Towards Theory of Deuteron-Carbon Scattering

Yuriy Uzikov
Joint Institute for Nuclear Research, Dubna, Russia

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- Motivation:

  Polarimetry for EDM measurements

  Andro: "We have to know what is what in the $d^{12}C$ elastic scattering"

  Gogi: "We have to know the $d^{12}C$ breakup x-section"

  Iraklii: "... and figure of merit, for different E and A"

  Yu. Senichev: " Lower energies are more preferable"
- Numerical results for $d^{12}C \to p(0) + X$ within the IA
- Capability of the Glauber model

  for the $\vec{p}\vec{d} \to pd$ at $\sim$ 100-200 MeV
- $\vec{d}\,^{12}C$- elastic scattering within the Glauber theory
- Plans to Future

$d^{12}C \to p(0) + X$ 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".

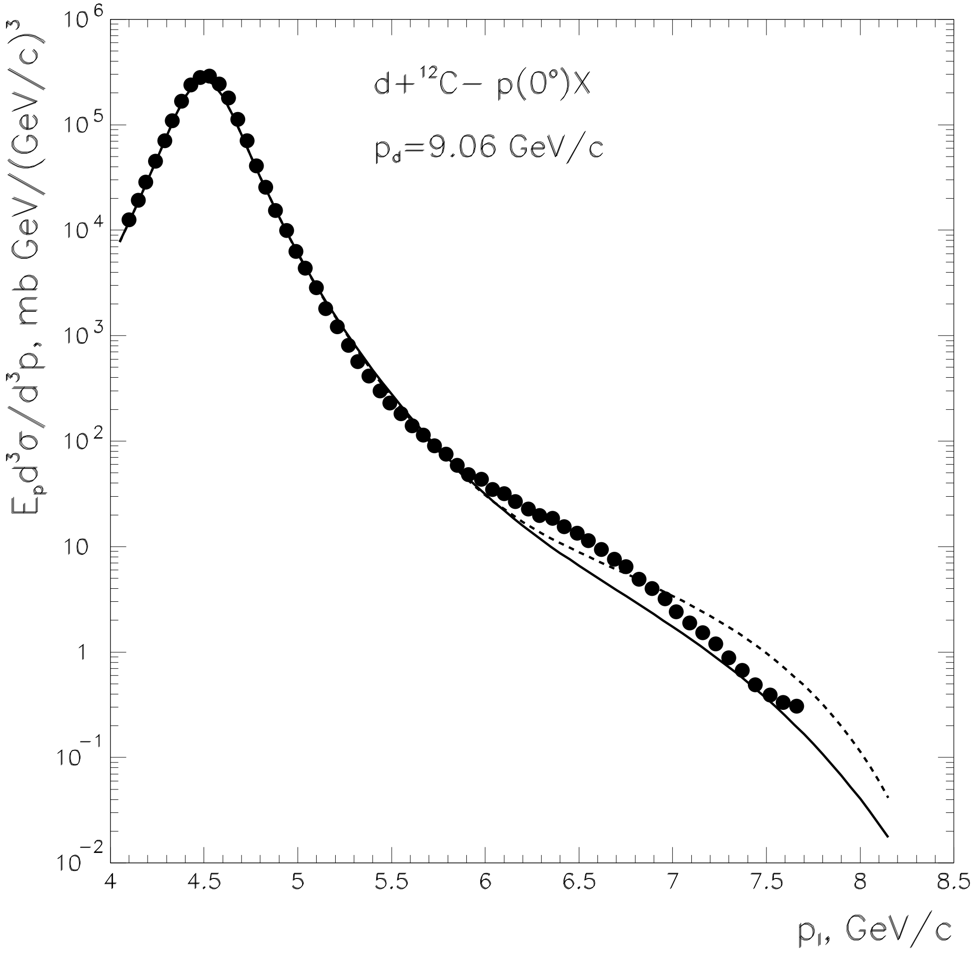
In practice after some approximations $\Longrightarrow$ impulse approximation /A.P. Kobushkin, L. Vizireva, J Phys. G8, 893 (1982)/

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.



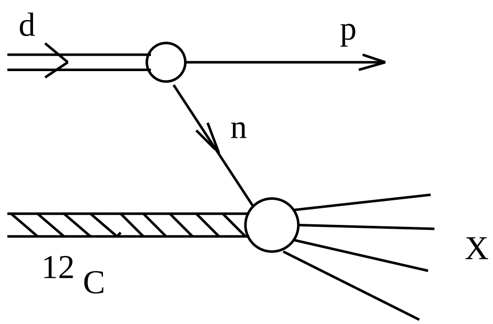
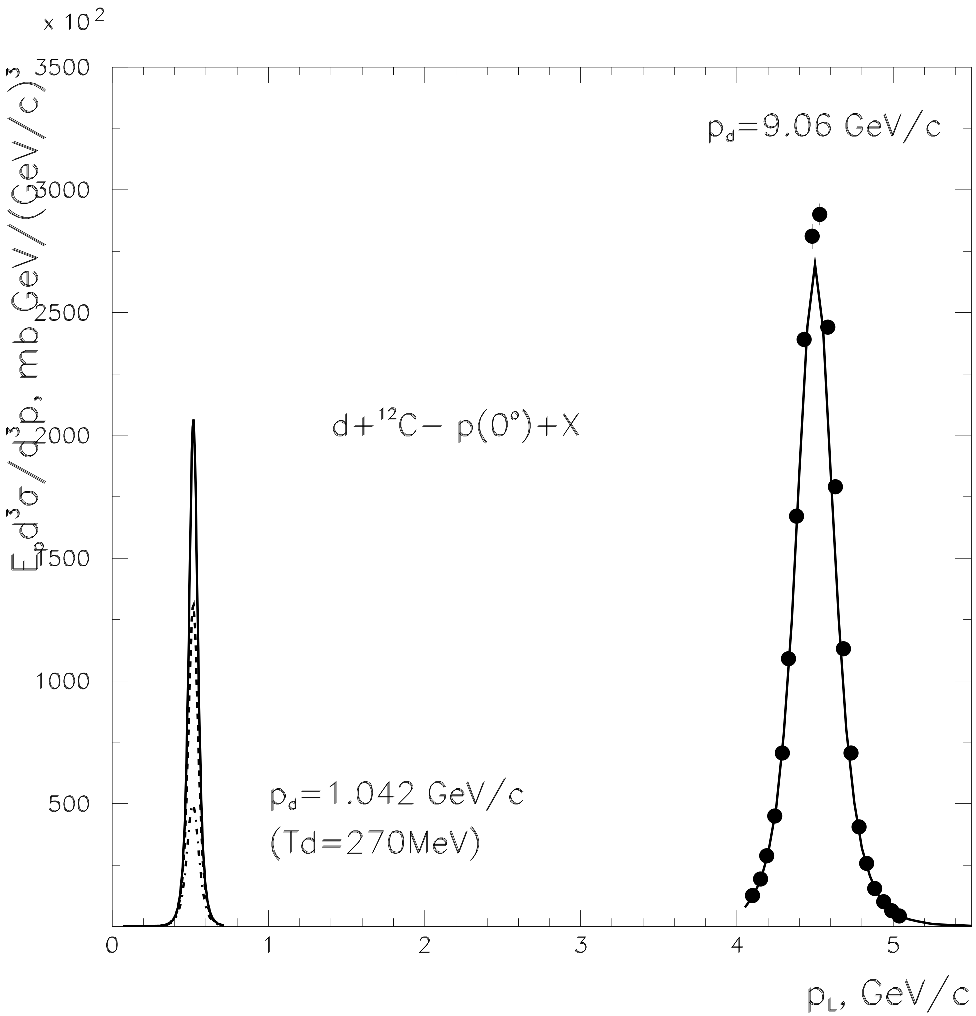
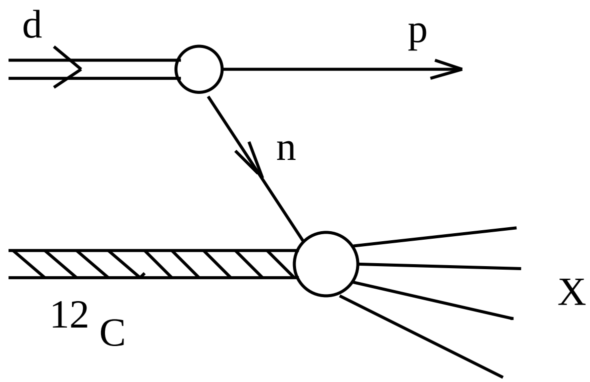


