

QUASI-ELASTIC KNOCK-OUT OF NUCLEON FROM SHORT-RANGE CORRELATED NN PAIR IN THE REACTION $^{12}\text{C}(p,2pN)^{10}\text{A}$

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

- Fluctons, SRC and others...
- $^{12}\text{C}(p,pd)^{10}\text{B}$ and $p\langle\text{NN}\rangle\rightarrow dp$ $pd\rightarrow\{pp\}_s n$
- Elements of formalism for $p+^{12}\text{C}\rightarrow p+p+N+^{10}\text{B}$ (BM@N)
- Numerical results for pp/pn ratio and SRC $c.m.$ momentum distribution
- Conclusion

♥ Dubna, 1957 M.G. Mesheryakov et al. ZHETF,
 $p+^{12}\text{C} \rightarrow d+X$ at 670 MeV; quasi-elastic knock-out of the
fast deuteron clusters

D.I. Blokhintsev (1957) : **fluctons** (6q) in nuclei
(Blokhintsev, Efremov, Lukjanov, Titov, 1978)

Two nucleons at short distances $r_{\text{NN}} < 0.5$ fm
with relative momentum $q > 1/r_{\text{NN}} = 0.4$ GeV/c;
Repulsive core in NN-potential $\rightarrow$ high-momentum part
of the w.f. of NN pair

♥ A.M. Baldin, Cumulative effect (1971).

♥ Search for high-momentum components of the nuclear wave
functions in eA-, pA- collisions.

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

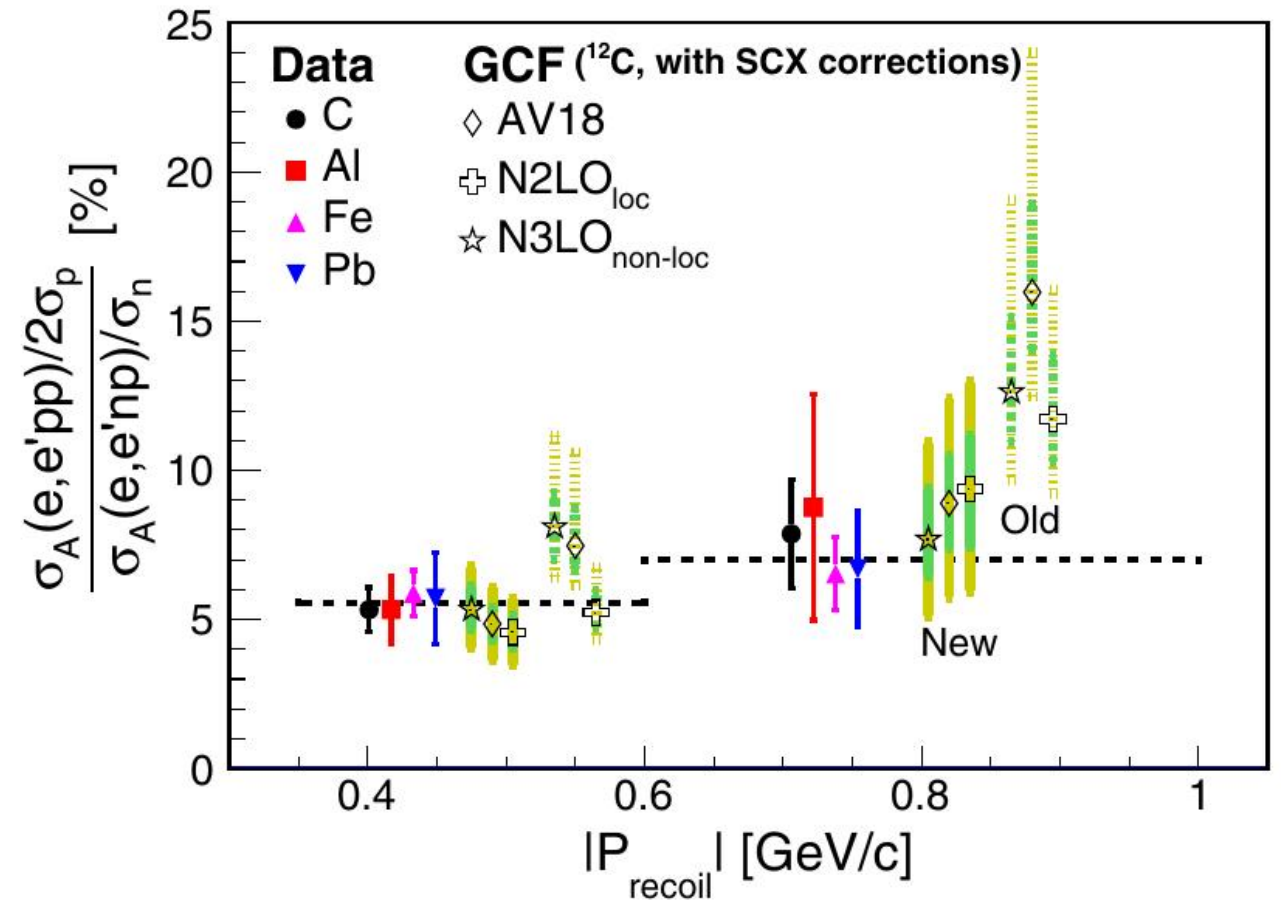
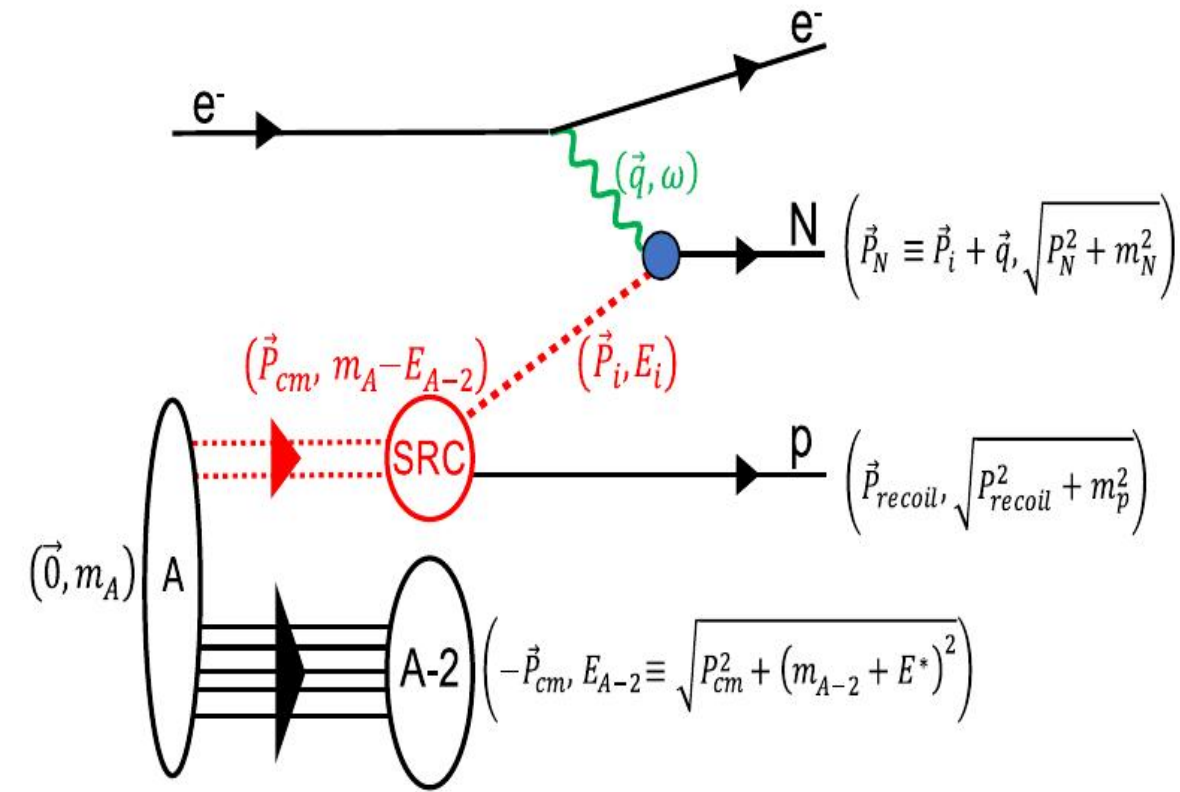
- * High-momentum part ($q > p_F$) accounts for 20% nucleons .
- * pn- SRC pairs dominate by factor of 20 as compared to **pp** and **nn** due to the tensor forces.
- * Factorization $n(p_1, p_2) = C n_{c.m.}(k_{cm}) n_{rel}(q)$
- * SRC are connected with neutrino-nucleus interaction, neutron stars structure, modification of the bound nucleon structure (**EMC effect**).

