SHORT-RANGE NN CORRELATIONS AND QUASI-DEUTERON CLUSTERS IN THE REACTION $^{12}C(p,2pN)^{10}A$

Yu.N. UZIKOV (DLNP, JINR, Dubna)

- Motivation: SRC and others…
- $^{12}C(p,pd)^{10}B$ and $pd\to dp$ $pd\to\{pp\}_s n$ at ~1 GeV
- Elements of formalism for $p+^{12}C\to p+p+N+^{10}B$ (BM@N)
- Numerical results for pp/pn ratio and SRC c.m. distribution
- Conclusion

NUCLEUS 2020, 17 October

- ♥ Dubna, 1957 M.G. Mesheryakov et al. ZHETF,
  $p + {}^{12}C \rightarrow d + X$ at 670 MeV; quasi-elastic knock-out of the fast deuteron clusters
  D.I. Blokhintsev (1957) : **fluctons** (6q) in nuclei
  Two nucleons being at short distances $r_{NN} < 0.5$ fm
  have a large relative momentum $q > 1/r_{NN} = 0.4$ GeV/c;
  Repulsive core in NN-potential → high-momentum part of the w.f. of NN pair

- ♥ Search for high-momentum components of the nuclear wave functions eA-, pA – elastic and inelastic scattering.
  A special attention was paid to the lightest nuclei – the deuteron, ${}^{3}He$, ${}^{4}He$ (A.Gilman, F.Gross,J.Phys.G:Nuc.Part.Phys.28 (2002)B13)

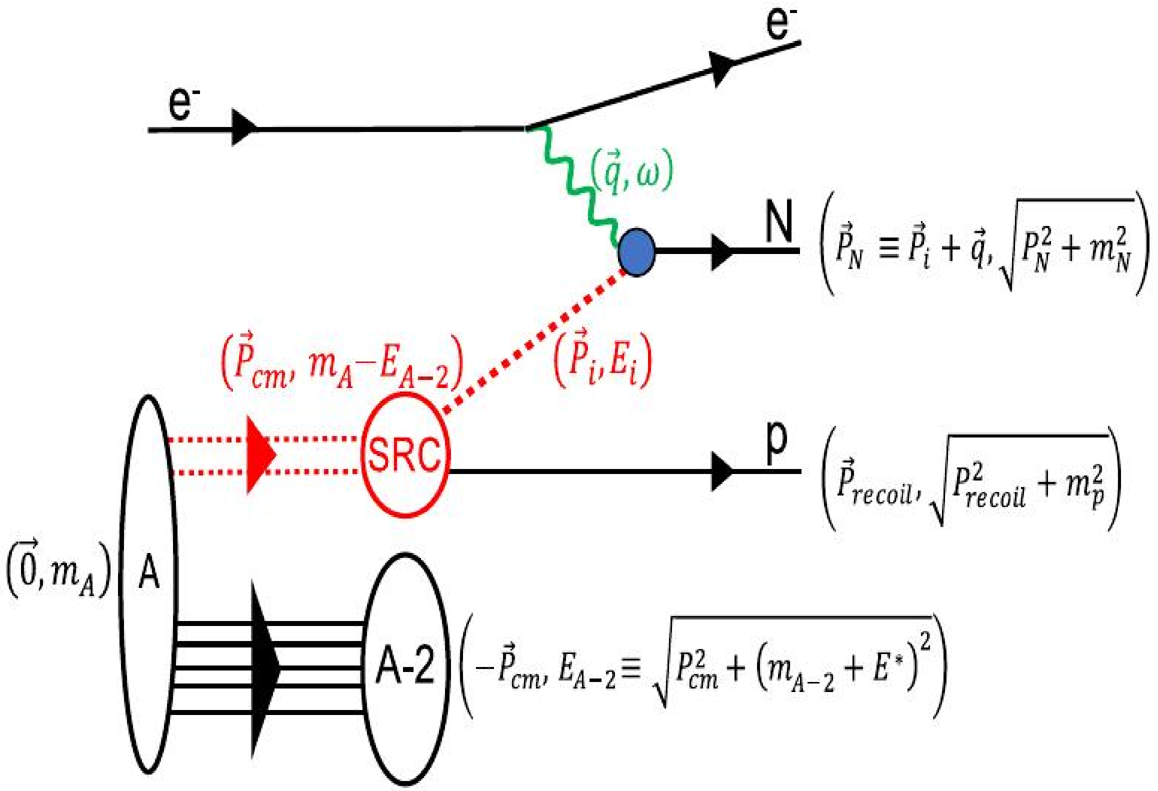
♥ A new trend in this study is investigation of short-range correlations (SRC) in nuclei – NN-pair in nucleus with almost zero c.m. momentum but large (equal) internal momenta $q_1=-q_2$, $q > p_F$ = 250-300 MeV/c. (**M.Strikman, L. Frankfurt, 1978**):

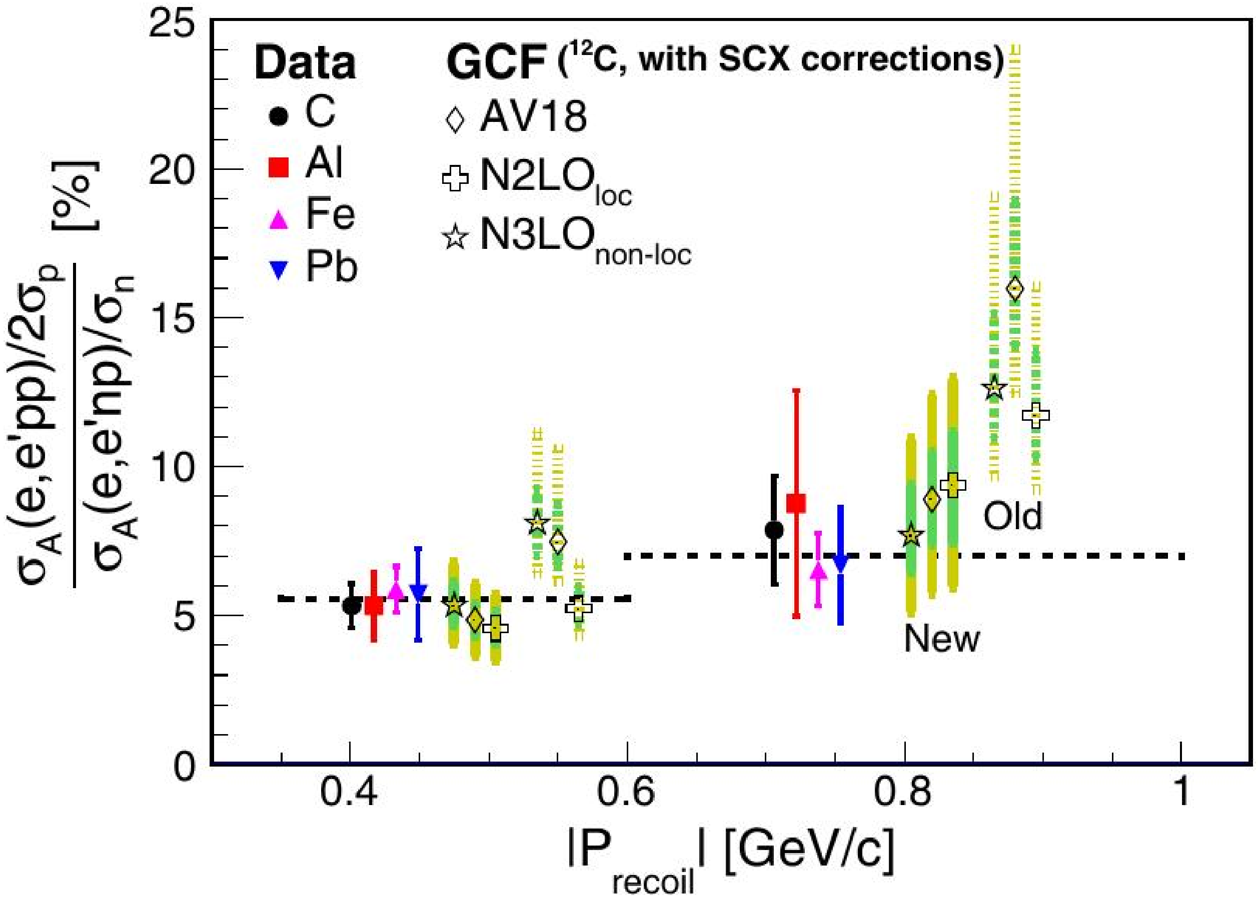
* High-momentum part ($q > p_F$) accounts for 20% nucleons .
* pn- SRC pairs dominate by factor of 20 as compared to pp- and nn- due to the tensor forces.
* SRC are connected with neutrino-nucleus interaction, neutron stars structure, modification of the bound nucleon structure (EMC effect).

Cioffi degli Atti, Phys. Rep. 590 (2015) 1
O. Hen et al. Rev. Mod. Phys. 89 (2017) 045002.

M.Duer et al. PRL 122 (2019) 172502 (CLAS Collabotration)

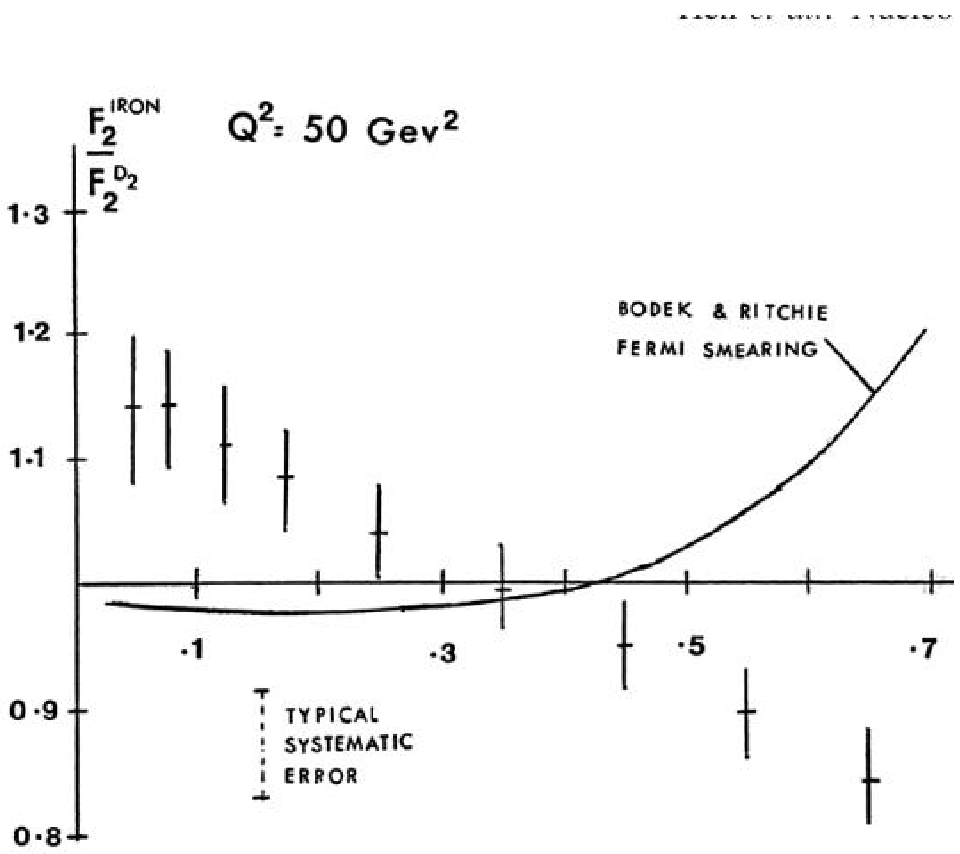
E_e=5 GeV,
A(e,e'np), A(e,e'pp)





