$d^{12}C$ Elastic Scattering in Three-Body Model

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CONTENT

- Motivation: Polarimetry for EDM measurements at COSY

(talks on September 11 by N. Nikolaev, A. Nass, A. Kononov).

The deuteron spin rotation in storage ring due to intrinsic EDM will be measured by $\vec{d}^{12}C$ elastic scattering with an accuracy $\sim 10^{-6}$.

/N.P.M. Brantes et al., NIMA 664 (2012) 49/

COSY: "We have to know what is what in the $d^{12}C$ elastic scattering, $d^{12}C$ breakup x-section and figure of merit for different energies (and different targets) ..."

- Capability of the Glauber model for the $\vec{p}\vec{d} \to pd$ at $\sim$ 100-200 MeV
- Numerical results for $d^{12}C \to p(0) + X$ within the IA
- $\vec{d}\,^{12}C$- elastic scattering within the Glauber theory similarly to the $\vec{d}\,p$-scattering

$d^{12}C \to p(0) + X$ *breakup within the IA*

Glauber theory for the reaction $d + A \to p + X$,

L. Bertocchi, D. Treleani, Nuovo Cim. 36 A, 1 (1976). "The cross section contains:

i) the deuteron breakup with elastic rescattering of the proton and neutron from the deuteron,

ii) the neutron absorption cross section, when the neutron participates in inelastic collisions only, while the proton scatters elastically".

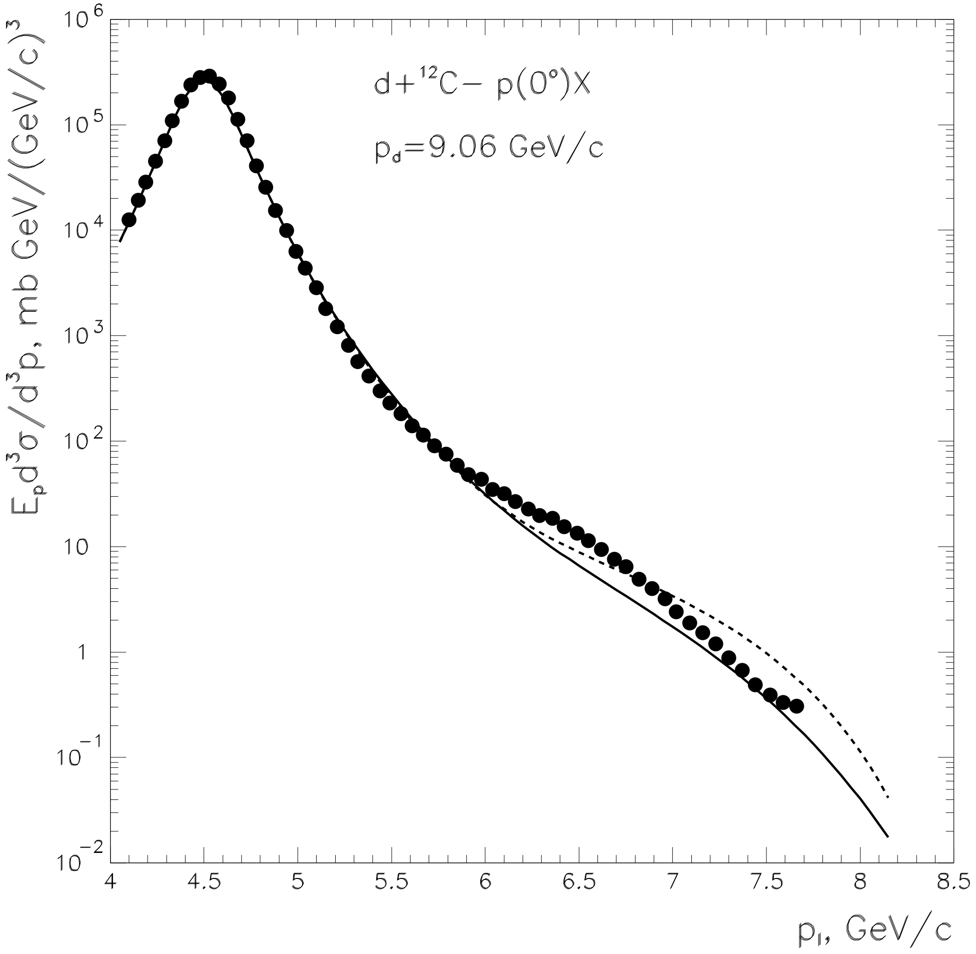
In practice after some approximations $\Longrightarrow$ impulse approximation /A.P. Kobushkin, L. Vizireva, J Phys. G8, 893 (1982)/

Relativistic effecs by B.L.G.Backer, L.A. Kondratyuk, M.V. Terentjev NPA (1979):

$$E_p \frac{d^2\sigma}{d^3p_p} = \frac{I_2}{I_1} \frac{\mathcal{E}_d(\mathcal{E}_n + \mathcal{E}_p)\varepsilon_p(q)}{16\pi \mathcal{E}_n^2} \left[\frac{u^2(q) + w^2(q)}{(2\pi)^3}\right] (2J_A + 1)\sigma_{tot}^{M_X}(nA \to X) \quad (1)$$

$I_1 = p_d \cdot p_A$, $I_2 = p_n \cdot p_A$

$d^{12}C \to p(0) + X$: search for high-momentum components of the d.w.f.