Cioffi degli Atti, Phys. Rep. 590 (2015) 1

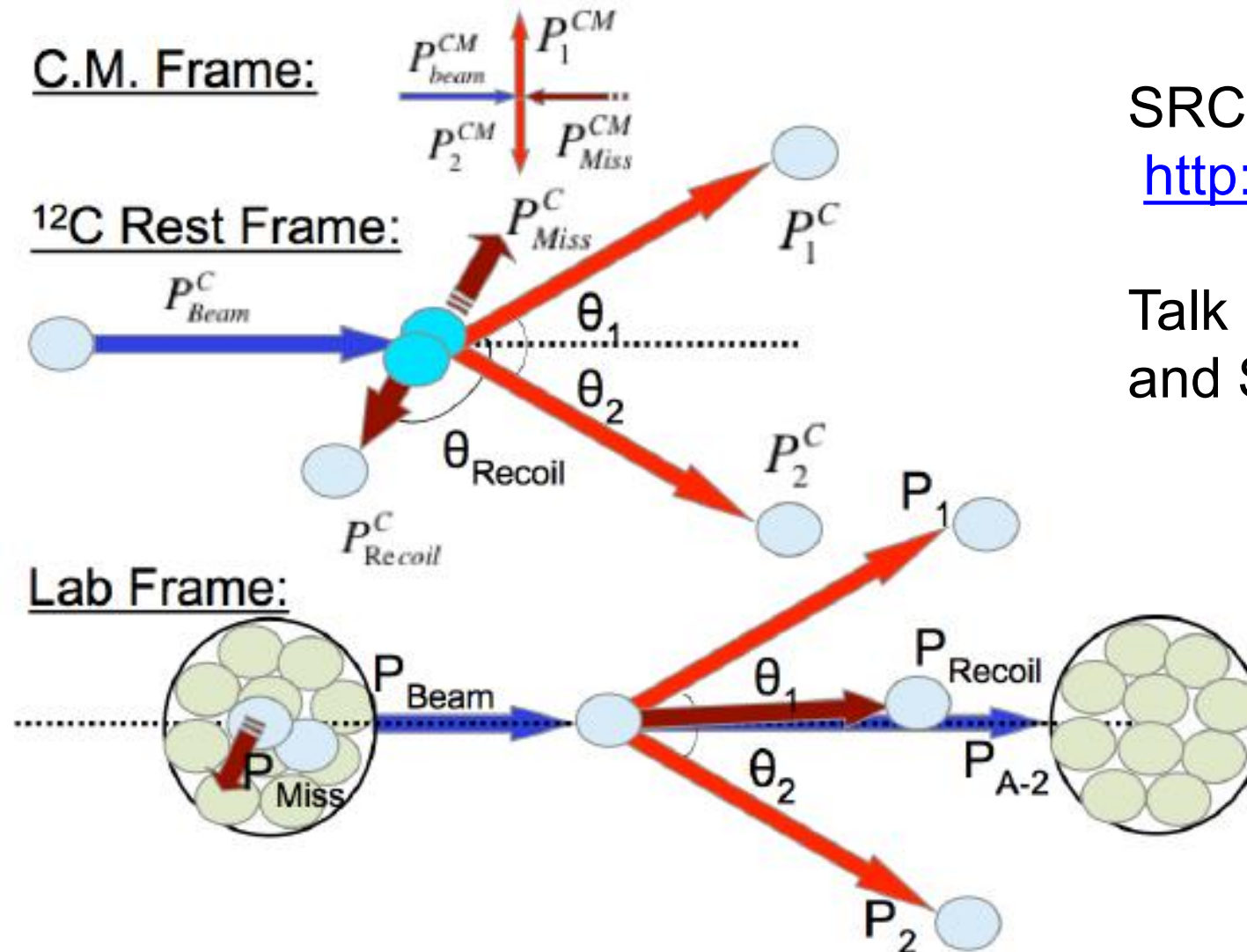
O. Hen et al. Rev. Mod. Phys. 89 (2017) 045002.

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

$E_e = 5 \text{ GeV}$,
 $A(e, e'np)$, $A(e, e'pp)$



Project of [BM@N](#) to study SRC in JINR with 4=GeV/c /nucleon beam of ^{12}C and proton target in Inverse kinematics

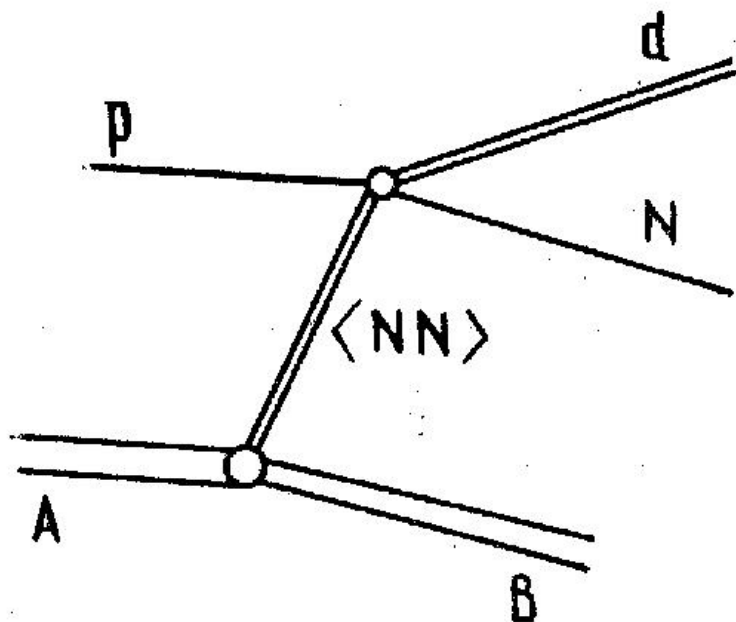


SRC@BMN proposal

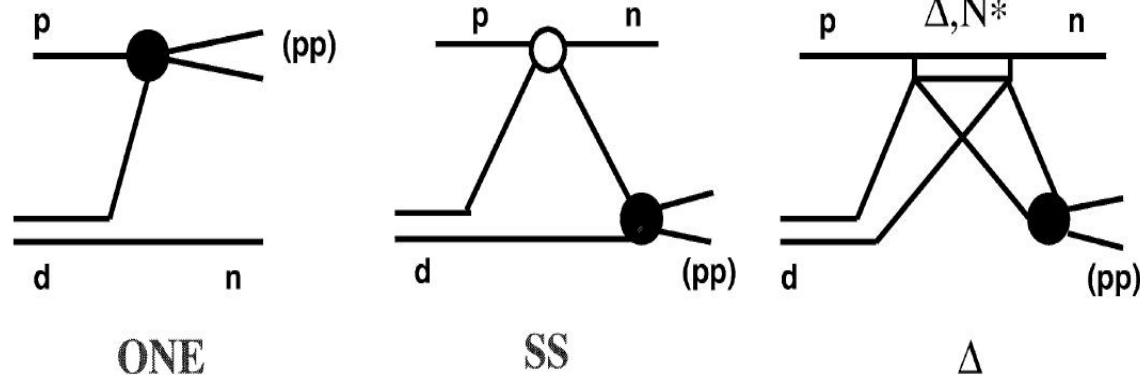
<http://bmnshift.jinr.ru/wiki/doku.pho>

Talk by Mariya Patsyuk yesterday,
and S. Merts and V. Panin today

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



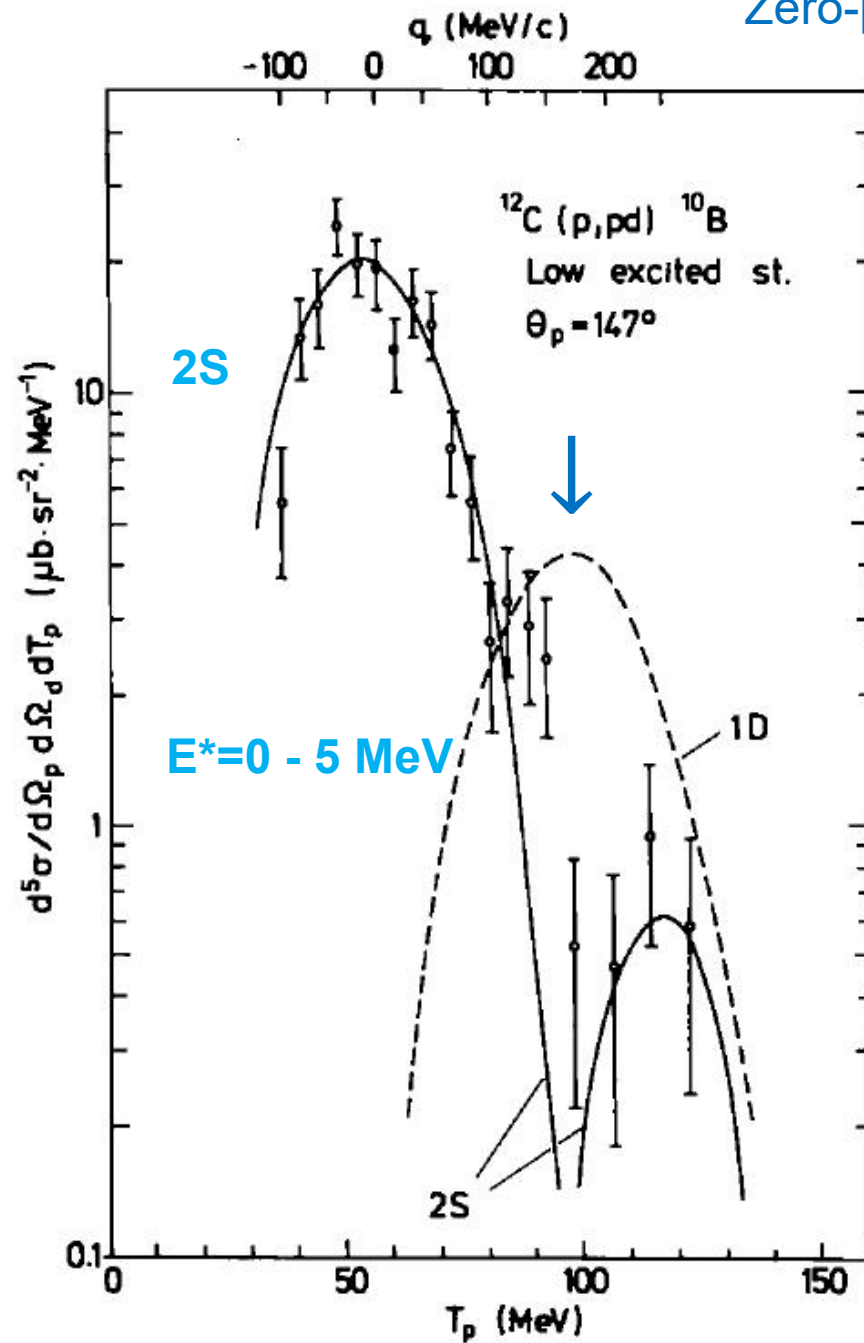
J. Haidenbauer, Yu.N. Uzikov / Physics Letters B 562 (2003) 227–233



