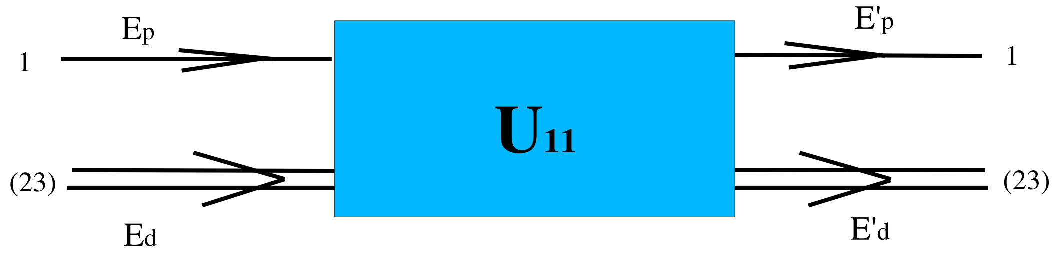
N.B. Ladygina

Deuteron-proton elastic scattering at intermediate energies

- $dp \rightarrow dp$ reaction is considered at the deuteron kinetic energy from 500 MeV up to 1200 MeV.
- The theoretical model is suggested to describe differential cross sections and polarization observables in this energy range.
- The calculation results are presented in comparison with the data.

dp-elastic scattering



The matrix element of the transition operator U_{11} defines reaction amplitude

$$U_{dp\to dp} = \delta(E_d + E_p - E'_d - E'_p)\mathcal{J} =< 1(23)|[1 - P_{12} - P_{13}]U_{11}|1(23) >$$

Alt-Grassberger-Sandhas equations for rearrangement operators:

$$\begin{aligned} U_{11} &= t_2 g_0 U_{21} + t_3 g_0 U_{31} \\ U_{21} &= g_0^{-1} + t_1 g_0 U_{11} + t_3 g_0 U_{31} \\ U_{31} &= g_0^{-1} + t_1 g_0 U_{11} + t_2 g_0 U_{21} \end{aligned}$$

Iterating AGS-equations up to second order terms over t one obtains

$$\mathcal{J}_{dp\to dp} \;=\; \mathcal{J}_{ONE} + \mathcal{J}_{SS} + \mathcal{J}_{DS}$$

One-Nucleon-Exchange

$$\mathcal{J}_{ONE} = -2 < 1(23)|P_{12}g_0^{-1}|1(23) >$$

Single-Scattering

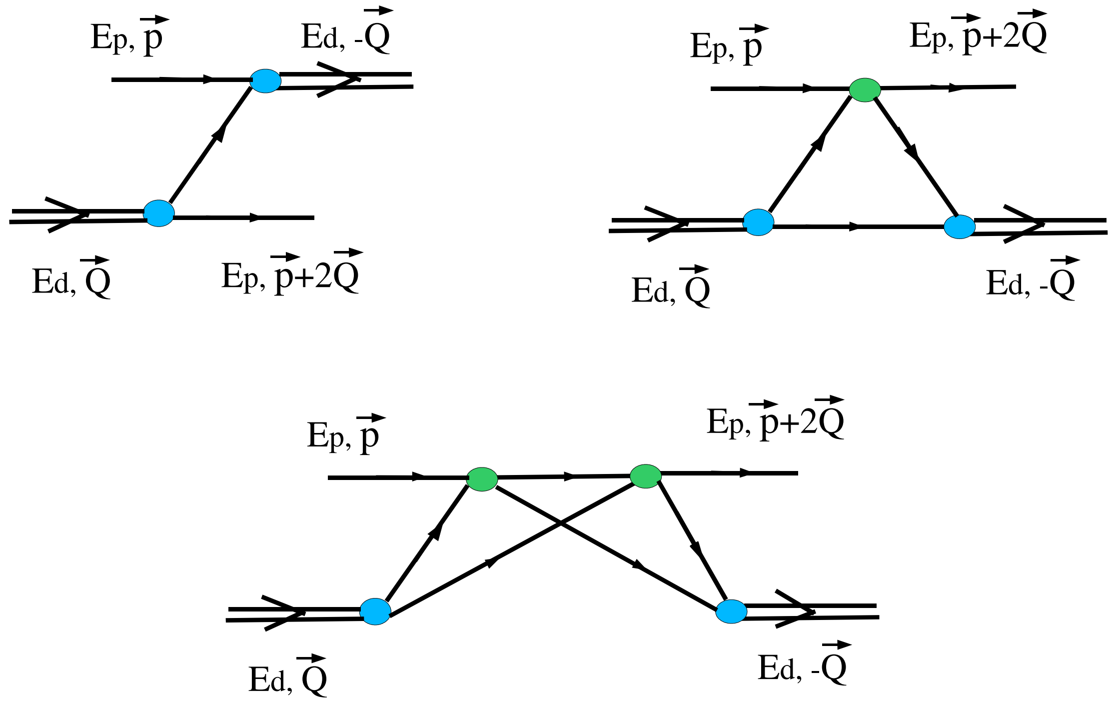
$$\mathcal{J}_{SS} = 2 < 1(23)|t_3^{sym}|1(23) >$$

Double-Scattering

$$\mathcal{J}_{DS} = 2 < 1(23)|t_3^{sym} g_0 t_2^{sym}|1(23) >,$$

where notations for antisymmetrized operators have been introduced

$t_2^{sym} = [1 - P_{13}]t_2$ **and** $t_3^{sym} = [1 - P_{12}]t_3$.



Ep, $\vec{p}$
Ed, -$\vec{Q}$
Ed, $\vec{Q}$
Ep, $\vec{p}$+2$\vec{Q}$
Ep, $\vec{p}$
Ep, $\vec{p}$+2$\vec{Q}$
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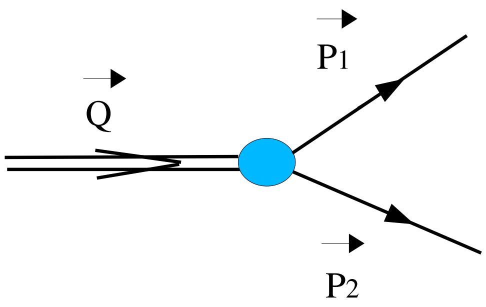