Figure 1: The invariant cross section of the reaction $d +^{12} C \to p(0^\circ)$ X), at $p_d = 9.06$ GeV/c (V. Ableev, 1991) versus lab. momentum of the final proton in comparison with the IA for the CD Bonn (dashed) and Paris (full) d.w.f.

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



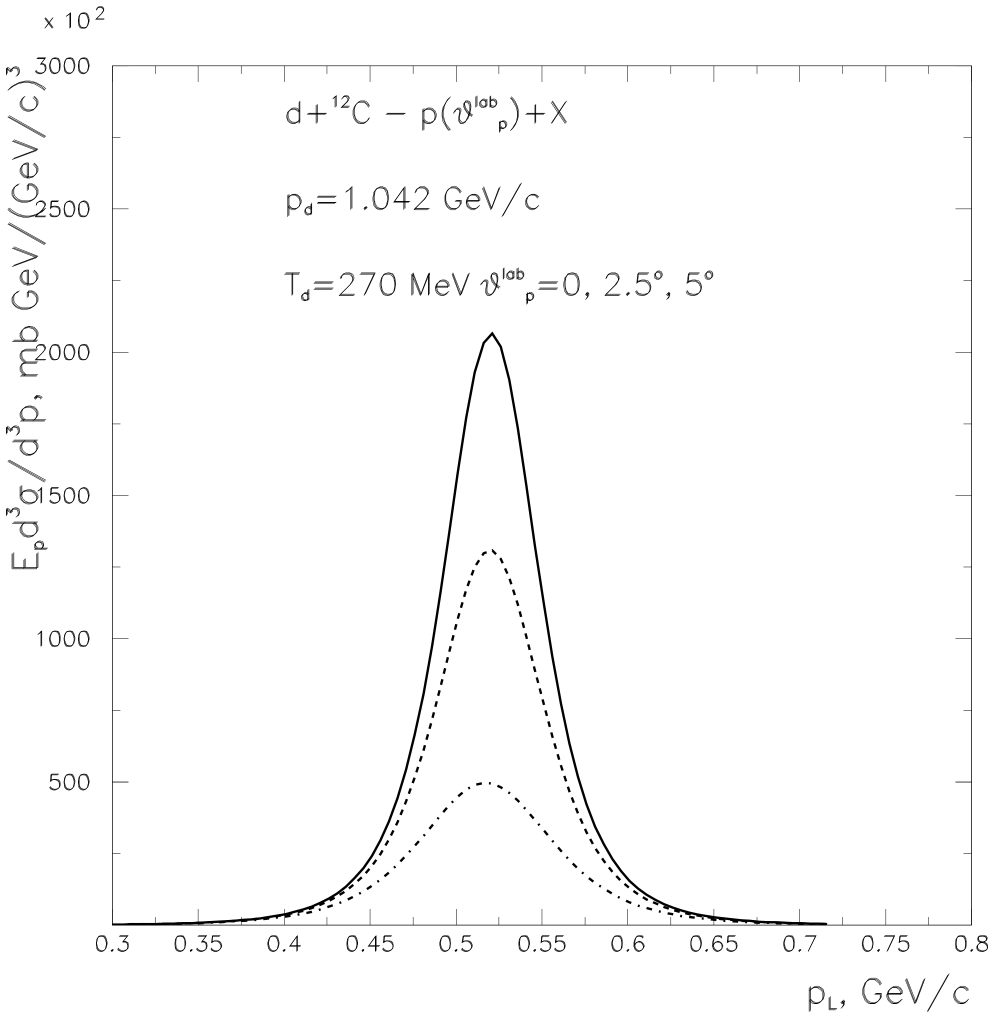


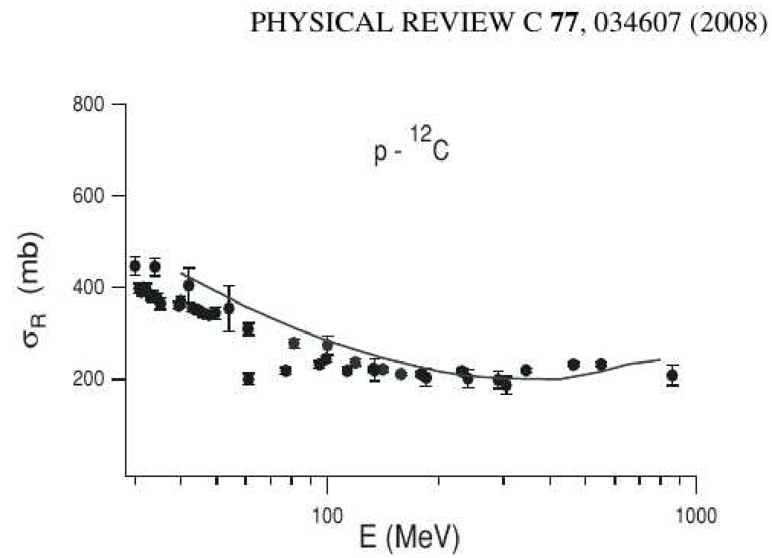
Curves: the IA calculation

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

$\sigma_{tot}^{R}(n^{12}C \to X) = 260$ mb, from B.Abu-Ibrahim et al. Phys. Rev. C 77, 034607 (20098)

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





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

$\sigma_{tot}^R(n^{12}C \to X) = 260$ mb, B.Abu-Ibrahim et al. PRC 77, 034607 (20098)

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

$(2+1)^2(2\frac{1}{2}+1)^2 = 36$ 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. ($Z \upuparrows \hat{\mathbf{k}}$, $X \upuparrows \hat{\mathbf{q}}$ $Y \upuparrows \hat{\mathbf{n}}$)

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

– –

$$+(T_{13} + T_{14}\boldsymbol{\sigma}\hat{\mathbf{n}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{q}}) + (\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{k}})\right] + T_{15}(\boldsymbol{\sigma}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{k}}) + T_{16}(\boldsymbol{\sigma}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{q}}) +$$
$$T_{17}(\boldsymbol{\sigma}\hat{\mathbf{k}})\left[(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})\right] + T_{18}(\boldsymbol{\sigma}\hat{\mathbf{q}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})\right]$$