EMC- effect and SRC

O. Hen et al. Rev. Mod. Phys. 89 (2017) 045002



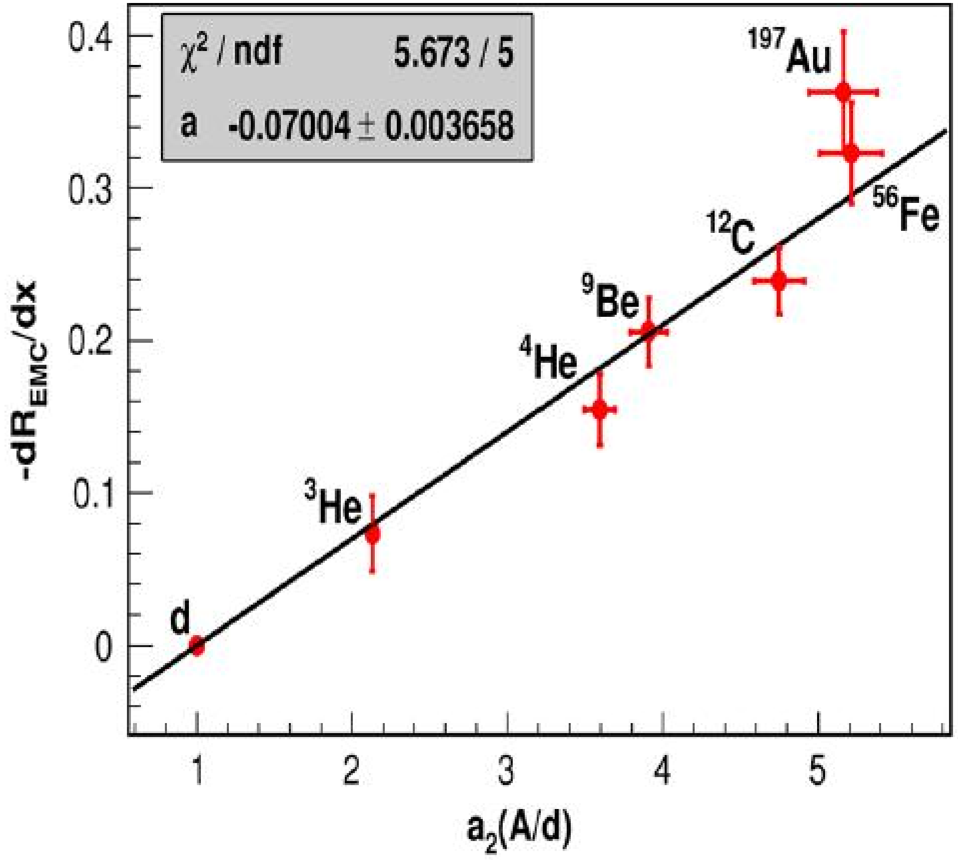
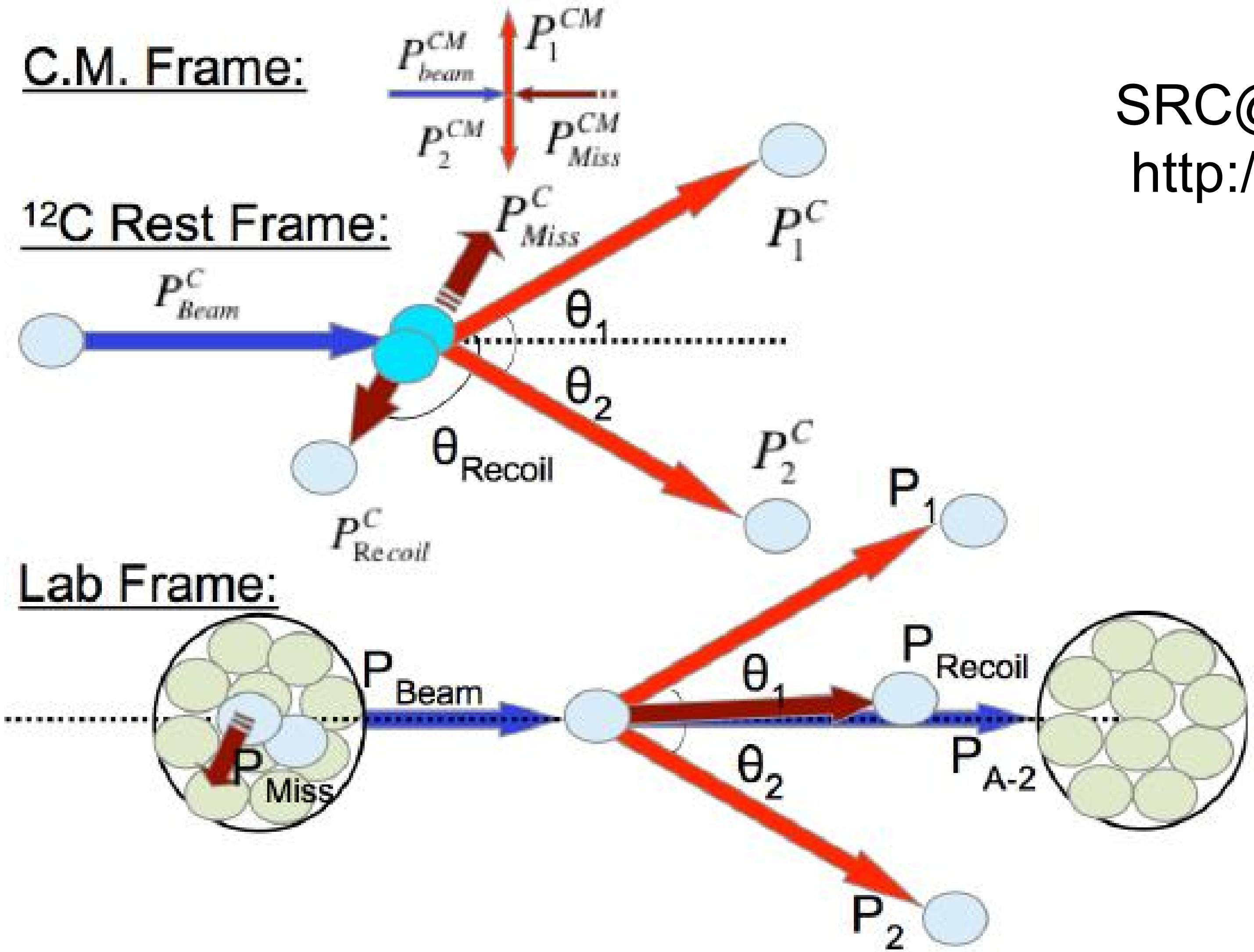


FIG. 34. The slope of the EMC effect (R_{EMC}, ratio of nuclear to deuteron cross section) for $0.35 \leq x_A \leq 0.7$ plotted vs $a_2(A)$, the SRC scale factor (the relative probability that a nucleon belongs to an SRC NN pair) for a variety of nuclei. The fit parameter $a = -0.070 \pm 0.004$ is the intercept of the line constrained to pass through the deuteron (and is therefore also the negative of the slope of that line). From Hen *et al.*, 2013.

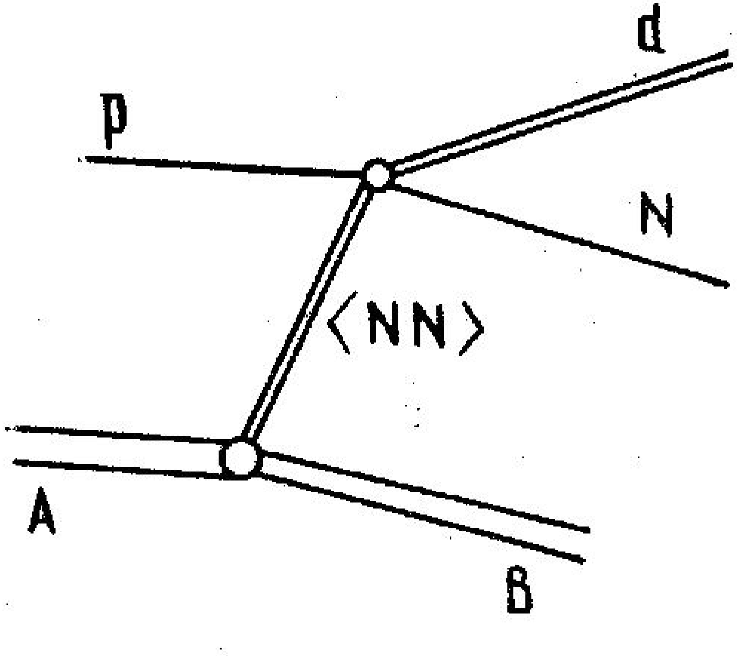
V.Kim' talk yesterday

Project of BM@N to study SRC in JINR with 4=GeV/c /nucleon beam of ^{12}C and proton target. Inverse kinematics allows to detect all final particles including the residual nucleus.

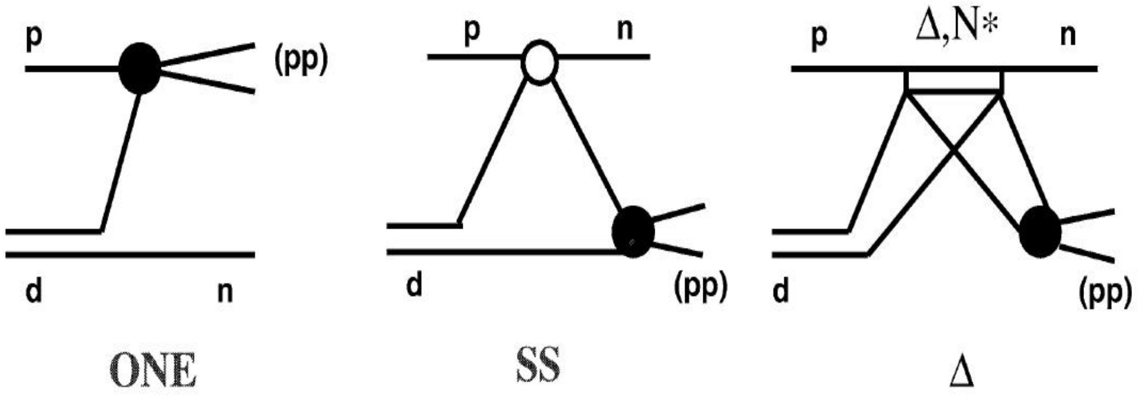


SRC@BMN proposal
http://bmnshift.jinr.ru/wiki/doku.pho

Quasi-elastic knockout of fast deuteron clusters $^{12}C(p,pd)^{10}B$ and hard $pd \to dp$