Lorenz transformation

$$L(\vec{u})p_1 = (E^*, \vec{p})$$
$$L(\vec{u})p_2 = (E^*, -\vec{p})$$

with velocity

$$\vec{u} = \frac{\vec{p}_1 + \vec{p}_2}{E_1 + E_2}$$

The c.m. energy of one of the nucleons E^* is related with Mandelstam variable s by

$$E^* = \sqrt{s}/2 \quad .$$

Let's introduce new variables $\vec{Q}$ and $\vec{k}$ which can be expressed through $\vec{p}_1$ and $\vec{p}_2$

$$\vec{Q} = \vec{p}_1 + \vec{p}_2$$
$$\vec{k} = \frac{(E_2 + E^*)\vec{p}_1 - (E_1 + E^*)\vec{p}_2}{E_1 + E_2 + 2E^*} \quad .$$

A two-nucleon state in the $(\vec{p}_1, \vec{p}_2)$ system is connected with a two-nucleon state in the center-of-mass by the relation

$$|\vec{p}_1, \vec{p}_2 >= J^{-1/2}(\vec{p}_1, \vec{p}_2) W_{1/2}(\vec{p}_1, \vec{u}) W_{1/2}(\vec{p}_2, \vec{u}) |\vec{k}, \vec{Q} > \quad ,$$

where $W_{1/2}$ Wigner rotation operator

$$W_{1/2}(\vec{p}_i, \vec{u}) = exp\left\{-i\omega_i(\vec{n}_i\vec{\sigma}_i)/2\right\} = cos(\omega_i/2)[1 - i(\vec{n}_i\vec{\sigma}_i)tg(\omega_i/2)]$$

The wave function of the bound state transforms in the same way as the state of a single particle

$$W(L_{\vec{u}'})|\vec{P} >= \sqrt{\frac{E_{\vec{Q}}}{E_{\vec{P}}}} \; W_1(\vec{Q}, \vec{u}')|\vec{Q} > \quad ,$$

where the W_1 is the Wigner rotation operator for spin 1 particle

$$W_1(\vec{Q}, \vec{u}') = exp\left\{-i\omega(\vec{n}'\vec{S})\right\}$$

and

$$L(\vec{u}')\vec{P} = \vec{Q}$$

The deuteron wave function in the rest has the standard form

$$< m_p m_n|\Omega_d|\mathcal{M}_d >= \frac{1}{\sqrt{4\pi}} < m_p m_n| \left\{ u(k) + \frac{w(k)}{\sqrt{8}}[3(\vec{\sigma}_1\hat{k})(\vec{\sigma}_2\hat{k}) - (\vec{\sigma}_1\vec{\sigma}_2)] \right\} |\mathcal{M}_d >$$

$u(k)$ and $w(k)$ - $S-$ and $D-$ components of the deuteron.

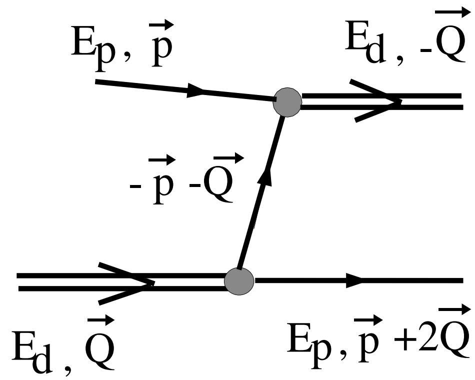
Then the deuteron wave function in the moving frame is

$$< \vec{p}_1\ \vec{p}_2, m_1 m_2|\Omega_d|\vec{Q}, \mathcal{M}_d > \ \sim\ < \vec{k}\vec{Q}, m_1' m_2'|W^{\dagger}_{1/2}(\vec{p}_1, \vec{u})W^{\dagger}_{1/2}(\vec{p}_2, \vec{u})\Omega_d|\vec{0}, \mathcal{M}_d >$$

Deuteron wave function in the moving frame

$$
\begin{aligned}
< \vec{p}_1\, \vec{p}_2, m_1 m_2 | \Omega_d | \vec{Q}, \mathcal{M}_d > \;=\; & < \vec{p}_1\, \vec{p}_2, m_1 m_2 | g_1(\vec{k}, \vec{Q}) + g_2(\vec{k}, \vec{Q})(\vec{\sigma}_1 \vec{n})(\vec{\sigma}_2 \vec{n}) + \\
& + \; g_3(\vec{k}, \vec{Q})(\vec{\sigma}_1 \vec{\sigma}_2) + g_4(\vec{k}, \vec{Q})(\vec{\sigma}_1 \hat{k})(\vec{\sigma}_2 \hat{k}) + \\
& + \; g_5(\vec{k}, \vec{Q})[(\vec{\sigma}_1 + \vec{\sigma}_2)\vec{n}] + \\
& + \; g_6(\vec{k}, \vec{Q})[(\vec{\sigma}_1 \hat{k})(\vec{\sigma}_2 \vec{n} \times \hat{k}) + (\vec{\sigma}_1 \vec{n} \times \hat{k})(\vec{\sigma}_2 \hat{k})] | \vec{Q}, \mathcal{M}_d >
\end{aligned}
$$

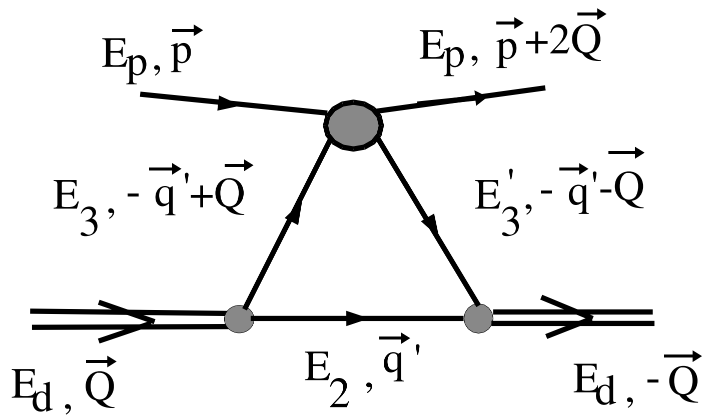
g_i are combinations of the $S-$ and $D-$ components of the deuteron wave function (u and w)



(a)

One nucleon exchange scattering

$$\mathcal{J}_{ONE} = -\frac{1}{2}(E_d - E_p - \sqrt{m_N^2 + \vec{p}^{\,2} - \vec{Q}^2}) \cdot$$
$$< \vec{p}' m'; -\vec{Q}\mathcal{M}'_d | \Omega_d^\dagger(23)[1 + (\vec{\sigma}_1 \vec{\sigma}_2)]\Omega_d(23)|\vec{Q}\mathcal{M}_d; \vec{p} m >$$



(b)

