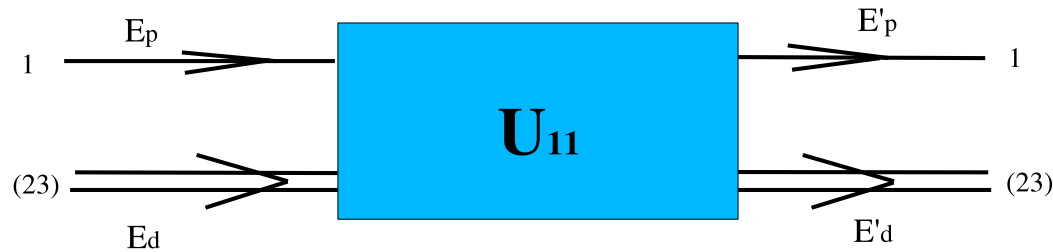


Deuteron-proton elastic scattering at intermediate energies

N.B. Ladygina

- $dp \rightarrow dp$ 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

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

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

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

One-Nucleon-Exchange

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

Single-Scattering

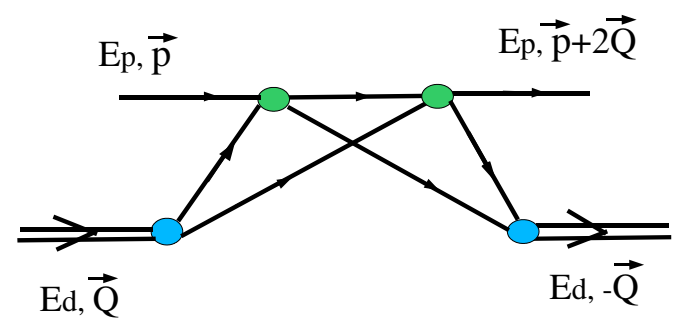
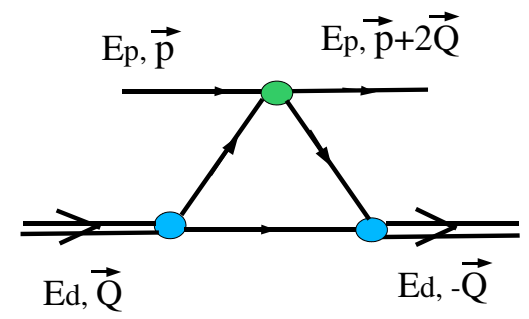
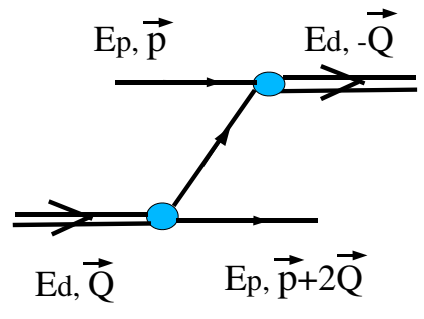
$$\mathcal{J}_{SS} = 2 \langle 1(23) | t_3^{sym} | 1(23) \rangle$$

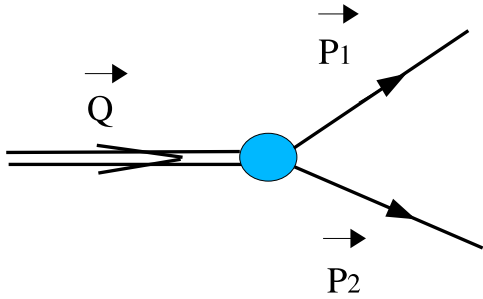
Double-Scattering

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

where notations for antisymmetrized operators have been introduced

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





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

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

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

$$\vec{Q} = \vec{p}_1 + \vec{p}_2$$

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

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

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

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

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

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

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

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

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

$u(\mathbf{k})$ and $w(\mathbf{k})$ - S - and D - components of the deuteron.

