scattering data



Pf = |**P**d/2 - **P**p|
Pd is neutron momentum at the final state.
Pp is the incident proton momentum

1. **Good scaling of the data suggest a reflection of momentum distribution in deuteron.**
2. **However the bump near 300 MeV/c is larger than expected by the D-wave component by *** interactions.**



Trials to explain the bump

- **Double scattering effects**

  S. A. Gurvitz, PRC 22 (1980) 725

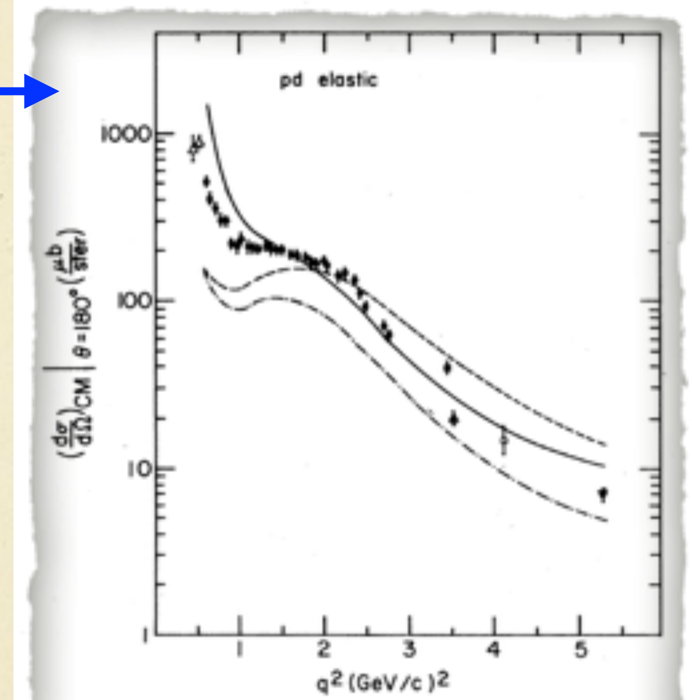


FIG. 14. $d\sigma_{pd}/d\Omega_{c.m.}|_{\theta_{c.m.}=180°}$ as a function of q^2. Data (Ref. 18, 21); (Ref. 22); (Ref. 24); (Ref. 28); (Ref. 29). Legends: as in Fig. 9.

- **Effects of pions and isobars**

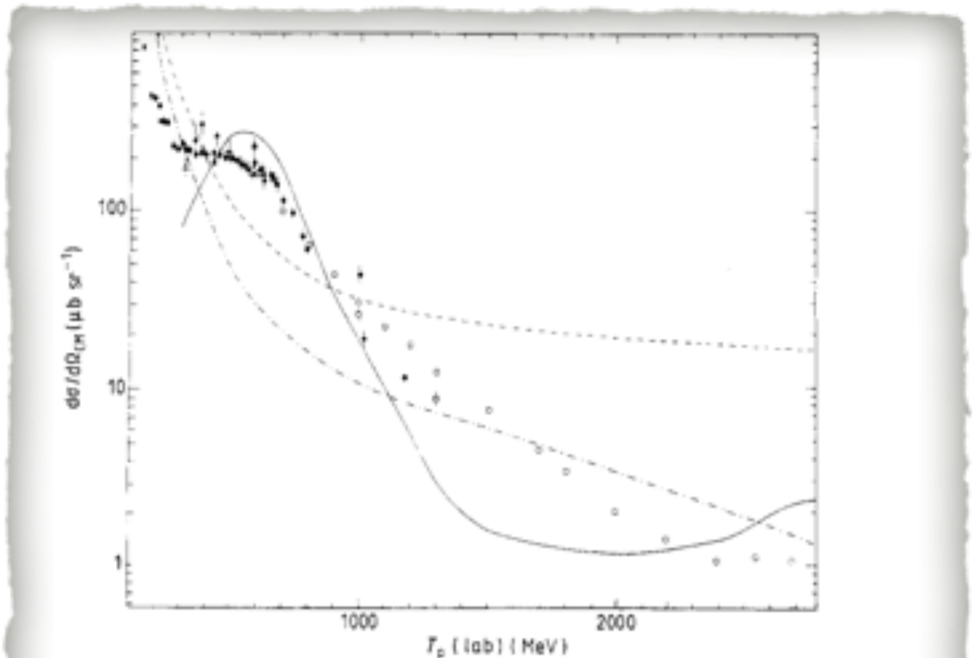


Figure 1. Experimental $\theta_p = 180°$ excitation function compared with three calculations. The open circles are the data of this experiment, the other results come from Igo *et al* (1972), Banaigs *et al* (1973), Dubal *et al* (1974) and Bonner *et al* (1977). The broken curve is the ONE calculation with the formula given by Noble and Weber (1974), the chain curve is the ONELFD calculation with the formula of Kondratyuk and Schevchenko (1979). The full curve is the OPE calculation with the formula given by Barry (1972, 1973).

P. Berthet et al., J. Phys. G 8 (1982) L111.

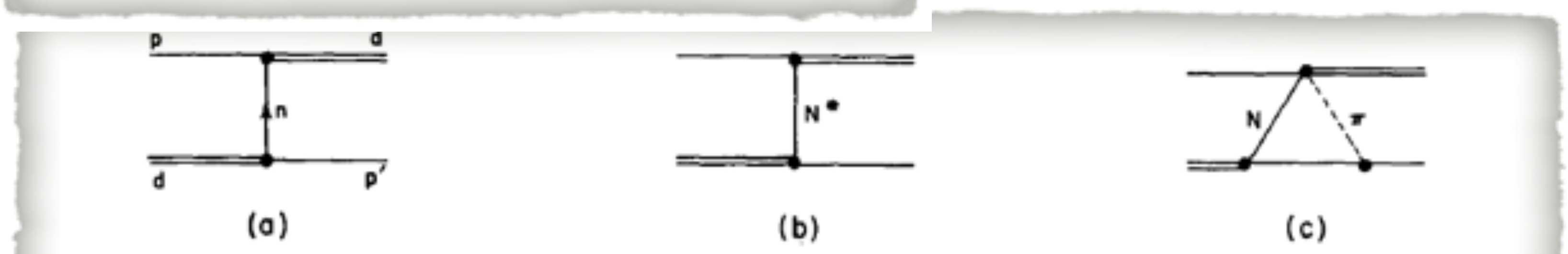
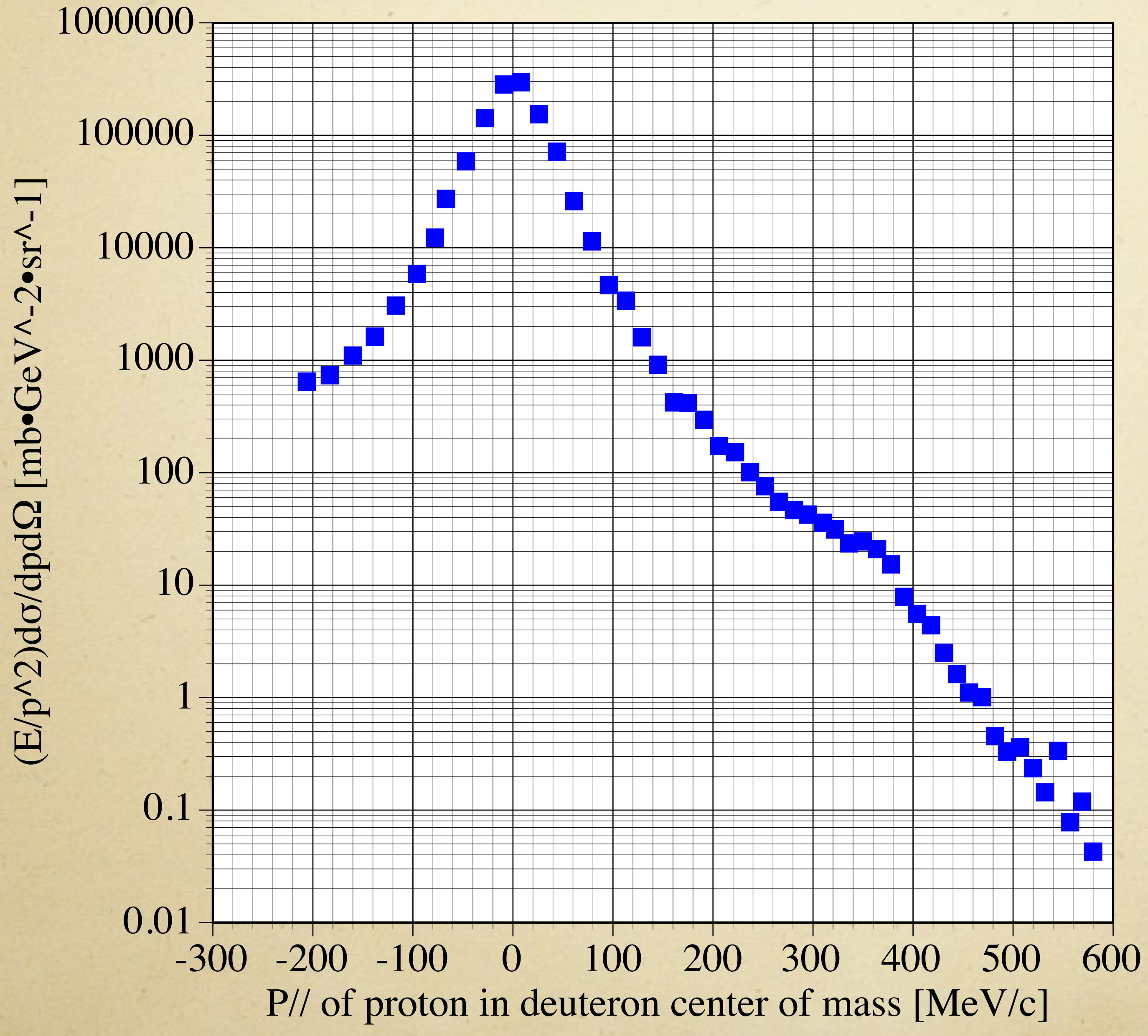


Fig. 1. (a) Neutron exchange mechanism. (b) N*-isobar exchange mechanism. (c) Pion-nucleon exchange mechanism.