Single scattering

$$\mathcal{J}_{SS} \;=\; \int d\vec{q}\,' < -\vec{Q}\mathcal{M}'_d|\Omega^{\dagger}_d|\vec{q}\,'m'', -\vec{Q}-\vec{q}\,'m'_3 >$$

$$< \vec{p}\,'m', -\vec{Q}-\vec{q}\,'|\frac{3}{2}t^1_{12}+\frac{1}{2}t^0_{12}|\vec{p}m, \vec{Q}-\vec{q}\,'m'_2 >< \vec{q}\,'m'', \vec{Q}-\vec{q}\,'m'_2|\Omega_d|\vec{Q}\mathcal{M}_d >$$

Nucleon-Nucleon t-matrix

W.G.Love, M.A.Franey, Phys.Rev.C24, 1073 (1981)

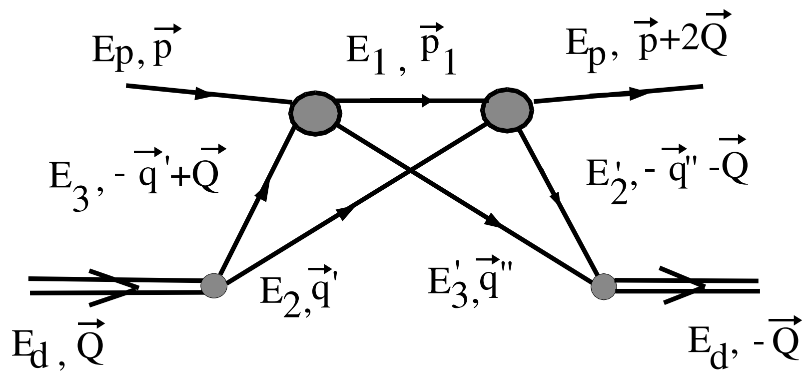
N.B.Ladygina,nucl-th/0805.3021

$$< \kappa' m_1' m_2' | t | \kappa m_1 m_2 > \; = \; < \vec{\kappa}' m_1' m_2' | A + B(\vec{\sigma}_1 \hat{N}^*)(\vec{\sigma}_2 \hat{N}^*) + C(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{N}^* + D(\vec{\sigma}_1 \hat{q}^*)(\vec{\sigma}_2 \hat{q}^*) + F(\vec{\sigma}_1 \hat{Q}^*)(\vec{\sigma}_2 \hat{Q}^*) | \vec{\kappa} m_1 m_2 >$$

where the orthonormal basis is combinations of the nucleons relative momenta in the initial $\vec{\kappa}$ and final $\vec{\kappa}'$ states

$$\hat{q}^* = \frac{\vec{\kappa} - \vec{\kappa}'}{|\vec{\kappa} - \vec{\kappa}'|} \quad , \quad \hat{Q}^* = \frac{\vec{\kappa} + \vec{\kappa}'}{|\vec{\kappa} + \vec{\kappa}'|} \quad , \quad \hat{N}^* = \frac{\vec{\kappa} \times \vec{\kappa}'}{|\vec{\kappa} \times \vec{\kappa}'|}$$

$$< \vec{p}' \vec{p}_3'; m' m_3' | t | \vec{p} \vec{p}_3; m m_3 > \sim < \kappa' m_1' m_2' | W^{\dagger}_{1/2}(\vec{p}') W^{\dagger}_{1/2}(\vec{p}_3') \; t \; W_{1/2}(\vec{p}) W_{1/2}(\vec{p}_3) | \kappa m_1 m_2 >$$