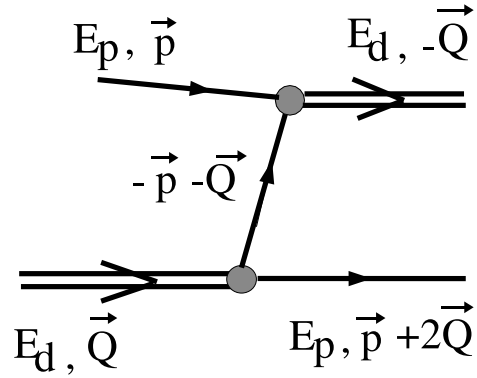
Then the deuteron wave function in the moving frame is

$$\langle \vec{p}_1 \vec{p}_2, m_1 m_2 | \Omega_d | \vec{Q}, \mathcal{M}_d \rangle \sim \langle \vec{k} \vec{Q}, m'_1 m'_2 | W_{1/2}^\dagger(\vec{p}_1, \vec{u}) W_{1/2}^\dagger(\vec{p}_2, \vec{u}) \Omega_d | \vec{0}, \mathcal{M}_d \rangle$$

Deuteron wave function in the moving frame

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

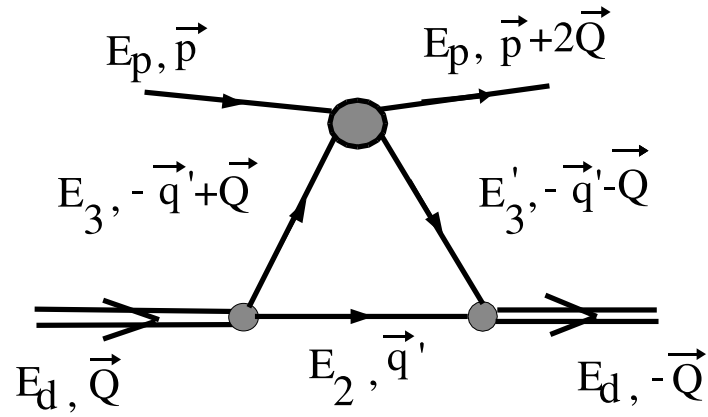
g_i are combinations of the S - and D - components of the deuteron wave function (u and w)



(a)

One nucleon exchange scattering

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



(b)

Single scattering

$$\mathcal{J}_{SS} = \int d\vec{q}' \langle -\vec{Q} \mathcal{M}'_d | \Omega_d^\dagger | \vec{q}' m'', -\vec{Q} - \vec{q}' m'_3 \rangle$$

$$\langle \vec{p}' m', -\vec{Q} - \vec{q}' | \frac{3}{2} t_{12}^1 + \frac{1}{2} t_{12}^0 | \vec{p} m, \vec{Q} - \vec{q}' m'_2 \rangle \langle \vec{q}' m'', \vec{Q} - \vec{q}' m'_2 | \Omega_d | \vec{Q} \mathcal{M}_d \rangle$$

Nucleon-Nucleon t -matrix

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

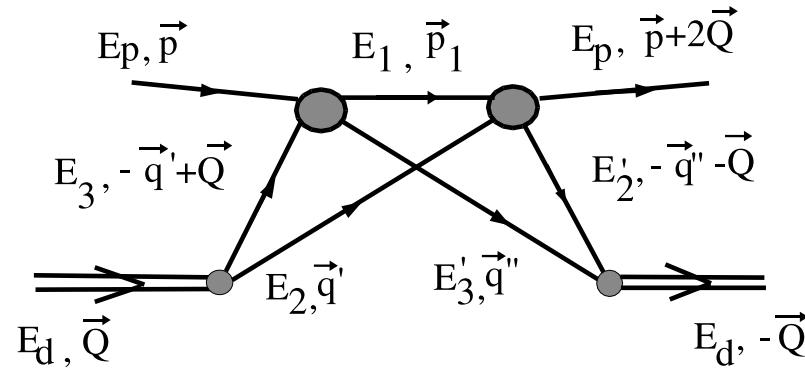
N.B.Ladygina,nucl-th/0805.3021

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

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

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

$$\langle \vec{p}' p'_3; m'_1 m'_3 | t | \vec{p} p_3; m m_3 \rangle \sim \langle \kappa' m'_1 m'_2 | W_{1/2}^\dagger(\vec{p}') W_{1/2}^\dagger(\vec{p}_3) t W_{1/2}(\vec{p}) W_{1/2}(\vec{p}_3) | \kappa m_1 m_2 \rangle$$