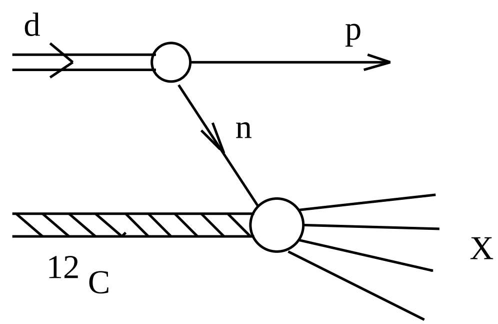
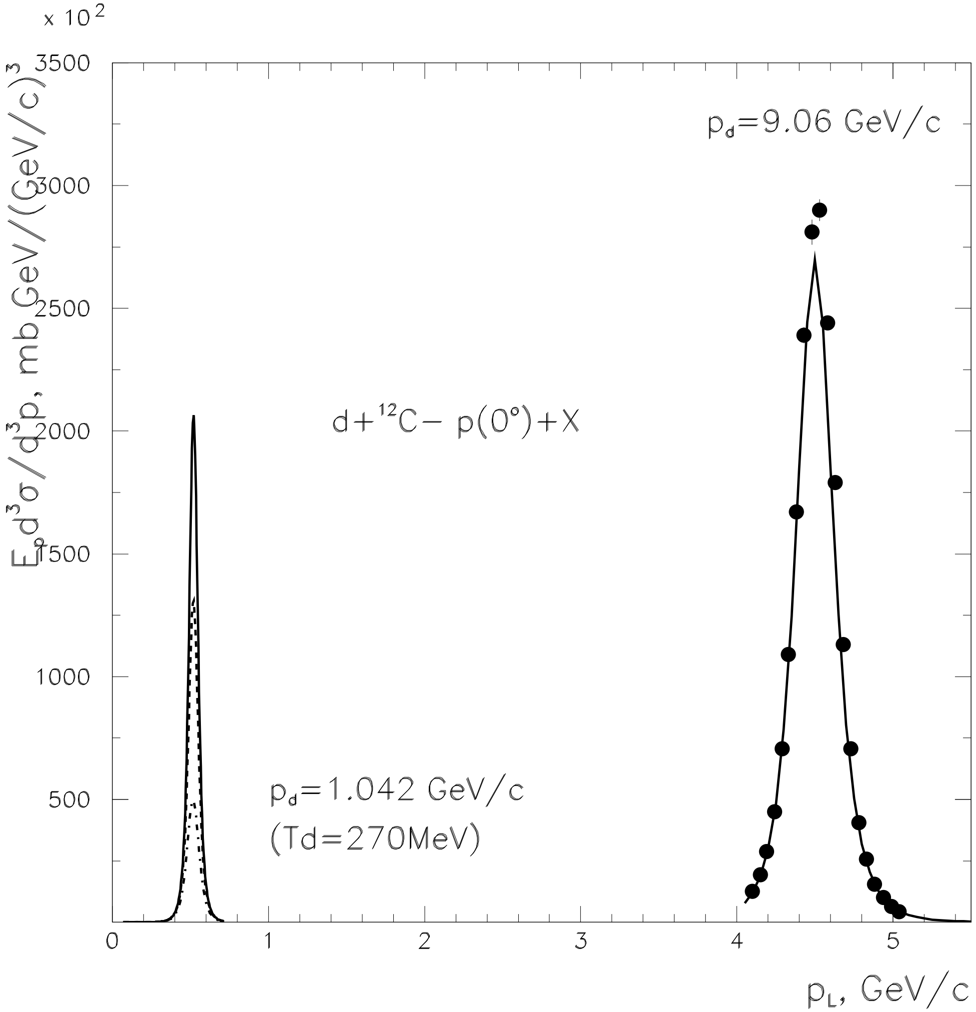
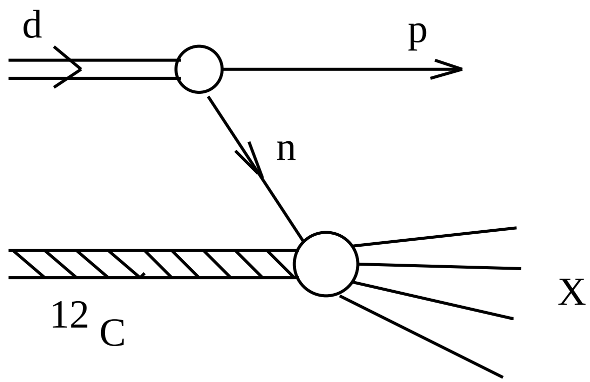


Figure 1: The invariant cross section of the reaction $d +^{12} C \to p(0^{\circ})$ X), at $p_d = 9.06$ GeV/c (V. Ableev, 1991) versus lab. momentum of the final proton in comparison with the IA for the CD Bonn (dashed) and Paris (full) d.w.f.

$d^{12}C \to p(0^\circ) + X$ *within the IA at* $T_d = 270$ *MeV and* $p_d = 9$ *GeV/c*

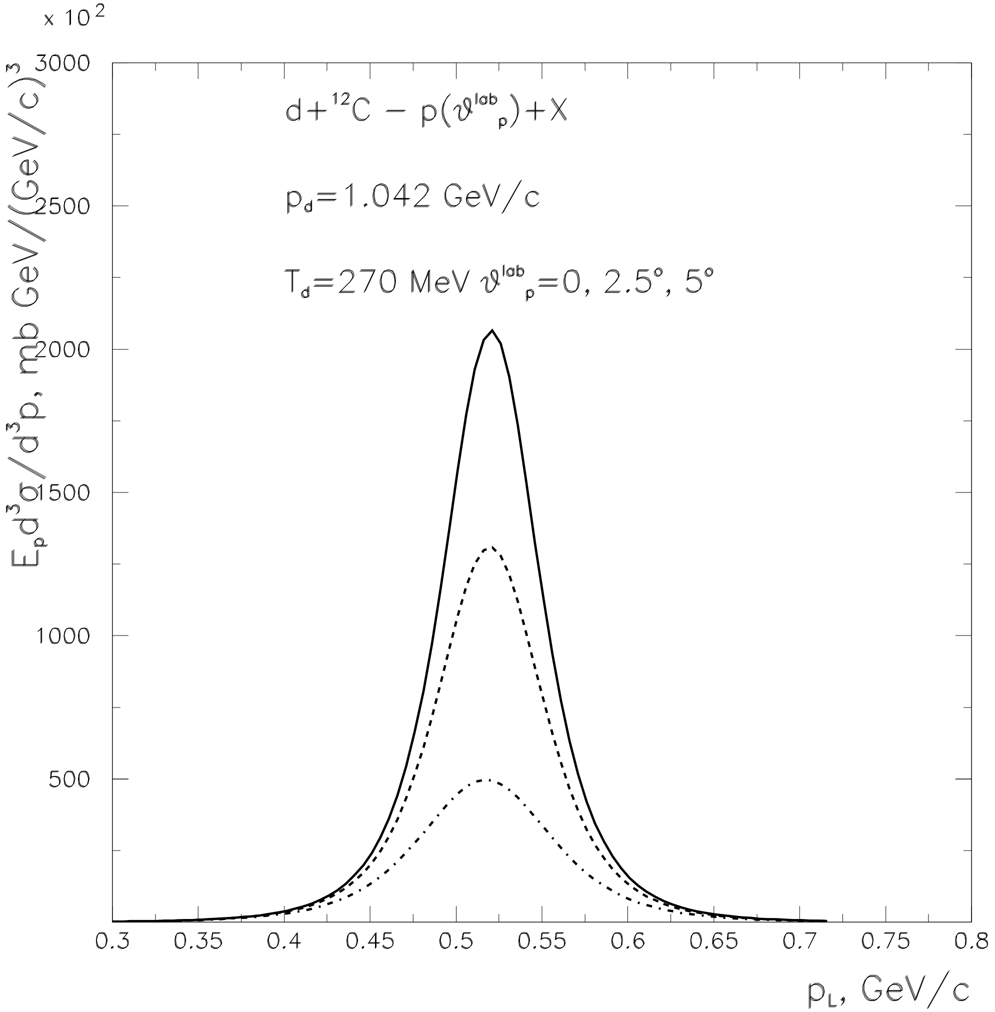


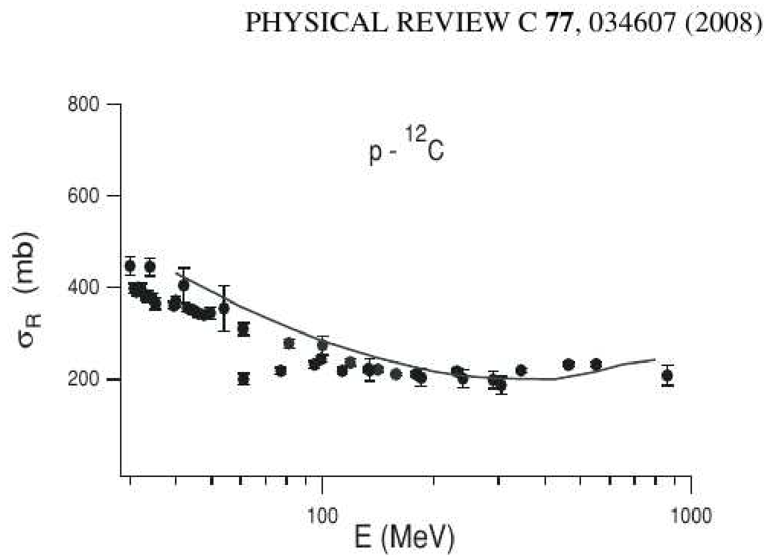


Curves: the IA calculation

Data at $P_d = 9.06 GeV/c$: V.G. Ableev et al. JETP lett. 47, 649 (1988)