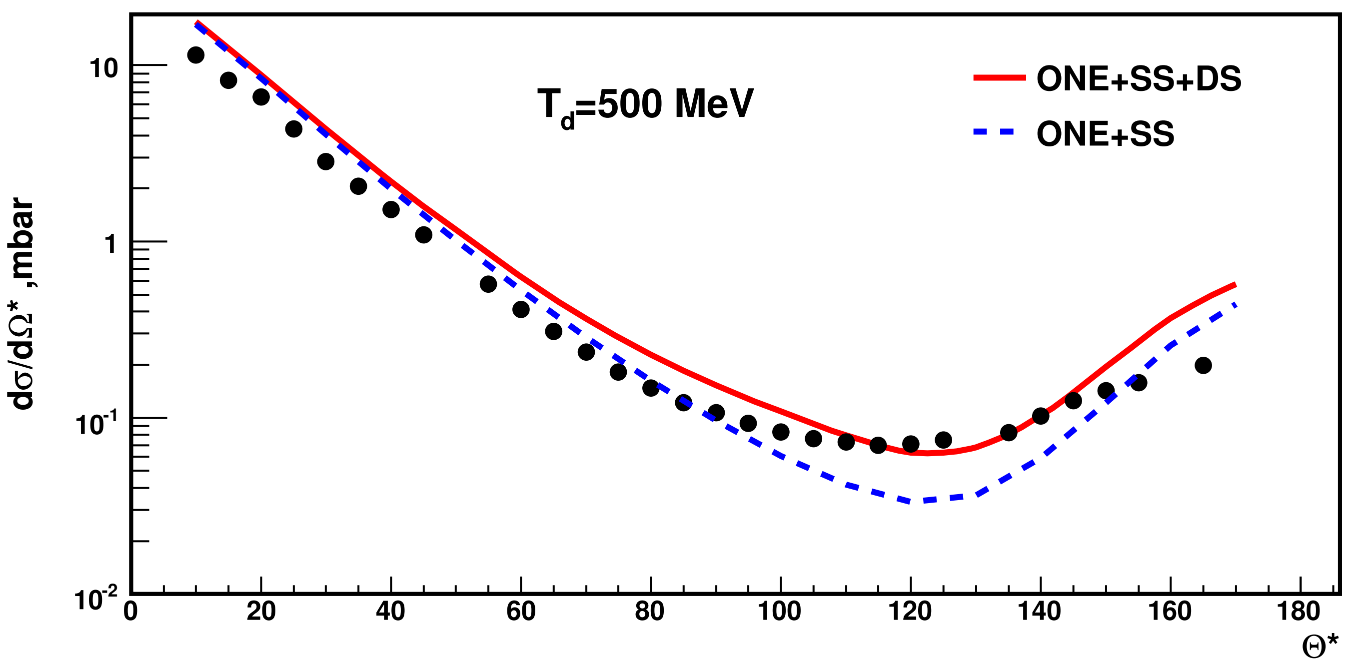


Double scattering

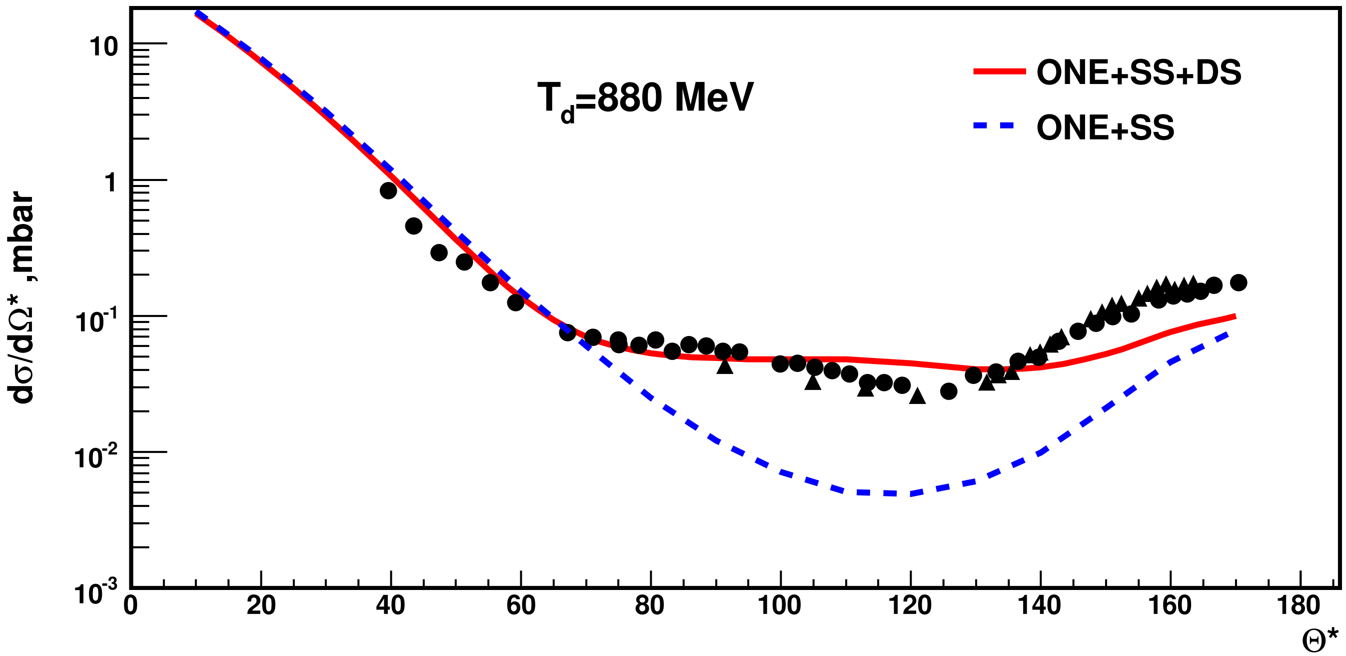
(c)

$$\mathcal{J}_{DS} = NN' \int d\vec{q}\,' \int d\vec{q}'' < -\vec{Q}\mathcal{M}'_d|\Omega_d^\dagger|\vec{q}\,'m'_2, \vec{Q} - \vec{q}\,'\ m'_3 >$$
$$< m'm'_2m'_3|\Big\{ t^1_{12}(\sqrt{s'_{12}}, \vec{\kappa}, \vec{\kappa}\ ')t^1_{13}(\sqrt{s_{13}}, \vec{k}, \vec{k}') +$$
$$\frac{1}{4}[t^1_{12}(\sqrt{s'_{12}}, \vec{\kappa}, \vec{\kappa}\ ') + t^0_{12}(\sqrt{s'_{12}}, \vec{\kappa}, \vec{\kappa}\ ')][t^1_{13}(\sqrt{s_{13}}, \vec{k}, \vec{k}') + t^0_{13}(\sqrt{s_{13}}, \vec{k}, \vec{k}')]\Big\}$$
$$\frac{1}{E_d + E_p - E'_1 - E'_2 - E'_3 + i\varepsilon}|mm_2m_3 >< -\vec{Q} - \vec{q}\ ''\ m_2, \vec{q}\ ''\ m_3|\Omega_d|\mathcal{M}_d >$$

$$\frac{1}{E - E' + i\varepsilon} = \mathcal{P}\frac{1}{E - E'} - i\pi\delta(E - E')$$

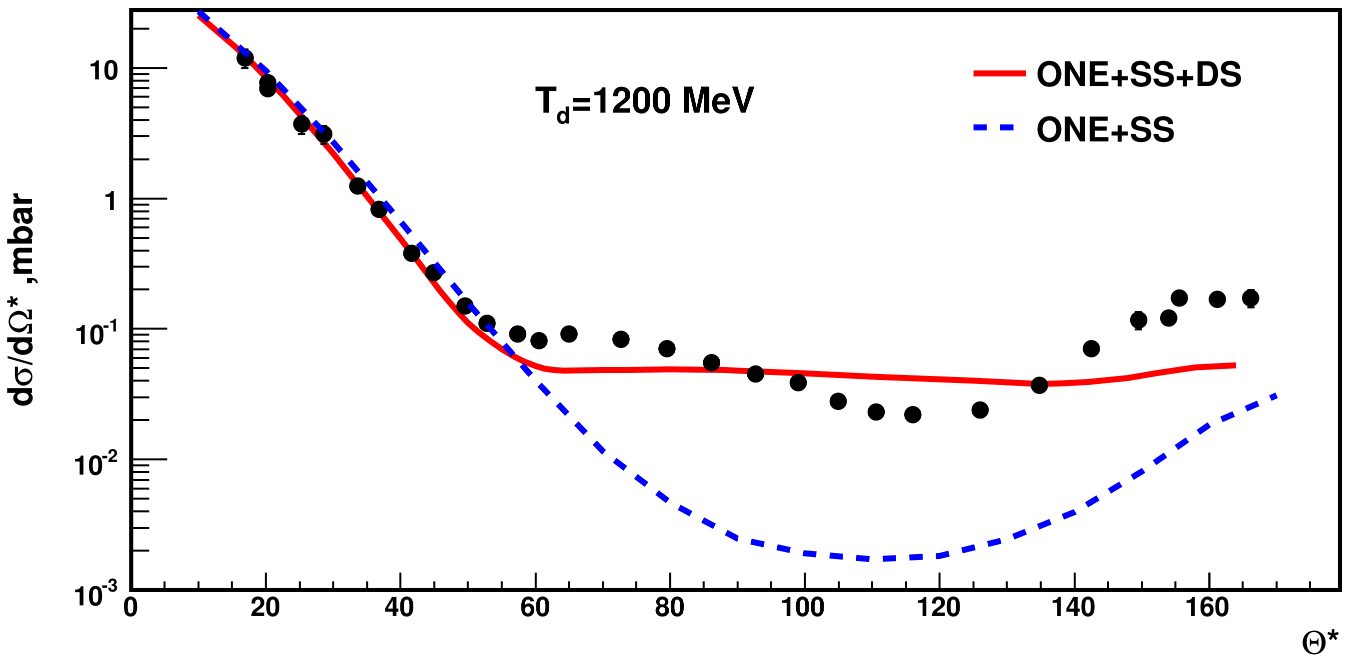


●- K.Hatanaka et al., Phys.Rev.C66, 044002 (2002)