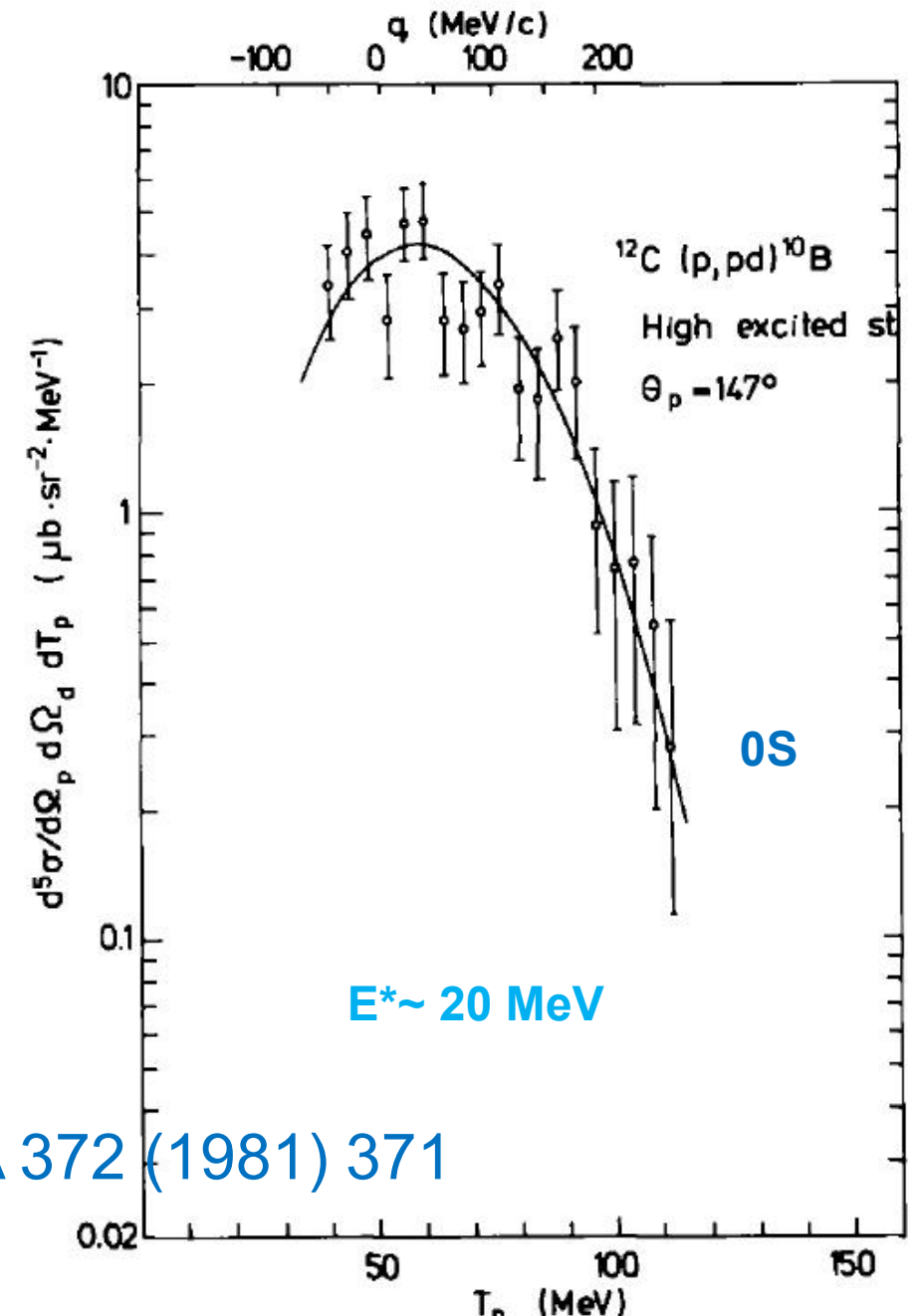
Mechanisms of the breakup reaction $pd \rightarrow (pp)n$. The same mechanisms are used for the reaction $pd \rightarrow dp$.

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

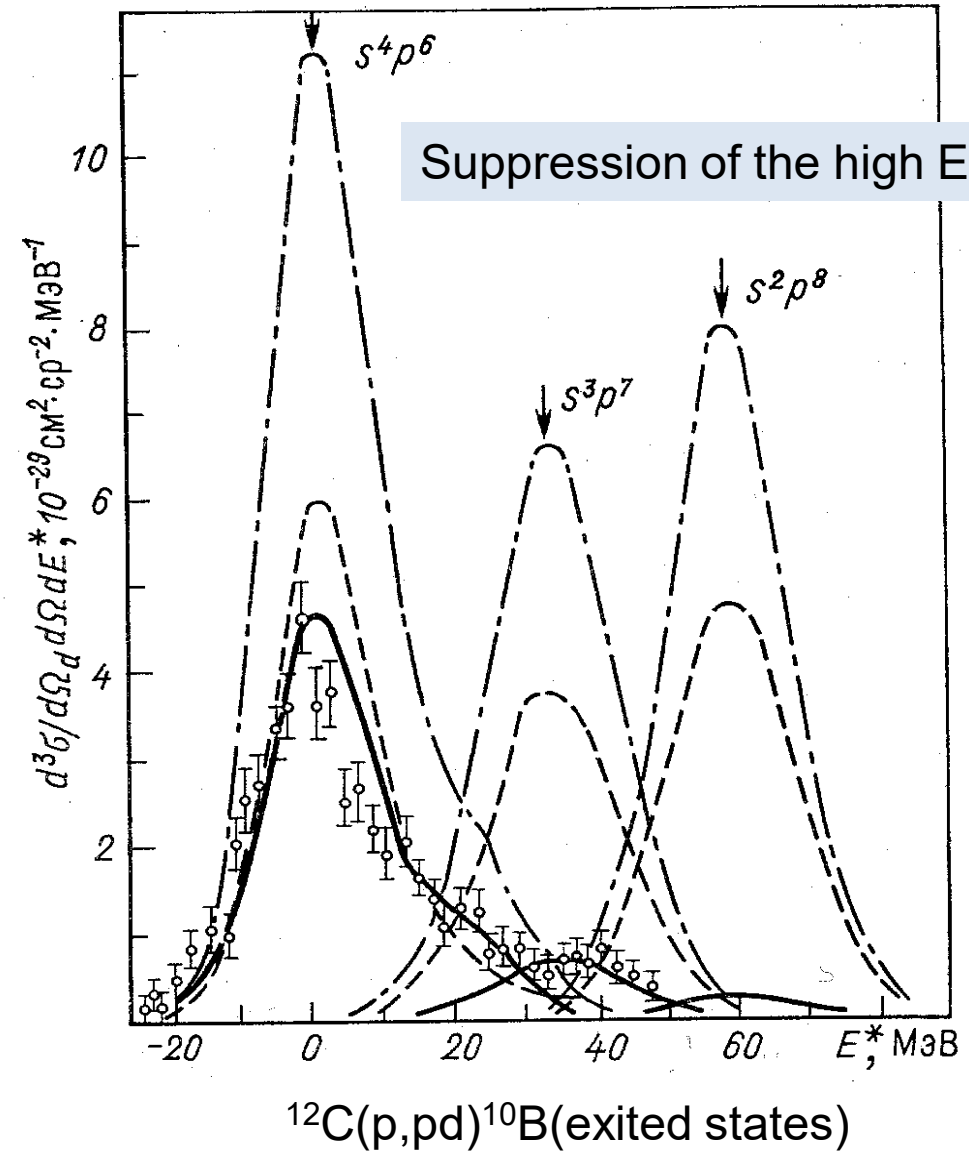
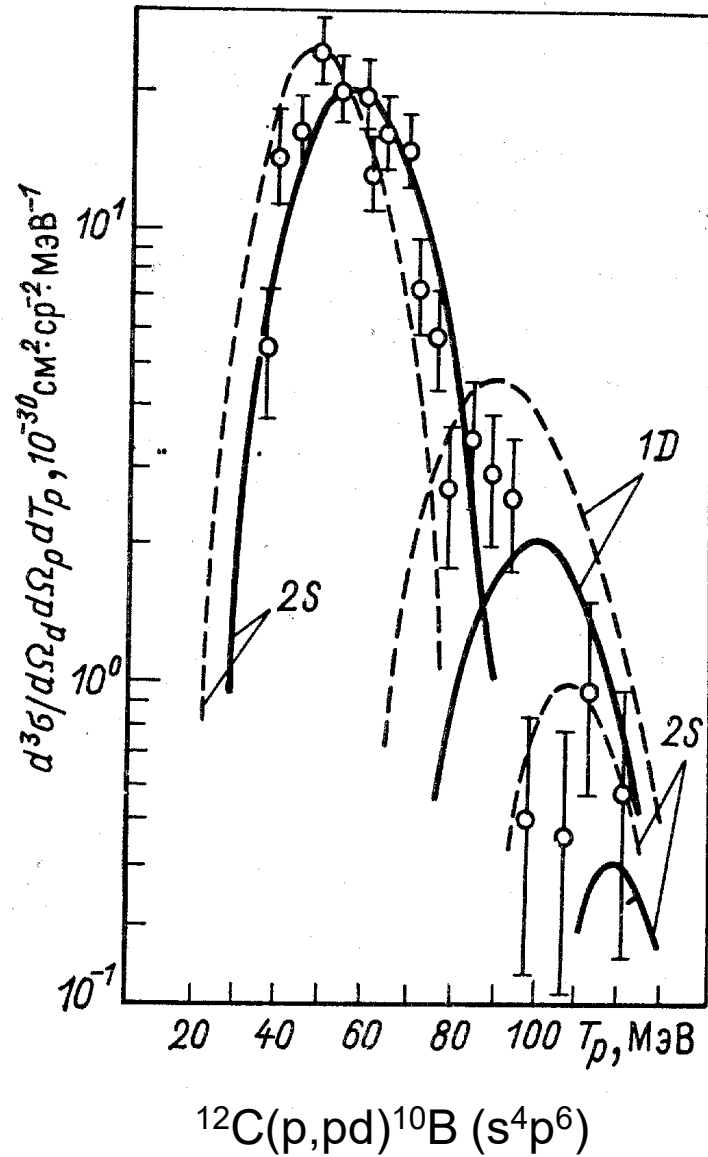
Zero-point at $q \approx 180 \text{ MeV}/c$