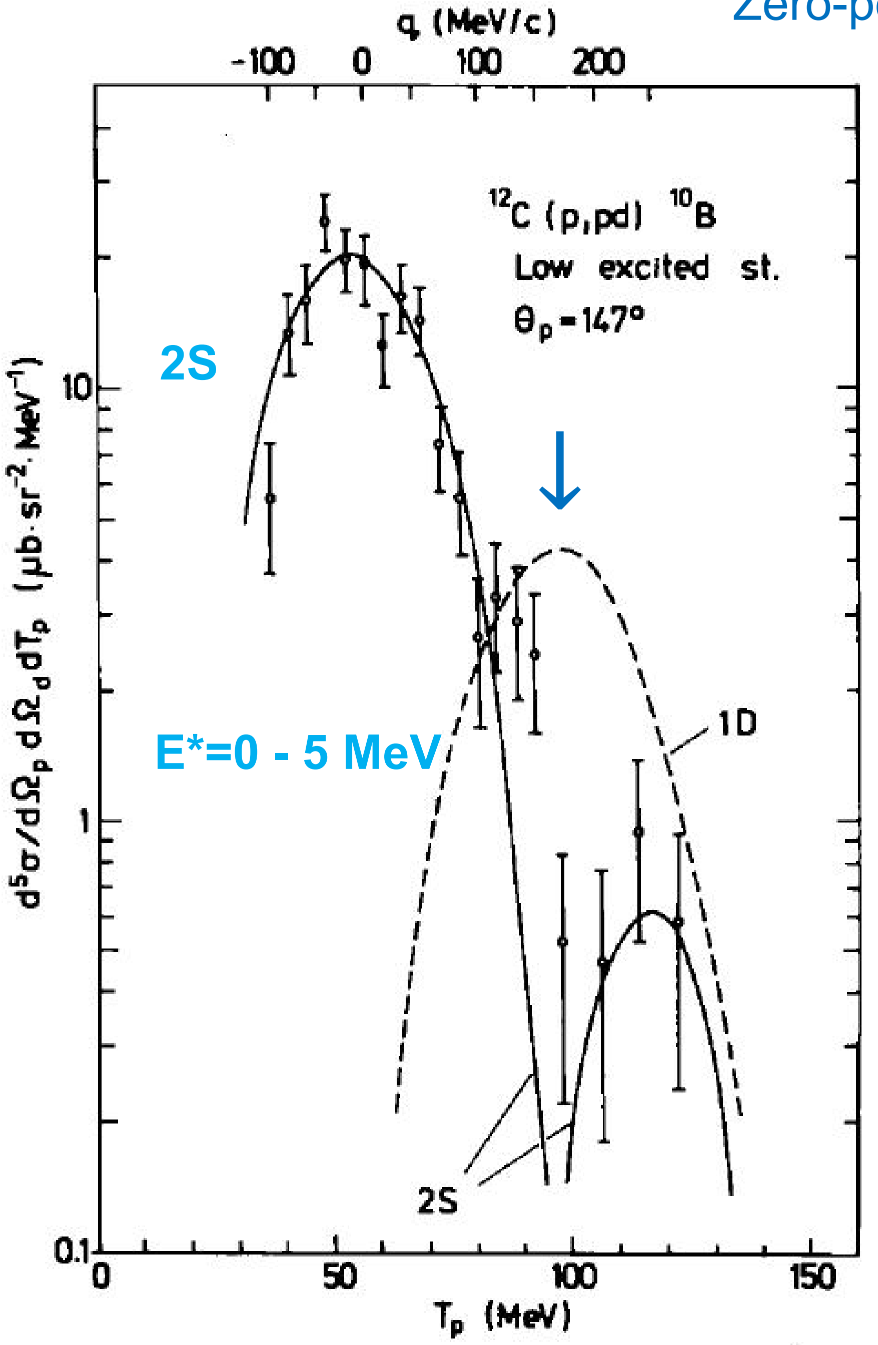
J. Haidenbauer, Yu.N. Uzikov / Physics Letters B 562 (2003) 227–233

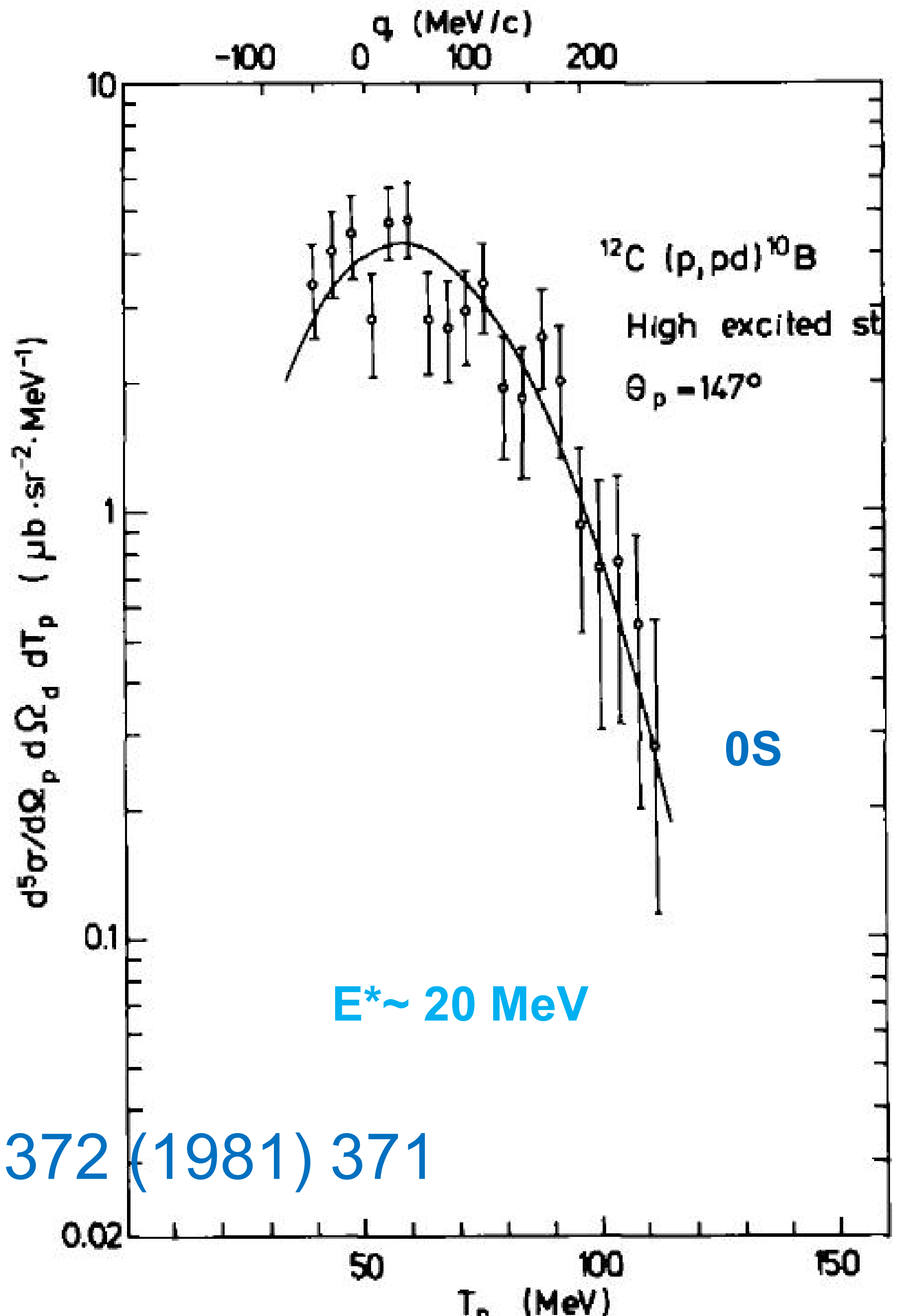


Mechanisms of the breakup reaction $pd \to (pp)n$. The same mechanisms are used for the reaction $pd \to dp$.

M.A.Zhusupov, Yu.N.U. PEPAN 18 (1987) 323; J.Haidenbauer, Yu.N.U. PLB 562 (2003)