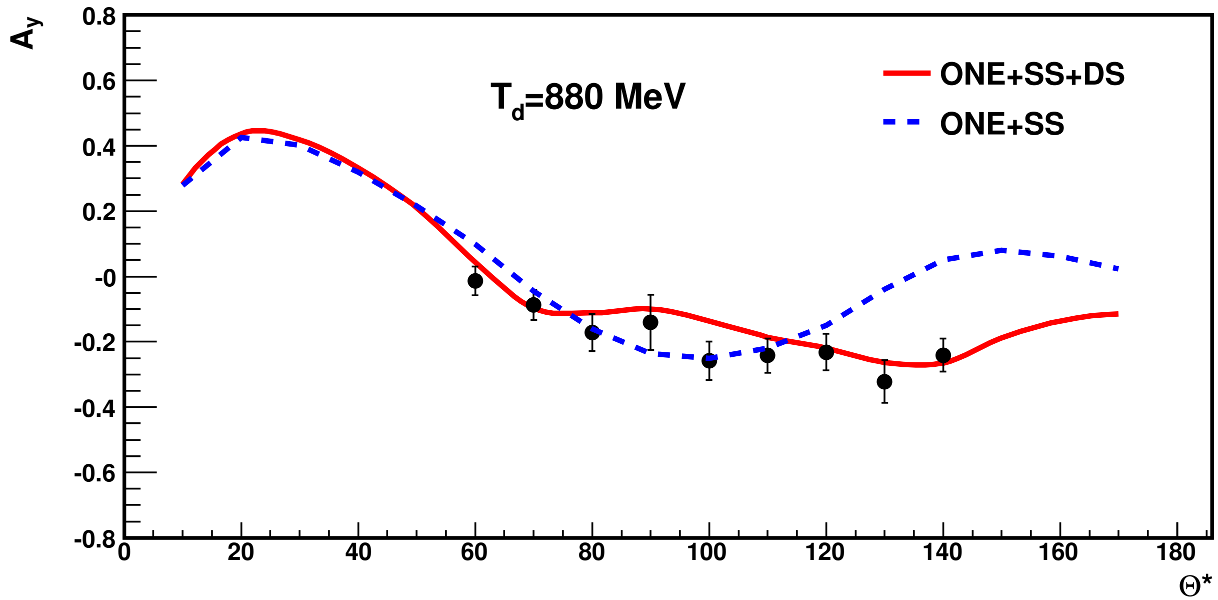


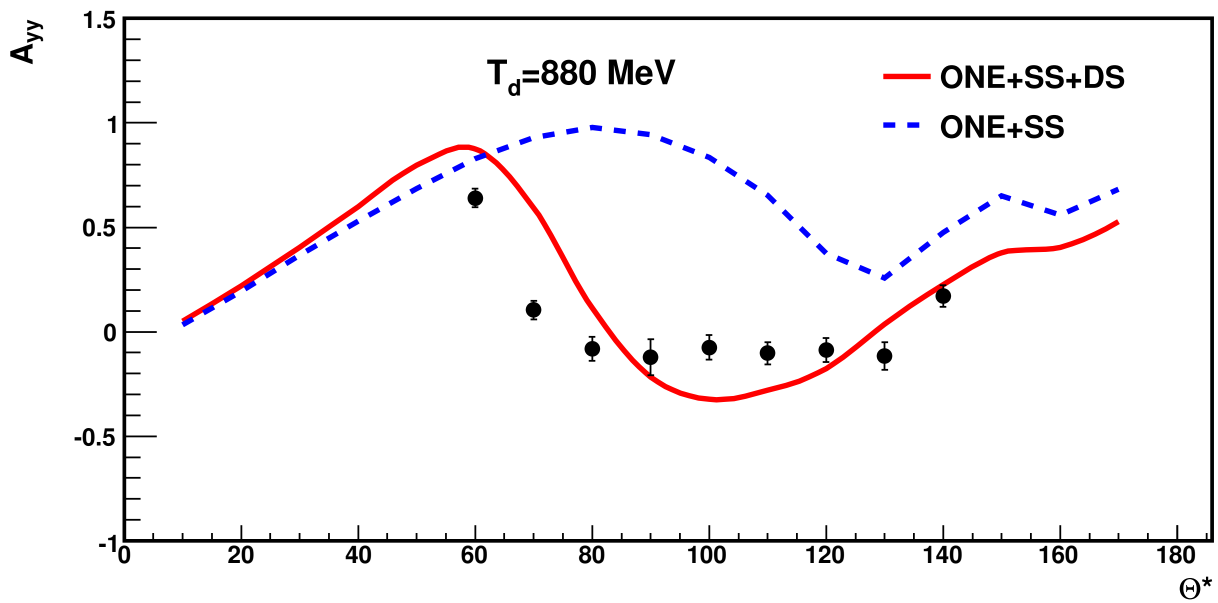
▲ - N.E.Booth et al., Phys.Rev.D4, p.1261 (1971), $\boldsymbol{T_d = 850 MeV}$

● - J.C.Alder et al., Phys.Rev.C6, p.2010 (1972), $\boldsymbol{T_d = 940 MeV}$



● - E.T.Boschitz et al., Phys.Rev.C6, p.457 (1972)





● NUCLOTRON data, LNS collaboration

Conclusions

- The deuteron-proton elastic scattering reaction is considered in the deuteron energy range from 500 MeV up to 1200 MeV.

- The theoretical model for description of this process is suggested. This model is based on the multiple scattering expansion formalism taking relativistic kinematics and relativistic spin theory into account. The one-nucleon-exchange, single-scattering, and double-scattering contributions into reaction amplitude are taken into consideration. It was shown that the double-scattering effect increases with the energy.

- The experimental data on the differential cross section are described at three deuteron energies: 500, 880, and 1200 MeV. The description of the polarization data on the vector, A_y, and tensor, A_{yy}, analyzing powers are also obtained at 880 MeV of the deuteron energy.