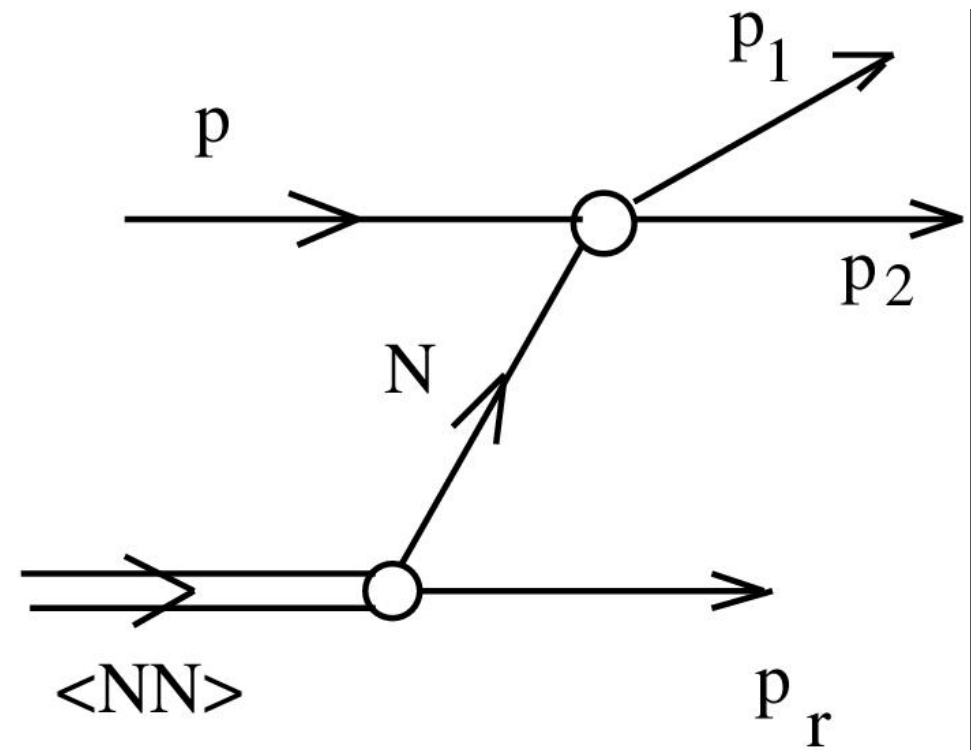
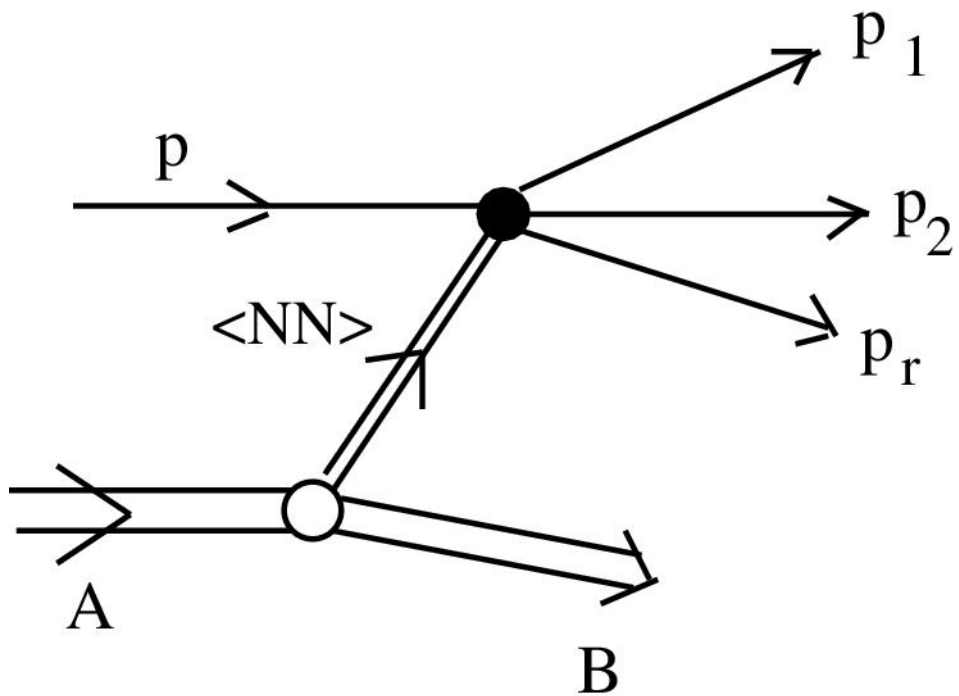
J. Erő et al. / Quasi-free scattering



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



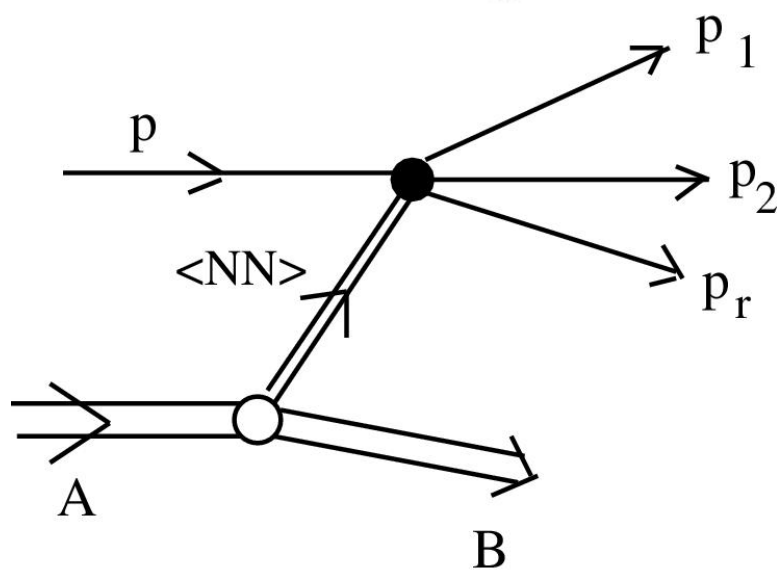
REACTION $^{12}\text{C} + p \rightarrow ^{10}\text{B} + p + p + n$



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

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

In the rest frame of A:



$$M(^{12}C \rightarrow ^{10}B + \langle NN \rangle) = - \left(\frac{A}{2} \right)^{1/2} \langle \Psi_A | \Psi_B, \Psi_{NN}, \Psi_{\nu A} \rangle$$

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

$$\varepsilon_A^{B+\langle NN \rangle} = m_B + m_{\langle NN \rangle} - m_A,$$

$$\mu = m_B m_{\langle NN \rangle} / (m_B + m_{\langle NN \rangle}),$$

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

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

/In future: ab initio microscopic calculations of A=12 system/

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

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

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

Mixing shell-model configurations:

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

$$|AN_A\alpha \rangle = \sum_{\beta\gamma\Lambda M_\Lambda N_B N_x \nu} \langle AN_A\alpha | A - xN_B\beta, \nu\Lambda M_\Lambda, xN_x\gamma \rangle \\ |BN_B\beta \rangle |xN_x\gamma \rangle |\nu\Lambda M_\Lambda \rangle .$$

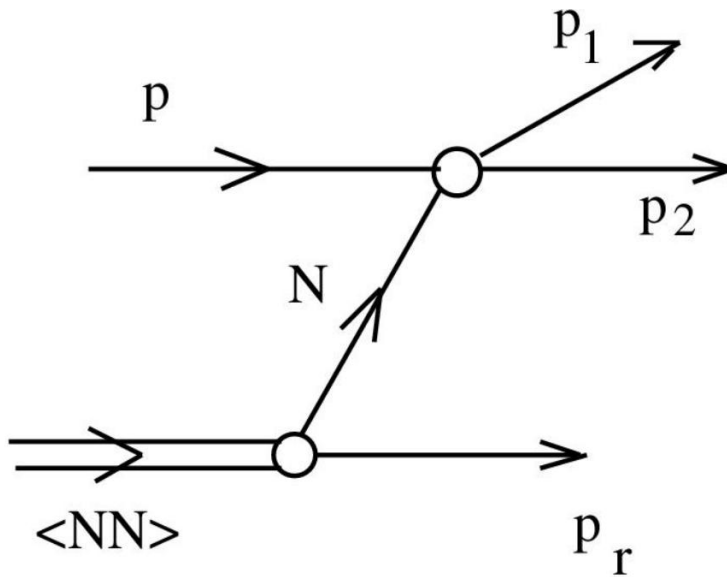
– *Matrix element of the $p + \langle NN \rangle \rightarrow p + p + N$* —————

In the Light front dynamics

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

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

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



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

SRC

— Momentum distribution in $\langle NN \rangle - {}^{10}\text{B}_5$ —————

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

TISM

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

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

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

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

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 $d - {}^{10}\text{B}$ system in m_N ;

r_0 is the h.o. shell model parameter;

$p_0^{h.o.} = \hbar/r_0$

The c.m. distribution in mean-field model

(Cioffi degli Atti, Simula, 1996)

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

$$n_{c.m.}(k_{c.m.}) = C \exp(-\alpha_{c.m.} k_{c.m.}^2) \quad \langle k_{c.m.}^2 \rangle = 3/2\alpha_{c.m.}$$