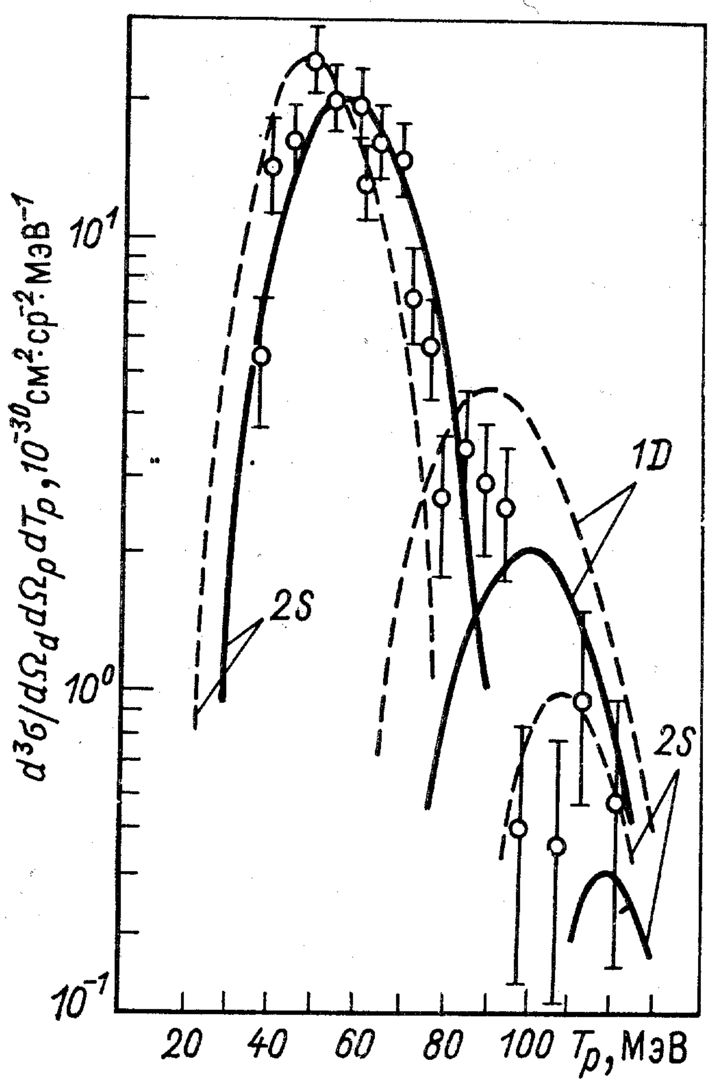
Zero-point at q ≈180 MeV/c



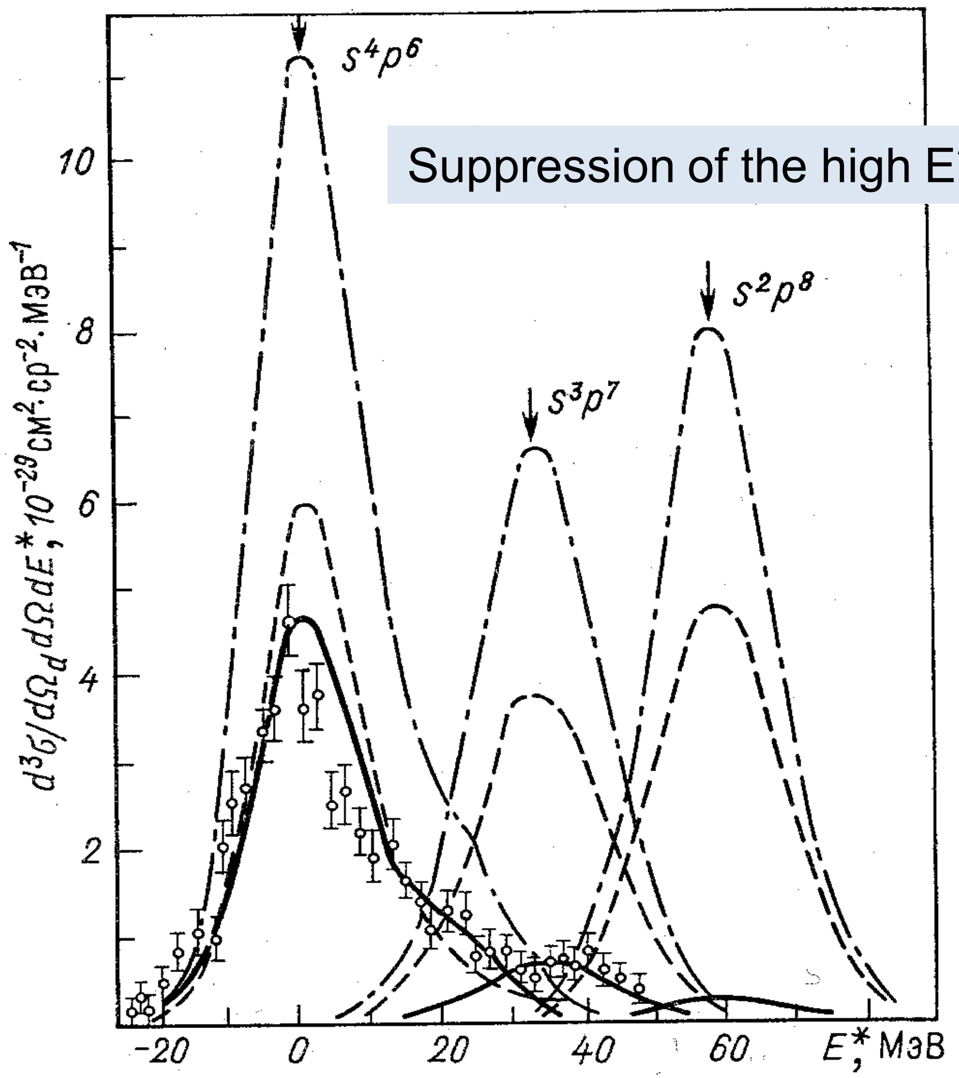


J.Ero et al. NPA 372 (1981) 371

M.A.Zhusupov,O.Imambejkov, Yu.N.U. Izv.AN SSSR (1986)



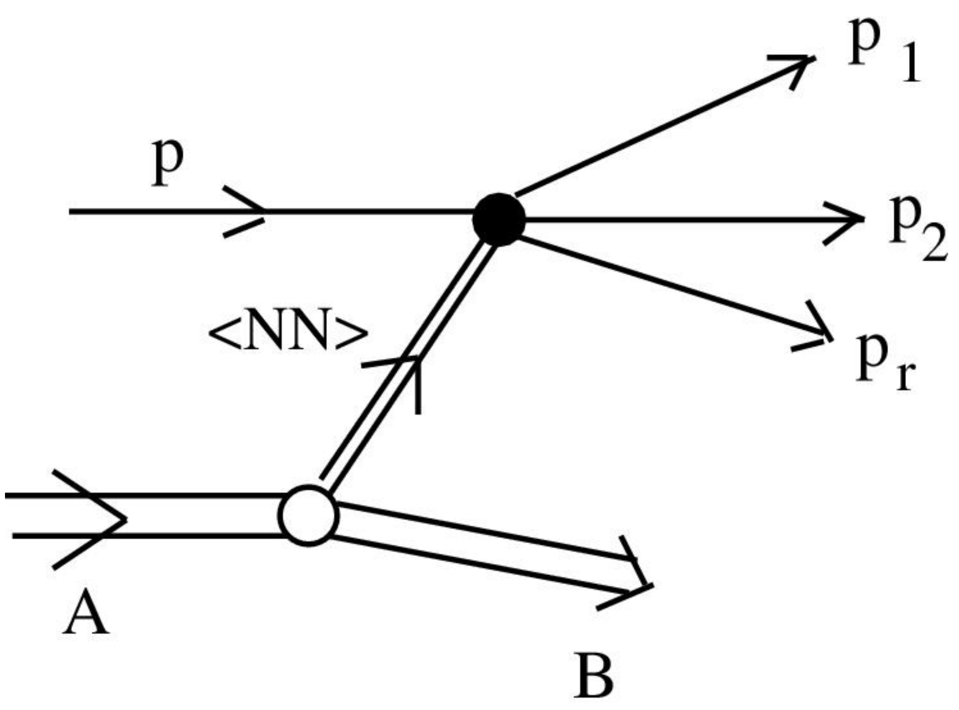
$^{12}C(p,pd)^{10}B$ (s^4p^6)

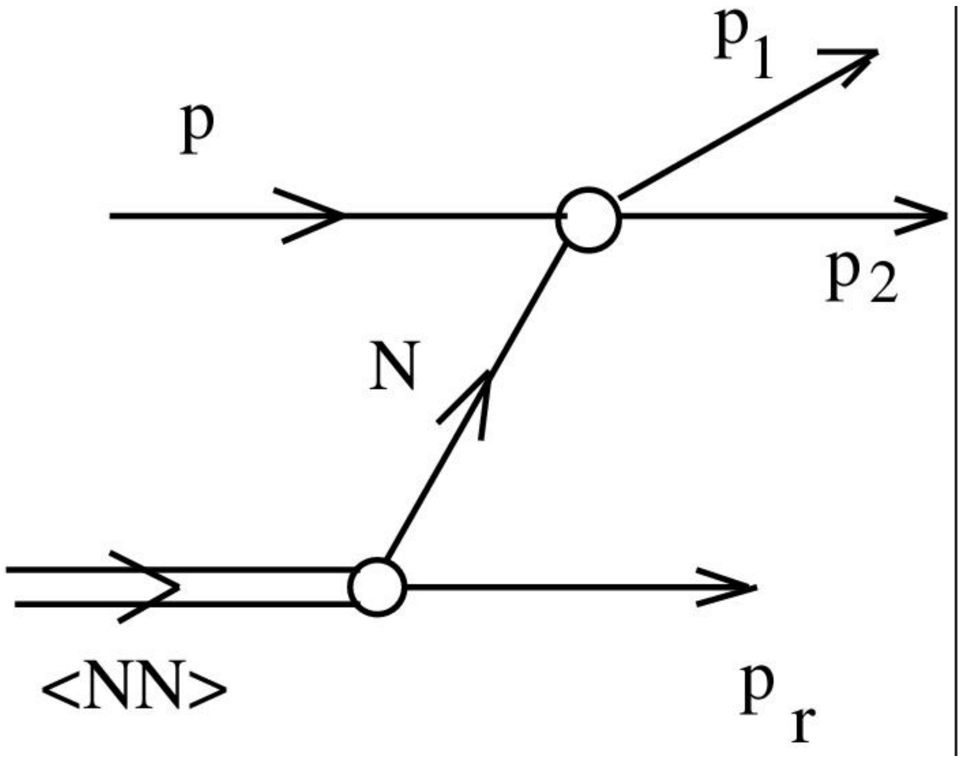


Suppression of the high E*

$^{12}C(p,pd)^{10}B$(exited states)

REACTION $^{12}C+p \rightarrow {}^{10}B+ P+P +N$





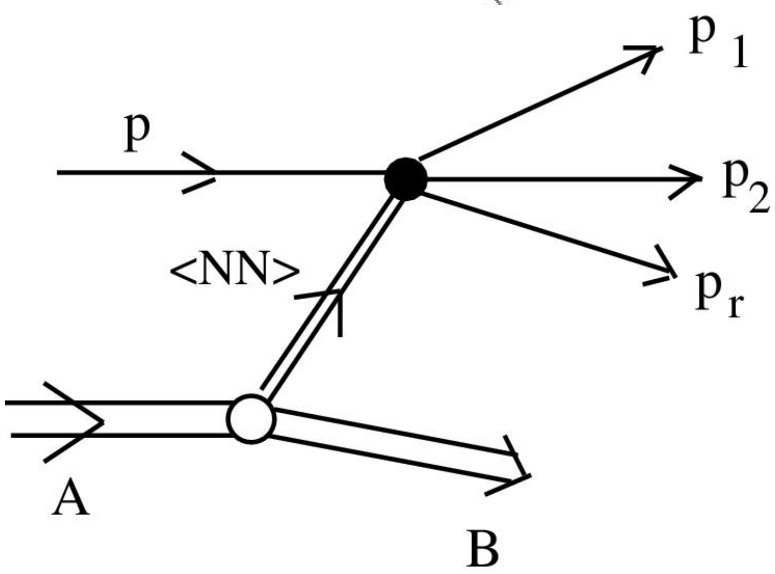
Matrix element

$$M_{fi} = M(A \to B + <NN>)\frac{1}{p_{NN}^2 - M_{NN}^2 + i\varepsilon}M(p<NN> \to ppN),$$

$$d\sigma = (2\pi)^4\delta^4(P_i - P_f)\frac{1}{4I}|M_{fi}|^2\Pi_{j=1}^n\frac{d^3p_j}{2E_j(2\pi)^3}$$

In the rest frame of A:

$$M(^{12}C \to {}^{10}B + <NN>) = -\left(\begin{array}{c}A\\2\end{array}\right)^{1/2} <\Psi_A|\Psi_B, \Psi_{NN}, \Psi_{\nu\Lambda}>$$



$$\times(\varepsilon_A^{B+<NN>} + \frac{q^2}{2\mu})\Psi_{\nu\Lambda M_\Lambda}(\mathbf{q})\sqrt{2m_A 2m_B 2m_{<NN>}},$$

$$\varepsilon_A^{B+<NN>} = m_B + m_{<NN>} - m_A,$$

$$\mu = m_B m_{<NN>}/(m_B + m_{<NN>}),$$

$$\mathbf{q} = \frac{m_B\mathbf{p}_{<NN>} - m_{<NN>}\mathbf{p}_B}{m_B + m_{<NN>}}$$

Yu.N. Uzikov, Izv. RAN. Ser. Fiz. 84 (2020) 580

Spectroscopic factors within the translationally-invariant shell model (TISM)

$$S^{x}{}_{A} = \binom{A}{x}^{1/2} < \psi_A | \psi_B \psi_{\nu\Lambda}(\mathbf{R}_{A-x} - \mathbf{R}_x)\psi_x >$$

$$\psi_A^{TISM} = |AN[f](\lambda\mu)\alpha LSTJMM_T >$$

$$N_A - N_B = N_x + \nu$$

Mixing shell-model configurations:

$$\psi_{J,T}^{A} = \sum_{[f]LS} \alpha_{[f]LS}^{A,JT} \, |AN[f](\lambda\mu)\alpha LSTJMM_T >$$

$$|AN_A\alpha >= \sum_{\beta\gamma\Lambda M_\Lambda N_B N_x \nu} < AN_A\alpha | A - xN_B\beta, \nu\Lambda M_\Lambda, xN_x\gamma >$$

$$|BN_B\beta > |xN_x\gamma > |\nu\Lambda M_\Lambda > .$$

– Matrix element for $p +^{12} C \rightarrow p + p + N +^{10} B$

$$M_{fi}(pA \rightarrow ppNB) = \left(\begin{array}{c} A \\ 2 \end{array} \right)^{1/2} \sum_{M_{J_d}, \bar{J}, \bar{M}, M_\Lambda} \sum_{\alpha_i, \alpha_f, N, \Lambda, \mathcal{L}} \alpha_i^{AJ_iT_i} \alpha_f^{A-2J_fT_f}$$

$$< A\alpha_i | A-2\,\alpha_f, N\Lambda; d' > (\Lambda M_\Lambda J_{d'} M_{J_{d'}} | \bar{J}\bar{M})(J_f M_{J_f} \bar{J}\bar{M} | J_i M_i)$$

$$(T_f M_{T_f} T_{d'} M_{T_{d'}} | T_i M_{T_i}) U(\Lambda L_{d'} \bar{J} S_{d'}; \mathcal{L} J_{d'}) \left\{ \begin{array}{ccc} L_f & S_f & J_f \\ \mathcal{L} & S_{d'} & \bar{J} \\ L_i & S_i & J_i \end{array} \right\}$$

$$[(2L_i+1)(2S_i+1)(2J_f+1)(2\bar{J}+1)]^{1/2} \Psi^{dist}_{N\Lambda M_\Lambda}(\mathbf{k}_B)$$