$d^{12}C \to p(0) + X$ *within the IA*





Curves: the IA calculation at $\theta_p^{lab} = 0,\ 2.5°, 5°$

$\sigma^R_{tot}(n^{12}C \to X) = 260$ mb, B.Abu-Ibrahim et al. PRC 77, 034607 (2008)

$$\frac{1}{2} + 1 \to \frac{1}{2} + 1$$

$(2+1)^2(2\frac{1}{2}+1)^2 = 36$ transition amplitudes

P-parity $\Longrightarrow$ 18 independent amplitudes

T-invariance $\Longrightarrow$ 12 independent amplitudes

Phenomenology of the $pd \to pd$ transition

$\hat{\mathbf{q}} = (\mathbf{p} - \mathbf{p}')$, $\hat{\mathbf{k}} = (\mathbf{p} + \mathbf{p}')/$, $\hat{\mathbf{n}} = [\mathbf{k} \times \mathbf{q}]$ – unit vect. ($Z \upuparrows \hat{\mathbf{k}}$, $X \upuparrows \hat{\mathbf{q}}$ $Y \upuparrows \hat{\mathbf{n}}$)

$$M = (A_1 + A_2 \boldsymbol{\sigma}\hat{\mathbf{n}}) + (A_3 + A_4 \boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})^2 + (A_5 + A_6 \boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}})^2 + A_7(\boldsymbol{\sigma}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{k}}) + A_8(\boldsymbol{\sigma}\hat{\mathbf{q}})\left[(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})\right] + (A_9 + A_{10}\boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}}) + A_{11}(\boldsymbol{\sigma}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{q}}) + A_{12}(\boldsymbol{\sigma}\hat{\mathbf{k}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})\right]$$

$A_1 \div A_{12}$ T-even P-even:
M. Platonova, V. Kukulin,PRC **81** (2010) 014004

The polarized elastic differential pd cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{pol} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left[1 + \frac{3}{2} p_j^p p_i^d C_{j,i} + \frac{1}{3} P_{ij}^d A_{ij} + \dots\right]. \quad (2)$$

$$C_{y,y} = Tr M S_y \sigma_y M^+ / Tr M M^+, \quad \dots \quad (3)$$

Glauber formalism for $pd \to pd$

$$\hat{M}(\mathbf{q},\mathbf{s}) =$$
$$\exp\left(\frac{1}{2} i\mathbf{q}\cdot\mathbf{s}\right) M_{pp}(\mathbf{q}) + \exp\left(-\frac{1}{2} i\mathbf{q}\cdot\mathbf{s}\right) M_{pn}(\mathbf{q}) +$$
$$+\frac{i}{2\pi^{3/2}} \int \exp\left(i\mathbf{q}'\cdot\mathbf{s}\right)\Big[M_{pp}(\mathbf{q}_1) M_{pn}(\mathbf{q}_2) + p \leftrightarrow n\Big] d^2\mathbf{q}'.$$

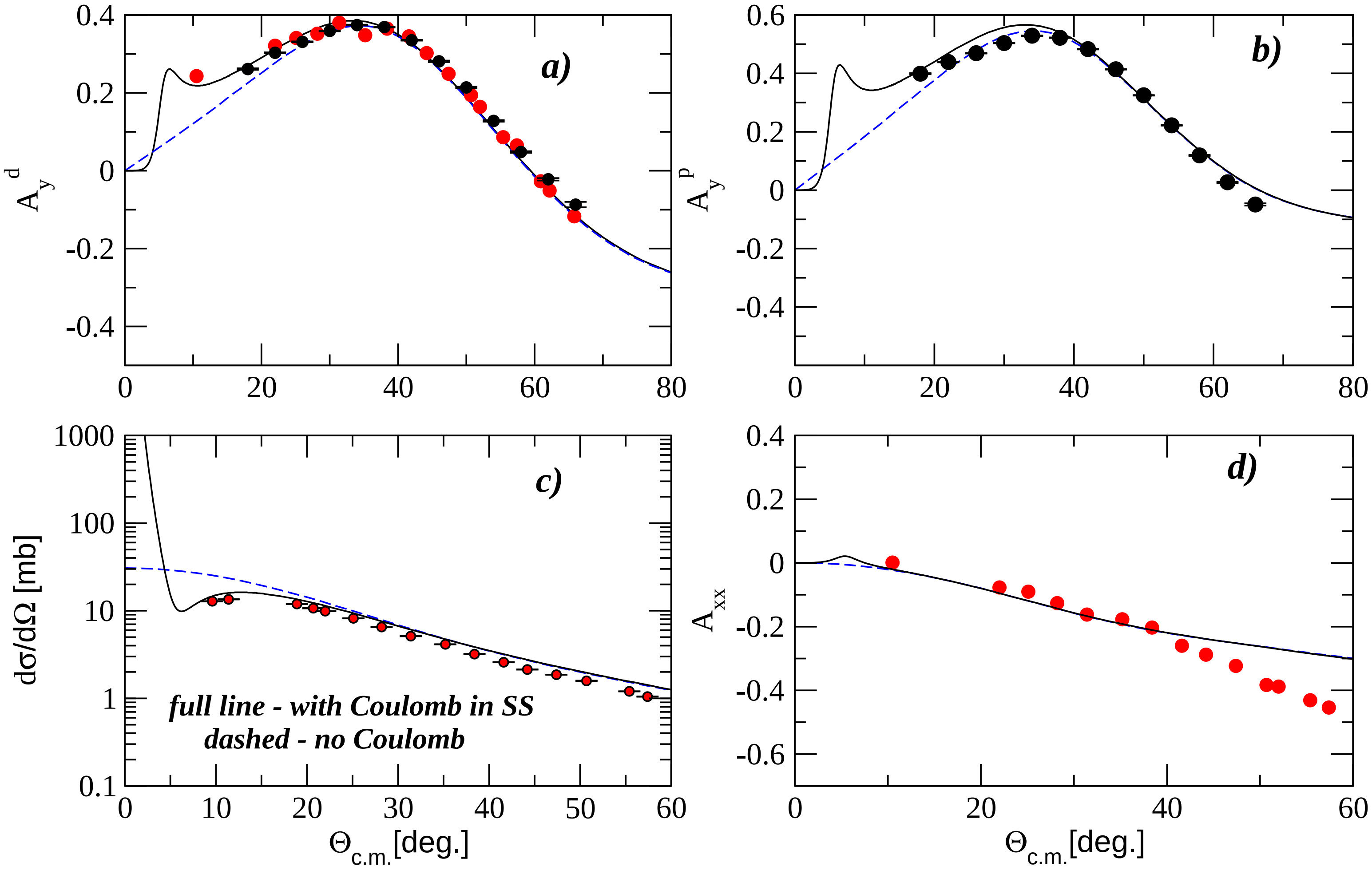
On-shell elastic pN scattering amplitude (**T-even, P-even**, from SAID)

$$\begin{aligned} M_{pN} &= A_N + (C_N\boldsymbol{\sigma}_1 + C'_N\boldsymbol{\sigma}_2)\cdot\hat{\mathbf{n}} + B_N(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{k}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{k}}) + \\ &+ (G_N - H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{n}}) + (G_N + H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{q}}) \end{aligned}$$

Spin formalism by M. Platonova, V. Kukulin, PRC **81** (2010) is transformed to the Madison reference frame in: A.Temerbayev, Yu.N. Uzikov, Yad. Fiz. 78 (2015)