Antisymmetrization effects are not taken into account

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

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

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

$$p_0 = ?$$

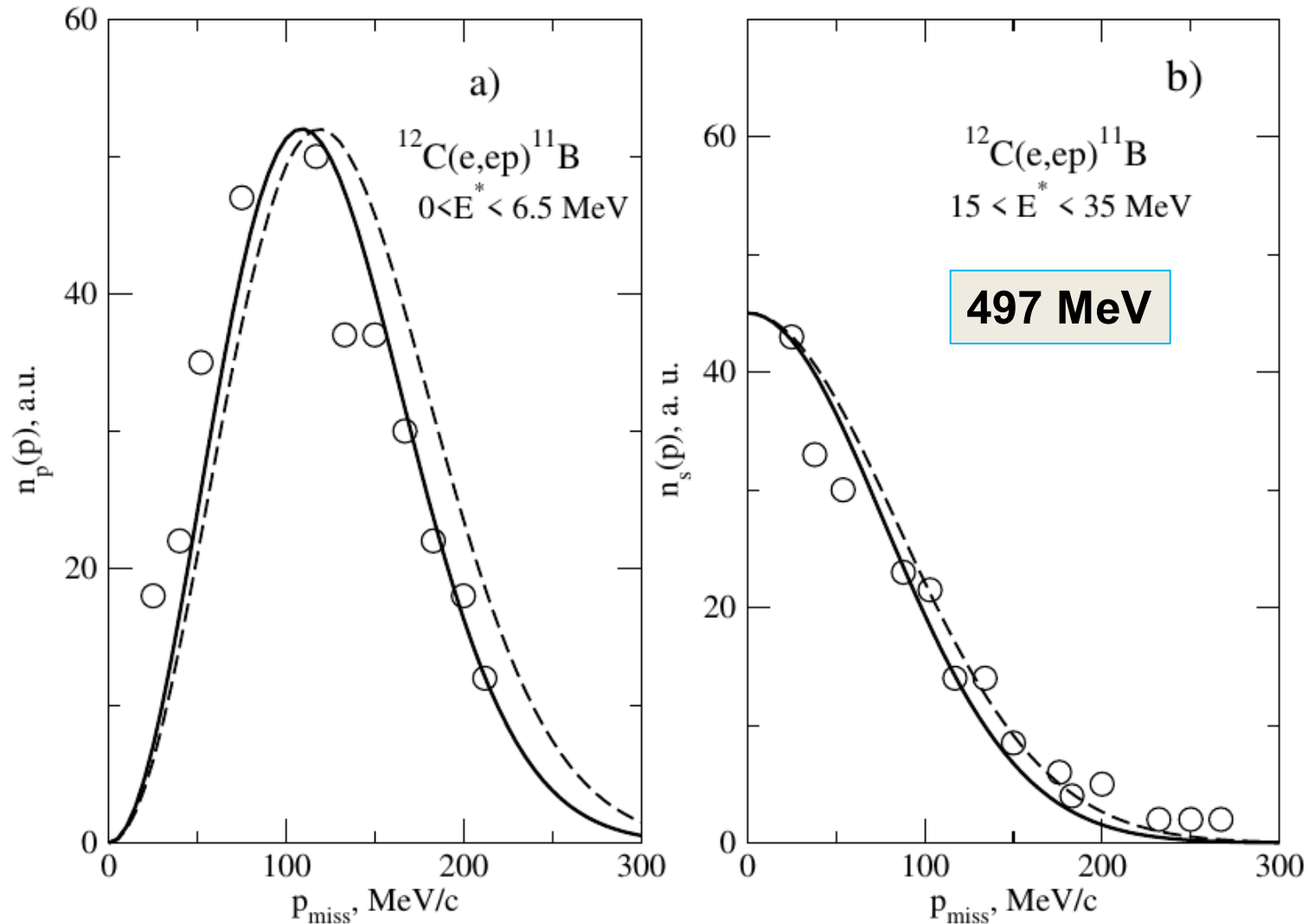


Fig. 2. Single nucleon momentum distribution in the reaction $^{12}\text{C}(e, ep)^{11}\text{B}$ at electron beam energy 497 MeV for the p-shell (a) and s-shell nucleons (b) corresponding to transitions to the states of the residual nucleus ^{11}B with excitation energy $0 < E^* < 6.5 \text{ MeV}$ and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

$$p_0 = 109 \text{ MeV} / c;$$

$$\alpha_{c.m.} = 0.96 \text{ fm}^2;$$

$$\sigma = h / 2\pi / \sqrt{2\alpha_{c.m.}};$$

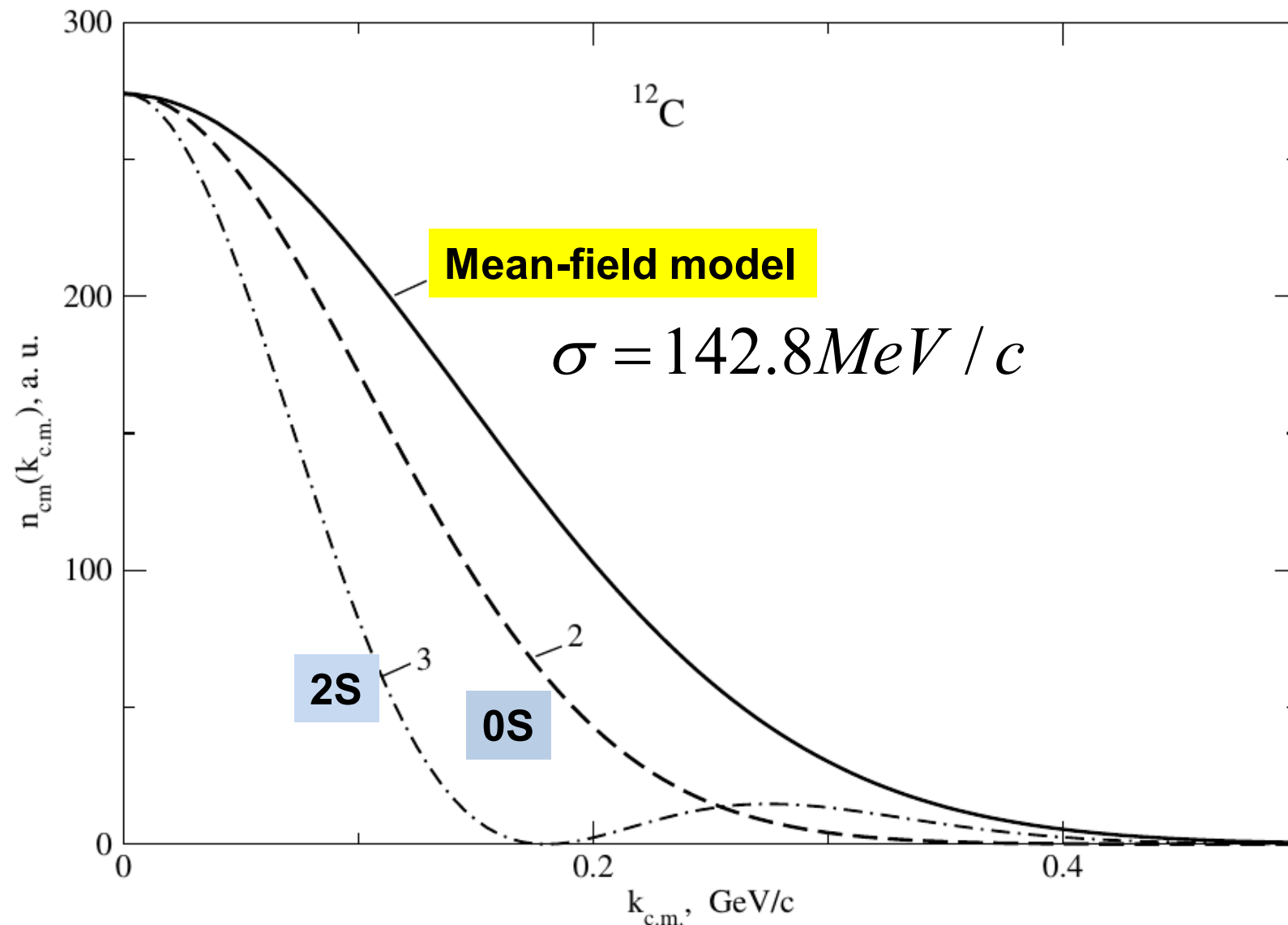
$$\sigma = 142.8 \text{ MeV} / c;$$

$$\sigma_{\text{exp.}} = (143 \pm 6) \text{ MeV} / c$$

The Charge form factor of ^{12}C is also well described

BM@N:

$$\sigma = (156 \pm 27) \text{ MeV} / c$$



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 $\alpha_{c.m.} = 0.95 \text{ fm}^2$ (full line) and the TISM wave function squared with $p_0 = 146.9 \text{ MeV/c}$ for the 0S-type (dashed), and 2S-type (dashed-dotted). All distributions are arbitrary normalized at $p_{c.m.} = 0$ to the same value.

pp/pn ratio

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

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

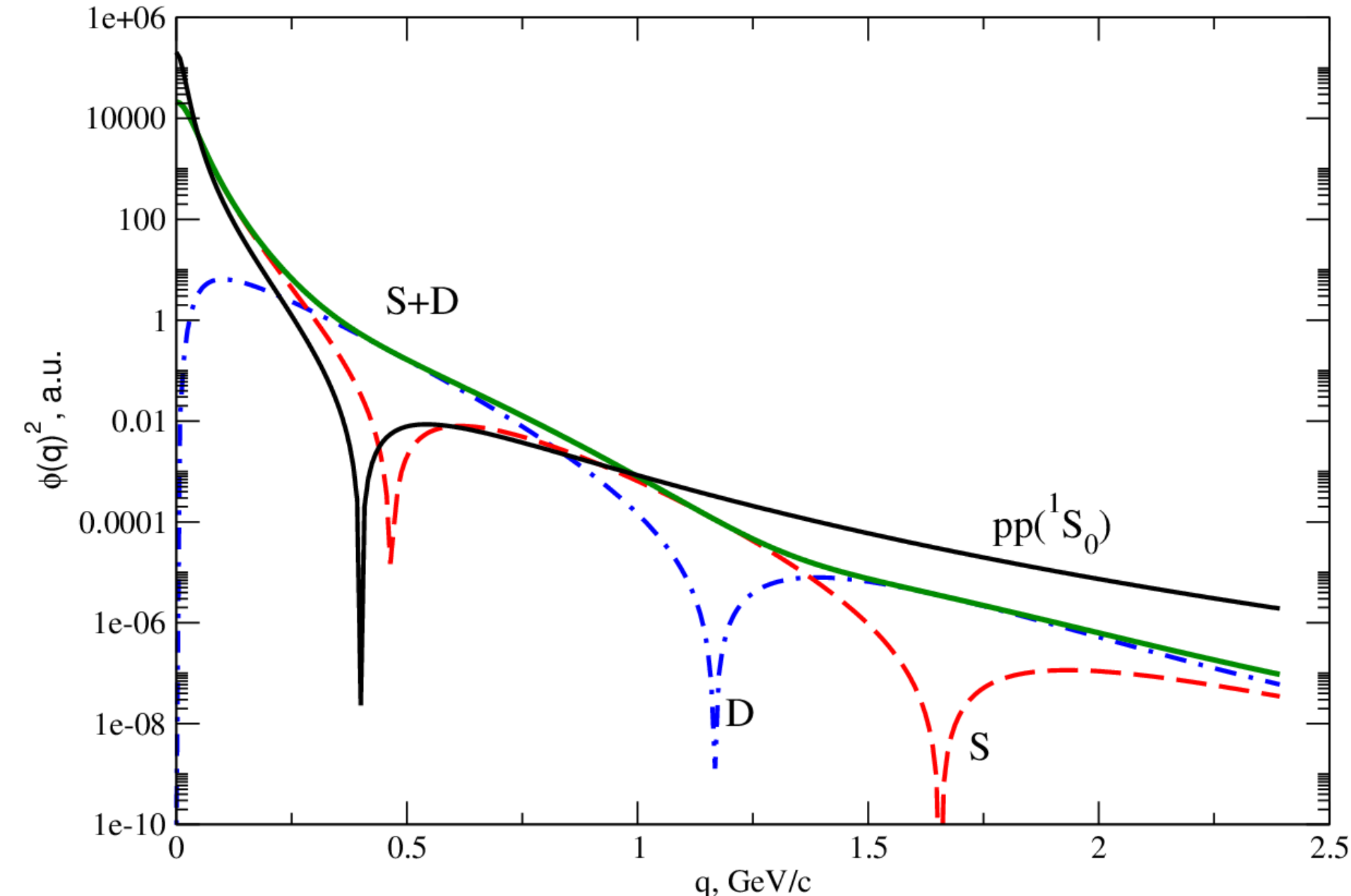
$$R = \frac{pp}{pn} = \frac{pp}{(pn)_{S=0T=1} + (pn)_{S=1T=0}} = \frac{1}{14} R_{rel}$$

$$^{12}\text{C} : |[444], L_i = 0, S_i = 0, T_i = 0, J_i = 0 >$$

$$PC(S = 1, T = 0) = PC(S = 0, T = 1)$$

pp pairs suppression by spectroscopic factors

pp and deuteron internal momentum distribution



pp(1S_0) scattering
Lensky V. et al.,
EPJ A26 (2005)107

CD – Bonn NN

pp/pn ratio

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

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

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

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

$q_{min}, \text{ GeV/c}$	R_{rel}	$q_{min}, \text{ GeV/c}$	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