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

$T_{13} \div T_{18}$ to TRIC

The polarized elastic differential pd cross section

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

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

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

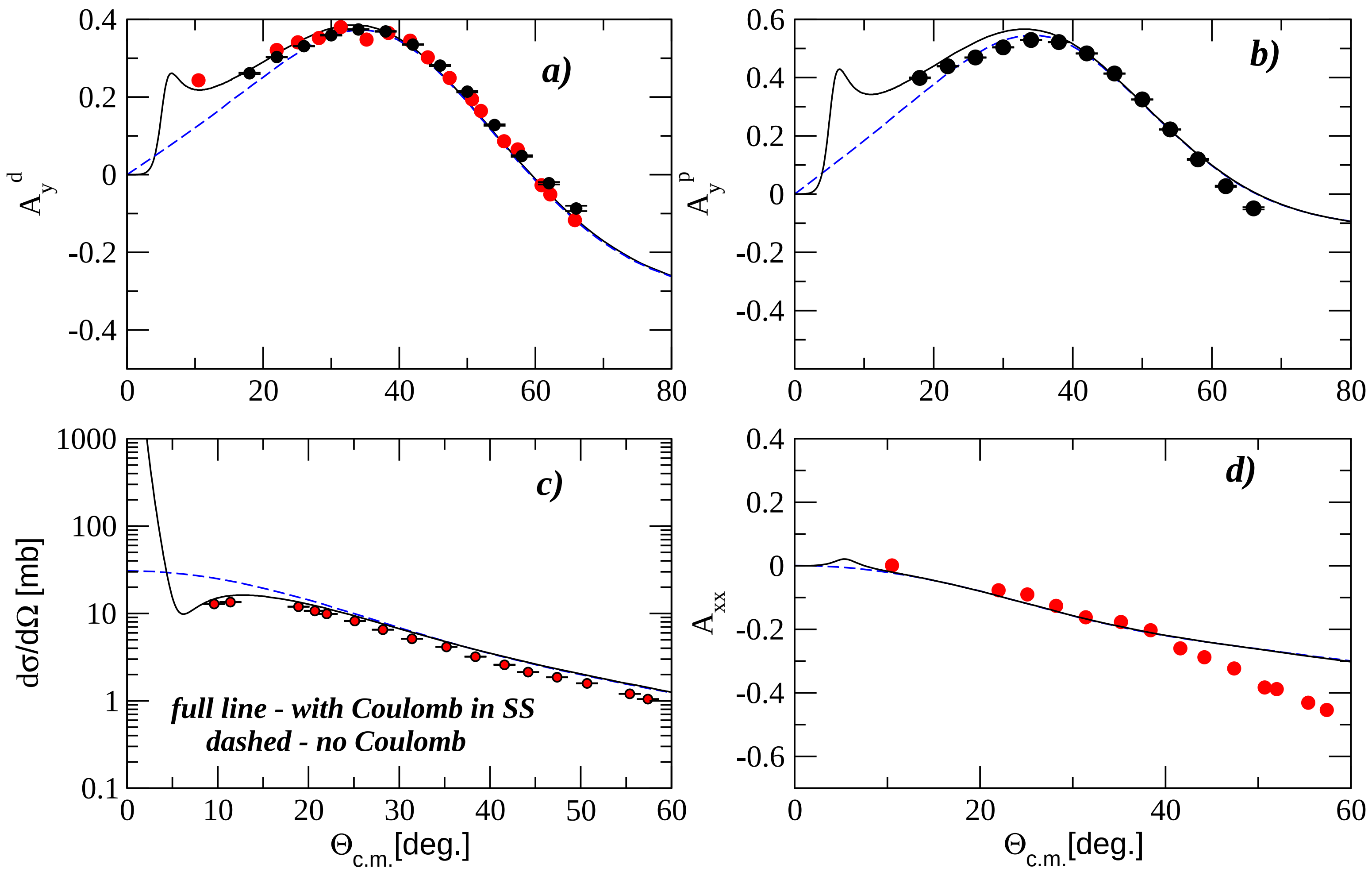
On-shell elastic pN scattering amplitude (**T-even, P-even**, from SAID)

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

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

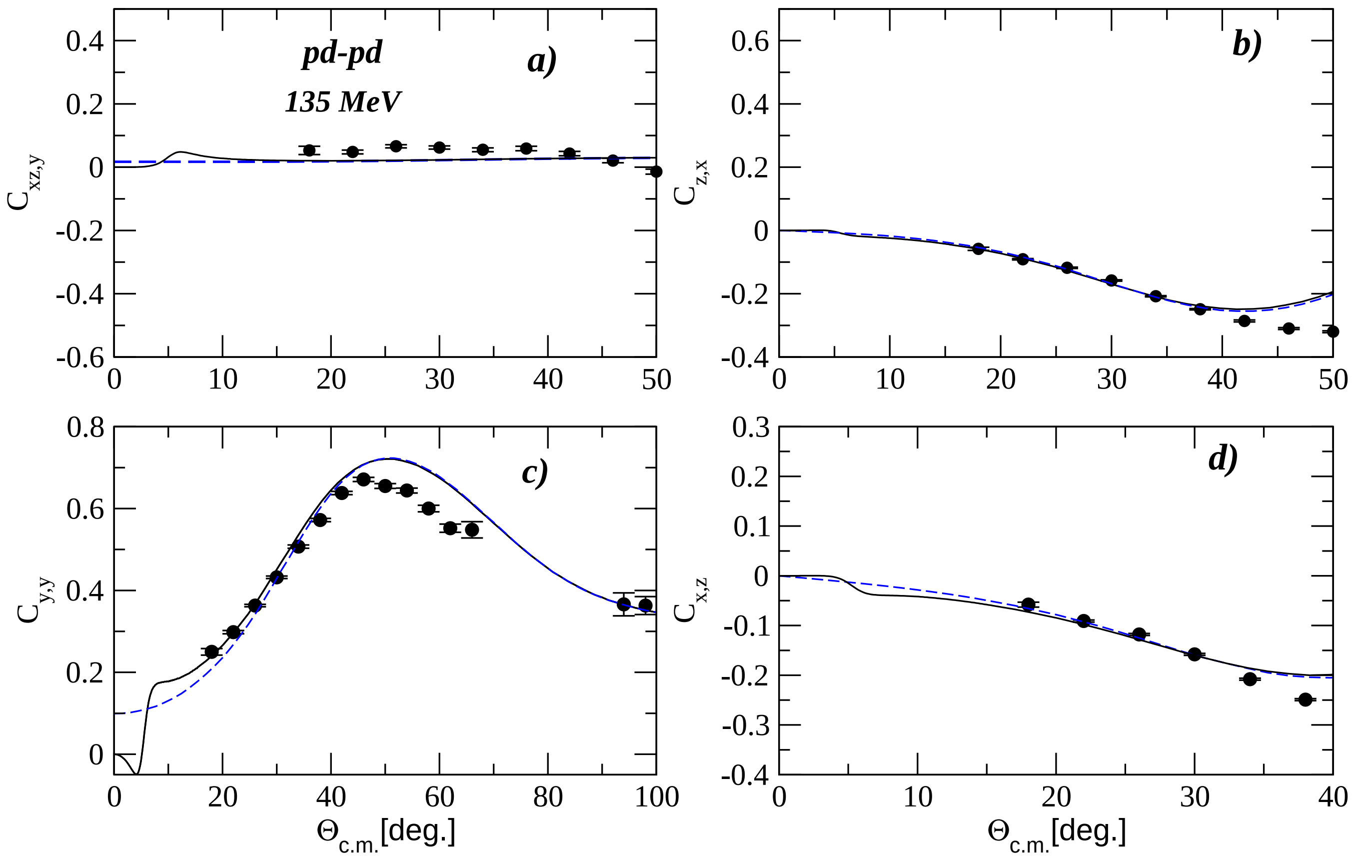
A.A. Temerbayev, Yu.N. Uzikov, Yad. Fiz. **78** (2015) 38 [Phys. At. Nucl. 78 (2015) 35]



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.