Test calculations: pd elastic scattering at 135 MeV

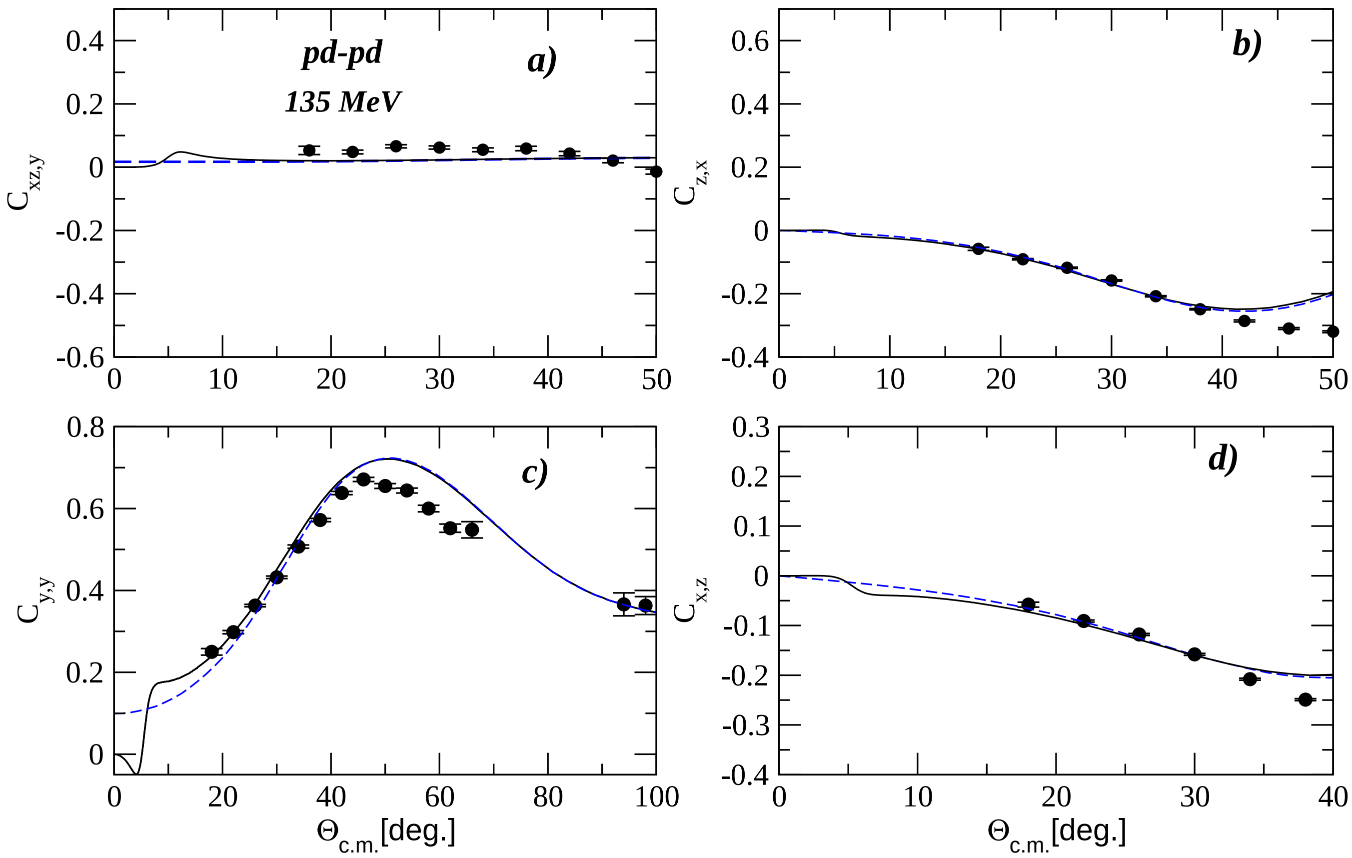
A.A. Temerbayev, Yu.N. Uzikov, Yad. Fiz. **78** (2015) 38 [Phys. At. Nucl. 78 (2015) 35]



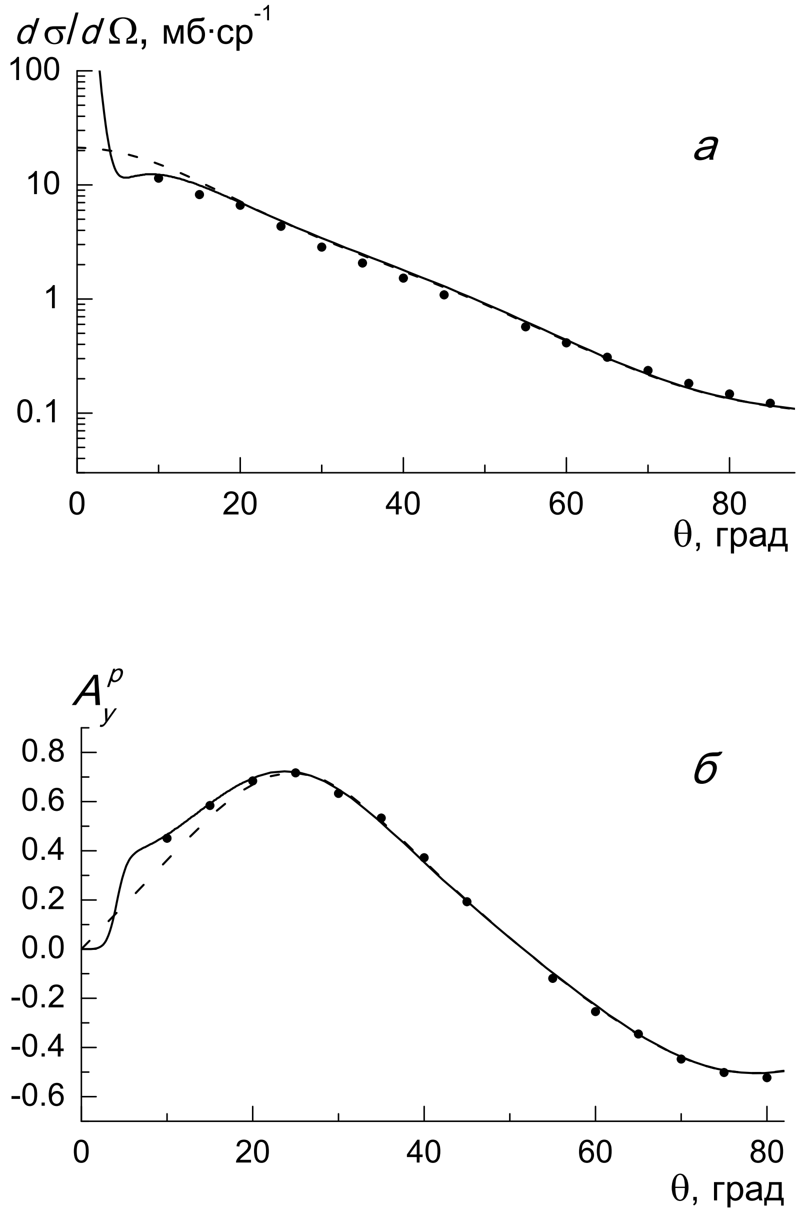
Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)
See also **Faddeev calculations**: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.