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

If $R=0.01$, then $R_{obs} \simeq 0.03$ due to charge-exchange in FSI (M.Duer et al. PRL 122 (2019))
 $R_{exp} \simeq 5\%$

— 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 $^{12}\text{C}(p, pd)^{10}\text{B}$ 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 knock-out of nucleon from SRC NN pairs from the ^{12}C in exclusive reaction $^{12}\text{C} + p \rightarrow p + p + N + ^{10}\text{B}$
- The corresponding formalism is developed in the plane-wave approximation taking into account relativistic effects in the $p + \langle NN \rangle \rightarrow p + N + N$ within the LFD approach.
- pp/pn ratio obtained within TISM is in agreement with the data.
- Observed in $^{12}\text{C}(e, epp)^{10}\text{B}$ S-wave $k_{c.m.}$ momentum distribution is a puzzle for TISM. Corresponding measurements of $^{12}\text{C}(p, pd)^{10}\text{B}$ at BM@N conditions for s^4p^6 and s^2p^8 will be very important.

2021:

Calculation of differential cross sections of the reactions $^{12}\text{C}(p,2p)^{11}\text{B}$, $^{12}\text{C}(p,2pN)^{10}\text{A}$ and pp/pn ratio in kinematics of the [BM@N](#) SRC experiment within the developed microscopic model with accounting for rescattering effects and S_A^x factors for NN pairs and comparison the results with incoming data.

This work is supported by RFBR grant 18-02-40046

Thank you for attention!

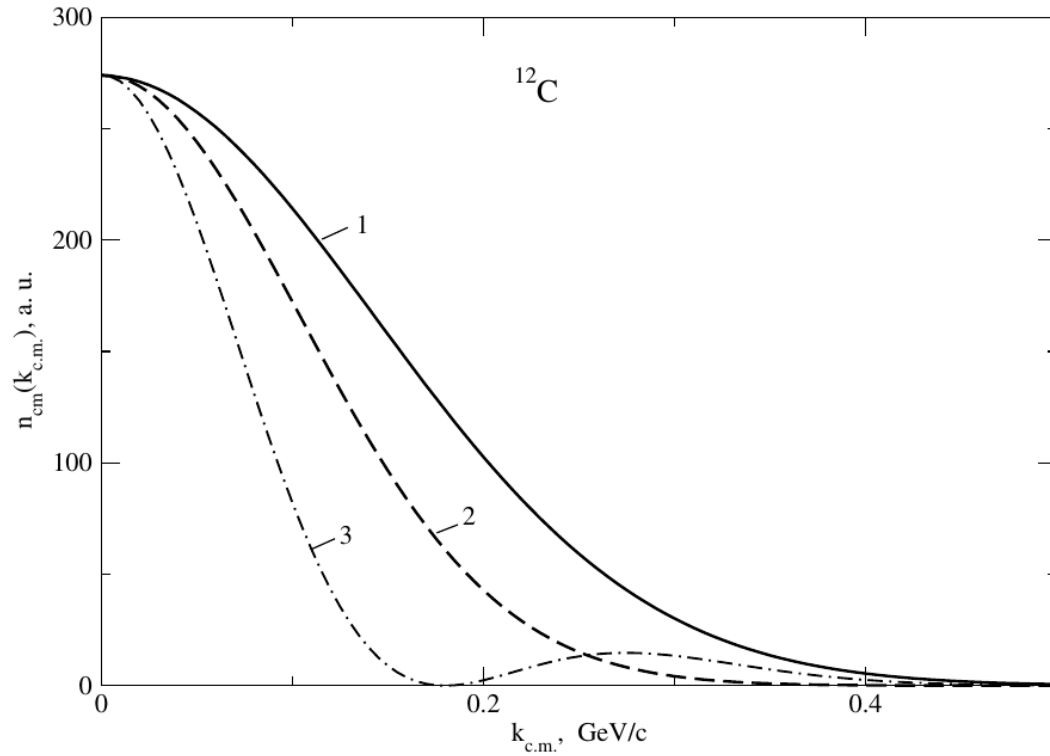
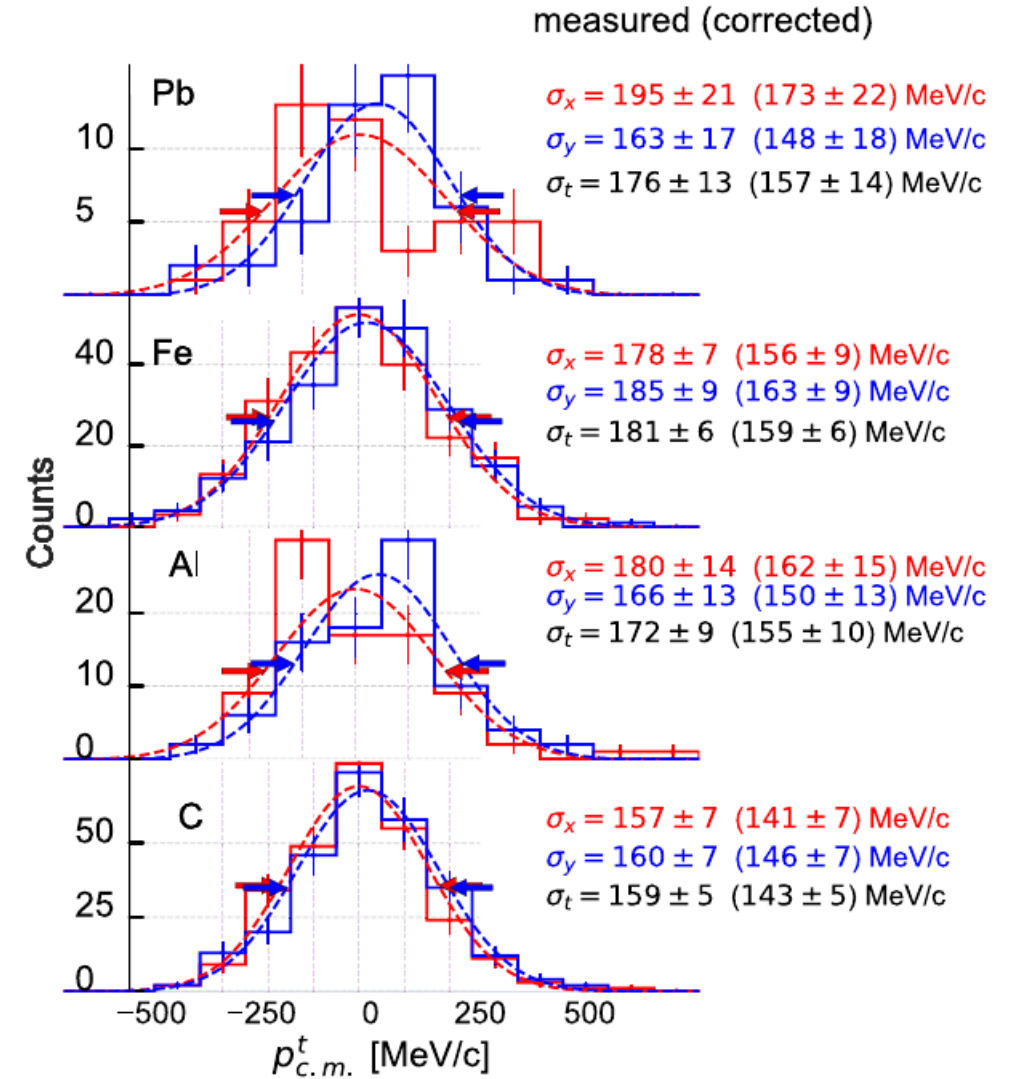


Fig. 3. Distribution over the c.m. momentum of the SCR pair $p_{c.m.}$ in the ^{12}C for the mean-field model with $\alpha_{c.m.} = 0.95 \text{ fm}^2$ (full line) and the TISM wave function squared with $p_0 = 146.9 \text{ MeV/c}$ for the $0S$ -type (dashed), and $2S$ -type (dashed-dotted). All distributions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