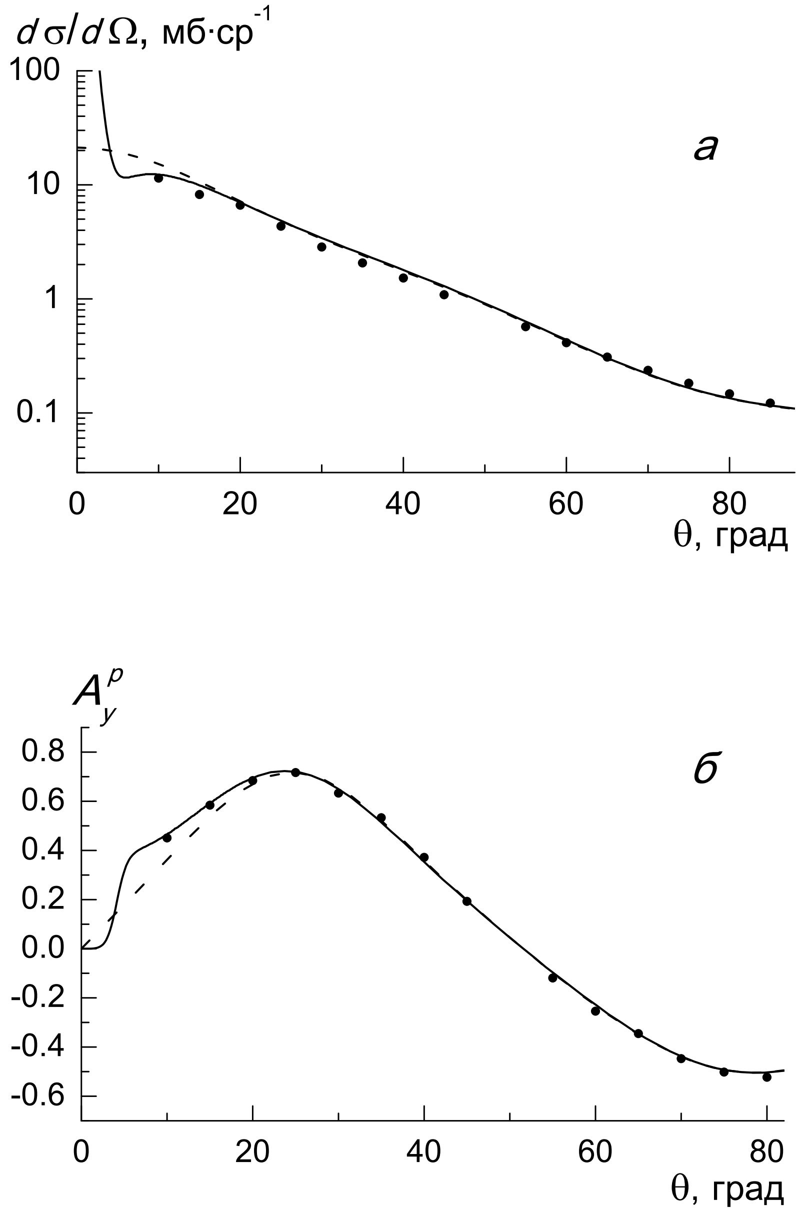
Test calculations-II: pd elastic scattering at 135 MeV

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)).

Test calculations-III: pd elastic scattering at 250 MeV. Yad.Fiz 78 (2015)



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

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

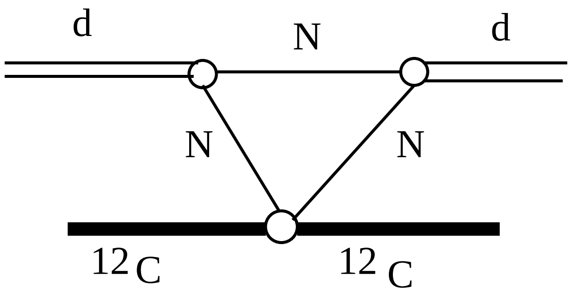
$$T_{fi} = e_\beta^{(\lambda')^*} T_{\beta\alpha}(\mathbf{k}, \mathbf{k}') e_\alpha^{(\lambda)} \tag{4}$$

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

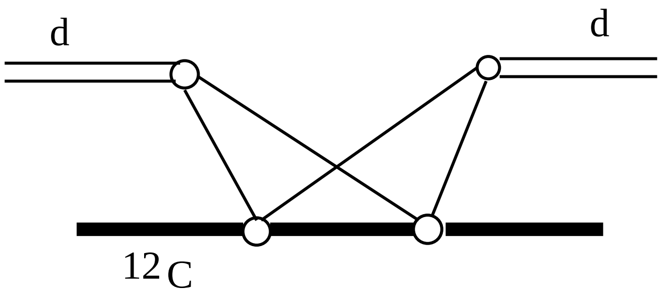
T-invariance:

$$\mathbf{D} = \mathbf{E}$$

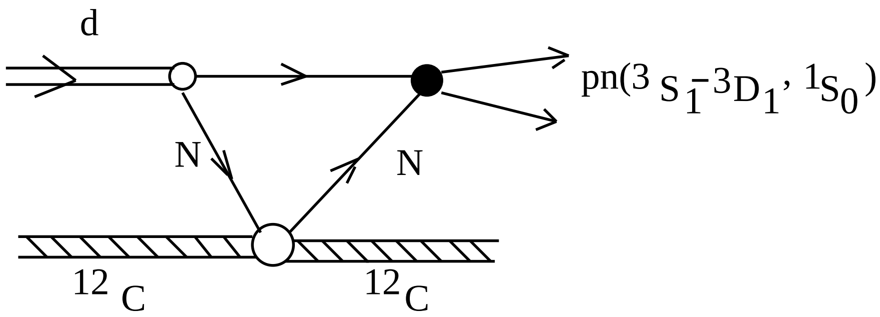
SS and DS mechanisms in the Glauber theory