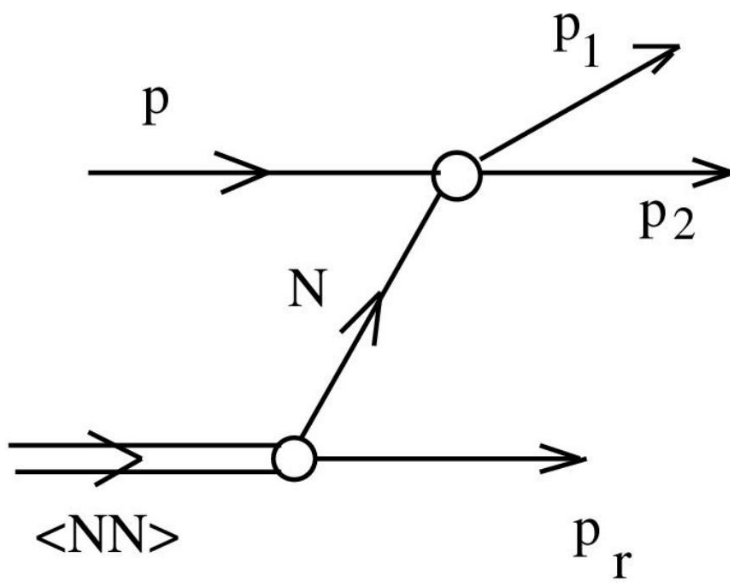
$$\times < \mathbf{p}_1\sigma_1, \mathbf{p}_2\sigma_2, \mathbf{p}_r\sigma_r | \hat{M}(p < NN > \rightarrow p_1 p_2 p_r) | \mathbf{p}\sigma_p, -\mathbf{k}_B \Psi_{NN} >$$

^{12}C: $L_i = S_i = J_i = 0, T_i = 0;\ |10B >= |s^4 p^6 >$

Matrix element of the $p+ < NN > \to p + p + N$

In the Light front dynamics

$$M_{fi}^{LFD}(p < NN > \to p_1 p_2) = \frac{\Psi_d^{LFD}(\mathbf{k}_\perp, \xi)}{1-\xi} M_{fi}(pN \to p_1 p_2),$$



$$\xi = \frac{p_r^+}{p_r^+ + p_N^+}, \quad \mathbf{q}_\perp = (1-\xi)\mathbf{p}_{r\perp} - \xi \mathbf{p}_{N\perp},$$

$$M_{pN}^2 = \frac{m_p^2 + \mathbf{p}_{N\perp}^2}{\xi(1-\xi)}.$$

$$\Psi_d^{LFD}(\mathbf{q}) = \sqrt{\varepsilon(\mathbf{q})}\varphi_d^{nonrel}(\mathbf{q})$$

Factorization of spin averaged $\overline{|M_{fi}|^2}$ for $S=0$ of the $< NN >$ pair and $\Lambda = 0$ in the $< NN > -B$ relative motion.
$M_{fi}(pN \to p_1 p_2)$ is connected to on-shell pN-pN scattering, via cross section $\frac{d\sigma}{dt}(s,t)$.

– Momentum distribution in $< NN > -^{10}B_5$

TISM

$N\Lambda = 20, 22$ for $|s^4p^6>$

$$R^2_{20} = \frac{6}{\sqrt{\pi}\ p_0^3}\left[1 - \frac{2}{3}\left(\frac{p}{p_0}\right)^2\right]^2 exp\left\{-\left(\frac{p}{p_0}\right)^2\right\}, \quad (1)$$

$$R^2_{22} = \frac{16}{15\sqrt{\pi}\,p_0^3}\left(\frac{p}{p_0}\right)^4 exp\left\{-\left(\frac{p}{p_0}\right)^2\right\} \quad (2)$$

$N\Lambda = 00$ for $|s^2p^8>$

$$R^2_{00} = \frac{4}{\sqrt{\pi}\,p_0^3} exp\left\{-\left(\frac{p}{p_0}\right)^2\right\}$$

where $p_0 = \sqrt{\mu}/r_0 = \sqrt{\mu}p_0^{h.o.}$;
$\mu = \frac{m_1 m_2}{m_1+m_2} = \frac{5}{3}$ – the reduced mass of the $d -^{10} B$ system in m_N;
r_0 is the h.o. shell model parameter;
$p_0^{h.o.} = \hbar/r_0$

Center mass motion of SRC NN pairs in nuclei

E.O. Cohen et al. Phys.Rev.Lett. **121** (2018) 092501

Hard breakup of a pp-SRC pair in a hard two-nucleons knockout $A(e,e'pp)$ reactions at recoil proton momentum $p_{rec} \geq 350$ MeV/c assuming factorization

$$d\sigma(e,e'pp) \sim n_{SRC}(\vec{p}_1,\vec{p}_2) \approx n^{A}_{c.m.}(\vec{p}_{c.m.})n^{NN}_{rel}(\vec{p}_{rel})$$

$n^{A}_{c.m.}(\vec{p}_{c.m.})$ is approximated by the 3-D Gaussian $g(x)g(y)g(z)$,
$g(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{x^2}{2\sigma^2}\right]$
$\underline{^{12}C}$:
$\sigma_x \approx \sigma_y \approx \sigma_z = (145 \pm 5)MeV/c$
i.e. $p_0 = \sqrt{2}(145 \pm 5)$MeV/c=$(205 \pm 7)$MeV/c

The c.m. distribution in mean-field model (Cioffi degli Atti, Simula, 1996)

$$< k_{c.m.}^2 >= \frac{2(A-2)}{A-1} < k^2 >$$

$$n_{c.m.}(k_{c.m.}) = C \exp(-\alpha_{c.m.} k_{c.m.}^2) \qquad < k_{c.m.}^2 >= 3/2\alpha_{c.m.}$$

$$\alpha_{c.m.} = \frac{3(A-1)}{4(A-2)} \frac{1}{2M < T >}$$

$$T_s = \frac{3}{2} \frac{p_0^2}{2M} \text{ and } T_p = \frac{5}{2} \frac{p_0^2}{2M}$$

$$< T >= \frac{4T_s + 8T_p}{12} = \frac{13}{6} \frac{p_0^2}{2M}$$

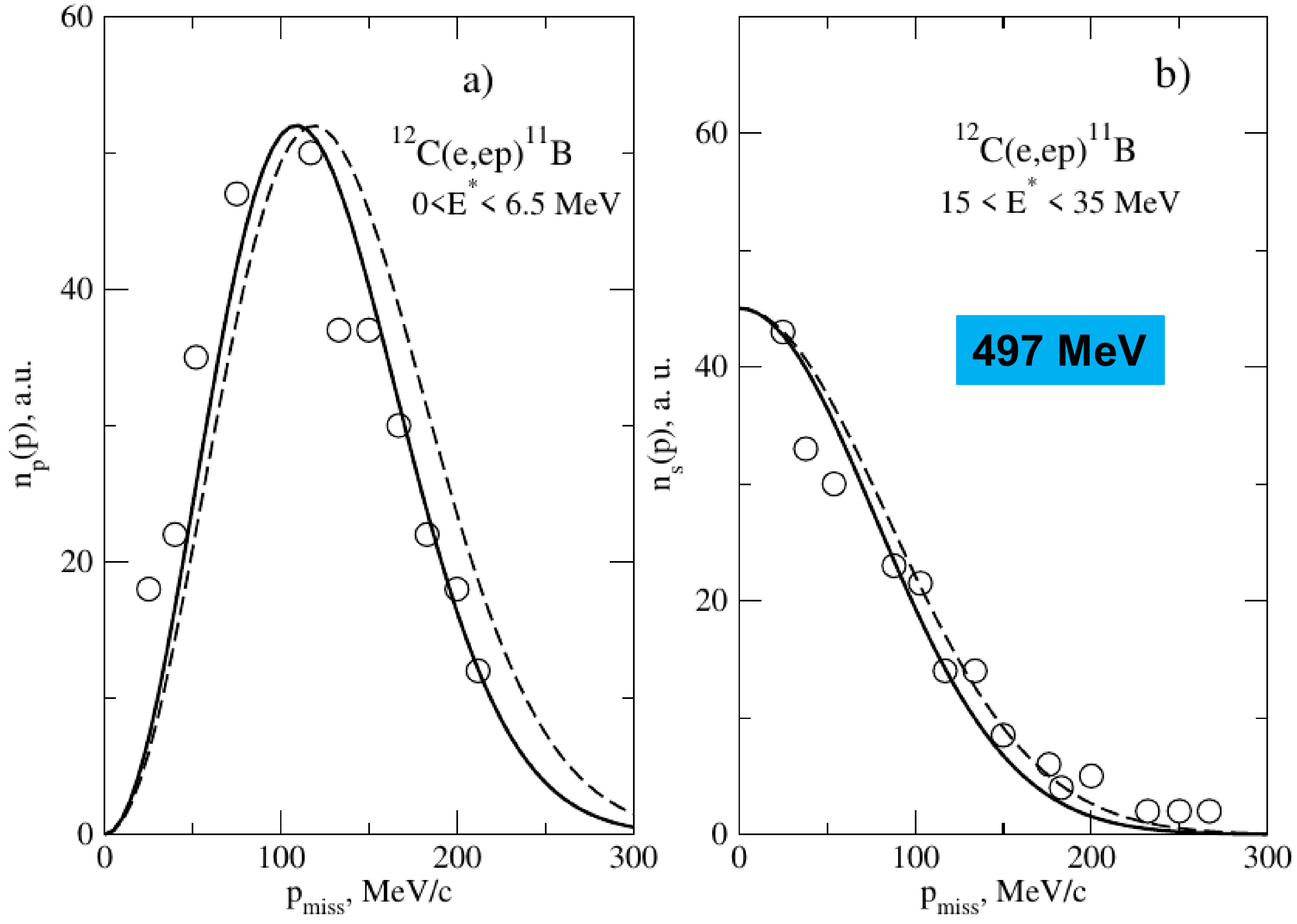
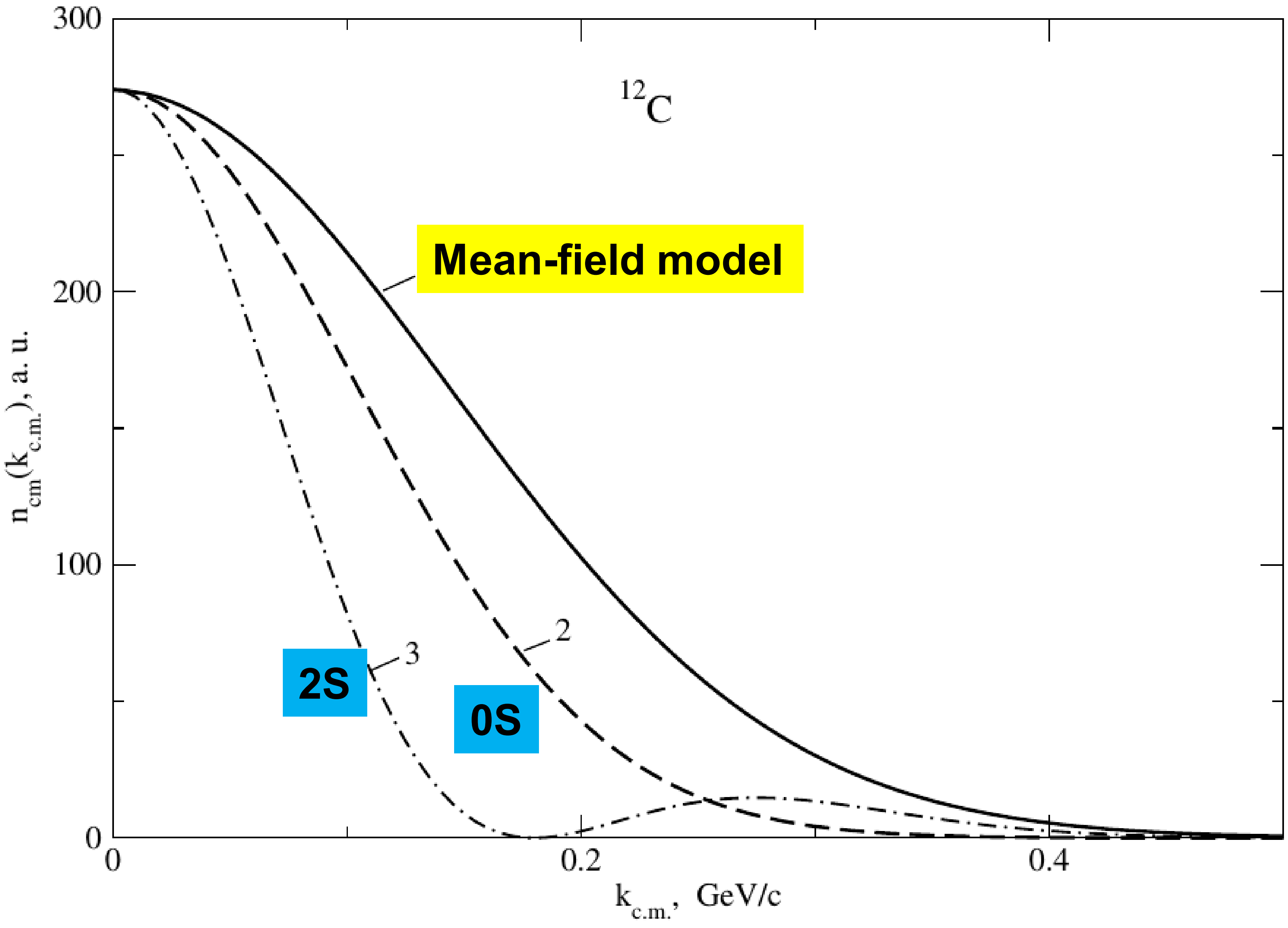