Test calculations-II: pd elastic scattering at 135 MeV

Yu.N. Uzikov, A.A. Temerbayev, Phys.Rev. C 92 (2015) 014002



Data: von B.Przewoski et al. PRC 74 (2006) 064003 Curves: the spin-dependent Glauber theory
Faddeev calculations give very similar results (A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC (2005)).


dσ/dΩ, мб·ср$^{-1}$
100
10
1
0.1
а
0
20
40
60
80
θ, град
A_y^p
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
б
0
20
40
60
80
θ, град

$$\vec{1} + 0 \to \vec{1} + 0$$

$(2+1)^2 = 9$ transition amplitudes
P-parity $\Longrightarrow$ 5 independent amplitudes
T-invariance $\Longrightarrow$ 4 independent amplitudes

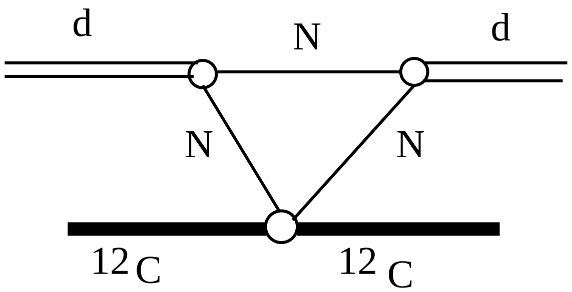
$$T_{fi} = e_\beta^{(\lambda')^*} T_{\beta\alpha}(\mathbf{k}, \mathbf{k}') e_\alpha^{(\lambda)} \tag{4}$$

$$\begin{aligned} T_{xx} = A, \quad T_{xy} = 0 \quad T_{xz} = E \\ T_{yx} = 0 \quad T_{yy} = B \quad T_{yz} = 0 \\ T_{zx} = D \quad T_{zy} = 0 \quad T_{zz} = C, \end{aligned}$$

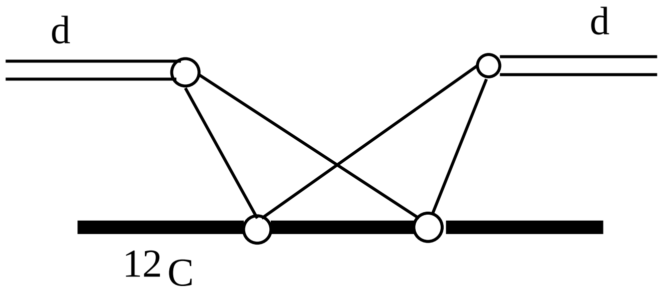
T-invariance:

$$D = E$$

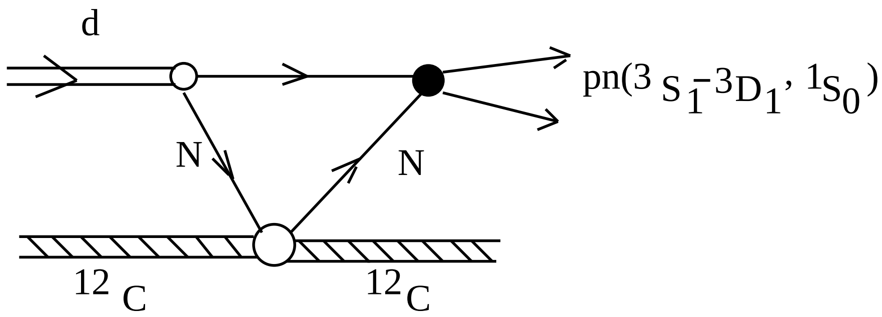
At the next step...



SS



DS



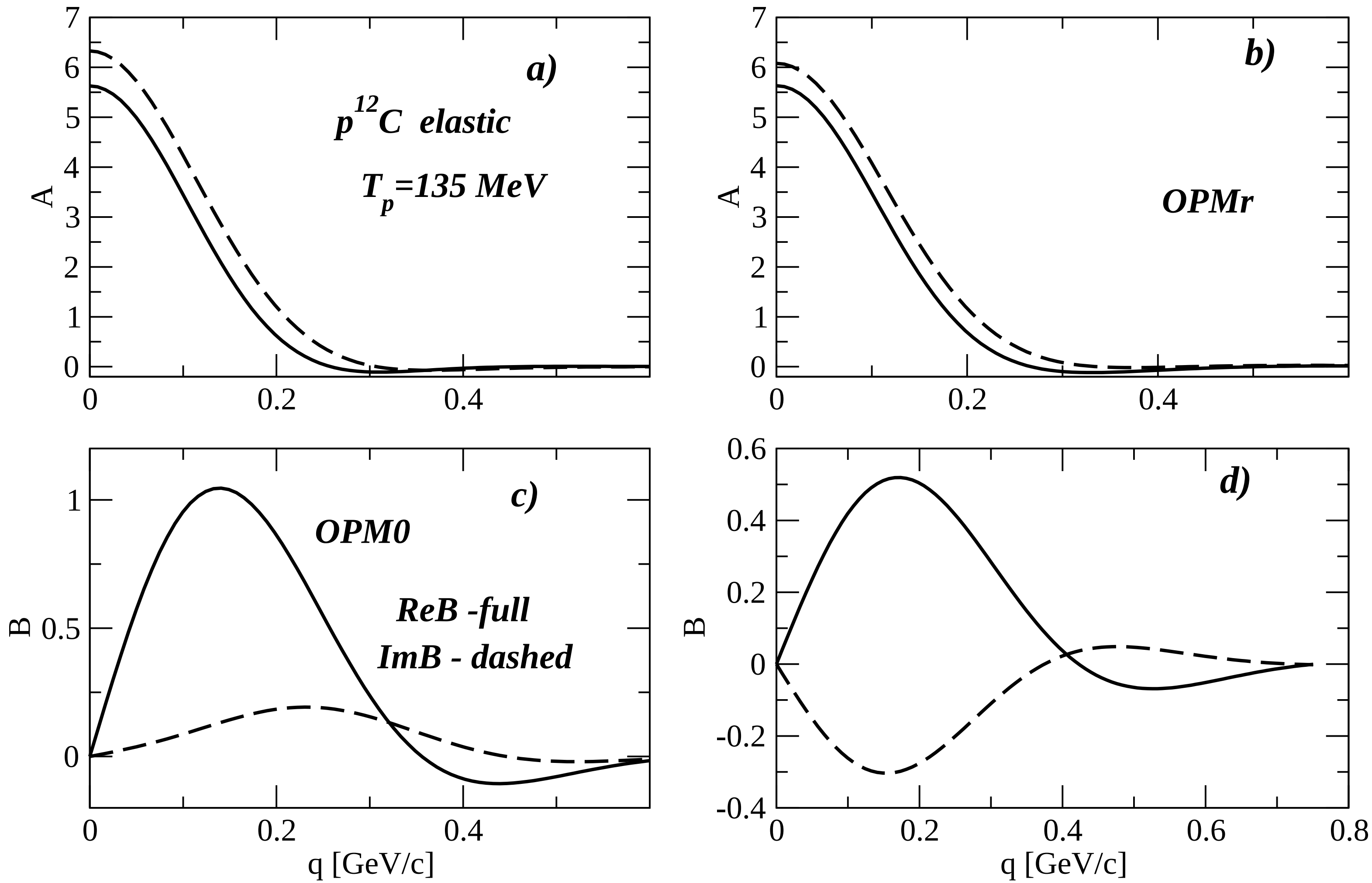
The Glauber formalism
as a modification of the $dp \to dp$
$Np \to Np$ on-shell $\Longrightarrow n^{12}C$ on-shell elastic