SS



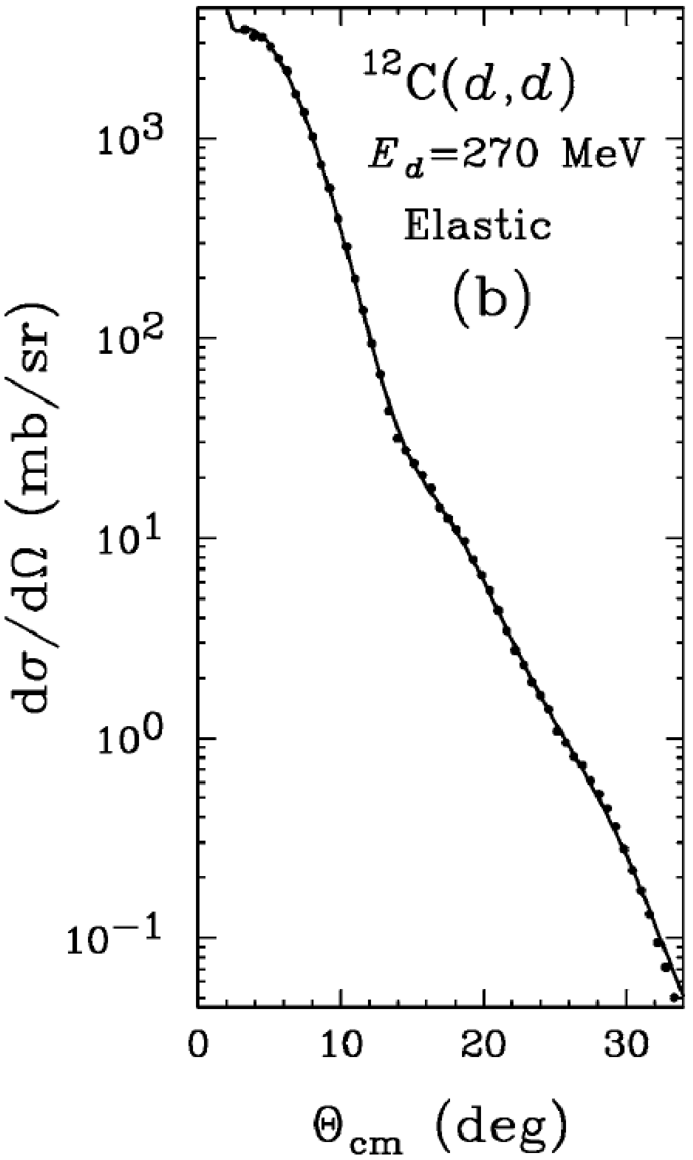
DS

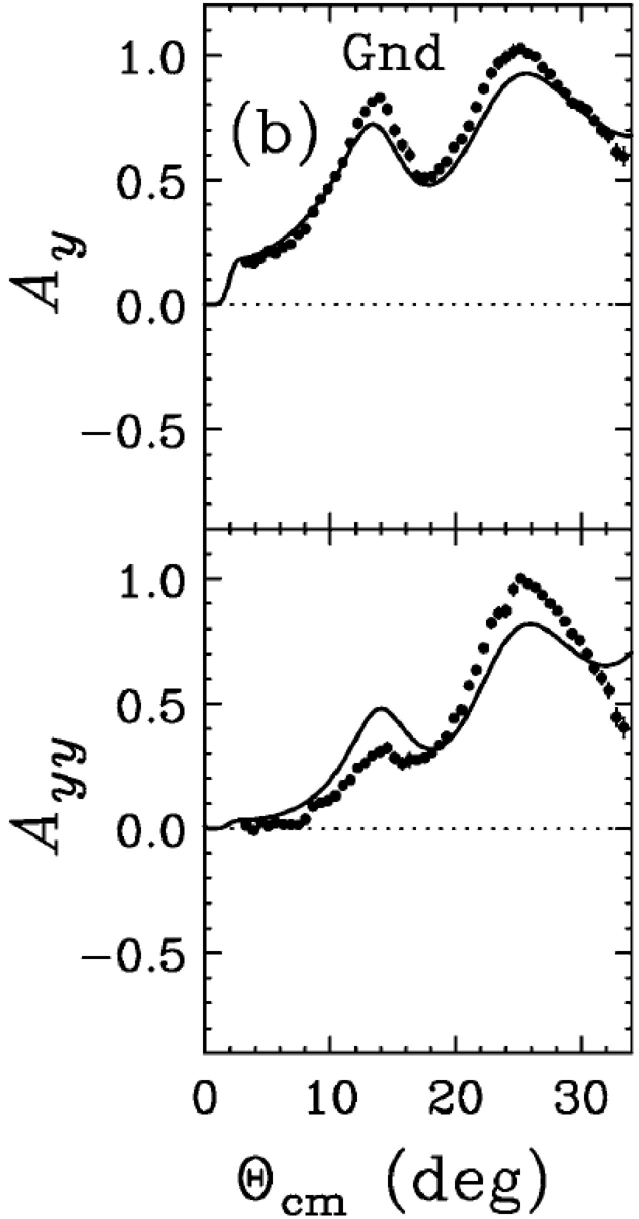


The Glauber formalism
as a modification of the $dp \to dp$:
$Np \to Np$ on-shell $\Longrightarrow n^{12}C$ on-shell elastic

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

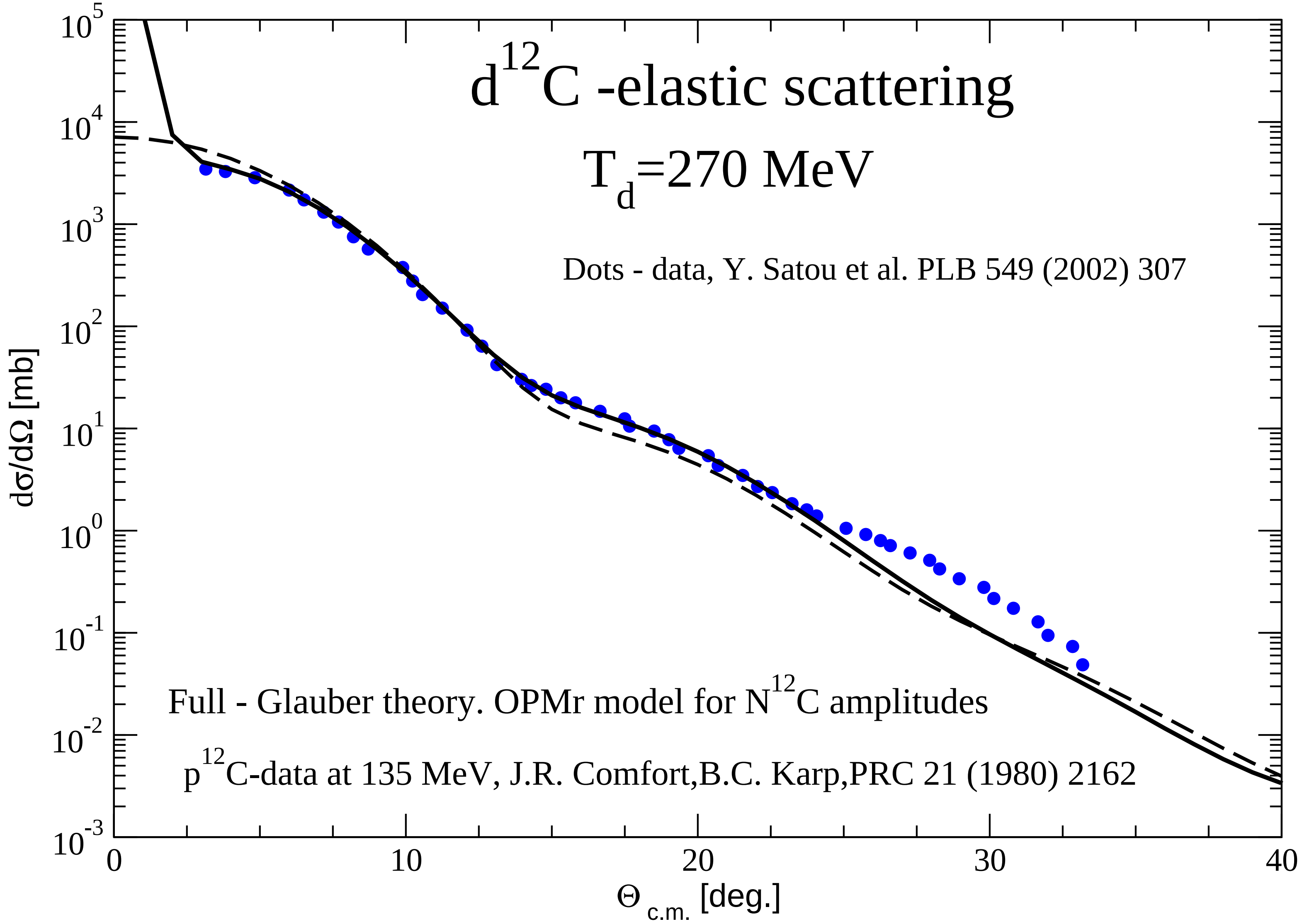
[1]. I. Satou et al. Phys.Lett.B 549 (2002) 307: $^{12}C(d,d')$at 270 MeV