Projectile fragmentation

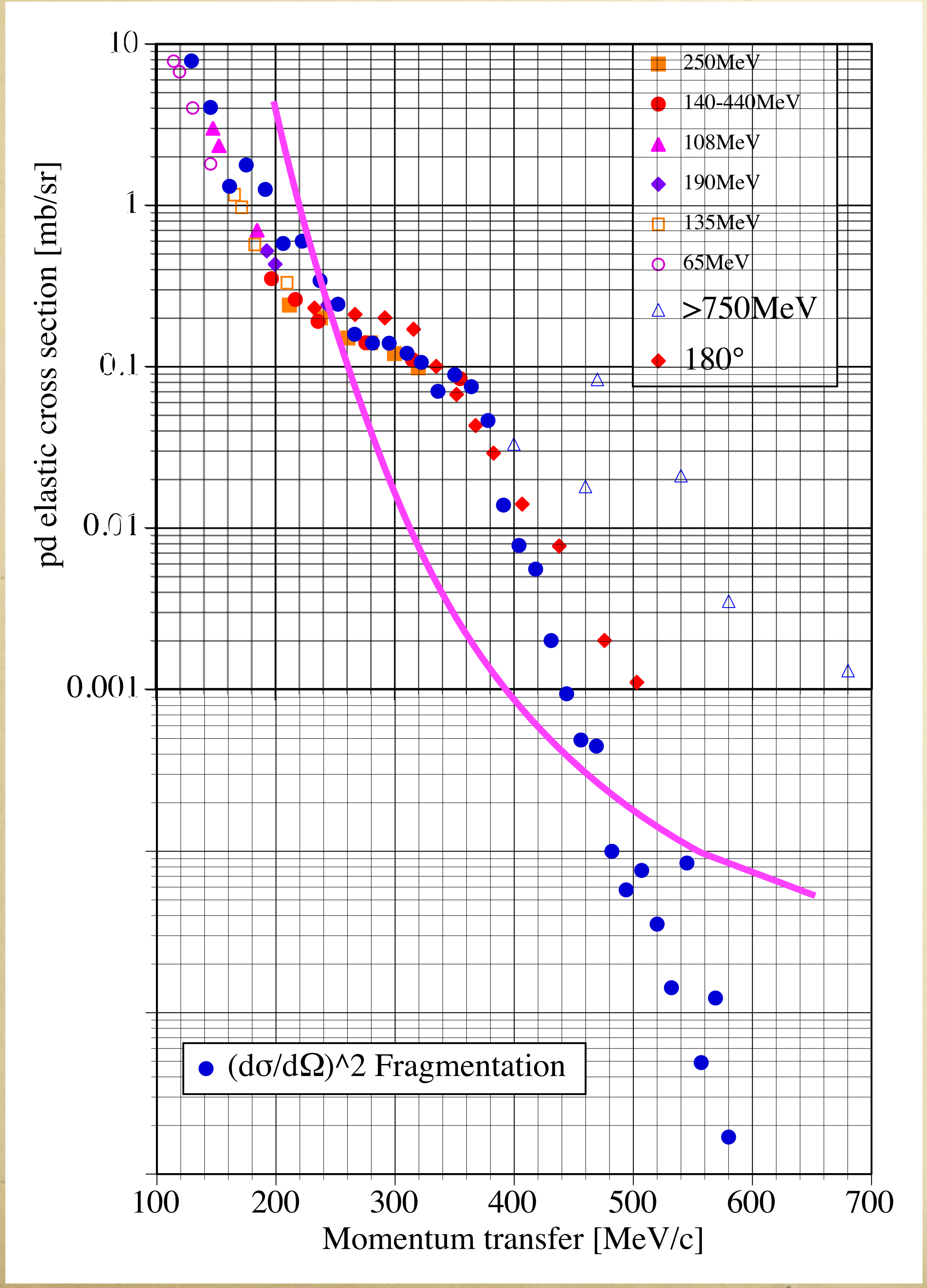
d+C -> p at 0 degrees, E_d=7.2 GeV

V. G. Ableev et al., Nucl. Phys. A 393 (1983) 491.



$$\sigma_f \propto |\psi(p)|^2$$

Overlay of pd elastic and d fragmentation



- σ_{el} and $(\sigma_f)^2$ are overlaid together.
- Their shapes are almost identical,
- and thus, experimentally, indicate that the distributions are reflecting the momentum distribution of nucleons in deuteron.
- But if we overlay the theoretical momentum distribution—-
- Why? We need to have a mechanism to change the structure of deuteron.

A trial to explain the distribution

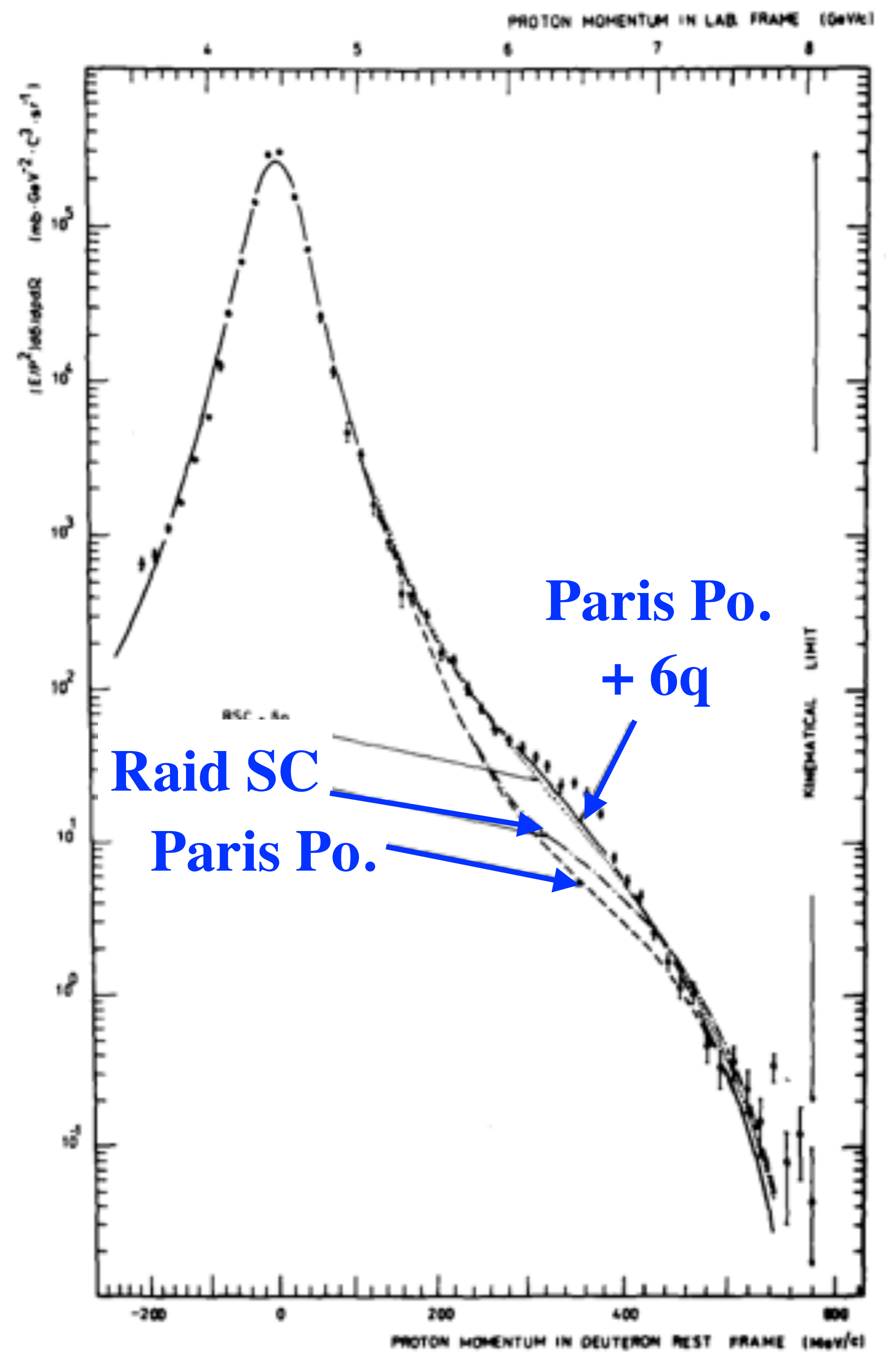


Fig. 2. Invariant cross sections for the reaction (1). The curves correspond to the hybrid model DWF calculations with the two-nucleon wave function of the Paris NN potential (solid) and the Reid soft-core one (dotted). The corresponding values of the 6q-admixture parameters are taken from table 3. The dashed and dashed-dot curves are the calculations with these wave functions but without the 6q-admixture.

- A trial in 1983, (NP A 393,491)
- Six-quark state

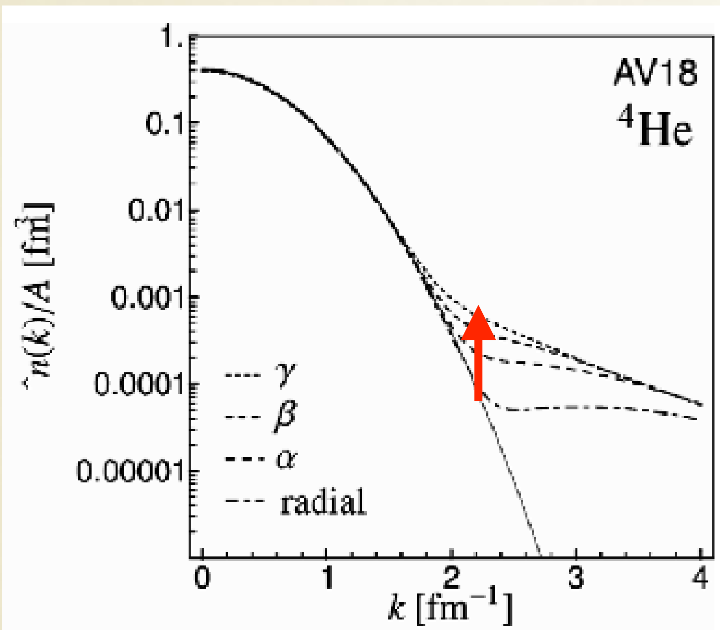
- **No studies has been done to consistently explain pd elastic and projectile fragmentation consistently since then.**

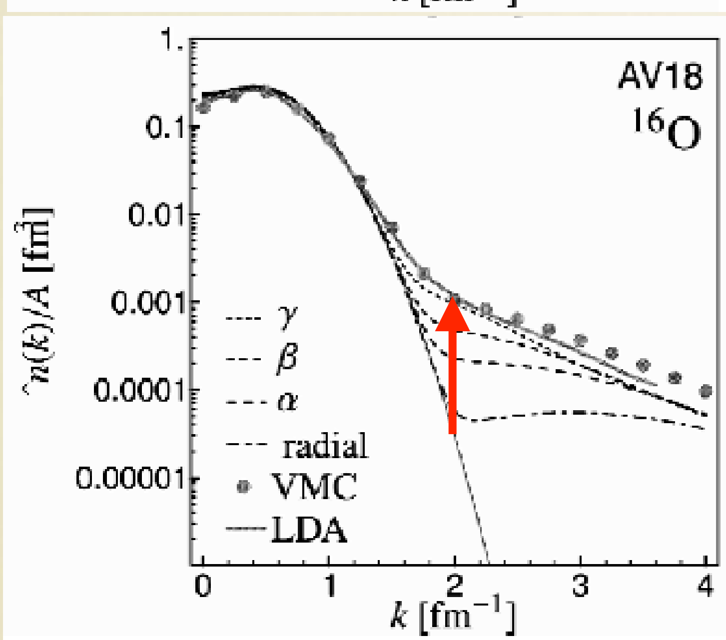
- **What is the properties of high-momentum nucleons?**