In analogy with the $dp \to \{pn\}_S + p$

$^{12}C\,N$ scattering amplitude

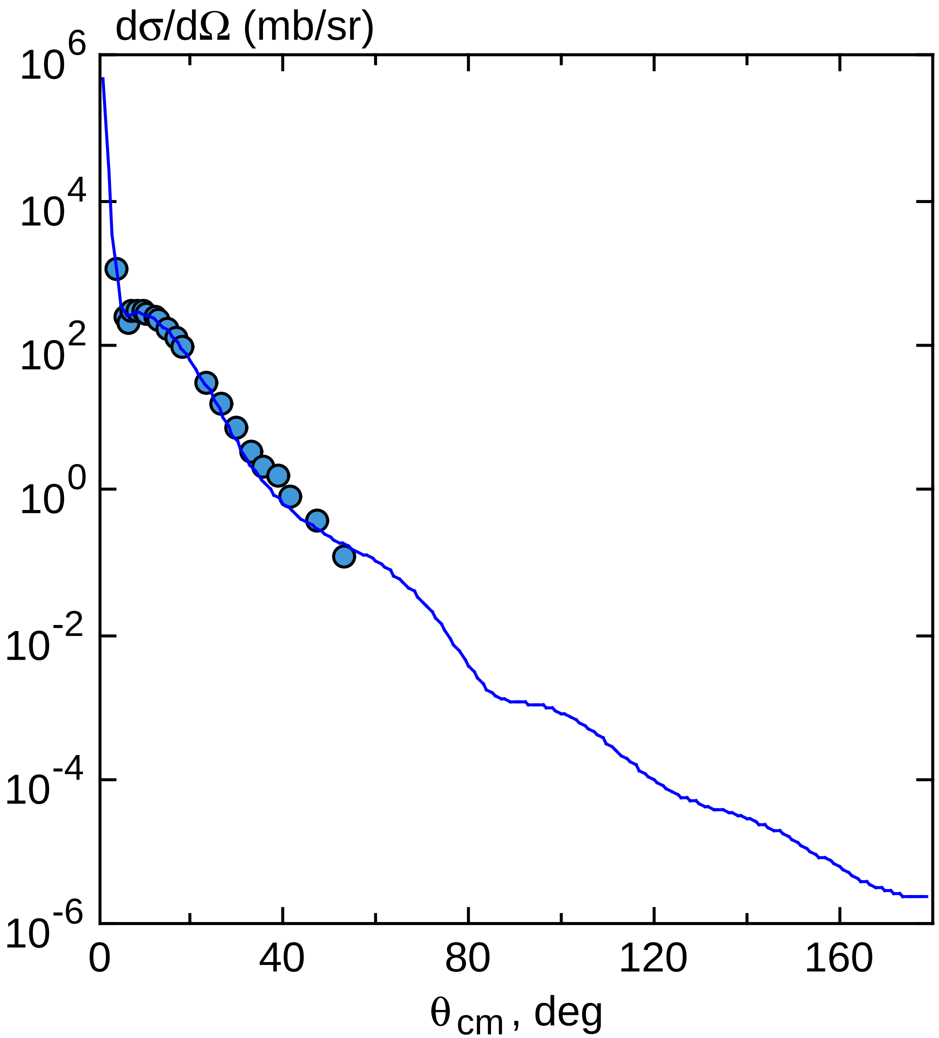
$$M_N(\mathbf{p},\mathbf{q};\boldsymbol{\sigma}_\mathbf{N}) \;=\; A_N + iB_N\boldsymbol{\sigma}_N\cdot\hat{\mathbf{n}}$$

A and B amplitudes of the p^{12}C-elastic scattering (OPM)



E.T. Ibraeva, Yu.N. U. Phys. At. Nucl. 81(2018) 479

OPM for p^{12}C-elastic at 135 MeV from http://nrv.jinr.ru



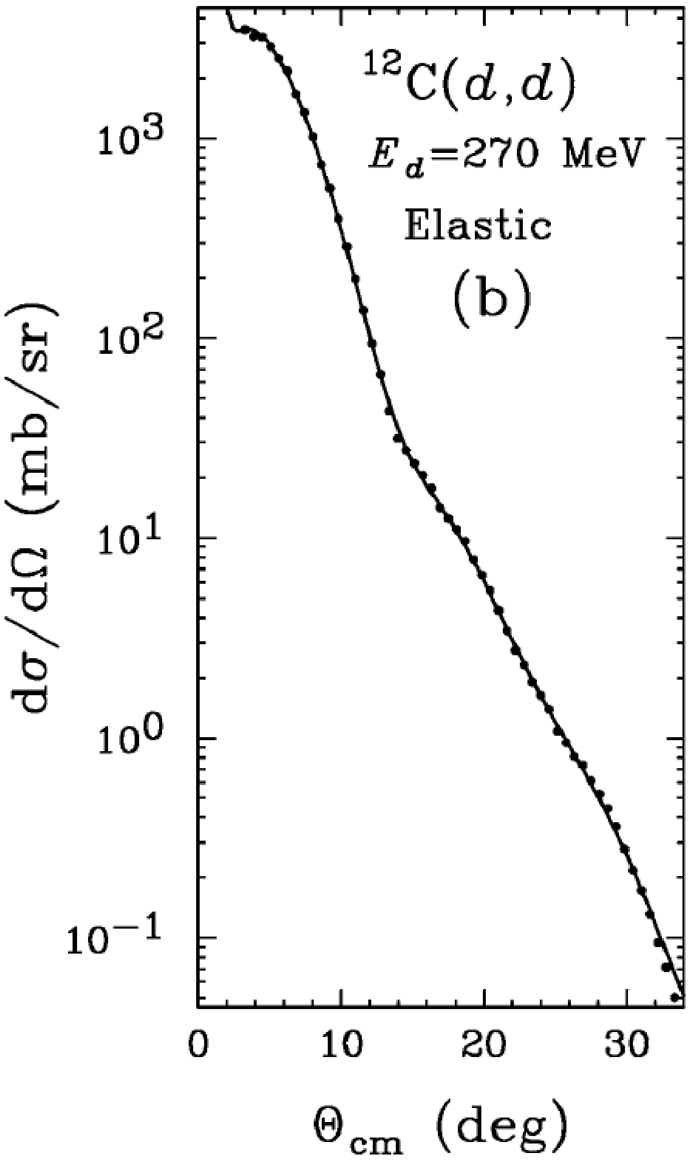
Data – J.L. Comfort, K.C.Karp, PRC 21 (1980) 2162

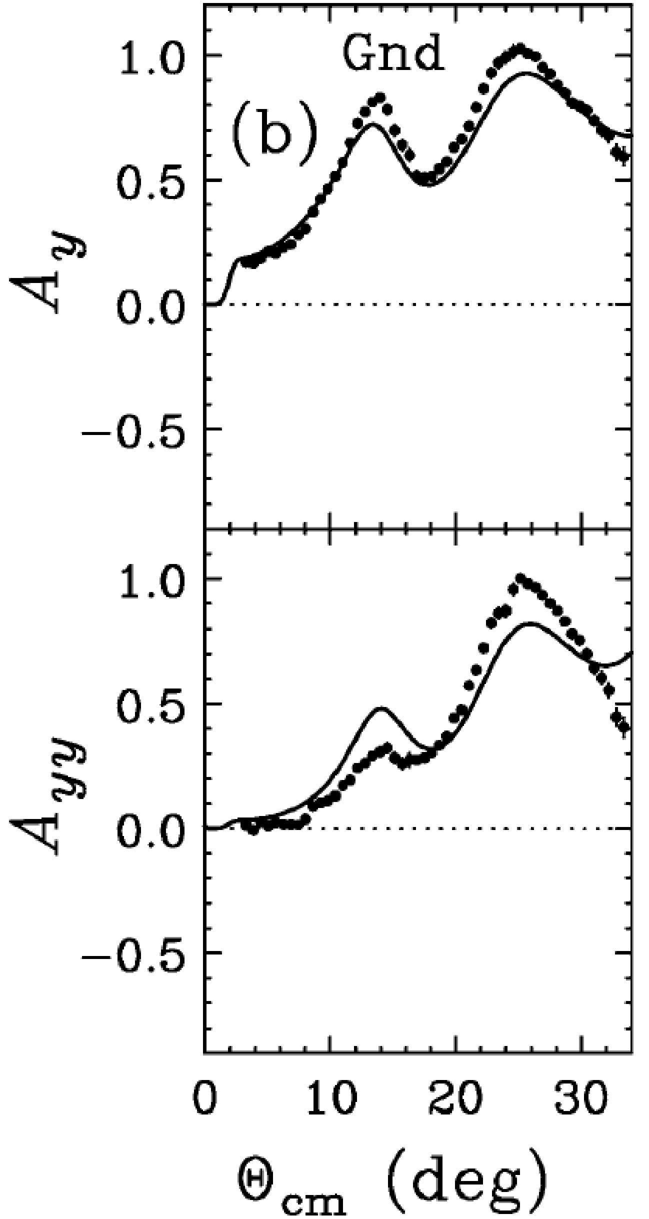
OPM:

$$U(r) = V_V(r)f(x_R) + iW_V(r)f(x_I) +$$
$$\left(V_{SO}\frac{1}{r}\frac{d}{dr}f(x_{RSO}) + iW_{SO}\frac{1}{r}\frac{d}{dr}f(x_{ISO})\right)(\mathbf{L}\cdot\mathbf{s}) -$$
$$-i4a_D W_D \frac{d}{dr}f(x_{RD}) + V_{Coul}(r); \qquad (5)$$

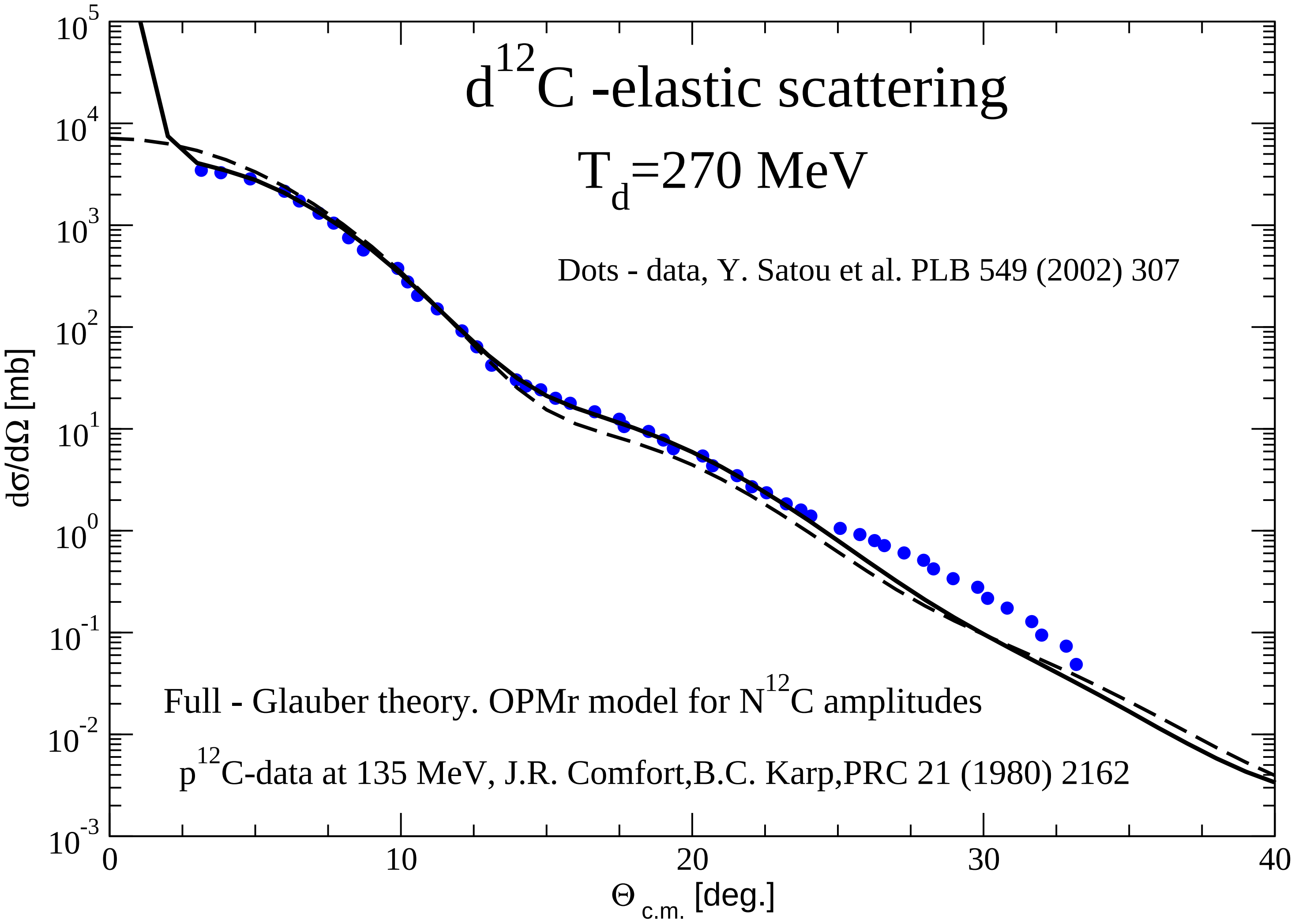
where $f(x_i) = [1 + \exp{(x_i)}]^{-1}$, $x_i = (r - R_i)/a_i$, $R_i = r_i A^{1/3}$.