EMC- effect and SRC

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

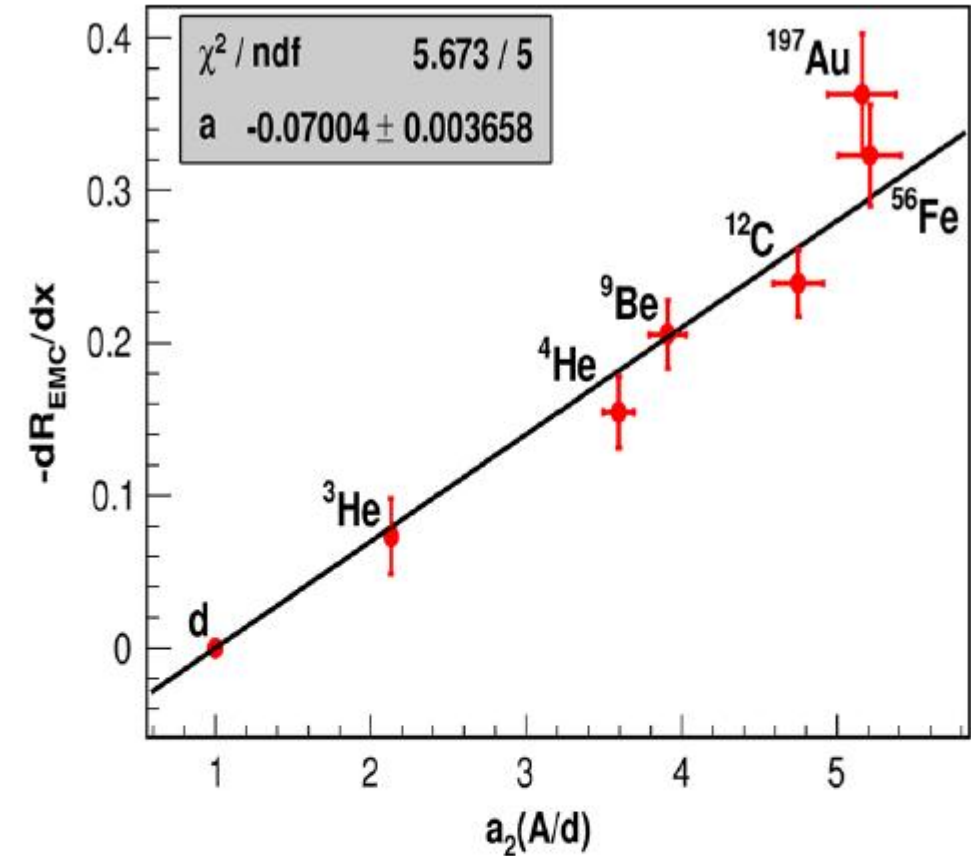
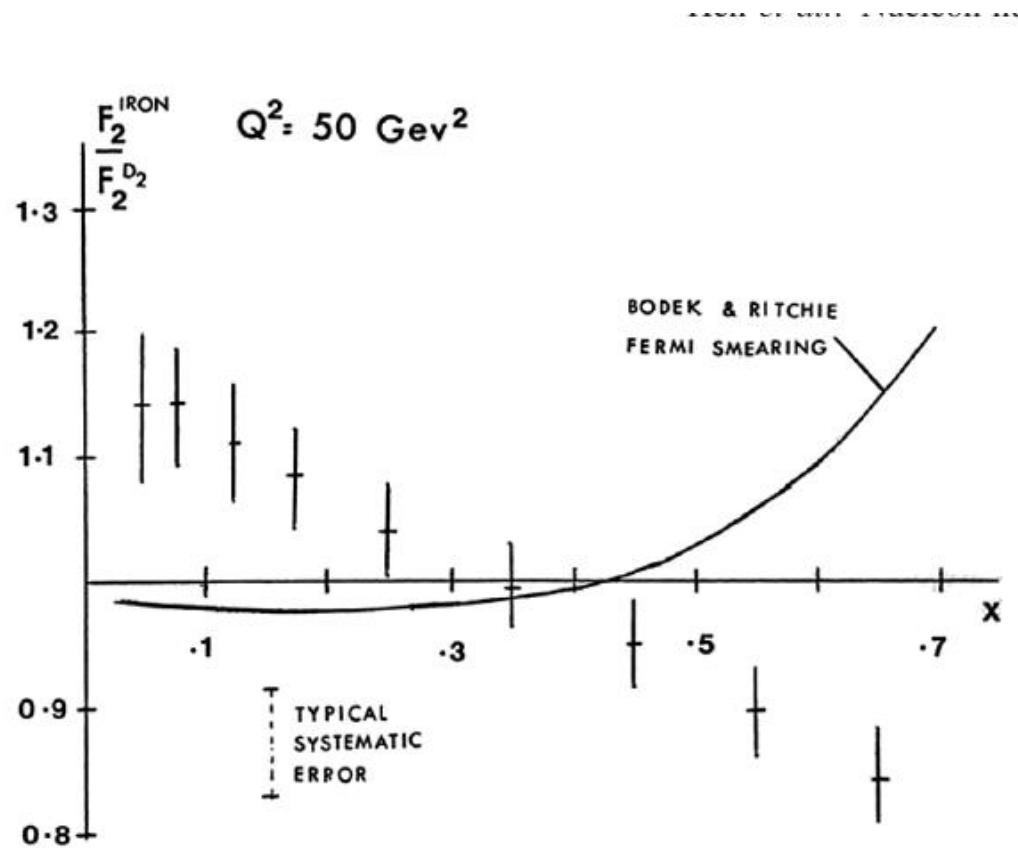


FIG. 34. The slope of the EMC effect (R_{EMC} , ratio of nuclear to deuteron cross section) for $0.35 \leq x_A \leq 0.7$ plotted vs $a_2(A)$, the SRC scale factor (the relative probability that a nucleon belongs to an SRC NN pair) for a variety of nuclei. The fit parameter $a = -0.070 \pm 0.004$ is the 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](#).

— 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

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

$n_{c.m.}^A(\vec{p}_{c.m.})$ is approximated by the 3-D Gaussian $g(x)g(y)g(z)$,

$$g(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{x^2}{2\sigma^2}\right]$$

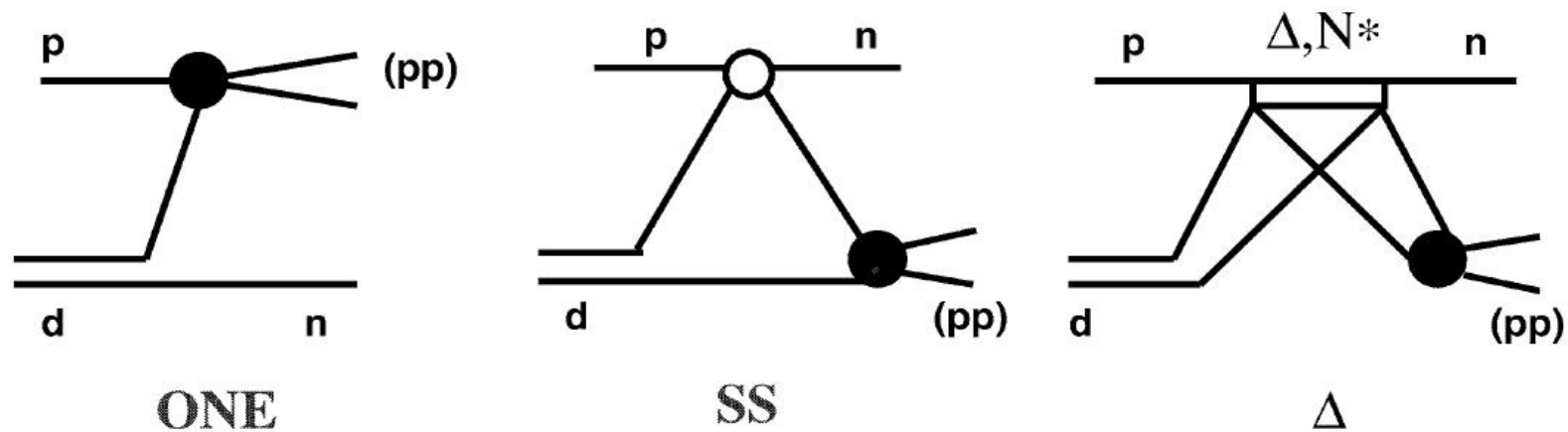
^{12}C :

$$\sigma_x \approx \sigma_y \approx \sigma_z = (145 \pm 5) \text{ MeV}/c$$

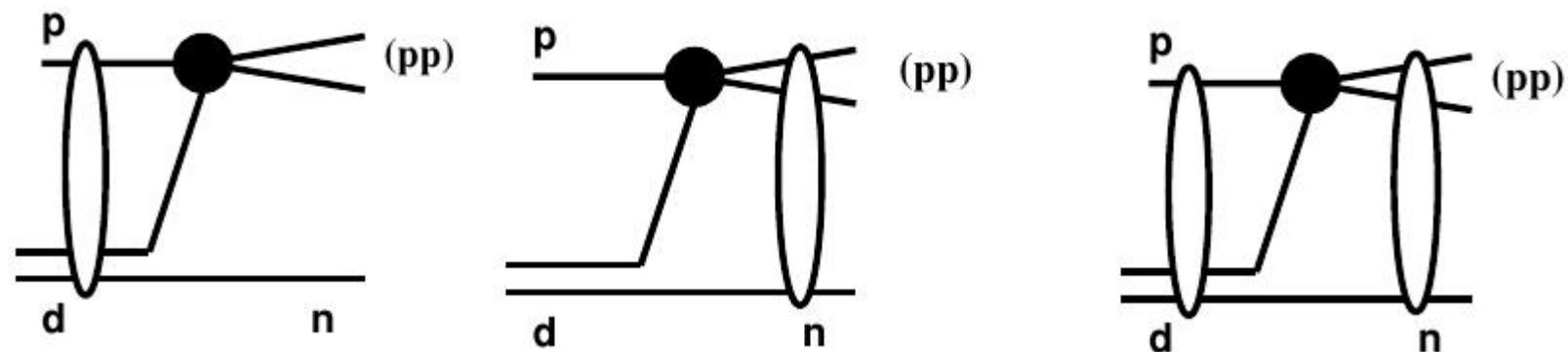
$$\text{i.e. } p_0 = \sqrt{2}(145 \pm 5) \text{ MeV}/c = (205 \pm 7) \text{ MeV}/c$$