Fig. 2. Single nucleon momentum distribution in the reaction $^{12}C(e, ep)^{11}B$ at electron beam energy 497 MeV for the p-shell (a) and s- shell nucleons (b) corresponding to transitions to the states of the residual nucleus ^{11}B with excitation energy $0 < E^* < 6.5$ MeV and $15 < E^* < 35$ MeV, respectively. The curves show the results of our calculations in the plane wave impulse



TISM

$$\nu = N_A - N_x - N_{A-x}$$

$$N_x = 0, N_A = 8$$

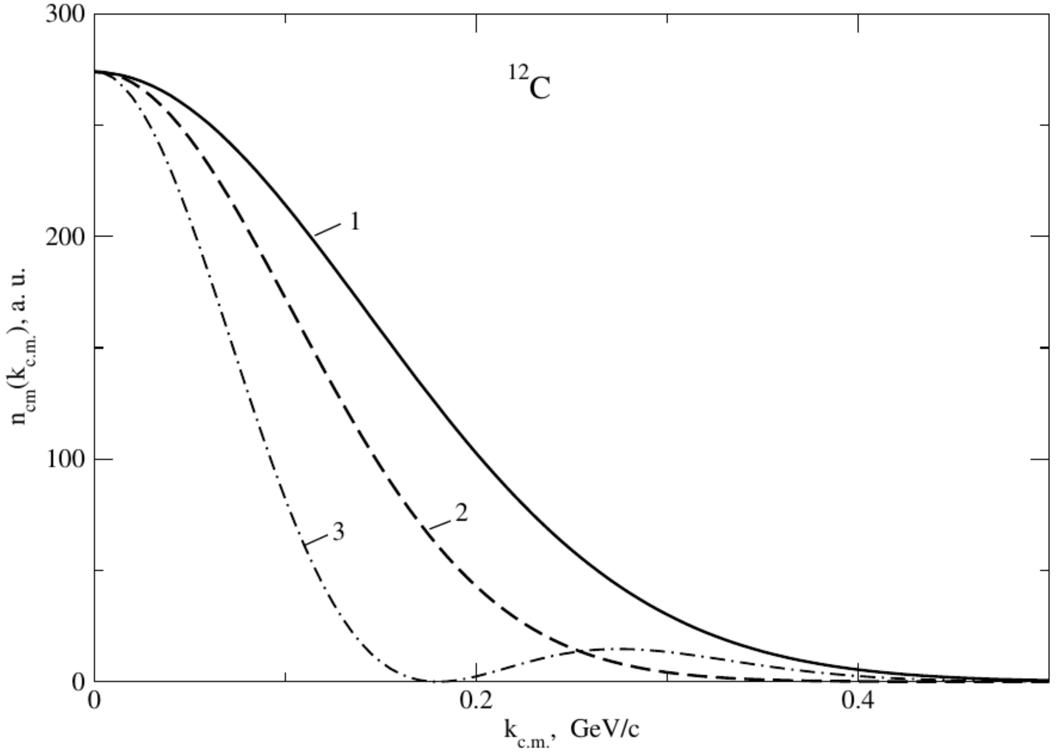
$$R_{\nu\Lambda}(k_{c.m.})$$

$$s^4 p^6, \nu = 2$$

$$s^2 p^8, \nu = 0$$

Fig. 3. Distribution over the c.m. momentum of the SCR pair $p_{c.m.}$ in the ^{12}C for the mean-field model with $\alpha_{c.m.} = 0.95\, fm^2$ (full line) and the TISM wave function squared with $p_0 = 146.9$ MeV/c for the $0S$-type (dashed), and $2S$-type (dashed-dotted). All distributions are arbitrary normalized at $p_{c.m.} = 0$ to the same value.

E. Cohen et. al. PRL 121 (2018) 092501



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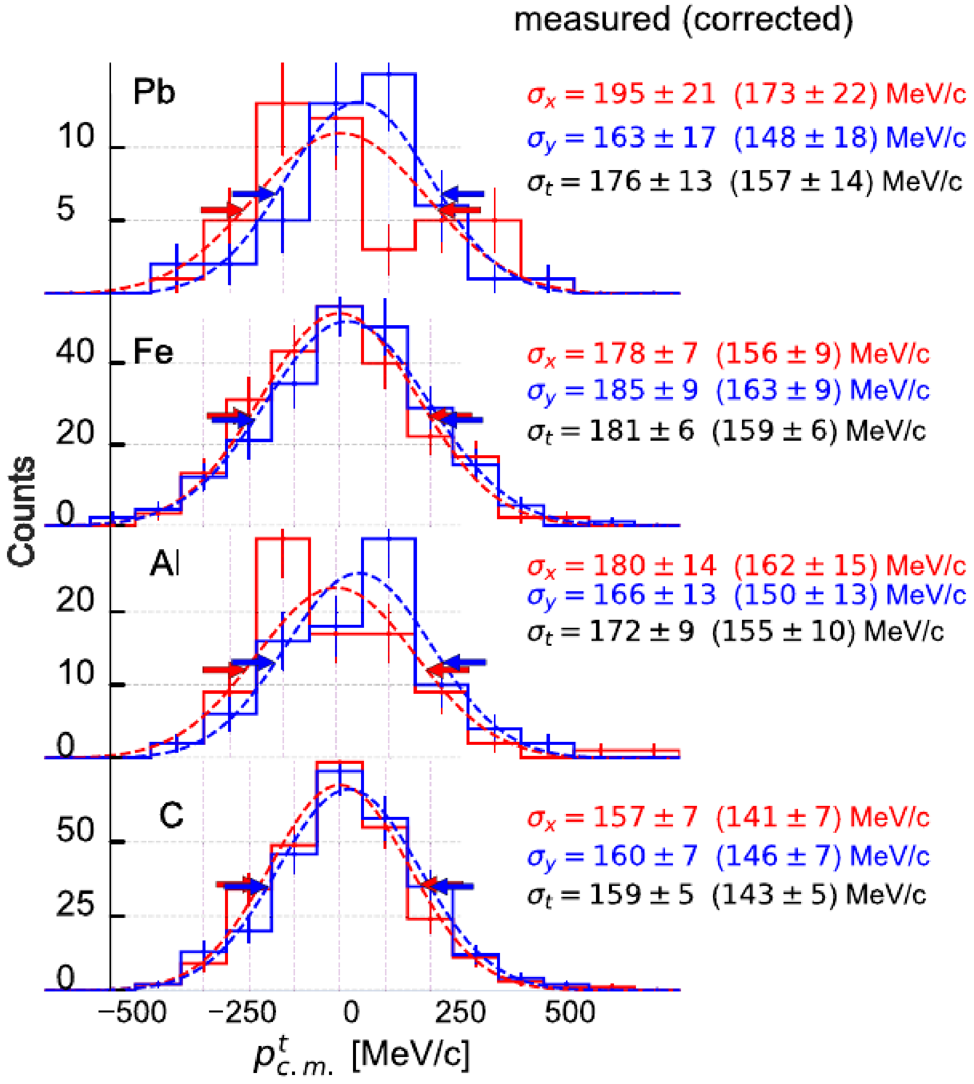
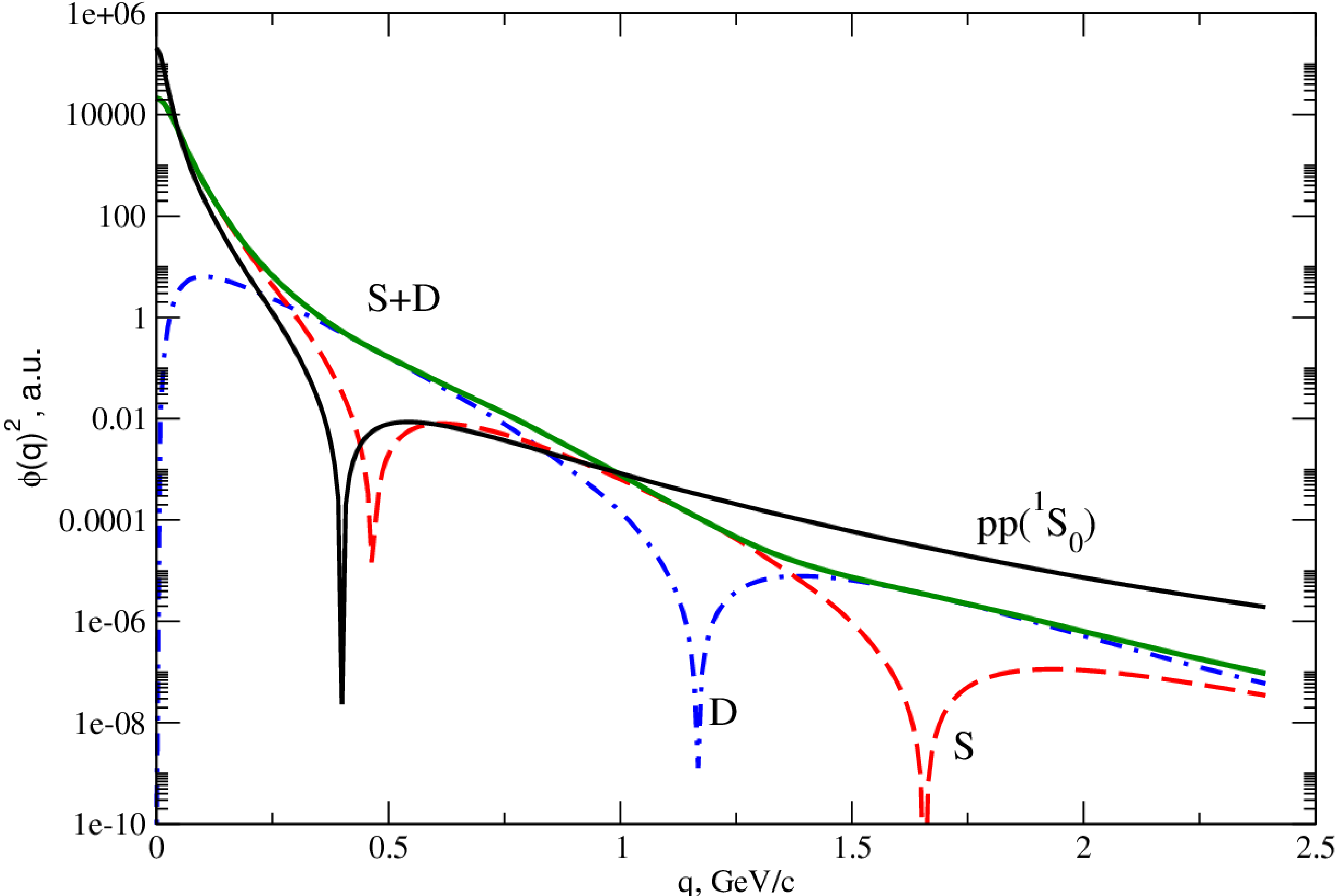