[1]. I. Satou et al. Phys.Lett.B 549 (2002) 307: $^{12}C(d,d')$at 270 MeV



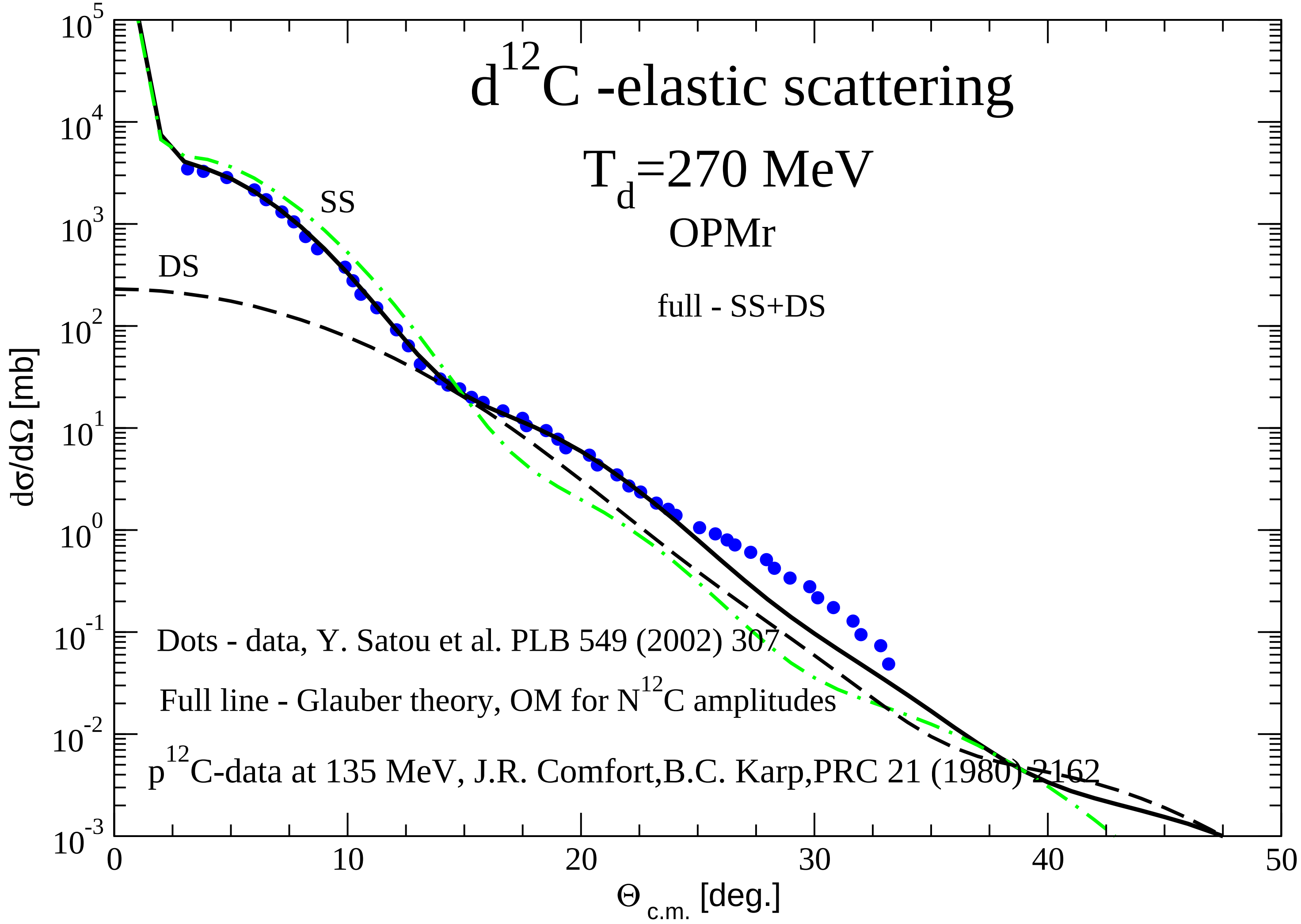


Only optical model was applied to the (elastic) existing $d^{12}C$ data in Ref.[1].



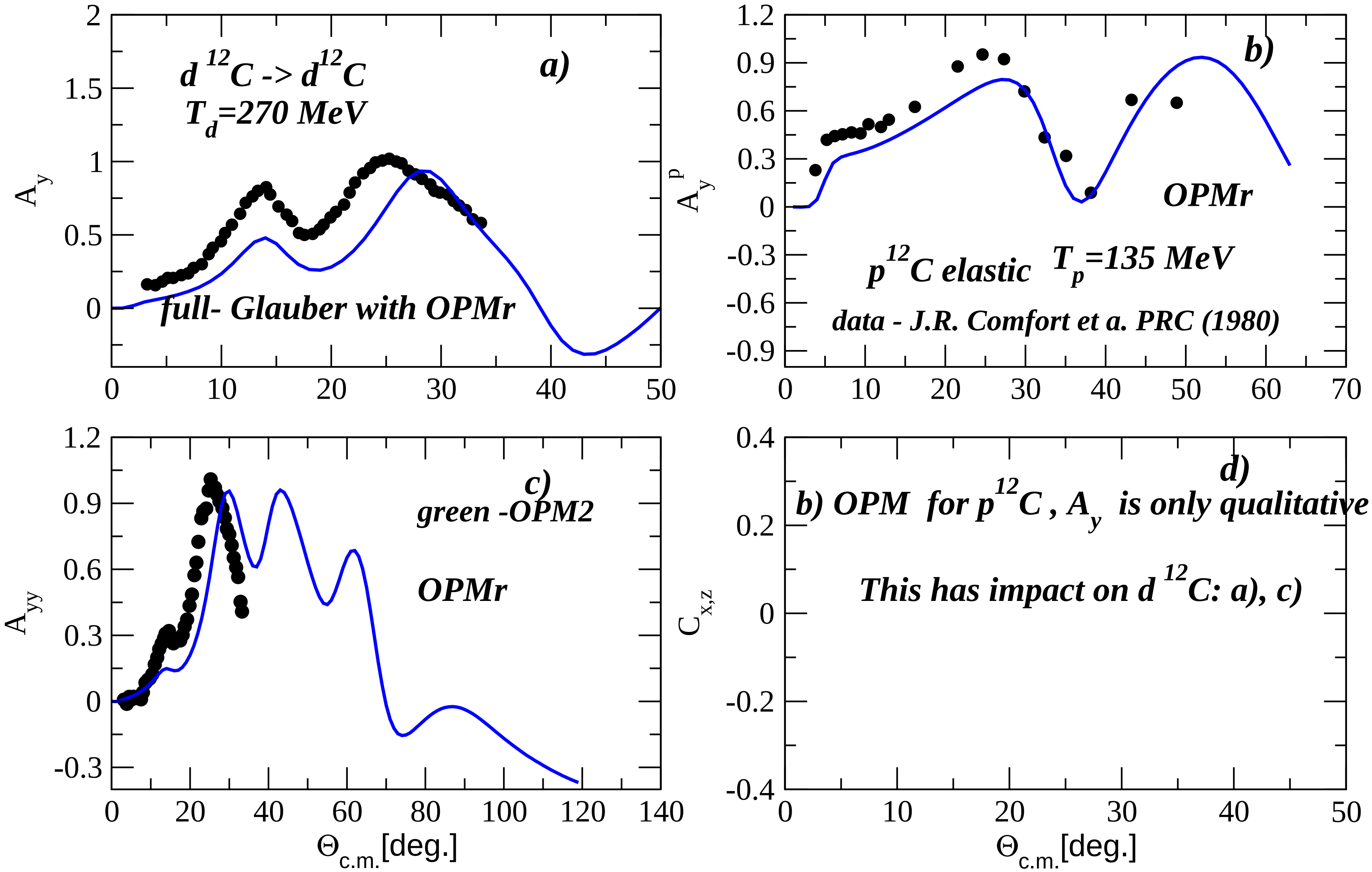
E.T. Ibraeva, Yu.N. Uzikov, Phys.At. Nucl. **81** (2018) 479 [Yad.Fiz. 81(2018) 451]

Glauber theory with the OPM for $N^{12}C$-elastic -II



E.T. Ibraeva, Yu.N. Uzikov, Phys.At. Nucl. **81** (2018) 479

Glauber theory with the OPM for $N^{12}C$-elastic -III



SUMMARY and OUTLOOK

- The cross section of the inclusive reaction $d +^{12} C \to p(0^\circ) + X$ is calculated within the IA at $T_d = 270$ MeV.

- $pd \to dp$**:**
  Agreement between the Glauber theory (full spin-dependence of the NN plus Coulomb) and the $pd \to pd$ data on $d\sigma/d\Omega$, A_y, $C_{y,y}$, $C_{xz,y}$ at energy 135 MeV is obtained in forward hemisphere.

- The same approach is used at these energies for the processes $d^{12}C \to d^{12}C$ with a similar accuracy of calculations.
  The first results for $d^{12}C \to d^{12}C$ elastic are encouraging.

- **Next step:**
  ⋆ Improve OPM for A_y in $p^{12}C \Longrightarrow A_y$, A_{yy} in $d^{12}C$.
  ⋆ Apply the full Glauber calculation to $p^{12}C$, $n^{12}C$ and then
  $\Longrightarrow d^{12}C \to d^{12}C$ and $d^{12}C \to \{pn\} +^{12} C$ with $E_{pn} = 0 - 5$ MeV.
  ⋆ Consider lower energies $T_p = 70 - 100$ MeV of the proton beam.

THANK YOU FOR ATTENTION!