So

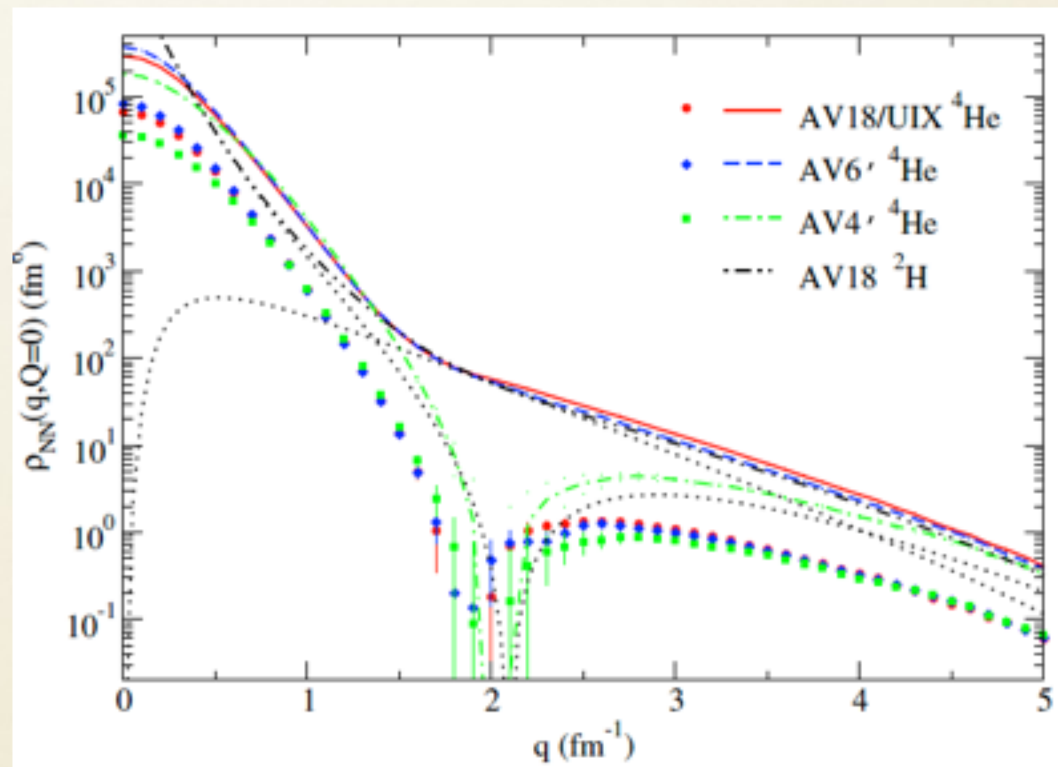
- pd elastic scattering and deuteron fragmentation show same "momentum distributions" of nucleons in deuteron
- The origin of the observed momentum distribution is not known.
- How about the momentum distribution in nuclei.

High-momentum components (Theoretical Predictions)





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



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

$^4He(p,d)^3He$ reaction

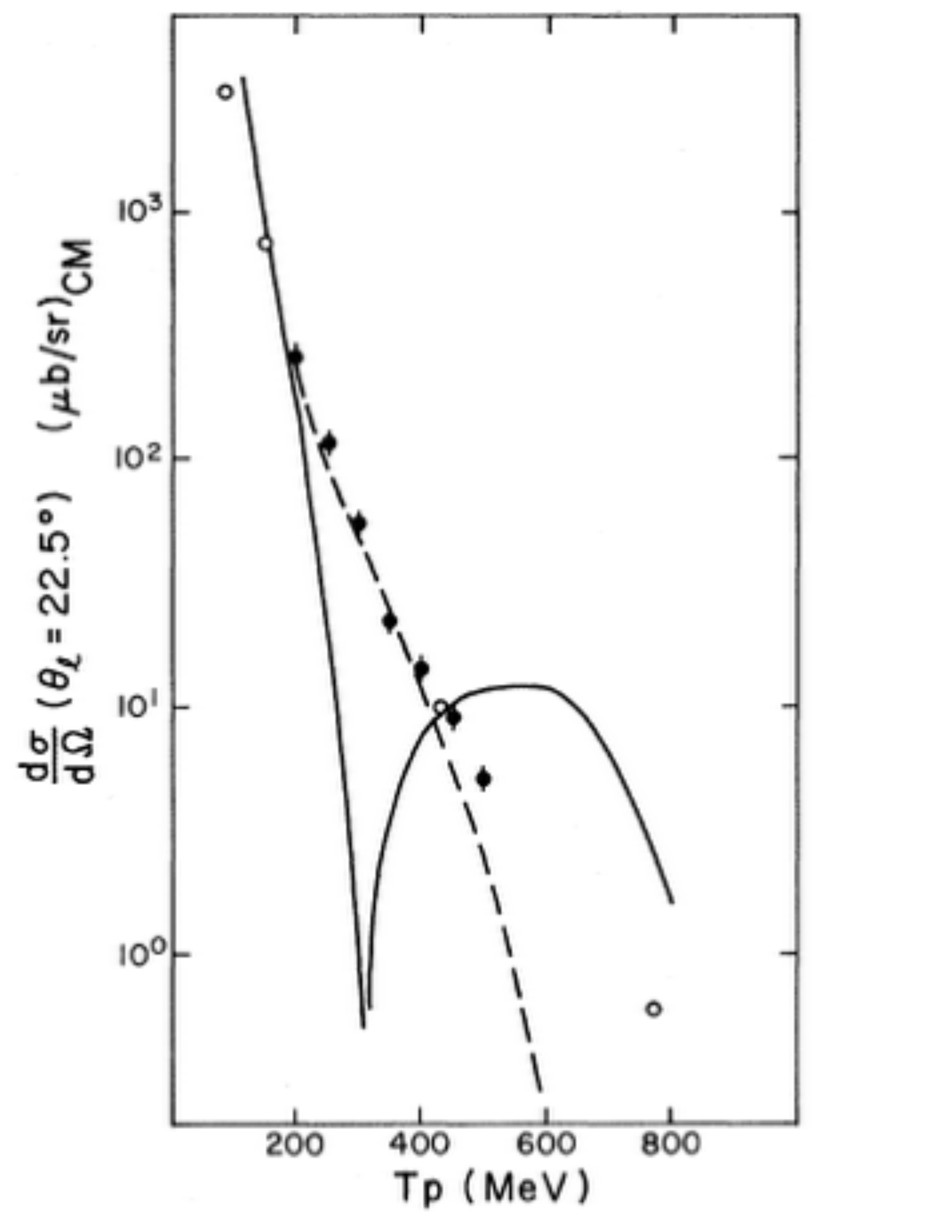


FIG. 2. Results on the differential cross section for $^4He(p,d)^3He$ at $\theta = 22.5°$ (lab) of the present experiment and of previous measurements at $T_p = 156$, 435, and 770 MeV (Refs. 8–10). The calculations shown are based on the pickup diagram (solid line) and the deuteron-proton triangle diagram (broken line); the normalization is arbitrary.

J. Källne et al., Phys. Rev. Lett. 41 (1978) 1638.

Energy dependence at 22.5 °

- Data shows rather structureless distribution that is very similar to the pd elastic scattering at θ_{cm}=180°.

Caution!
(p,d) scattering at a small angle correspond to the large angle scattering of pd elastic scattering near θ_{cm}=180°.

Explicit treatment of correlated nucleons

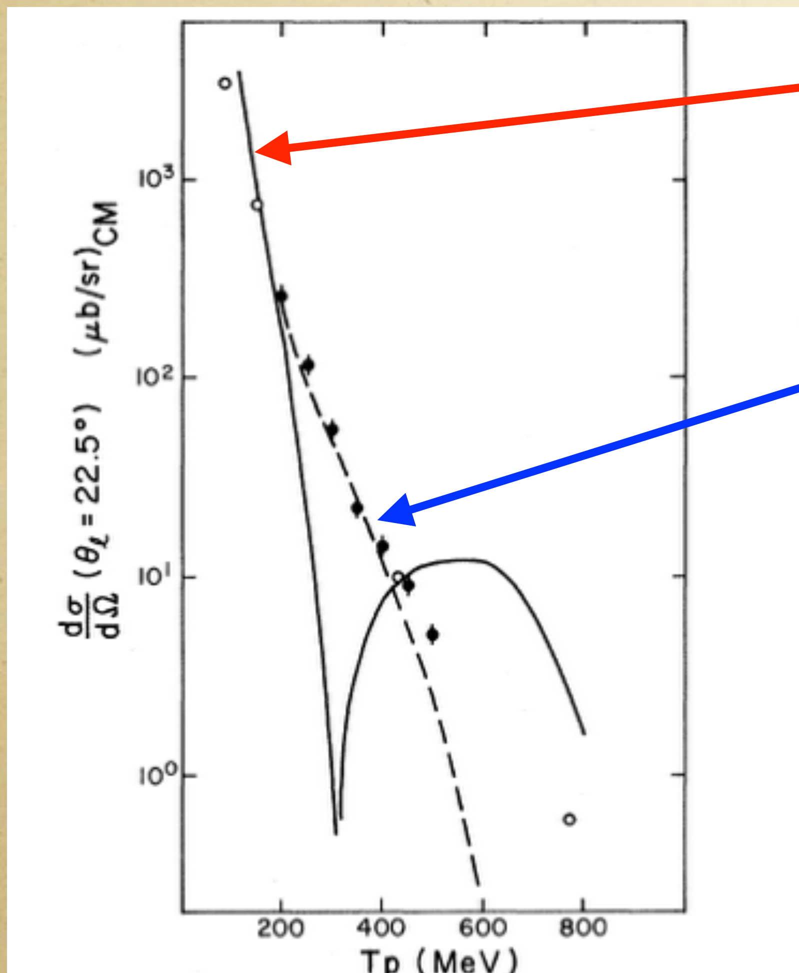


FIG. 2. Results on the differential cross section for ^{4}He(p,d)^{3}He at θ = 22.5° (lab) of the present experiment and of previous measurements at T_p = 156, 435, and 770 MeV (Refs. 8–10). The calculations shown are based on the pickup diagram (solid line) and the deuteron-proton triangle diagram (broken line); the normalization is arbitrary.

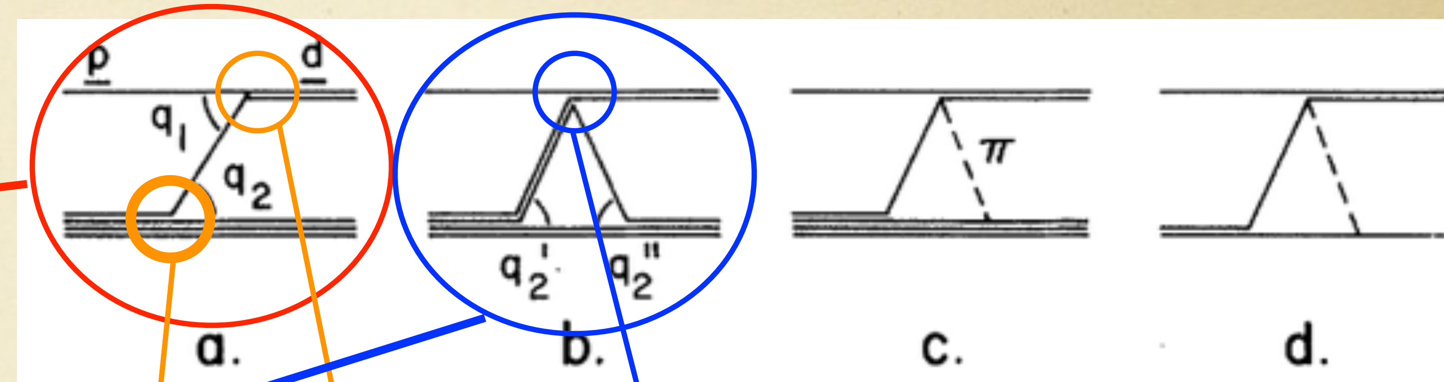


FIG. 4. Reaction diagrams discussed in the text for the reactions ^{4}He(p,d)^{3}He (a)–(c) and $pd \rightarrow dp$ (d).