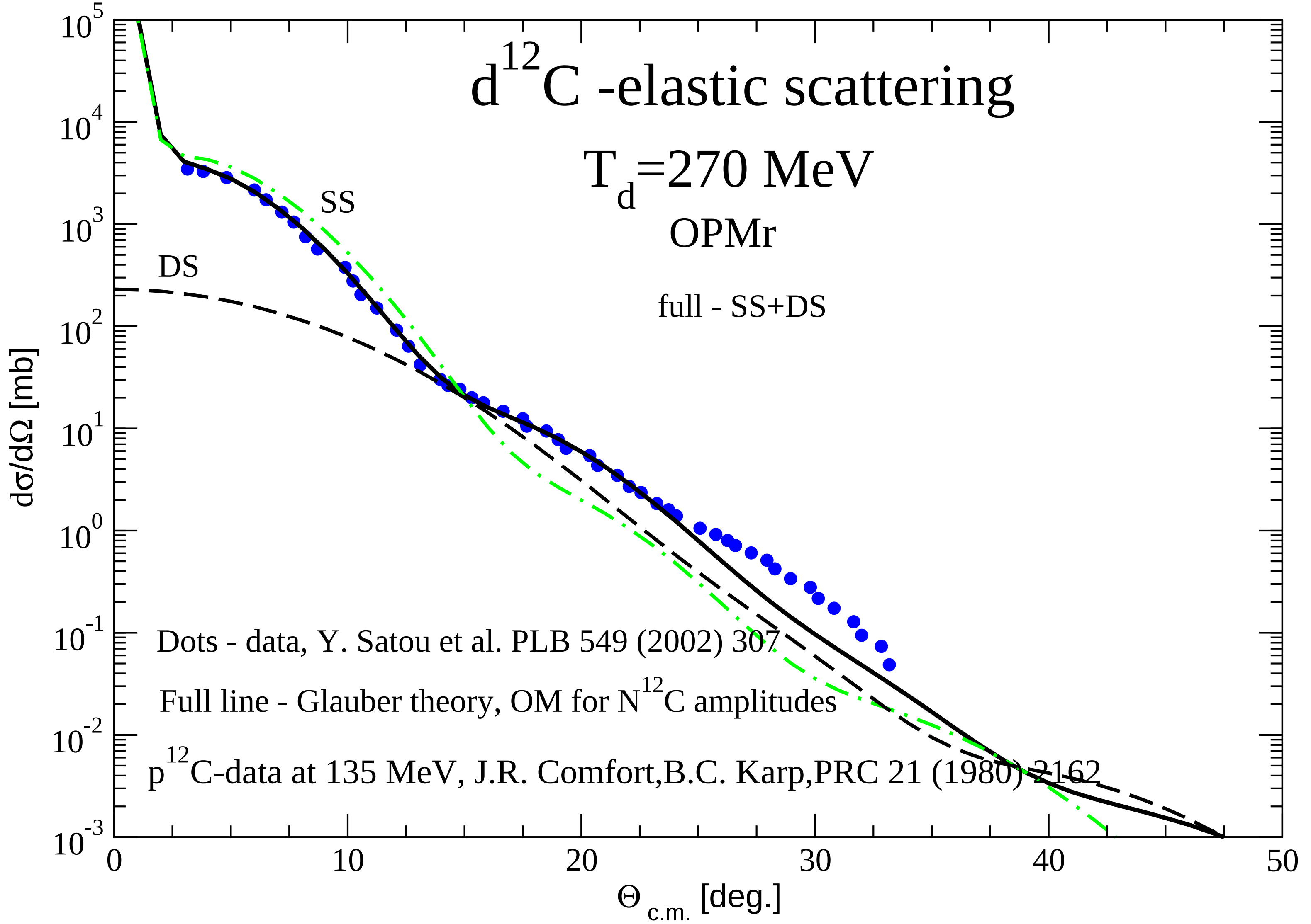




FIT: Only optical model was applied to the (elastic) existing data in Ref.[1].

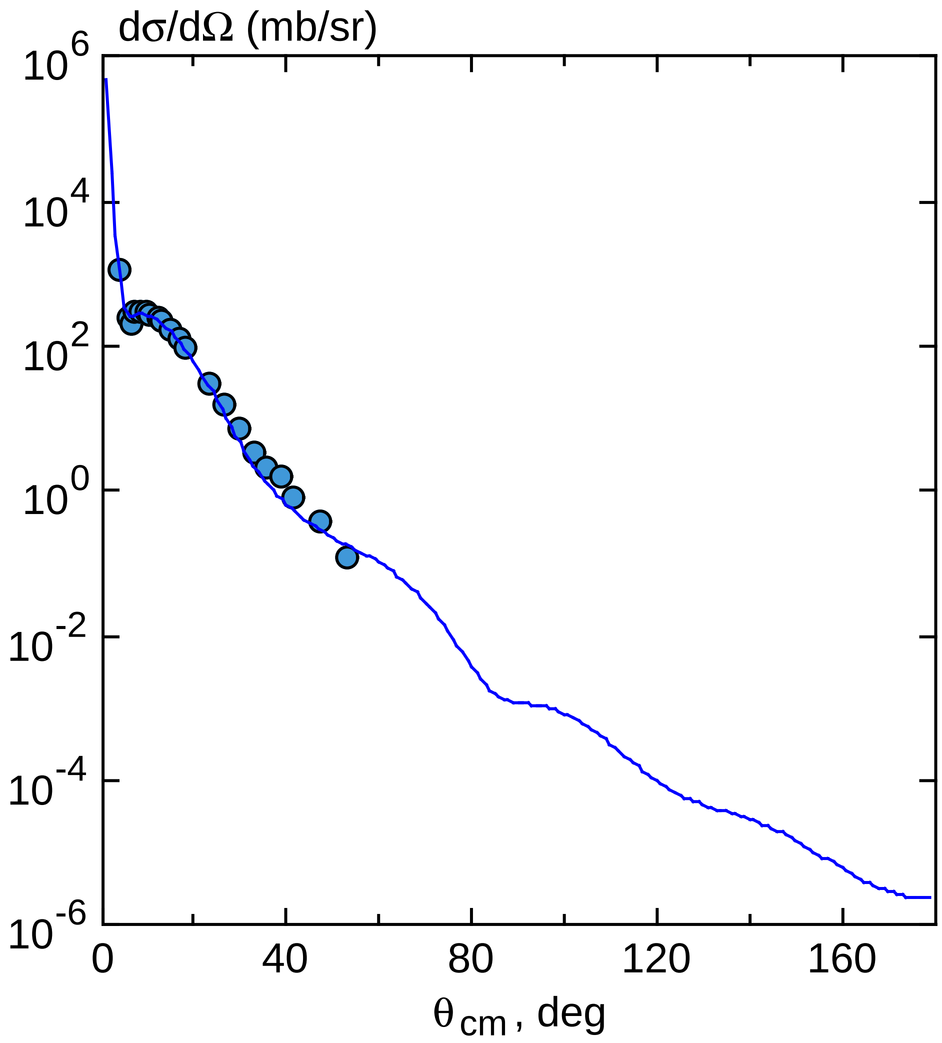
Glauber theory with the OPM for $N^{12}C$-elastic-I