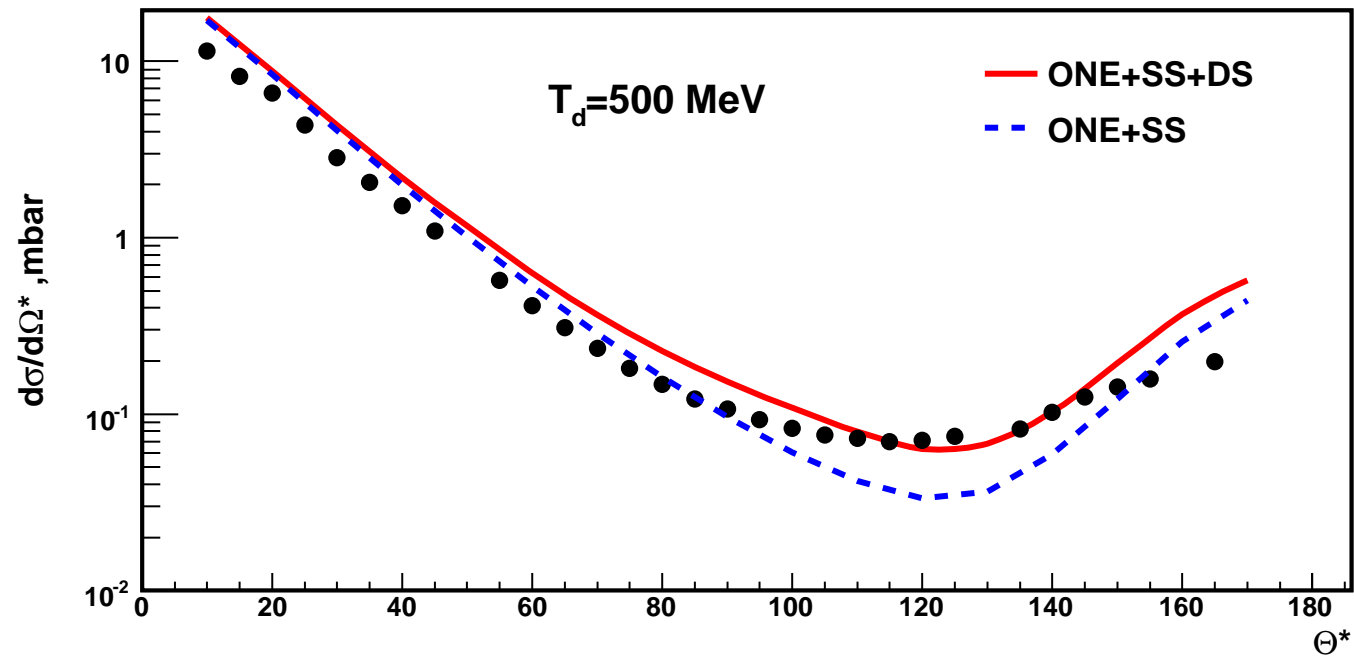


Double scattering

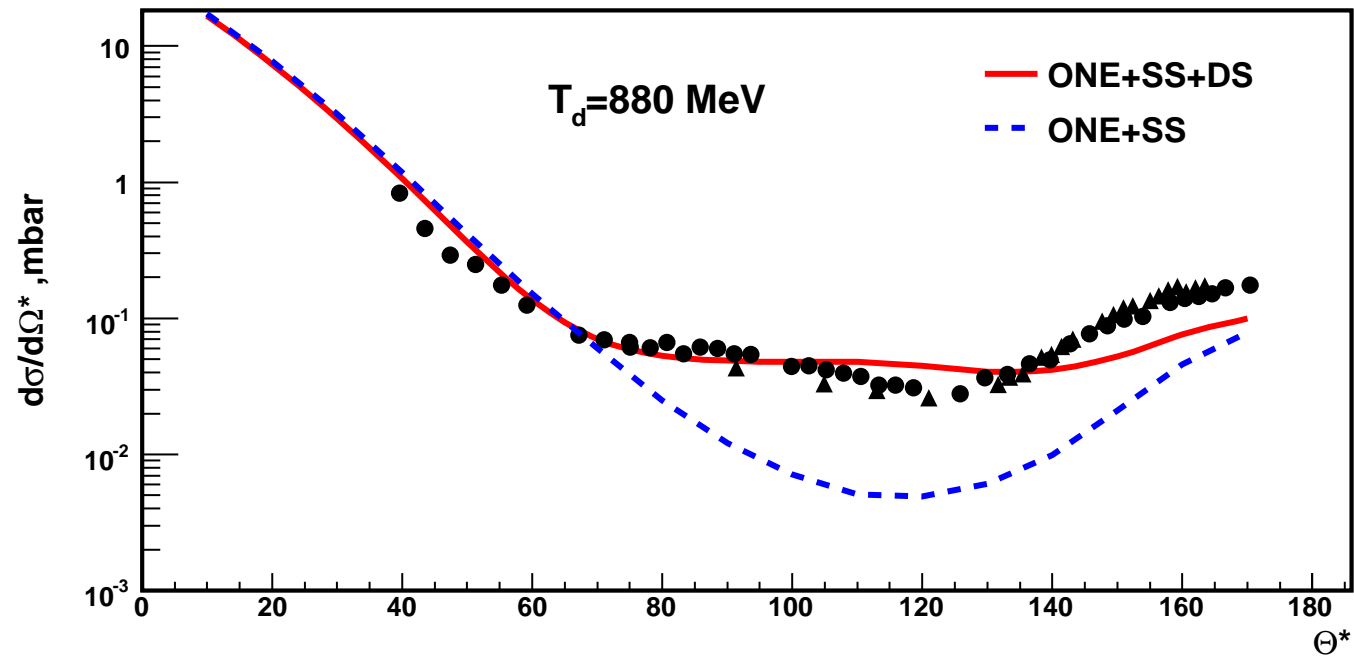
(c)