^{4}He(e,e'p)^{3}He

RSC

use pd elastic scattering data

View of quasi-free scattering on a correlated pair is relevant.

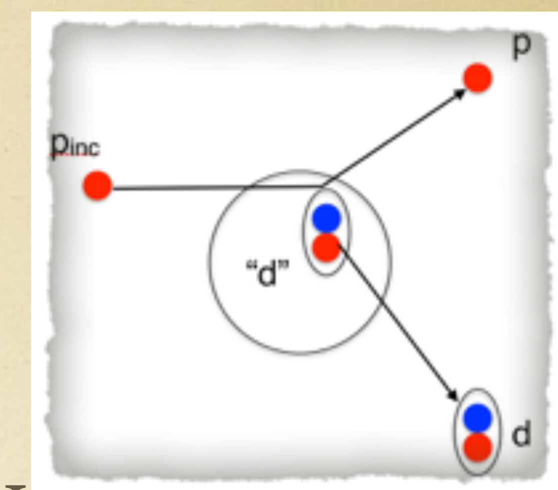
(p,d) and (p,Nd) reactions at high momentum transfer is sensitive to high-momentum nucleon

Observation of correlated nucleons

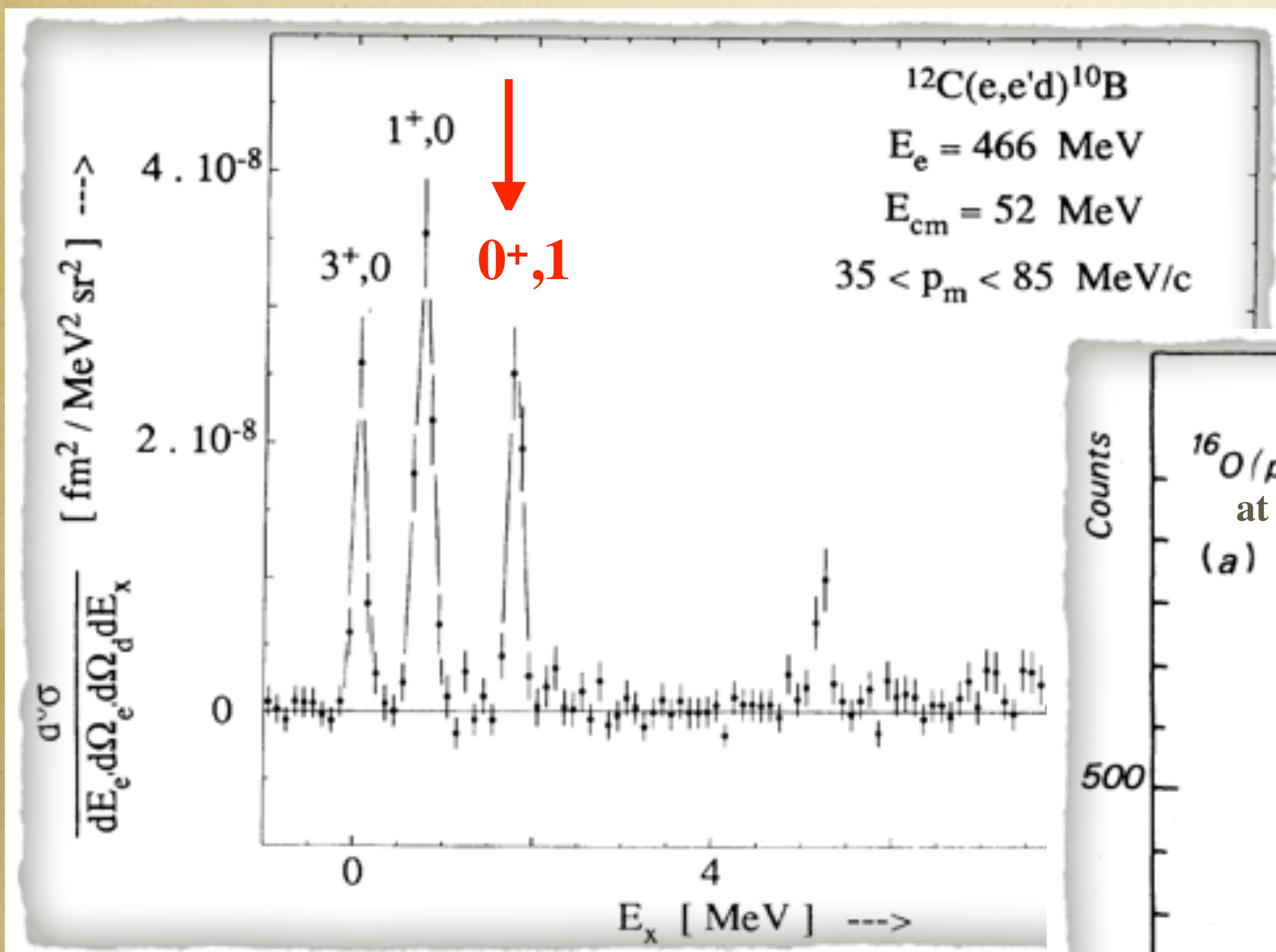
- pn correlation with *S*=1, *T*=0
- pn correlation with *S*=0, *T*=1
- pp and nn correlation with *S*=0, *T*=1