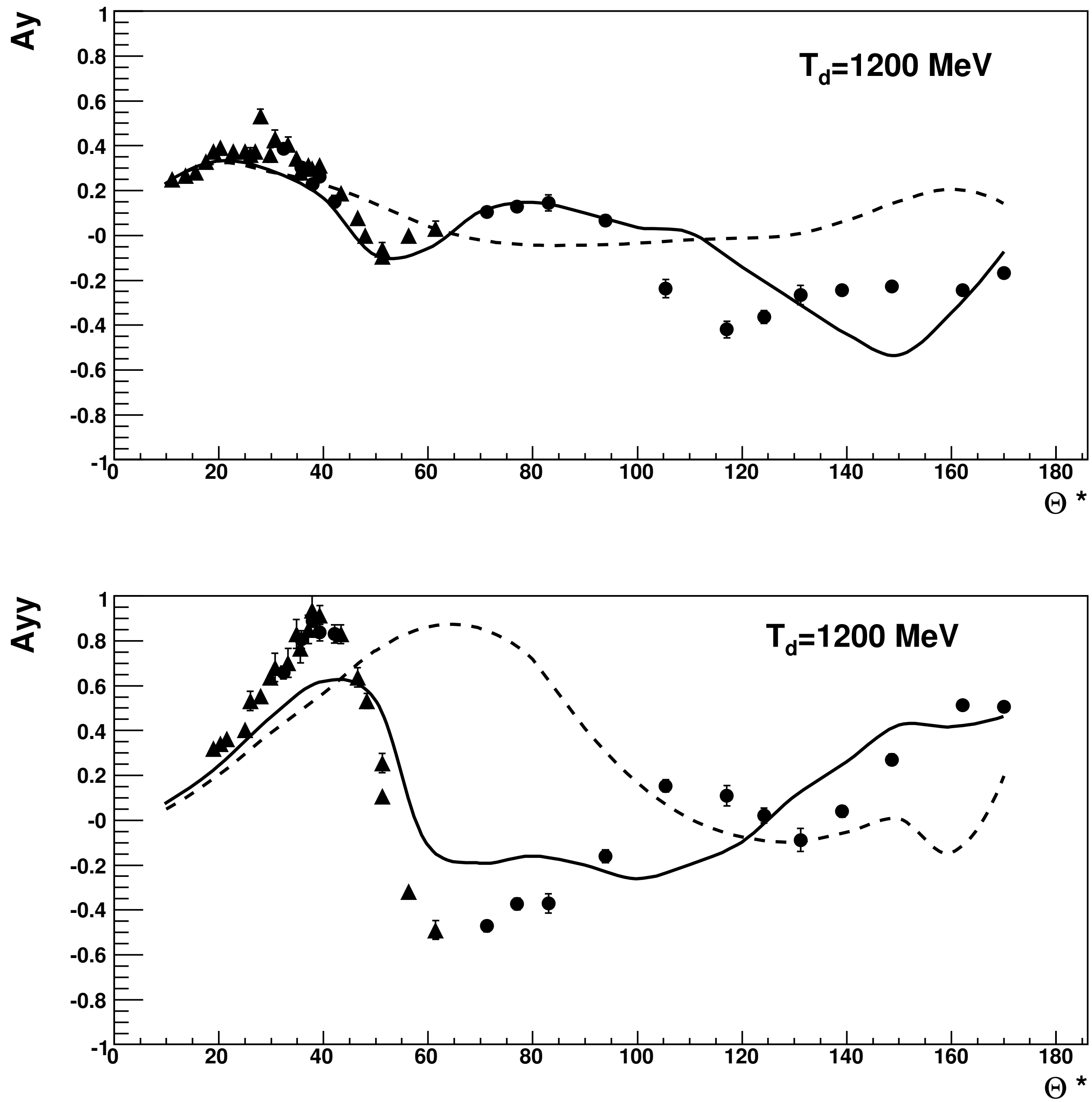
A good agreement between the theoretical predictions and experimental data was obtained.

Breit system

$$E_d = E'_d = \sqrt{M_d^2 + \vec{Q}^2}, \qquad E_p = E'_p = \sqrt{m^2 + \vec{p}^2}$$
$$(\vec{p}\vec{Q}) = -\vec{Q}^2$$