$$\begin{aligned}
\mathcal{J}_{DS} = & NN' \int d\vec{q}' \int d\vec{q}'' \langle -\vec{Q} \mathcal{M}'_d | \Omega_d^\dagger | \vec{q}' m'_2, \vec{Q} - \vec{q}' m'_3 \rangle \\
& \langle m' m'_2 m'_3 | \left\{ t_{12}^1(\sqrt{s'_{12}}, \vec{\kappa}, \vec{\kappa}') t_{13}^1(\sqrt{s_{13}}, \vec{k}, \vec{k}') + \right. \\
& \left. \frac{1}{4} [t_{12}^1(\sqrt{s'_{12}}, \vec{\kappa}, \vec{\kappa}') + t_{12}^0(\sqrt{s'_{12}}, \vec{\kappa}, \vec{\kappa}')] [t_{13}^1(\sqrt{s_{13}}, \vec{k}, \vec{k}') + t_{13}^0(\sqrt{s_{13}}, \vec{k}, \vec{k}')] \right\} \\
& \frac{1}{E_d + E_p - E'_1 - E'_2 - E'_3 + i\epsilon} | m m_2 m_3 \rangle \langle -\vec{Q} - \vec{q}'' m_2, \vec{q}'' m_3 | \Omega_d | \mathcal{M}_d \rangle
\end{aligned}$$