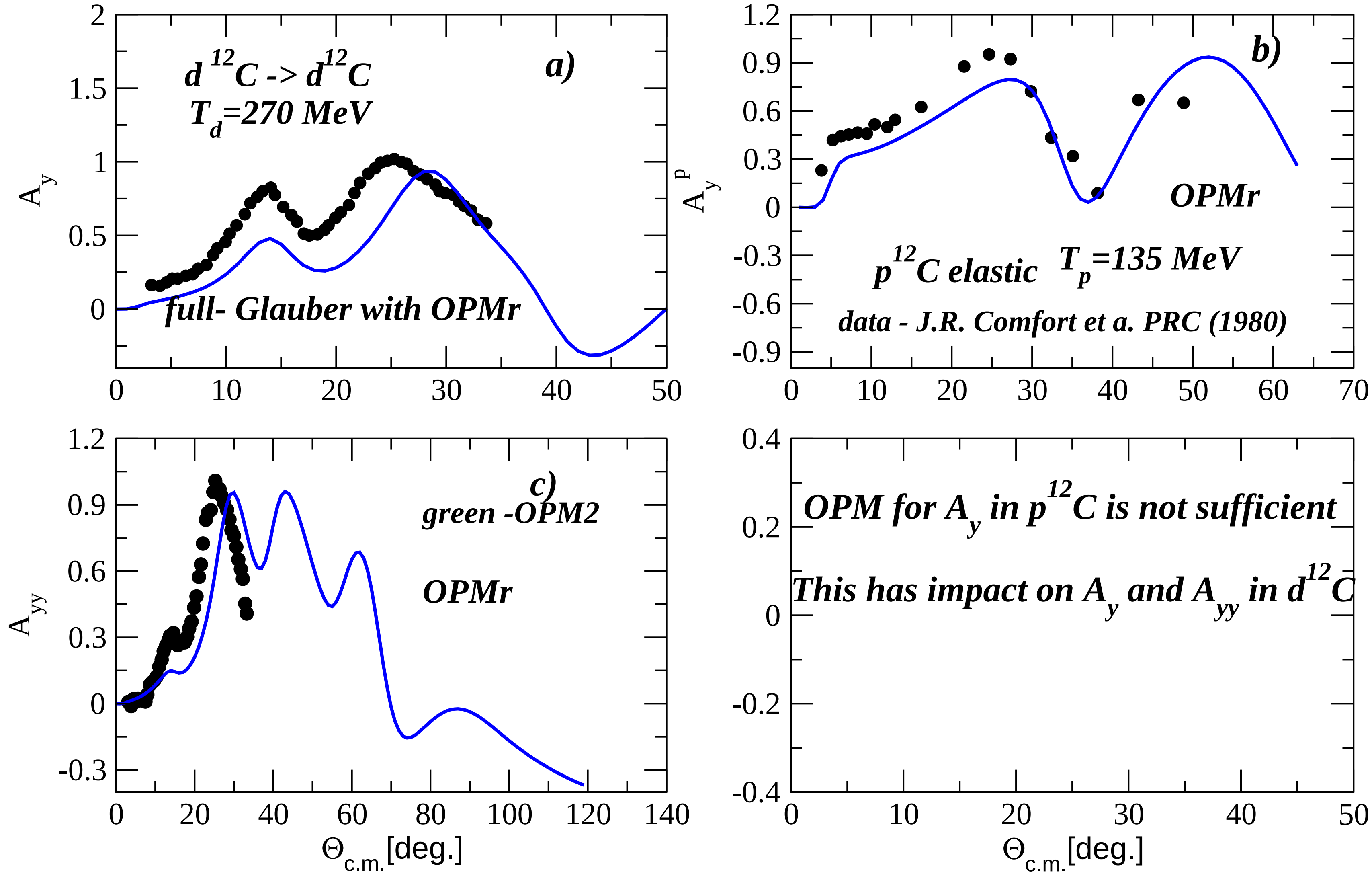
d12C -elastic scattering
Td=270 MeV
OPMr
full - SS+DS
SS
DS
Dots - data, Y. Satou et al. PLB 549 (2002) 307
Full line - Glauber theory, OM for N12C amplitudes
p12C-data at 135 MeV, J.R. Comfort,B.C. Karp,PRC 21 (1980) 2162
dσ/dΩ [mb]
Θ c.m. [deg.]