- Tensor interactions works only on *S*=1, *T*=0 pair

Previous data

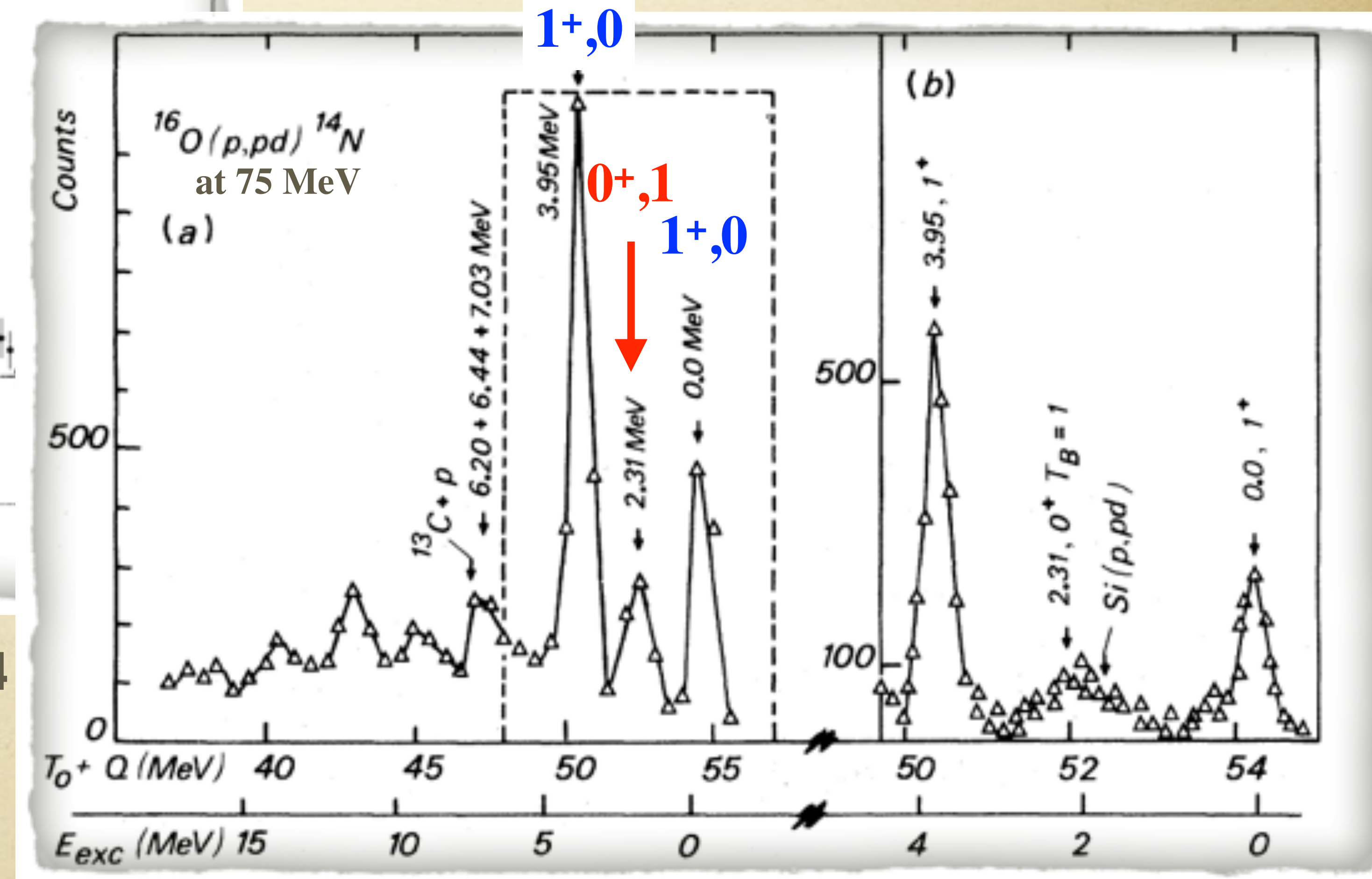


$^{12}C(e,e'd)^{10}B$ @466MeV



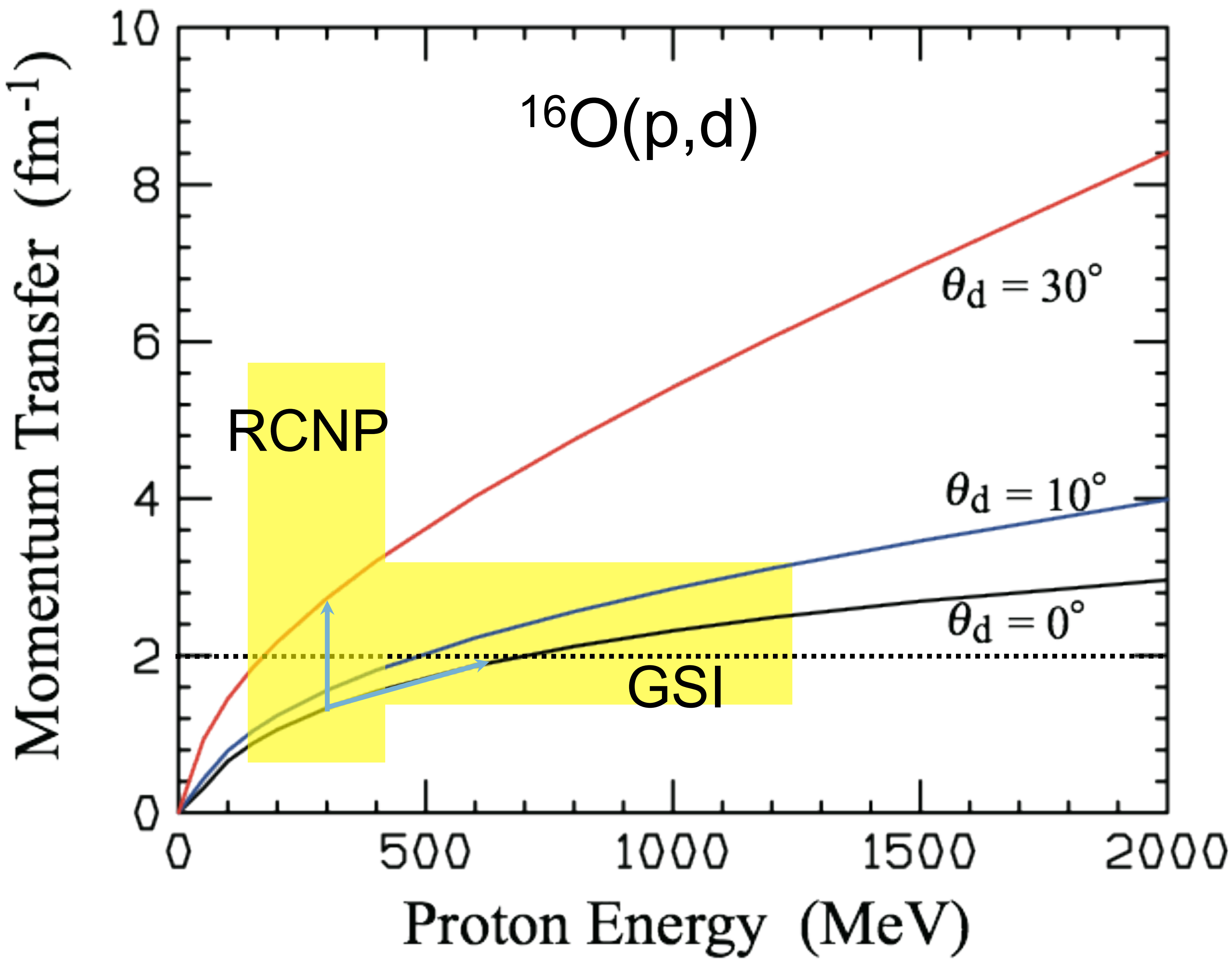
E. Ent et al., Phys. Rev. Lett. 62 (1989) 24

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



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

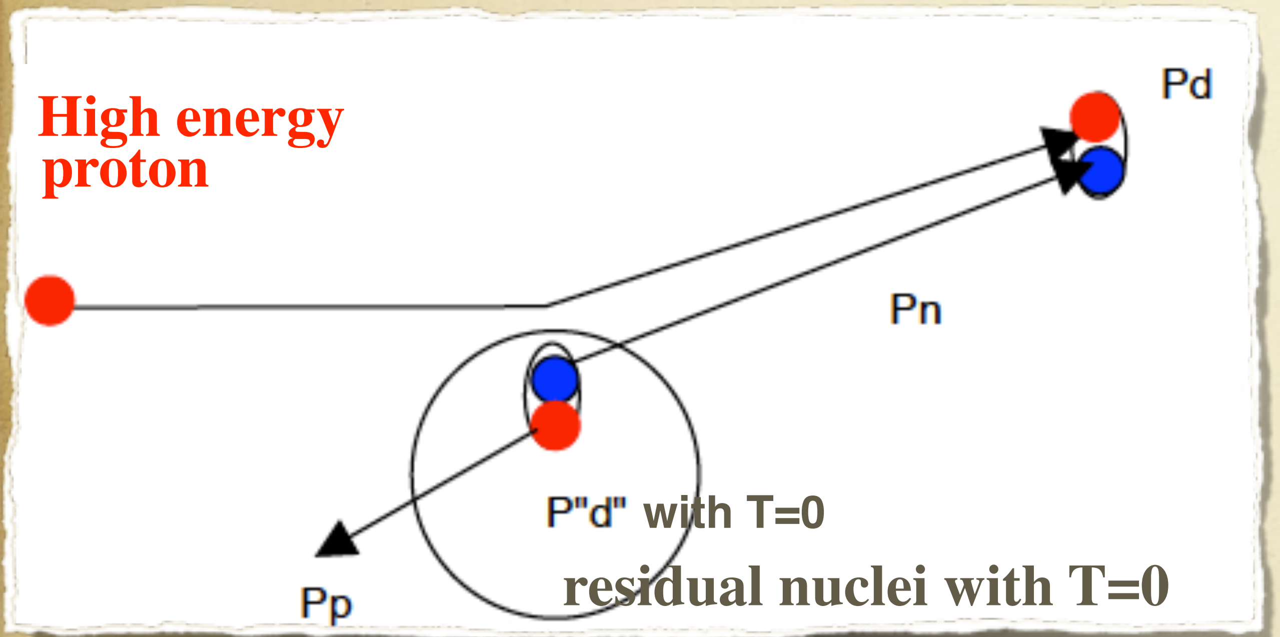
Momentum Transfer

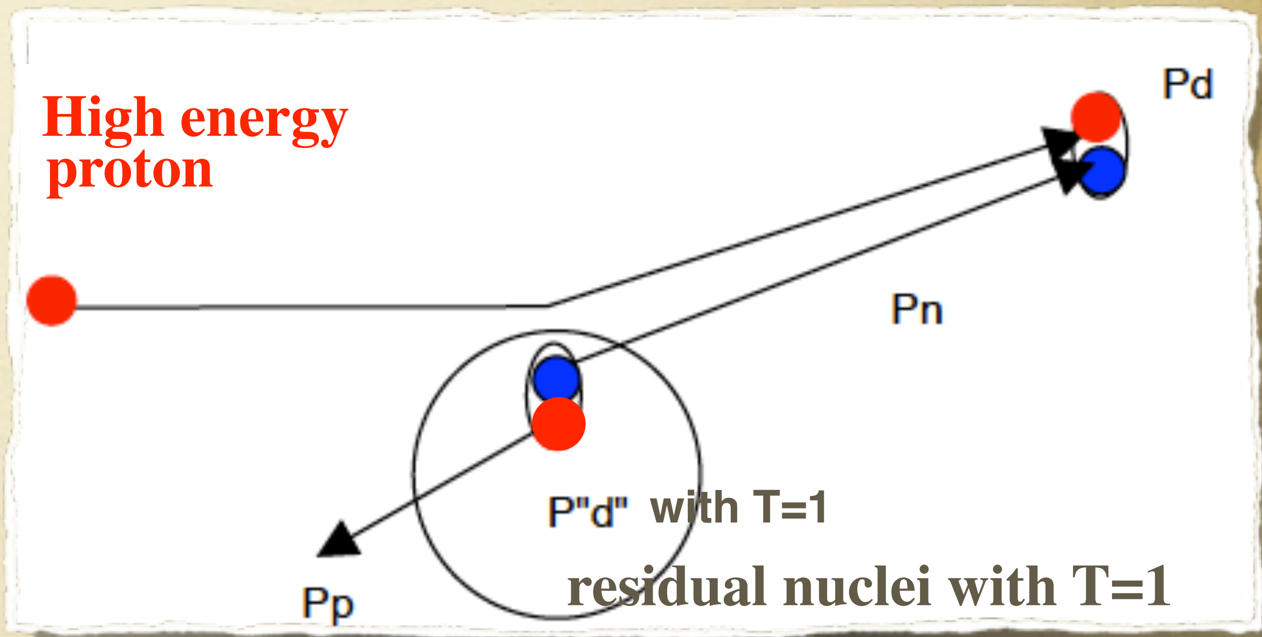


(S=1, T=0) or (S=0, T=1)?