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

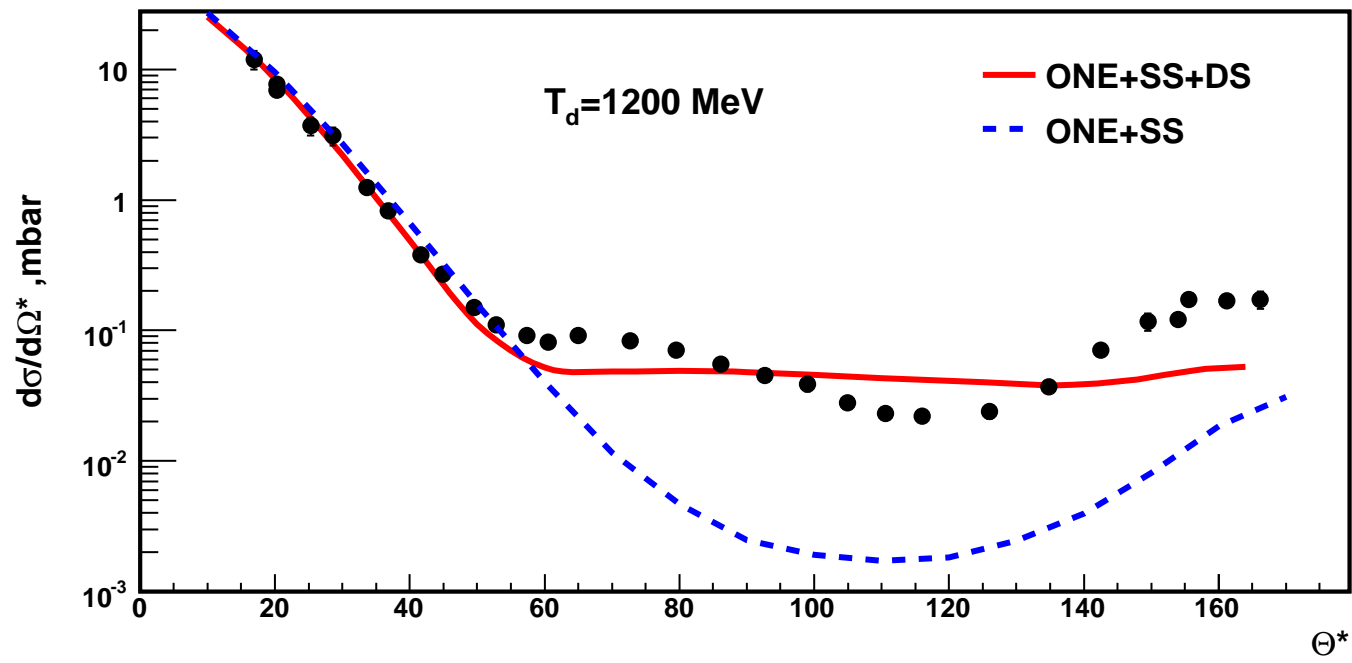


●- K.Hatanaka et al., Phys.Rev.C66, 044002 (2002)

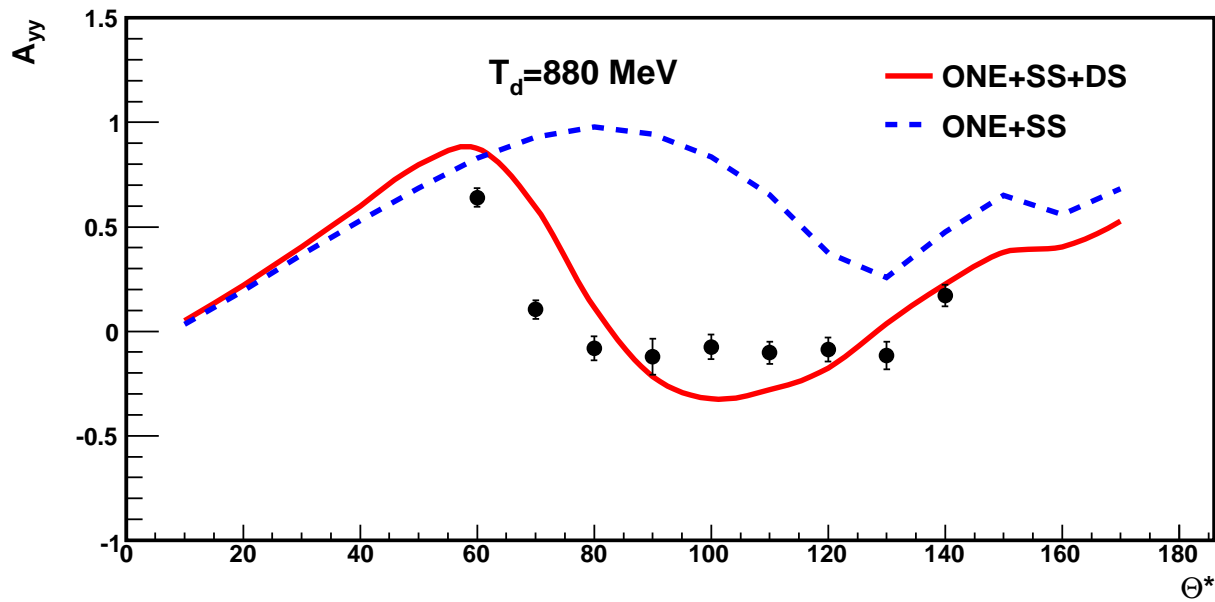
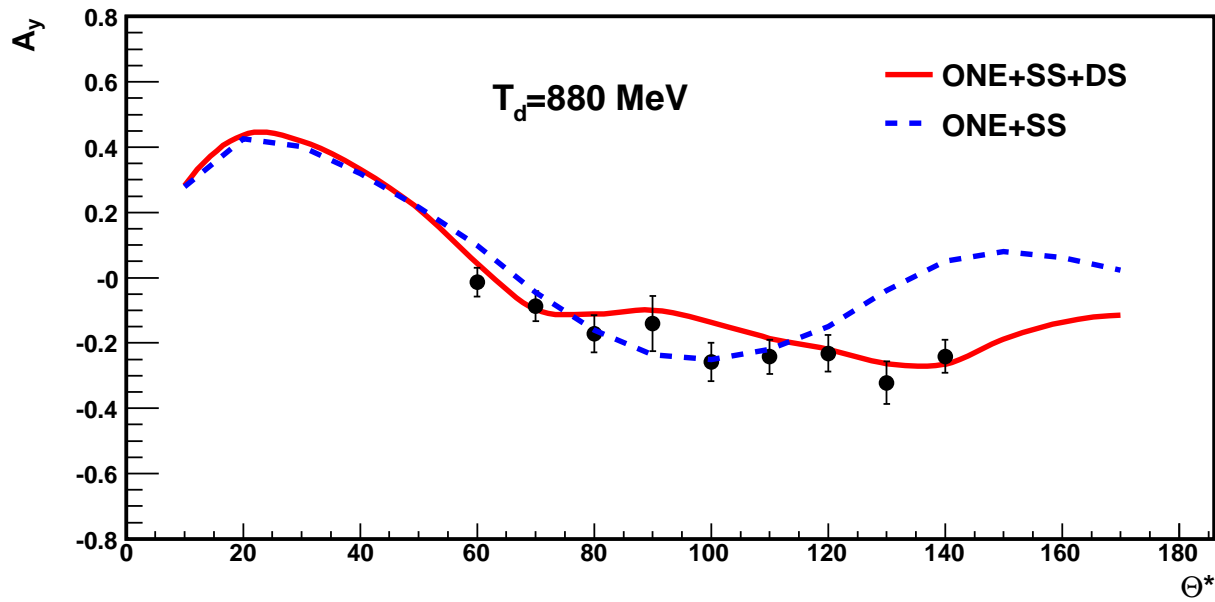