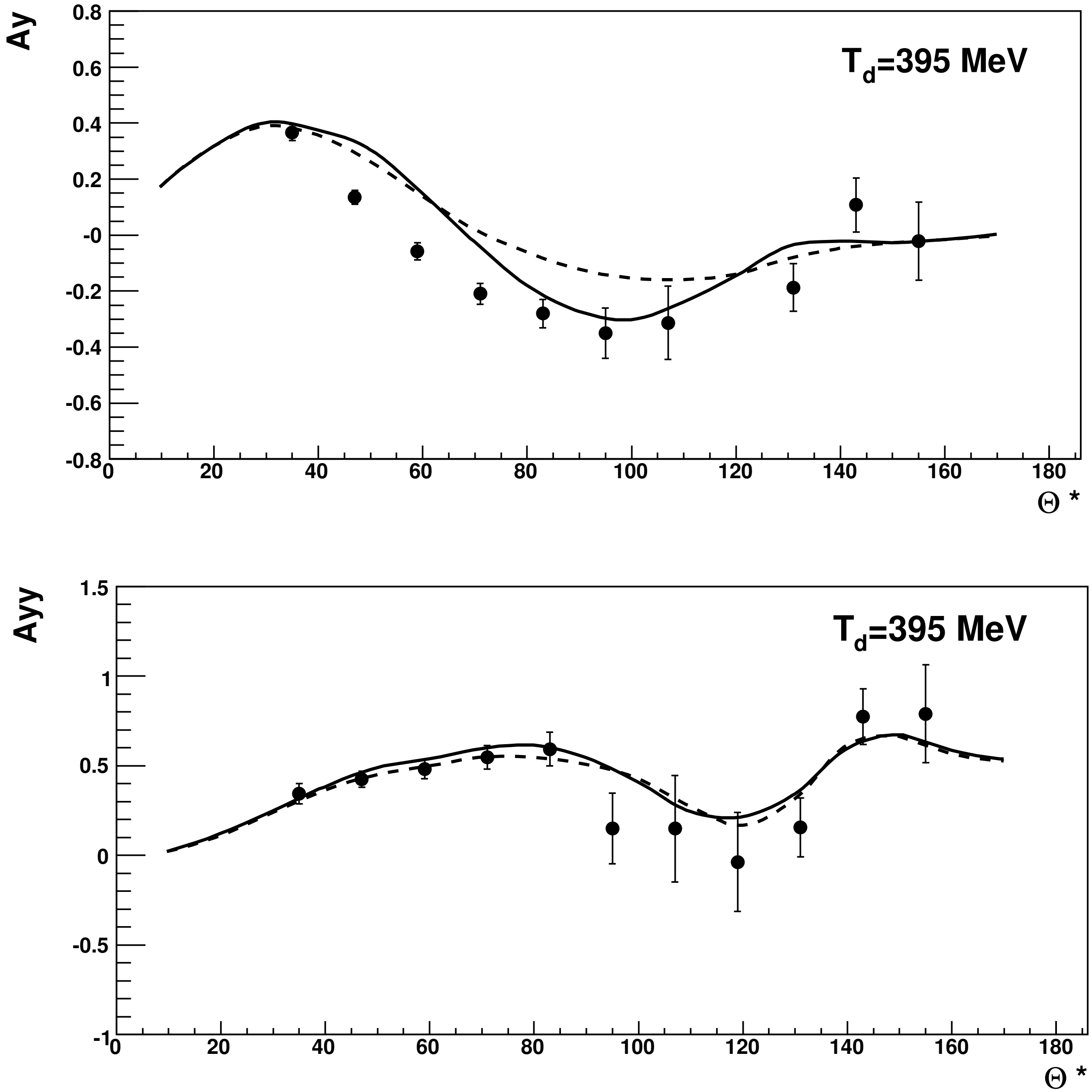
We take the orthonormal basis

$$\vec{z} = \frac{\vec{p} - \vec{p}'}{|\vec{p} - \vec{p}'|} = -\hat{Q}, \qquad \vec{x} = \frac{\vec{p} + \vec{p}'}{|\vec{p} + \vec{p}'|} = \widehat{p + Q}, \qquad \vec{y} = \vec{z} \times \vec{x} = \hat{p} \times \hat{Q}$$

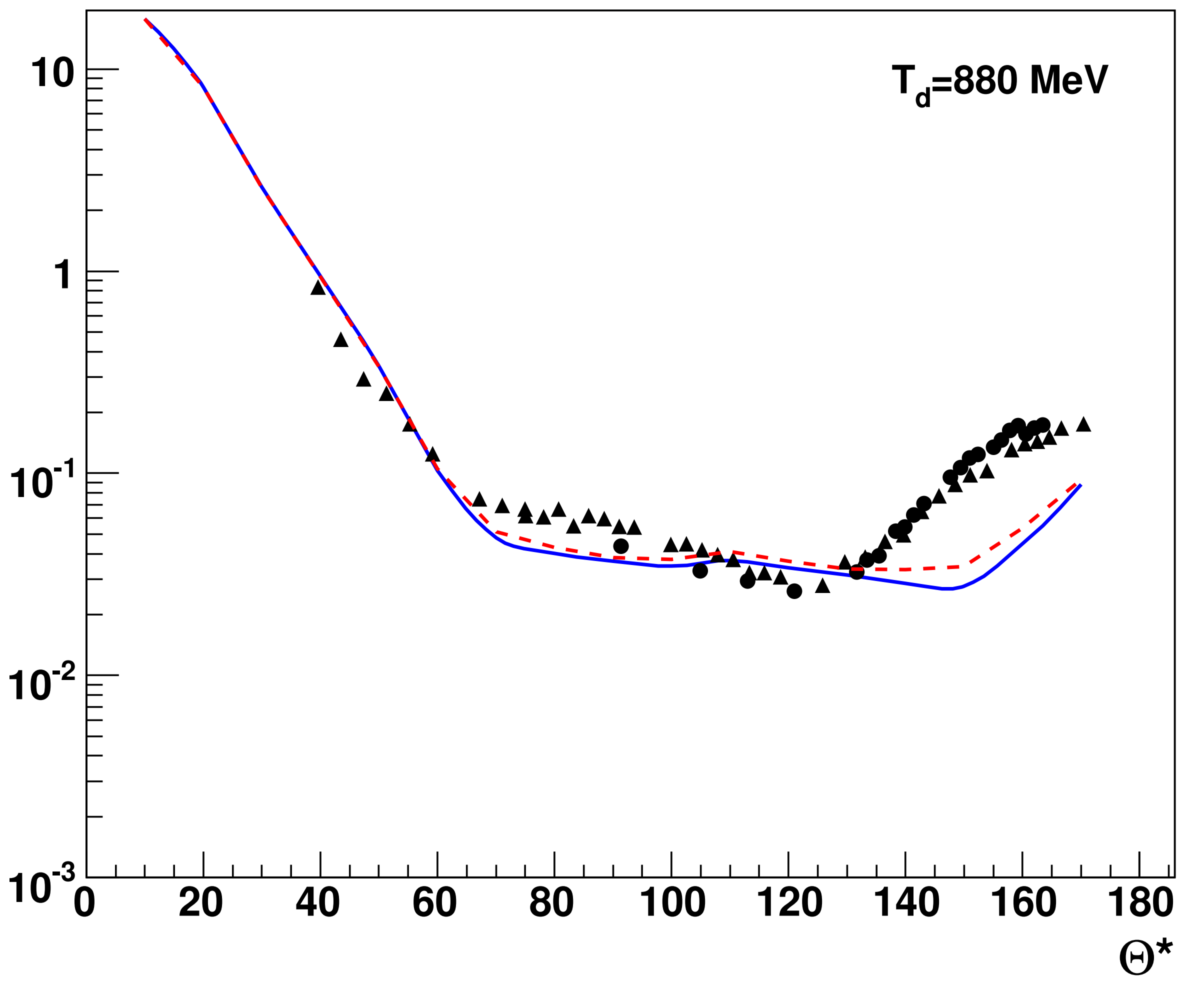


● - J.Arvieux et al., Nucl.Phys.A431, p.613 (1984)

△ - M.Haji-Saied et al., Phys.Rev. C36,p.2010 (1987)



● - M.Garcon et al., Nucl.Phys. A458, p.287 (1986)



△ - N.E.Booth et al., Phys.Rev.D4, p.1261 (1971)