pp and deuteron internal momentum distribution



pp(1S0) scattering
Lensky V. et al.,
EPJ A26 (2005)107

CD – Bonn NN

pp/pn ratio

$$S_A^x = \binom{A}{2}^{1/2} \frac{\sqrt{2J_f+1}}{\sqrt{2T+1}} PC(S,T),$$

$$\overline{|M_{fi}(A(p,2pN)B)|^2} \propto \frac{(2S+1)^2}{2T+1} n_{cm}(k_{c.m.}) n_{pN}(q_{rel}) |M^{pN}|^2 [I_{pN}\, PC(S,T)]^2,$$

$$R = \frac{pp}{pn} = \frac{pp}{(pn)_{S=0T=1} + (pn)_{S=1T=0}} = \frac{1}{14} R_{rel}$$

Table 1. The $(ST=01)/(ST=10)$ ratio R_{rel} versus q_{min} at $q_{max} = 1.0 \div 2.0$ GeV/c

q_{min}, GeV/c	R_{rel}	q_{min}, GeV/c	R_{rel}
0.2	0.15	0.6	0.27-0.3
0.3	0.06-0.07	0.7	0.39-0.54
0.4	0.09 -0.10	0.8	0.55-0.88
0.5	0.17-0.2	0.9	0.78-1.5

pp/pn ratio

$$R_{rel} = \int_{q_{\min}}^{q_{\max}} dq q^2 \psi^2{}_{pp;ST=01}(q) / \int_{q_{\min}}^{q_{\max}} dq q^2 \psi^2{}_{d;ST=01}(q);$$

$$\psi_{10}^2(q) = u^2(q) + w^2(q); \psi_{01}(q), pp({}^1S_0) - scattering;$$

$$\int_0^{\infty} dq q^2 \psi_{ST}^2(q) = 1;$$

$$R = \frac{pp}{pn} = \frac{pp}{(pn)_{S=0T=1} + (pn)_{S=1T=0}} = \frac{1}{14} R_{rel}$$

If R=0.01, then $R_{obs} \simeq 0.03$ due to charge-exchange in FSI (M.Duer et al. PRL 122 (2019))

.

$R_{\exp} \simeq 5\%$

PARENTAGE COEFFICIENTS of TISM

$$< AN_i = 8[f_i](\lambda_i\mu_i)\alpha_i L_i S_i T_i | A{-}2N_f[f_f](\lambda_f\mu_f)\alpha_f L_f S_f T_f, \nu\Lambda; N_x L_x S_x T_x : L_i S_i T_i >$$

N_f	6							
$[f_f]$	[442]							
$(\lambda_f\mu_f)$	(22)							
$\nu\Lambda$	00				22			
$N_x L_x$	22				00			
$^{2T_f+1\,2S_f+1}L_f$	$^{13}D_I$	$^{31}D_I$	$^{13}D_{II}$	$^{31}D_{II}$	$^{13}D_I$	$^{31}D_I$	$^{13}D_{II}$	$^{31}D_{II}$
PC	$\sqrt{\frac{1}{264}}$	$\sqrt{\frac{1}{264}}$	$-\sqrt{\frac{35}{792}}$	$\sqrt{\frac{35}{792}}$	$-\sqrt{\frac{3}{550}}$	$\sqrt{\frac{3}{550}}$	$-\sqrt{\frac{7}{110}}$	$\sqrt{\frac{7}{110}}$

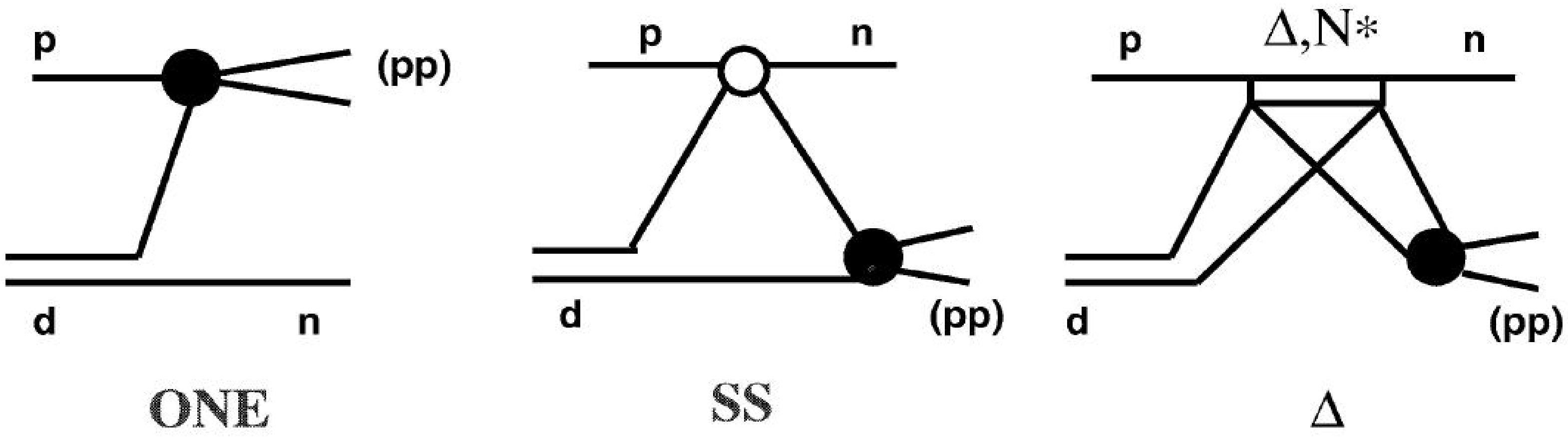
6						7				8	
[442]				[433]		[442]		[433]		[442]	
(22)				(03)		(13)		(13)		(04)	
00		20		11		11		00		00	
20		00		11		00		11		00	
^{31}S	^{13}S	^{31}S	^{13}S	$^{13}D_I$	$^{31}D_I$	$^{13}D_{II}$	$^{31}D_{II}$	$^{13}D_I$	$^{31}D_I$	$^{13}D_{II}$	$^{31}D_{II}$
$-\sqrt{\frac{2}{99}}$	$\sqrt{\frac{2}{99}}$	$-\sqrt{\frac{8}{275}}$	$\sqrt{\frac{8}{275}}$	$\sqrt{\frac{1}{55}}$	$\sqrt{\frac{9}{55}}$	$-\sqrt{\frac{21}{275}}$	$\sqrt{\frac{21}{275}}$	$\sqrt{\frac{3}{110}}$	$\sqrt{\frac{27}{110}}$	$\sqrt{\frac{3}{110}}$	$-\sqrt{\frac{3}{110}}$

CONCLUSION

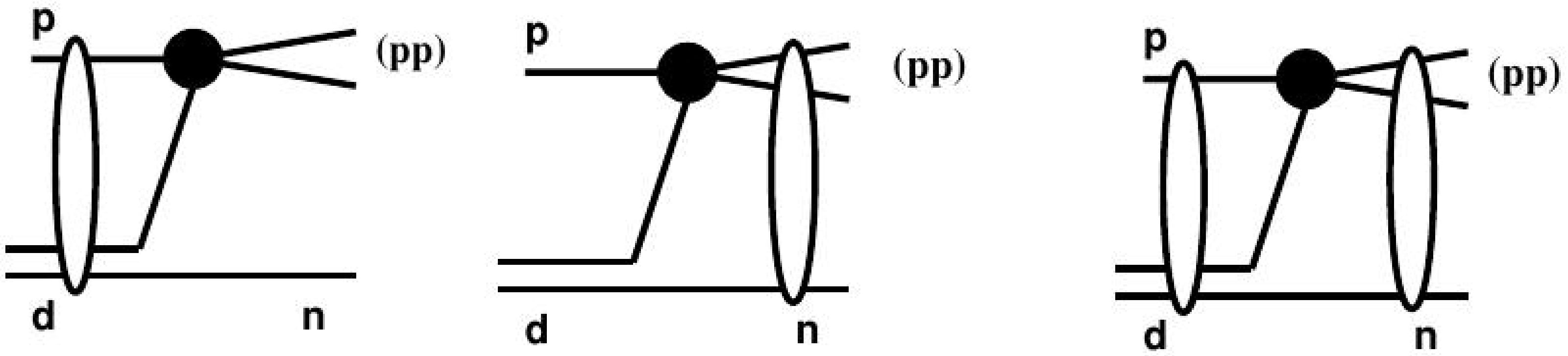
- Translationally-invariant shell model (TISM) applied for S_A^x and $n_{cm}(k_{cm})$ of the deuterons in the ^{12}C works reasonable well for the $^{12}C(p,pd)^{10}B$ reaction at 670 MeV with transition to the g.s. of ^{10}B (s^4p^6) and its excited states $E_B^* > 20$ MeV (s^2p^8).
- TISM can be applied to BM@N data on quasi-elastic knok-out of nucleon from SRC NN pairs from the ^{12}C in exclusive reaction $^{12}C + p \to p + p + N +^{10} B$
- The corresponding formalism is developed in the plane-wave approximation taking into account relativistic effects in the $p+ < NN > \to p + N + N$ within the LFD approach.
- pp/pn ratio obtained within TISM is in agreement with the data.
- Observed in $^{12}C(e,epp)^{10}B$ S-wave $k_{c.m.}$ momentum distribution is a puzzle for TISM. Corresponding measurements of $^{12}C(p,pd)^{10}B$ at BM@N conditions for $s^4p^6$and s^2p^8 will be very important.