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



mbox

Glauber theory for $d^{12}C$ -III



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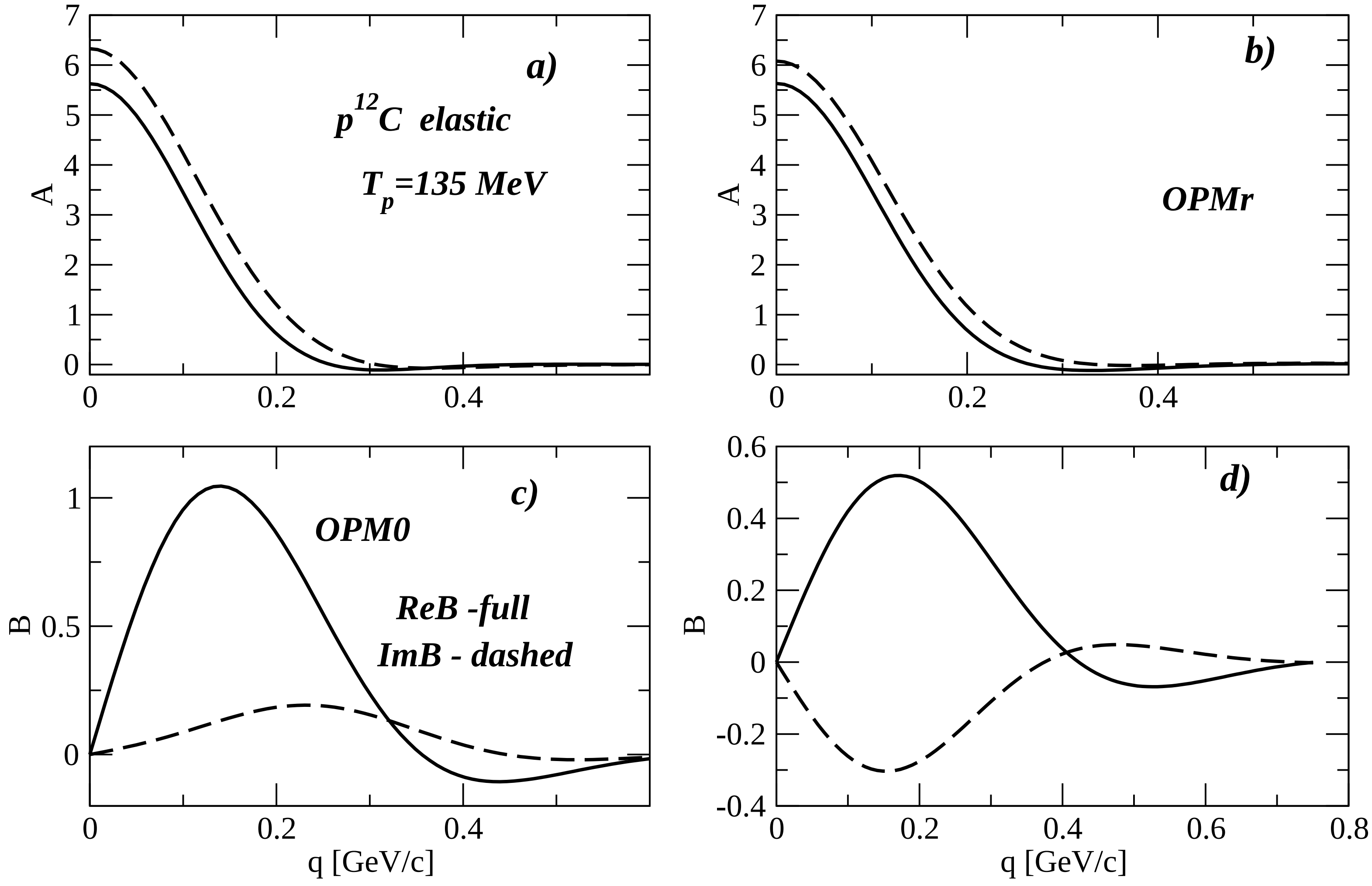
$$F = A + iB\mathbf{n}\boldsymbol{\sigma}$$



- 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 T-even,P-even 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 can be 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.

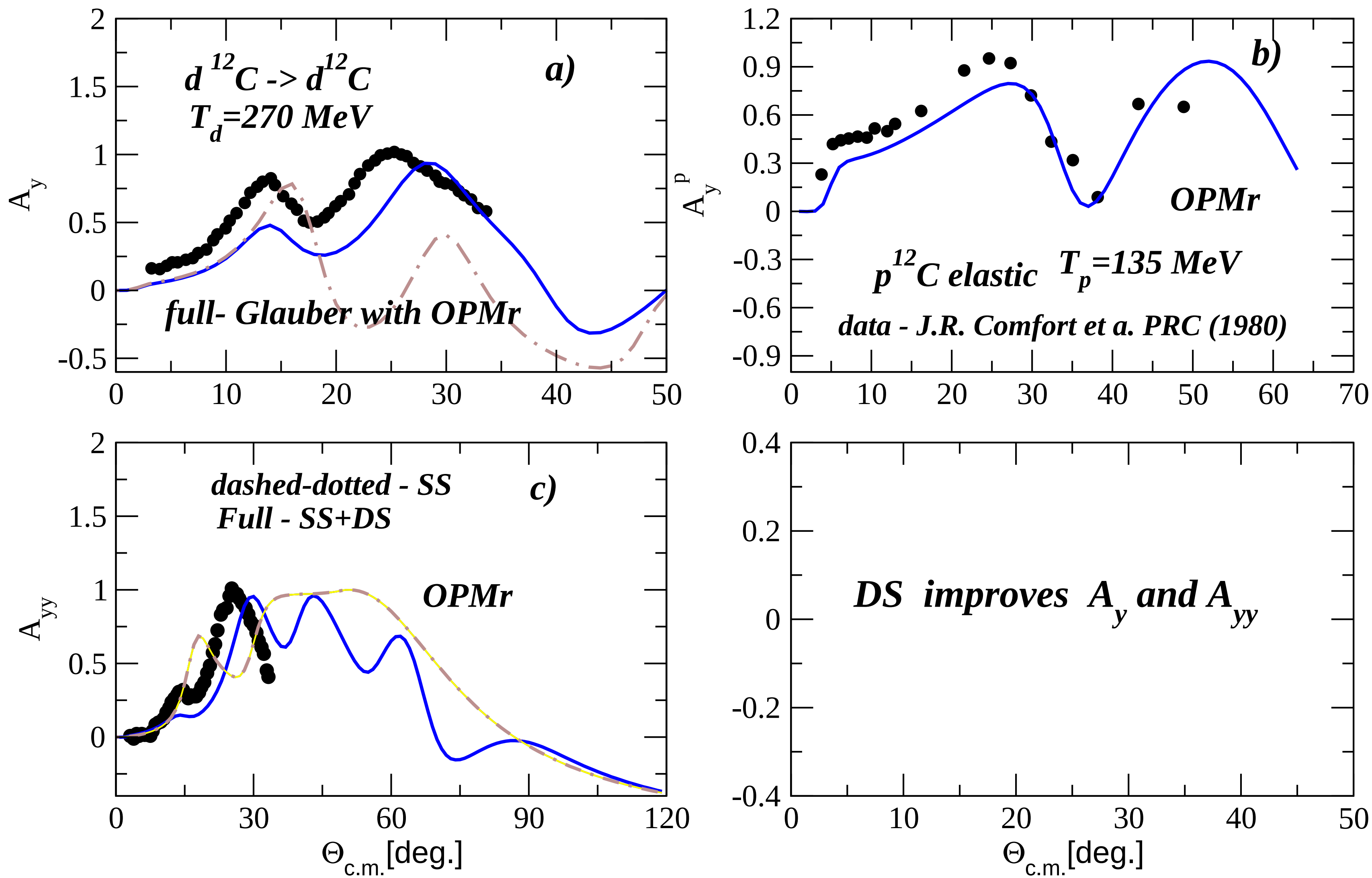
- **Next step:**
  ⋆ Improve OPM for A_y in $p^{12}C \Longrightarrow A_y$, A_{yy} in $d^{12}C$.
  ⋆ Apply the full Glauber calculation to $p^{12}C$, $n^{12}C$ and then
  $\Longrightarrow d^{12}C \to d^{12}C$ and $d^{12}C \to \{pn\} +^{12} C$ with $E_{pn} = 0 - 5$ MeV.
  ⋆ Consider lower energies $T_p = 50 - 120$ MeV of the proton beam.

THANK YOU FOR INVITATION

and

ATTENTION!

SS+DS in comparision with SS: Glauber theory with the OPM for $N^{12}C$



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