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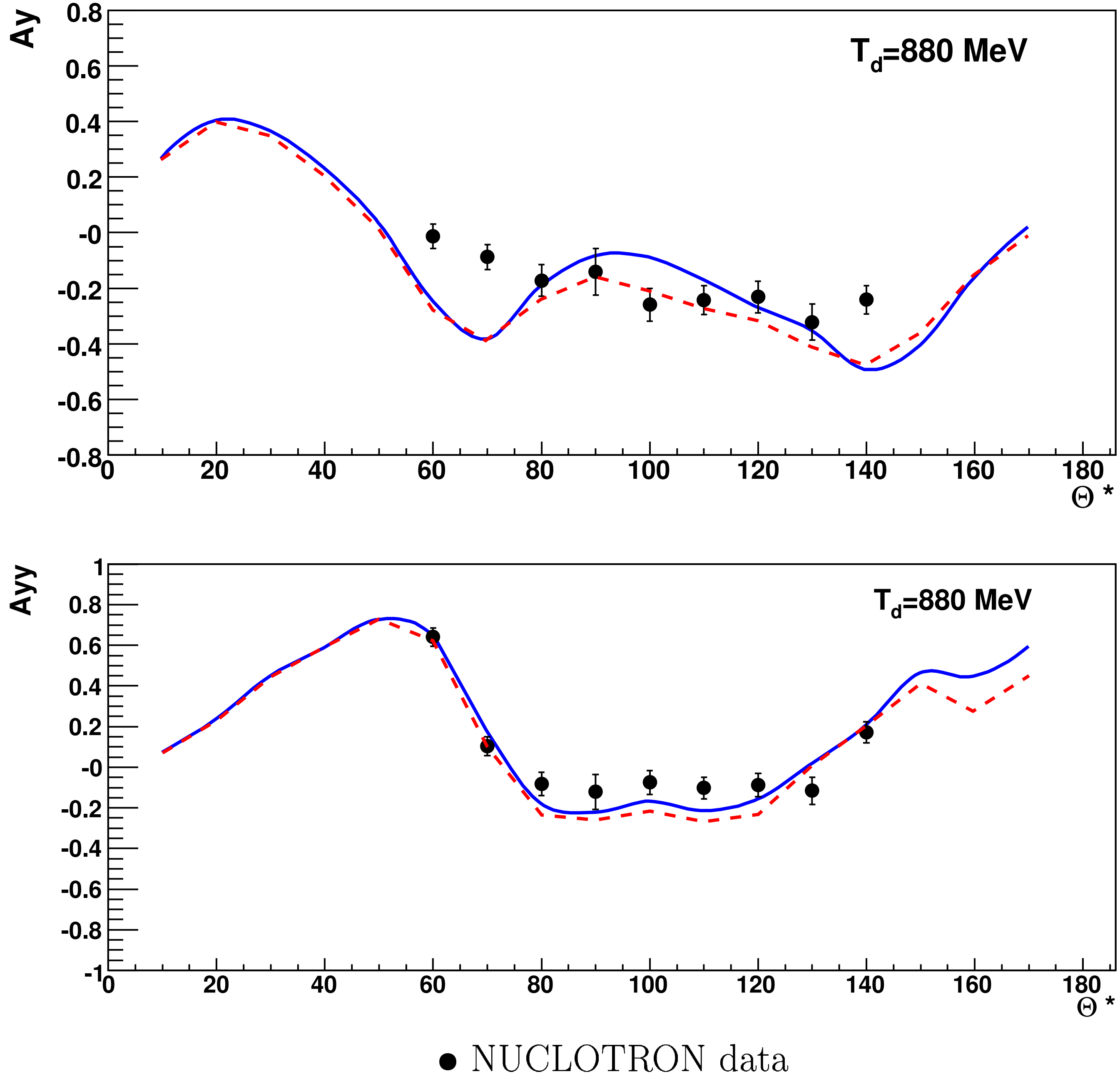
Ay
T_d=880 MeV
0.8
0.6
0.4
0.2
-0
-0.2
-0.4
-0.6
-0.8
0
20
40
60
80
100
120
140
160
180
Θ *
Ayy
T_d=880 MeV
1
0.8
0.6
0.4
0.2
-0
-0.2
-0.4
-0.6
-0.8
-1
0
20
40
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80
100
120
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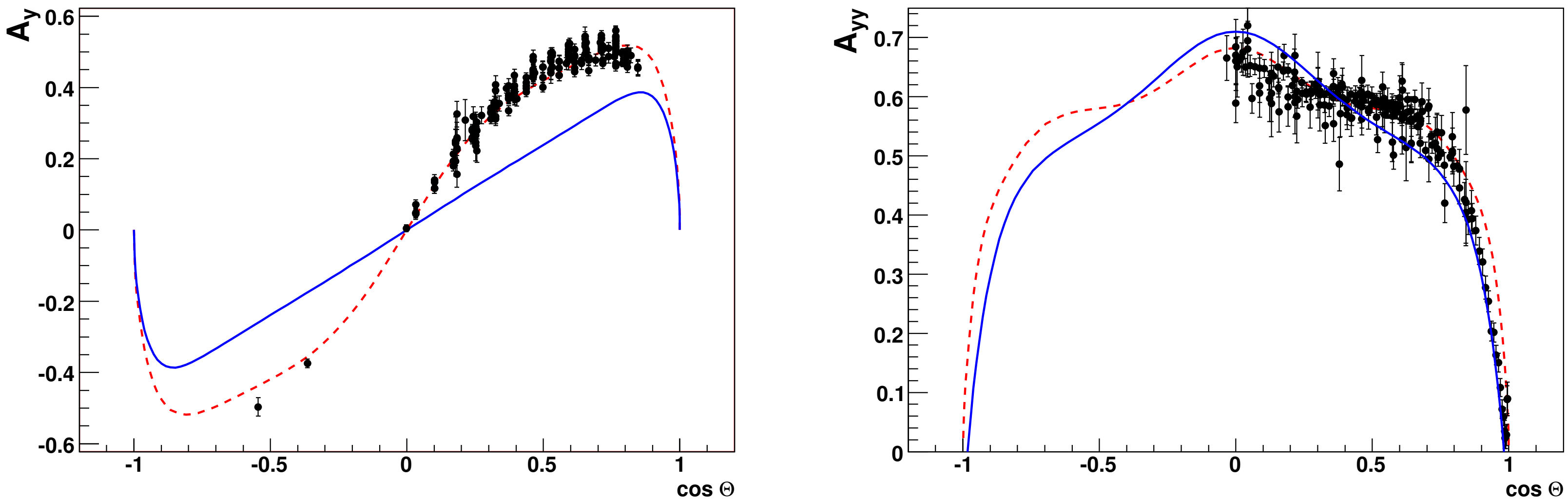
Θ *
NUCLOTRON data

pp, $T_{lab} = 800 MeV$



np, $\boldsymbol{T_{lab} = 800 MeV}$