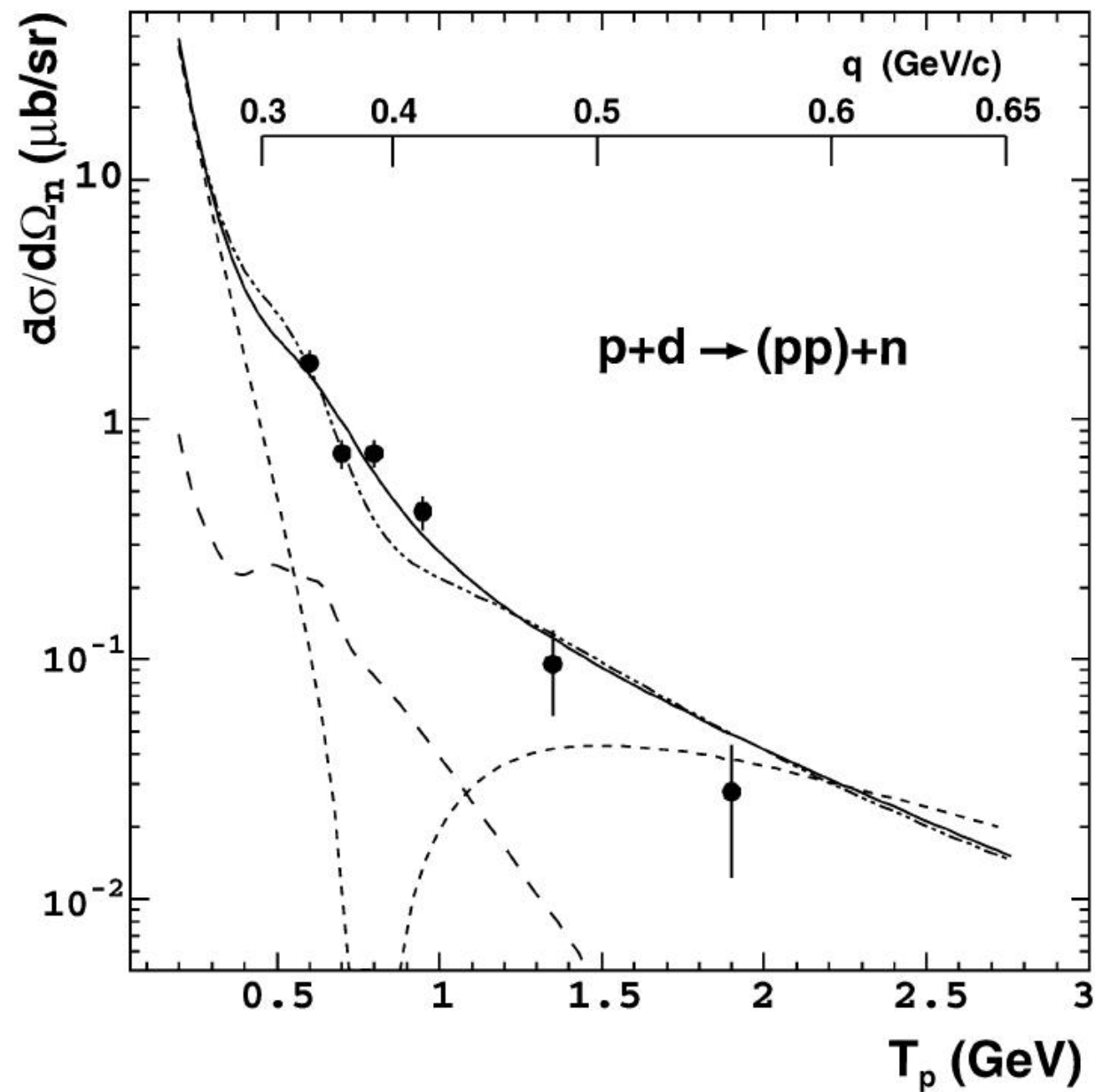
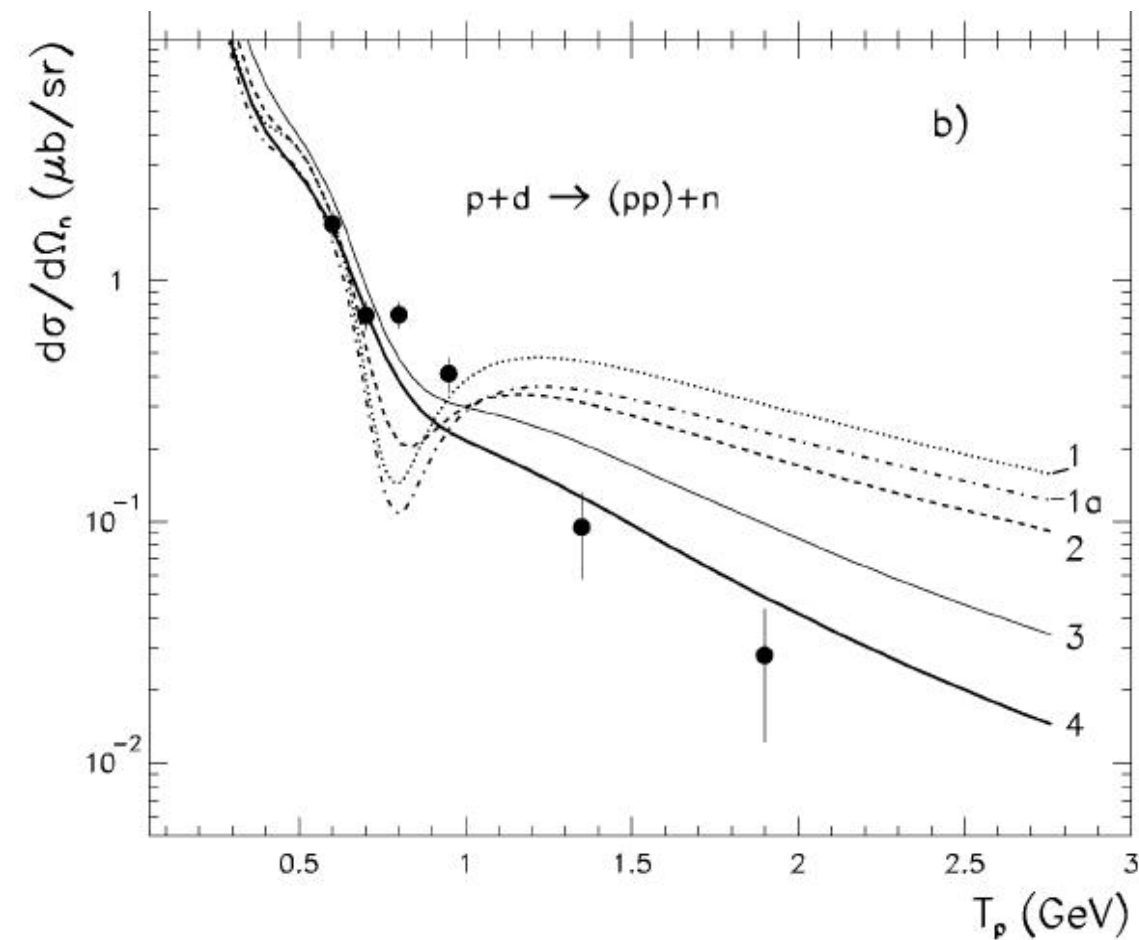
BACKWARD QUASI-ELASTIC

$pd \rightarrow (pp)_s n$ SCATTERING



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





Transition matrix element

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

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

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

How to take into account ISI and FSI?

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

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

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

$$<AN_A[f_A](\lambda_A\mu_A)\alpha_AL_AS_AT_A|$$

$$|A-xN_B[f_B](\lambda_B\mu_B)\alpha_B L_BS_BT_B;\nu\Lambda,xN_x[f_x](\lambda_x\mu_x)\alpha_x L_xS_xT_x(\mathcal{L}):L_AS_AT_A>$$

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

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

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

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

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

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

$$\underline{{}^4He}: \alpha = 2.4 \text{ fm}^2 \text{ or } p_0 = \hbar/\sqrt{\alpha} = 127.3 \text{ MeV}/c,$$

that is compatible with $p_0 = (144.6 \pm 18.2) \text{ MeV}/c$ from the deuteron knockout $^{12}C(p, pd)^{10}B$ from the α -core, (J.Erö et al., NPA 372, 1981), $|^{10}B\rangle = s^2p^8\rangle$

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

$$\begin{aligned}
 M_{fi}(pA \rightarrow ppNB) &= \left(\frac{A}{2} \right)^{1/2} \sum_{M_{J_d}, \bar{J}, \bar{M}, M_\Lambda} \sum_{\alpha_i, \alpha_f, N, \Lambda, \mathcal{L}} \alpha_i^{A J_i T_i} \alpha_f^{A-2J_f T_f} \\
 &< A\alpha_i | A-2\alpha_f, N\Lambda; d' > (\Lambda M_\Lambda J_{d'} M_{J_{d'}} | \bar{J} \bar{M}) (J_f M_{J_f} \bar{J} \bar{M} | J_i M_i) \\
 &(T_f M_{T_f} T_{d'} M_{T_{d'}} | T_i M_{T_i}) U(\Lambda L_{d'} \bar{J} S_{d'}; \mathcal{L} J_{d'}) \left\{ \begin{matrix} L_f & S_f & J_f \\ \mathcal{L} & S_{d'} & \bar{J} \\ L_i & S_i & J_i \end{matrix} \right\} \\
 &[(2L_i + 1)(2S_i + 1)(2J_f + 1)(2\bar{J} + 1)]^{1/2} \Psi_{N\Lambda M_\Lambda}^{dist}(\mathbf{k}_B) \\
 &\times < \mathbf{p}_1 \sigma_1, \mathbf{p}_2 \sigma_2, \mathbf{p}_r \sigma_r | \hat{M}(p < NN > \rightarrow p_1 p_2 p_r) | \mathbf{p} \sigma_p, -\mathbf{k}_B \Psi_{NN} > \\
 {}^{12}\text{C}: &L_i = S_i = J_i = 0, T_i = 0; |10B > = |s^4 p^6 >
 \end{aligned}$$

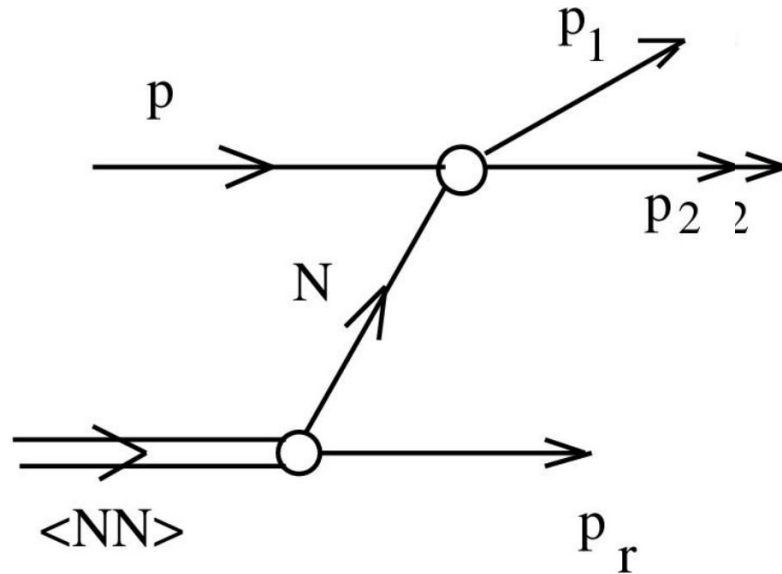
– Matrix element of the $p + \langle NN \rangle \rightarrow p + p + N$ –

In the Light front dynamics

$$M_{fi}^{LFD}(p + \langle NN \rangle \rightarrow p_1 p_2) = \frac{\Psi_d^{LFD}(\mathbf{k}_\perp, \xi)}{1 - \xi} M_{fi}(pN \rightarrow p_1 p_2),$$

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

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



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

SRC

Factorization of spin averaged $\overline{|M_{fi}|^2}$ for $S = 0$ of the $\langle NN \rangle$ pair and $\Lambda = 0$ in the $\langle NN \rangle - B$ relative motion.

$M_{fi}(pN \rightarrow p_1 p_2)$ is connected to on-shell pN-pN scattering, via cross section $\frac{d\sigma}{dt}(s, t)$.