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

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

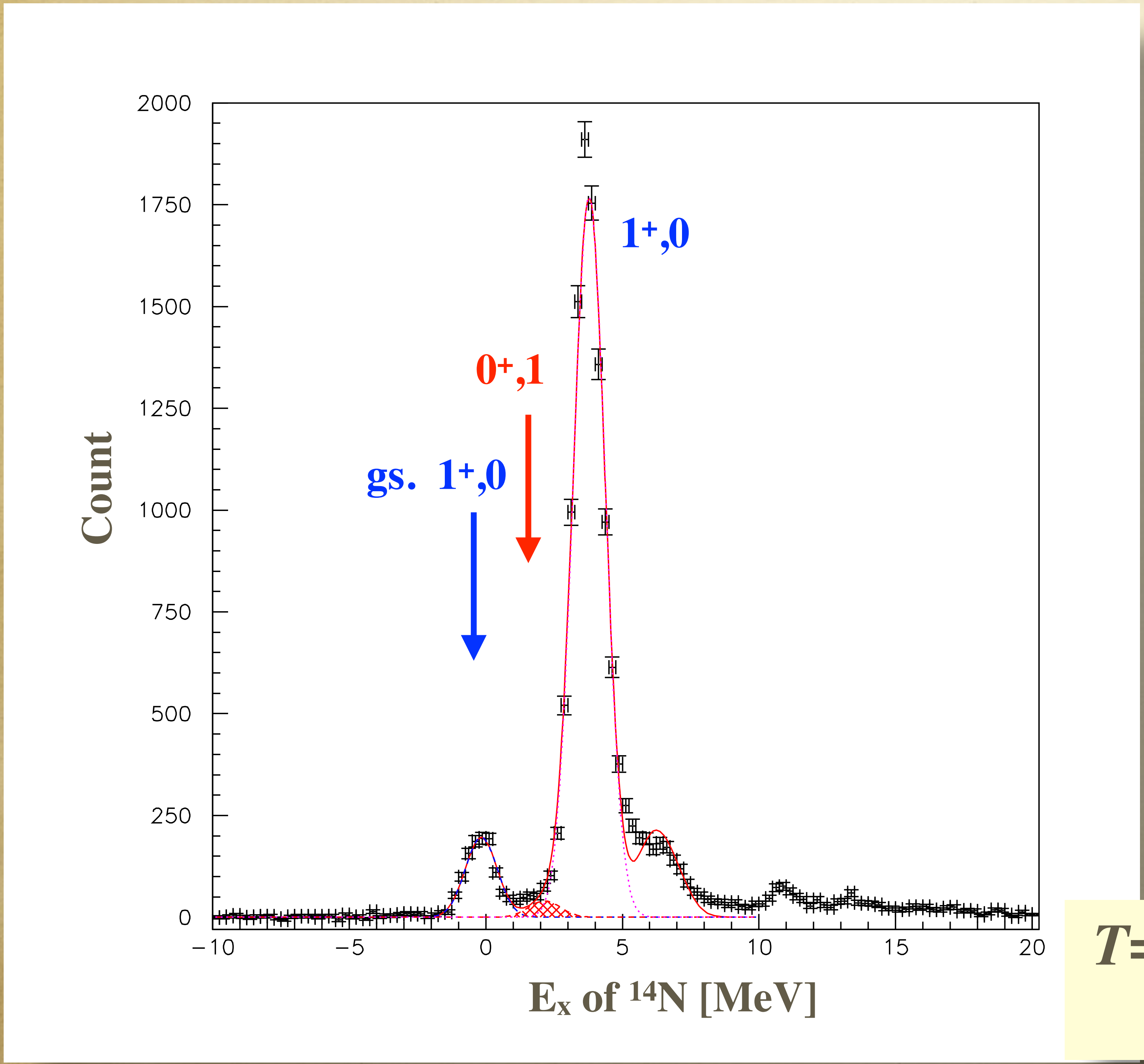


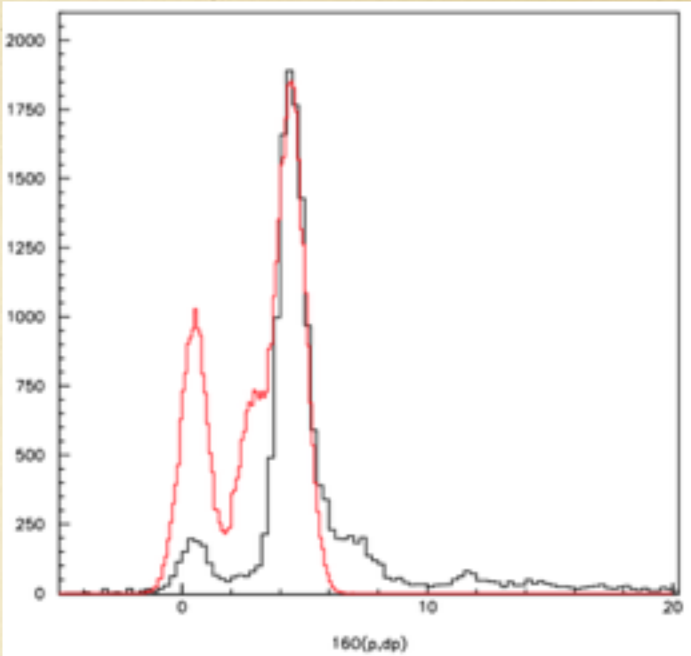


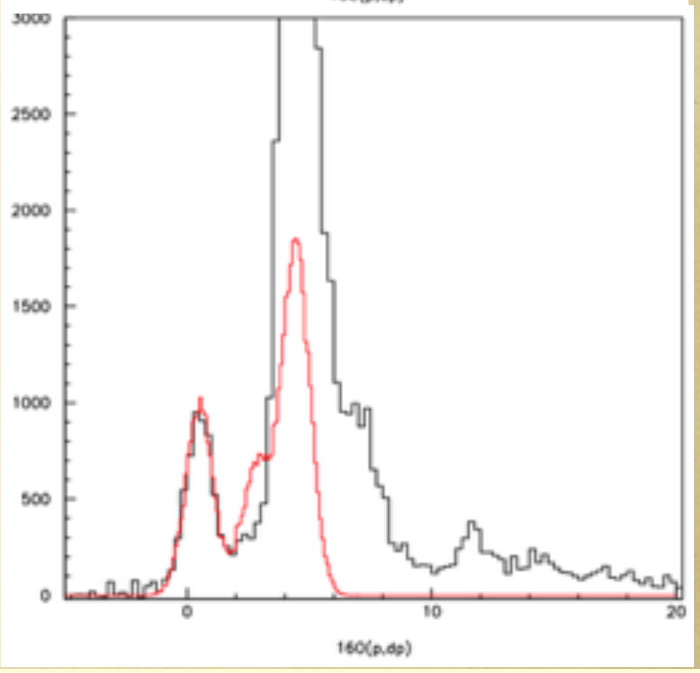
T of residual nuclei = *T* of "d"

T of residual nuclei = *T* of "NN"