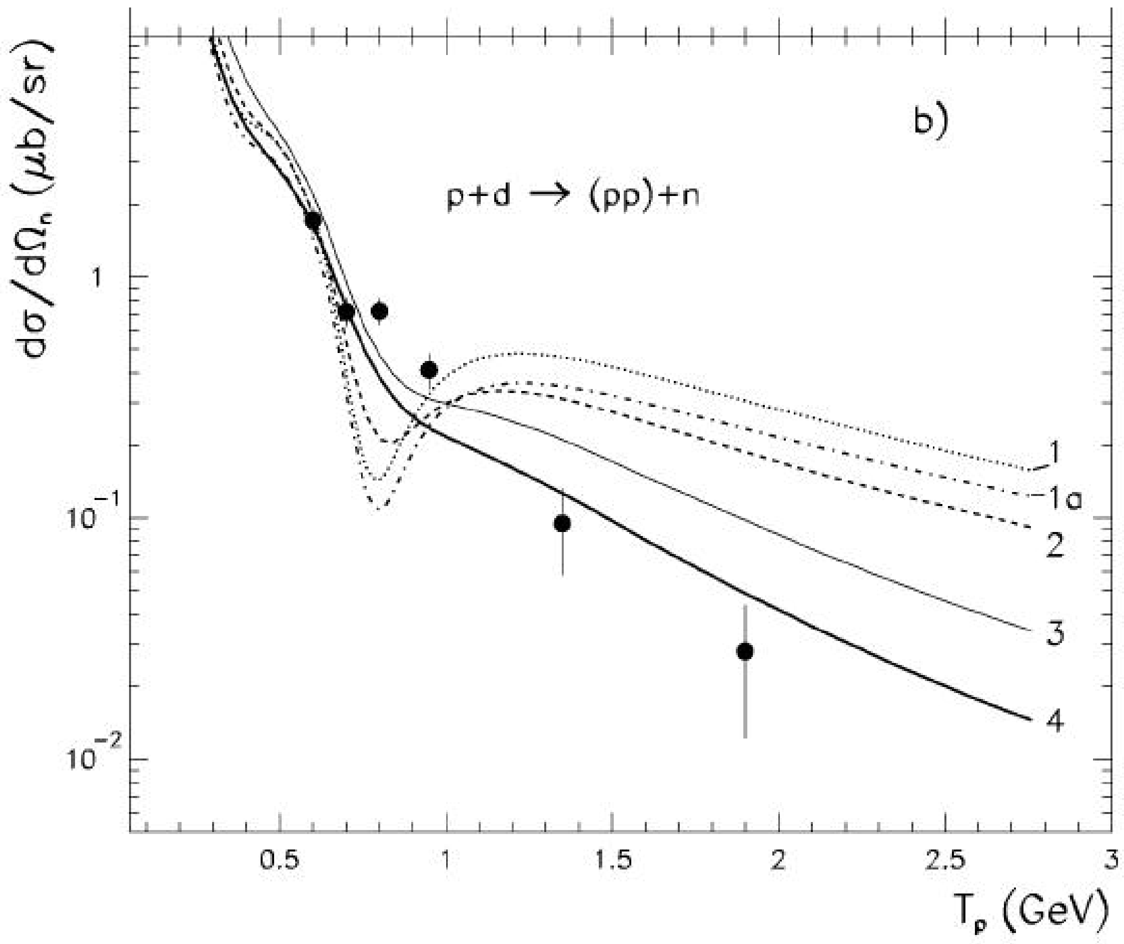
Thank you for attention!

BACKWARD QUASI-ELASTIC $pd \to (pp)_s\, n$ SCATTERING

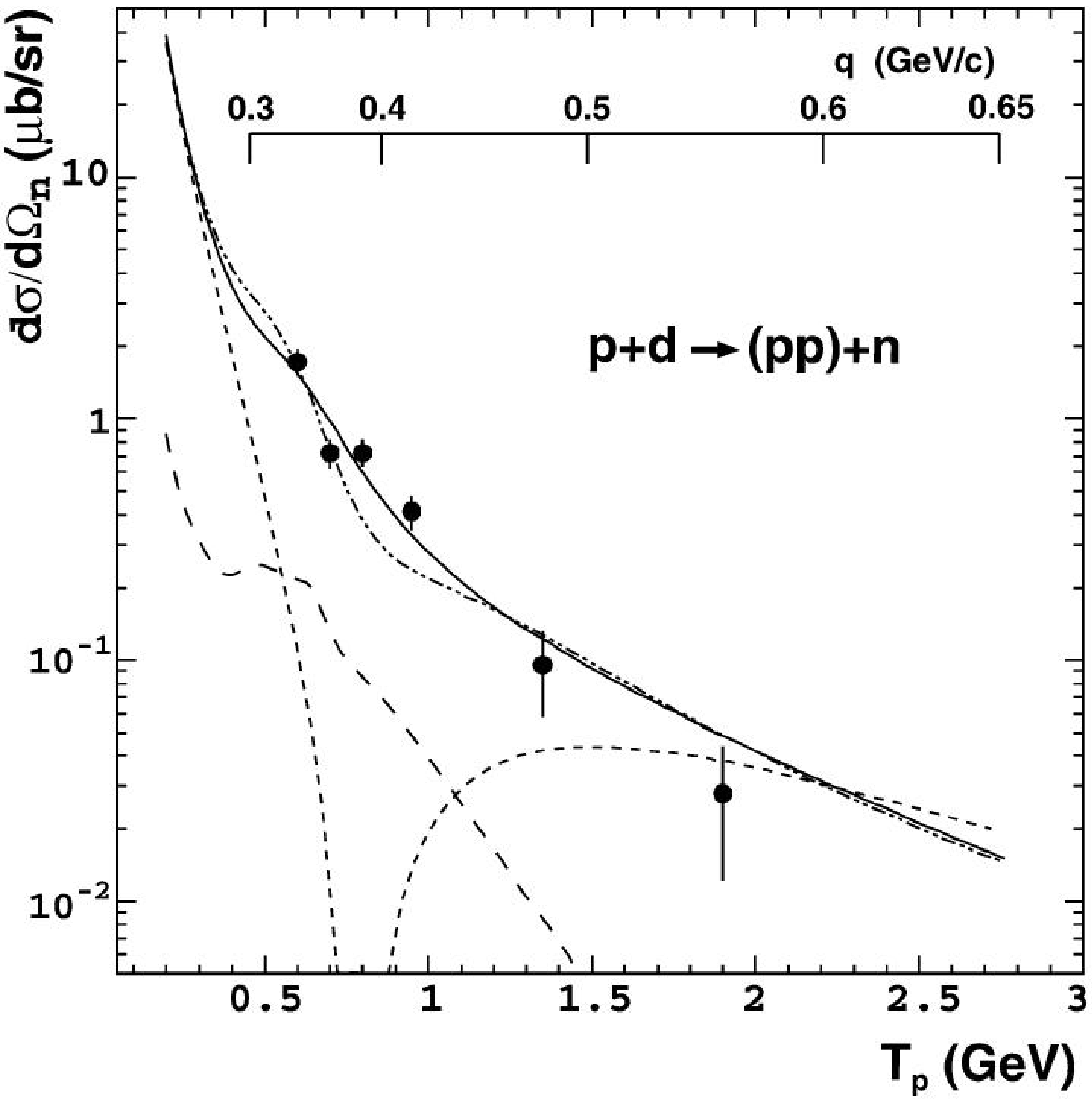


Mechanisms of the breakup reaction $pd \to (pp)n$. The same mechanisms are used for the reaction $pd \to dp$.





dσ/dΩ_n (μb/sr)
b)
p+d → (pp)+n
1
1a
2
3
4
1
10^-1
10^-2
0.5
1
1.5
2
2.5
3
T_p (GeV)



dσ/dΩ_n (μb/sr)
q (GeV/c)
0.3
0.4
0.5
0.6
0.65
p+d → (pp)+n
10
1
10^-1
10^-2
0.5
1
1.5
2
2.5
3
T_p (GeV)

Transition matrix element

$$T_{fi} = \binom{A}{x}^{1/2} \sum_{x' \ \nu\Lambda} < \psi_A | \psi_B \psi_{x'}, \psi_{\nu\Lambda} > \Phi_{\nu\Lambda}(\mathbf{k}_B) T^{px' \to Nx}.$$

$$T^{px' \to Nx} =< \mathbf{k}_N \mathbf{k}_x \chi_N \psi_x | \tau(px' \to Nx) | \mathbf{k}_p, -\mathbf{k}_B \chi_p \psi_{x'} >$$

$$N_A - N_B = N_x + \nu$$

How to take into account ISI and FSI?

$$S_A^x = \binom{A}{x}^{1/2} \sum_{\mathcal{L}\,\overline{J}\,\overline{M}} (J_B M_B \overline{J}\ \overline{M} | J_A M_A)(\Lambda M_\Lambda J_x M_x | \overline{J}\ \overline{M})$$

$$(T_B M_{T_B} T_x M_{T_x} | T_A M_{T_A}) U(\Lambda L_x J S_x; \mathcal{L} J_x)$$

$$[(2L_A + 1)(2S_A + 1(2J_B + 1)(2\overline{J} + 1)]^{1/2} \left\{ \begin{array}{ccc} L_B & S_B & I_B \\ L & S_x & \overline{J} \\ L_A & S_A & I_A \end{array} \right\}$$

$$< AN_A[f_A](\lambda_A \mu_A)\alpha_A L_A S_A T_A|$$

$$|A - xN_B[f_B](\lambda_B \mu_B)\alpha_B L_B S_B T_B; \nu\Lambda, xN_x[f_x](\lambda_x \mu_x)\alpha_x L_x S_x T_x(\mathcal{L}) : L_A S_A T_A >$$

Theoretical model: C.Ciofi degli Atti, S.Simula, PRC 53 (1996) 1689

$$n_{cm}(p) = (\frac{\alpha}{\pi}) \exp\left[-\alpha p^2\right] \quad (3)$$

$\alpha = 1$ fm^2 or $p_0 = \hbar/\sqrt{\alpha} = 197$ MeV/c

From the deuteron knock-out $^{12}C(p,pd)^{10}B$ from p-shell ($|^{10}B >= |s^4 p^6 >$) (J.Erö et al., 1981) one has

$\mathbf{p_0 = 155 MeV/c}$

(**not for 1S-wave distribution in Eq.(3), but for 2S Eq.(1)!**)

<u>^4He</u>: $\alpha = 2.4$ fm^2 or $p_0 = \hbar/\sqrt{\alpha} = 127.3$ MeV/c,
that is compatible with $p_0 = (144.6 \pm 18.2)$ MeV/c from the deuteron knockout $^{12}C(p,pd)^{10}B$ from the α-core, (J.Erö et al., NPA 372, 1981), $|^{10}B >= s^2 p^8 >$