(p,pd) at 400 MeV



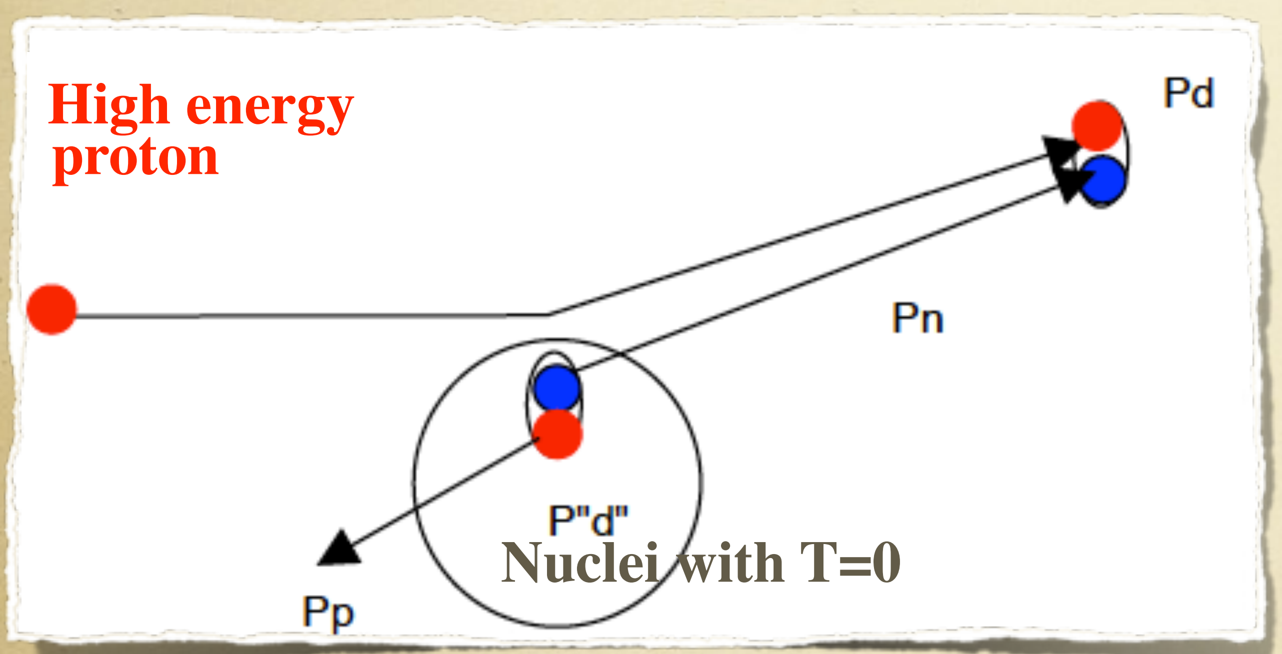


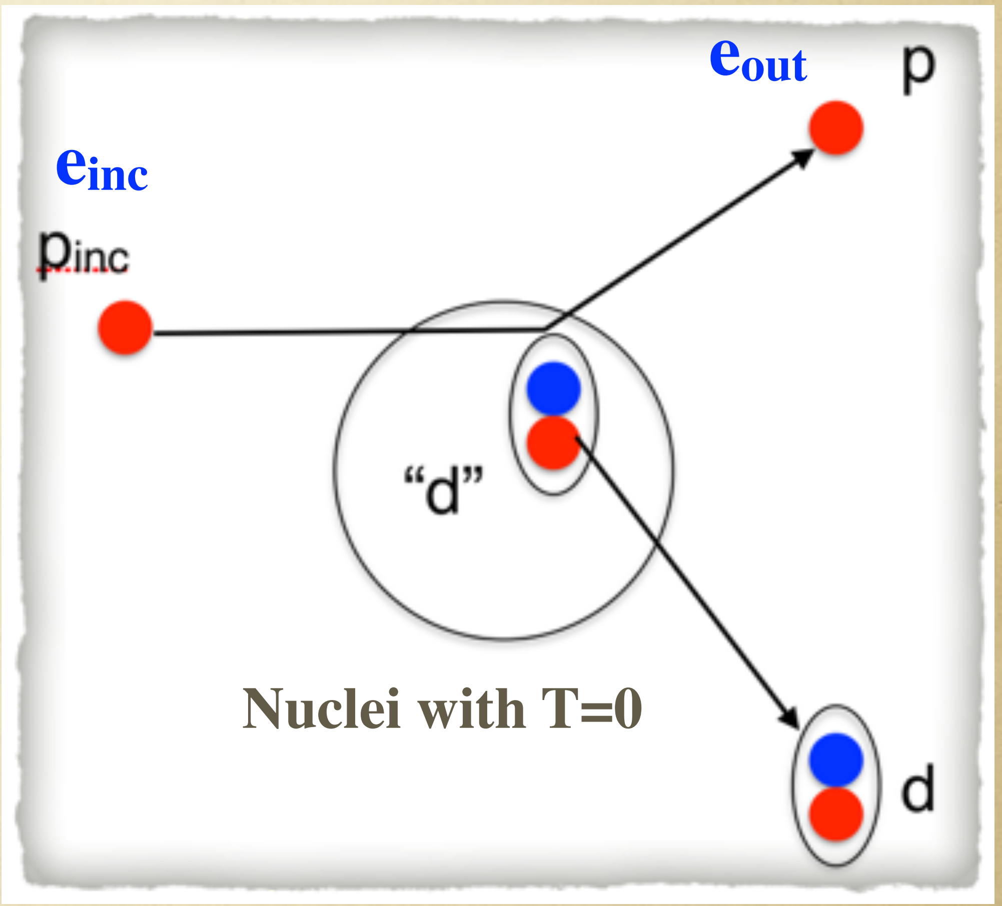


T=1 is strongly suppressed at high-momentum

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

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

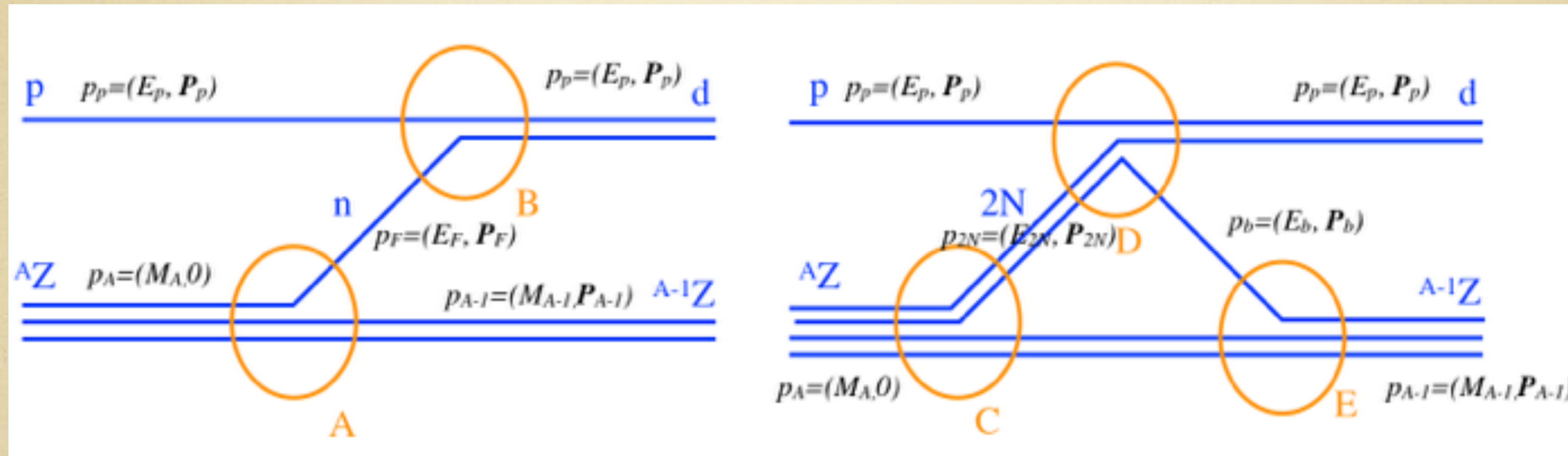




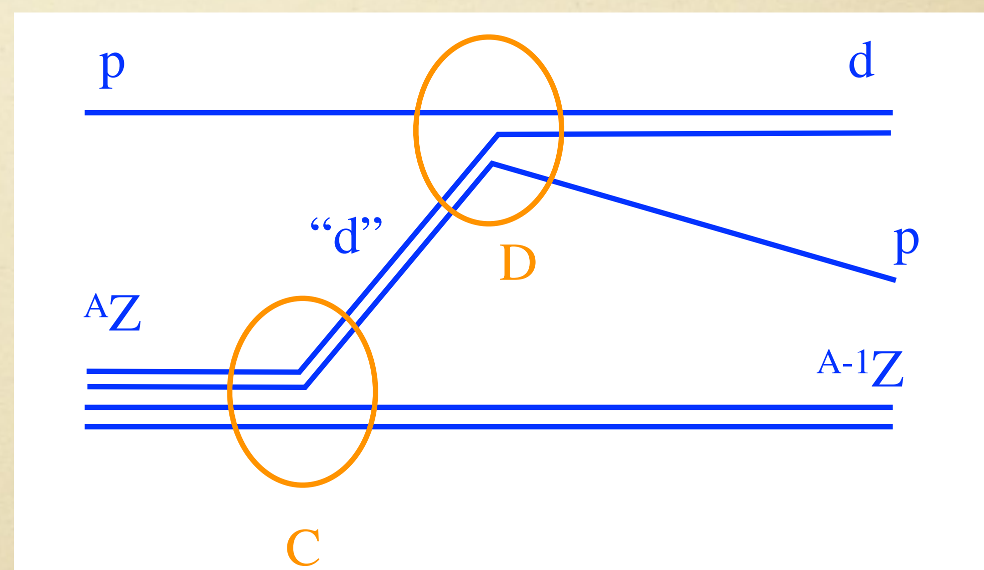
T of residual nuclei = *T* of "d"

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

(p,pd) and (p,d) reactions

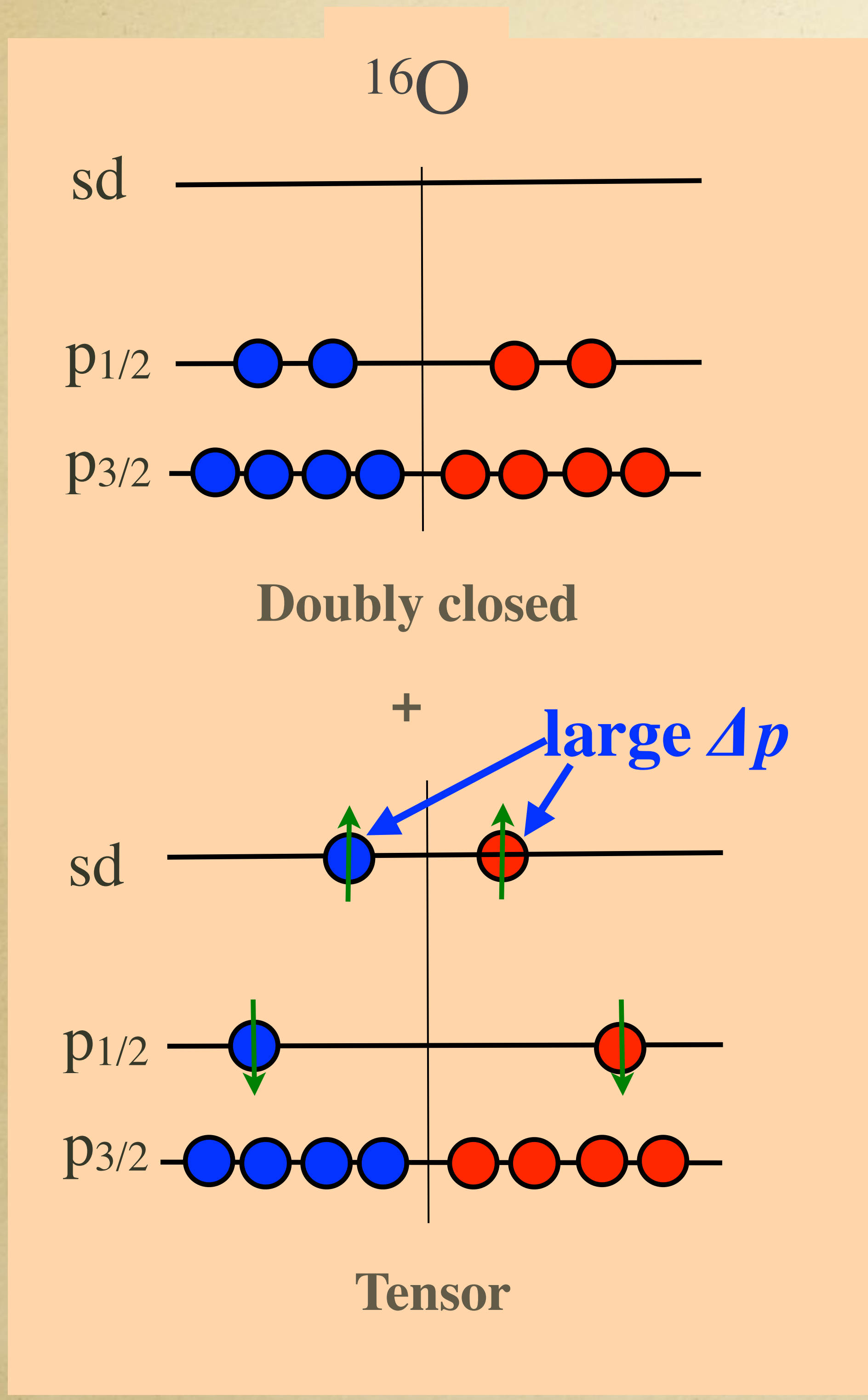


(p,d)

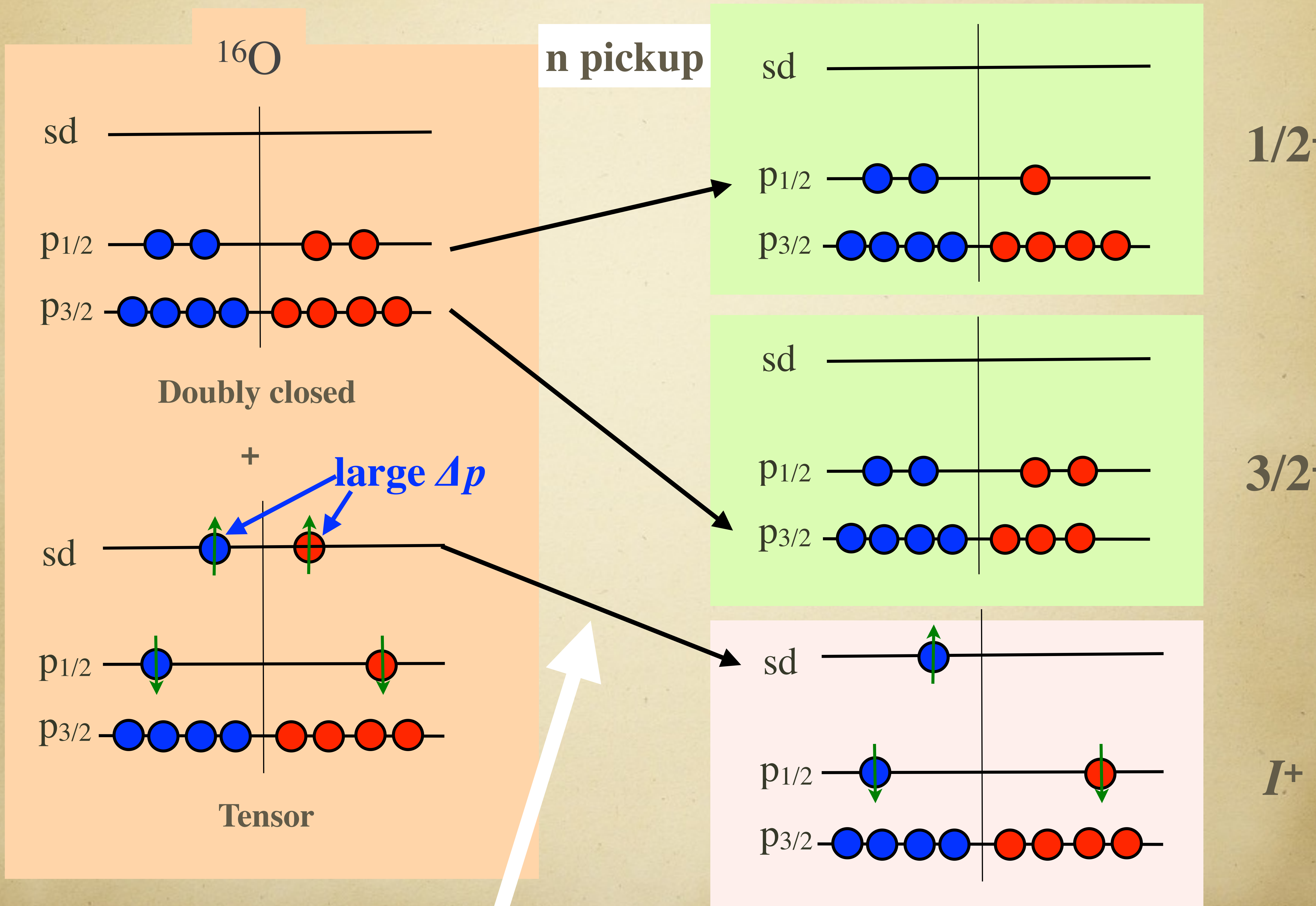


(p,pd)

^{16}O and (p,d) reaction
Another view

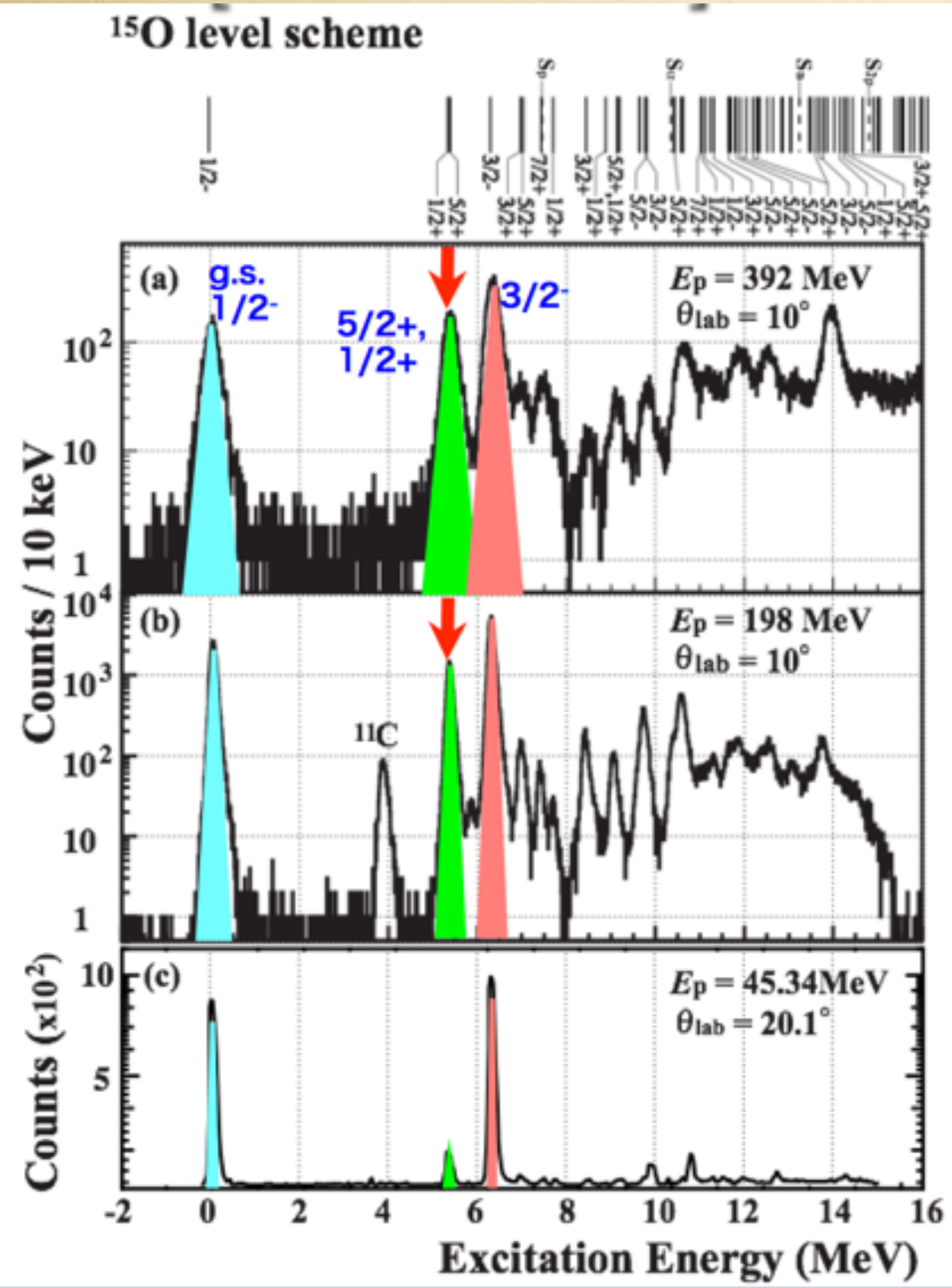


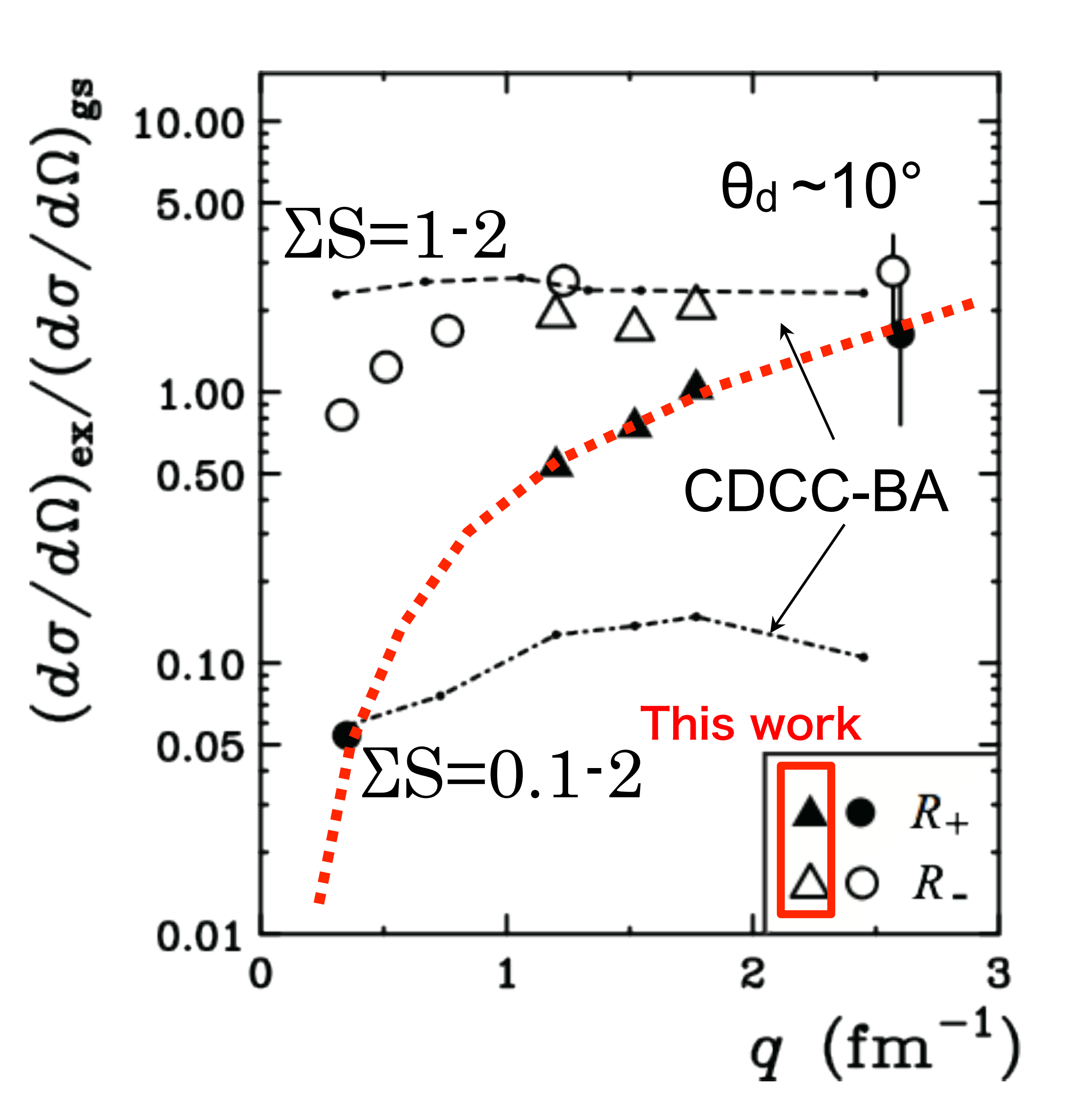
^{16}O and (p,d) reaction



Relatively larger cross section at high-momentum transfer

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

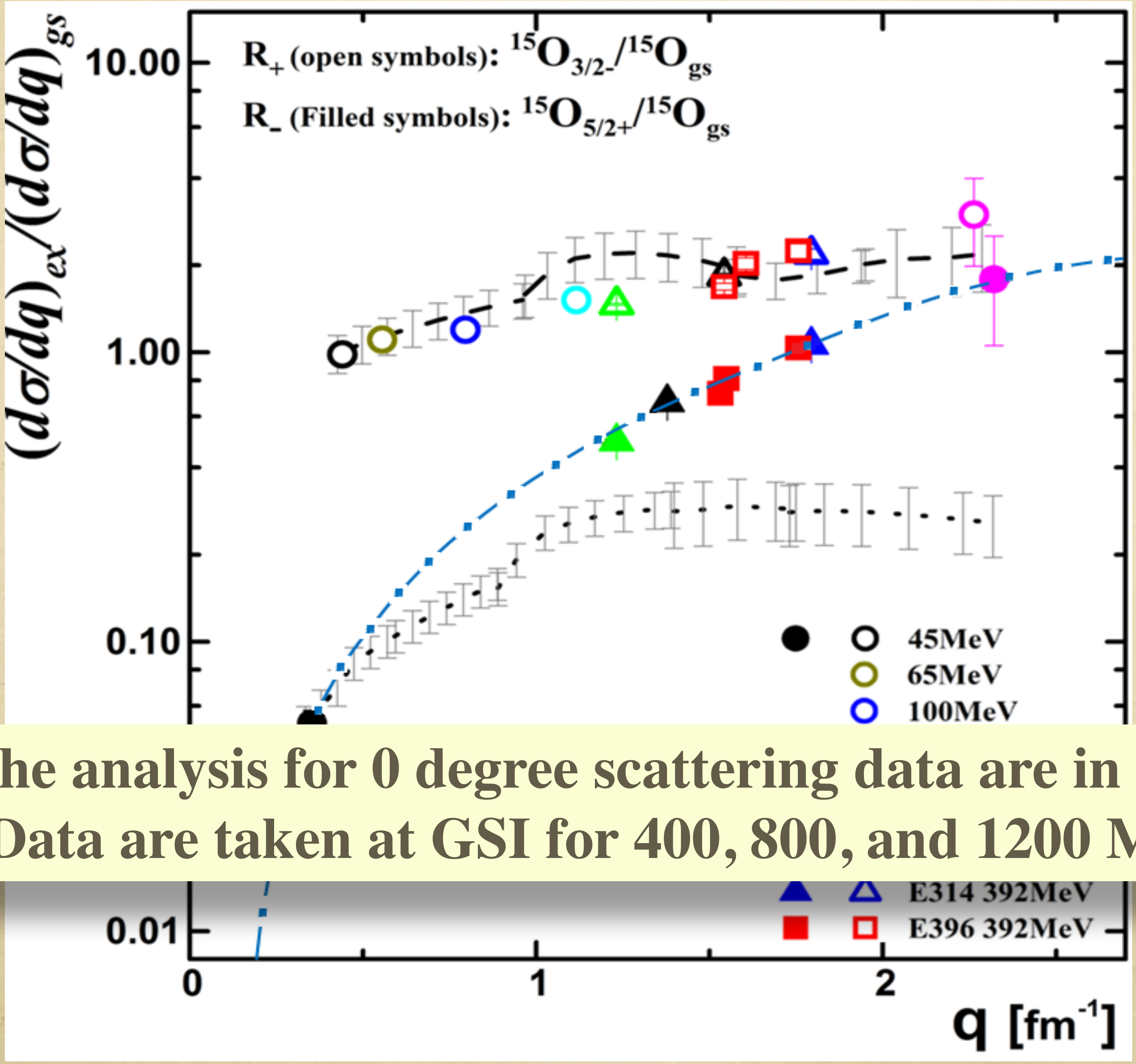




H.J.Ong et al., PLB725 (2013) 277.

Including angular distributions

Chenlei Guo, PhD thesis



Also the analysis for 0 degree scattering data are in progress.
Data are taken at GSI for 400, 800, and 1200 MeV

Summary

- High-momentum neutrons are observed in the ground state of ^{16}O by (p,d) and (p,pd) reactions
- A high-momentum neutron is associated with pn pair of *S*=1, *T*=0 consistent with the effect of tensor interactions.

- Tensor effects are strongly state dependent. It affects not only in the way just reduce the shell model components by 10~20% everywhere but the effect would be strongly state dependent. Also the binding energy may change suddenly due to the availability of orbitals.
- We are studying the difference between ^{12}C and ^{16}O.

Still discussion is qualitative because

- **Good enough theory is missing for high-energy and high-momentum transfer**
  - *Even (p,d) scattering theory is not trustworthy.*

- **Wave functions including tensor interactions (with high momentum) are not available yet.**

We plan to accumulate more systematic data on momentum dependence and others.

We need strong help from theoretician both in structures and reactions.

Collaborators

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