▲ - N.E.Booth et al., Phys.Rev.D4, p.1261 (1971), $T_d = 850 \text{ MeV}$

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



● - 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.

Заключение

- Представлена модель для описания dp - упругого рассеяния при кинетических энергиях дейтрона 400-1200 МэВ. Учтены вклады однонуклонного обмена, однократного рассеяния и двойного перерассеяния.
- Описаны экспериментальные данные по дифференциальным сечениям, векторной и тензорной анализирующим способностям при трех энергиях: 395, 880 и 1200 МэВ.
- Показано, что с ростом энергии важность вкладов двойного перерассеяния увеличивается.

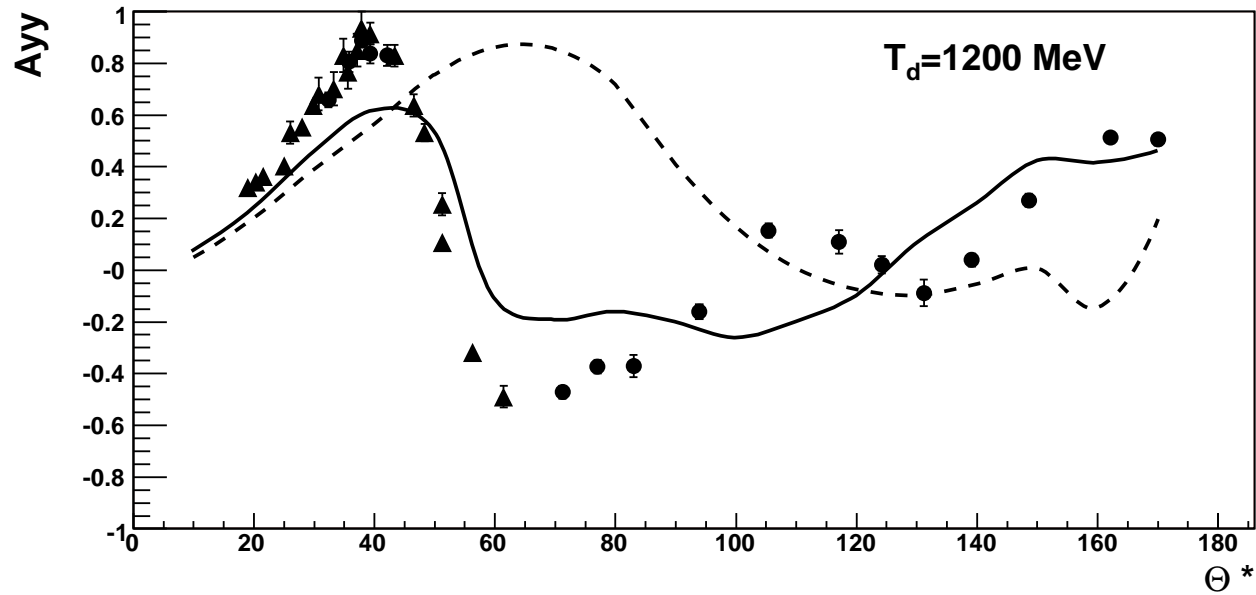
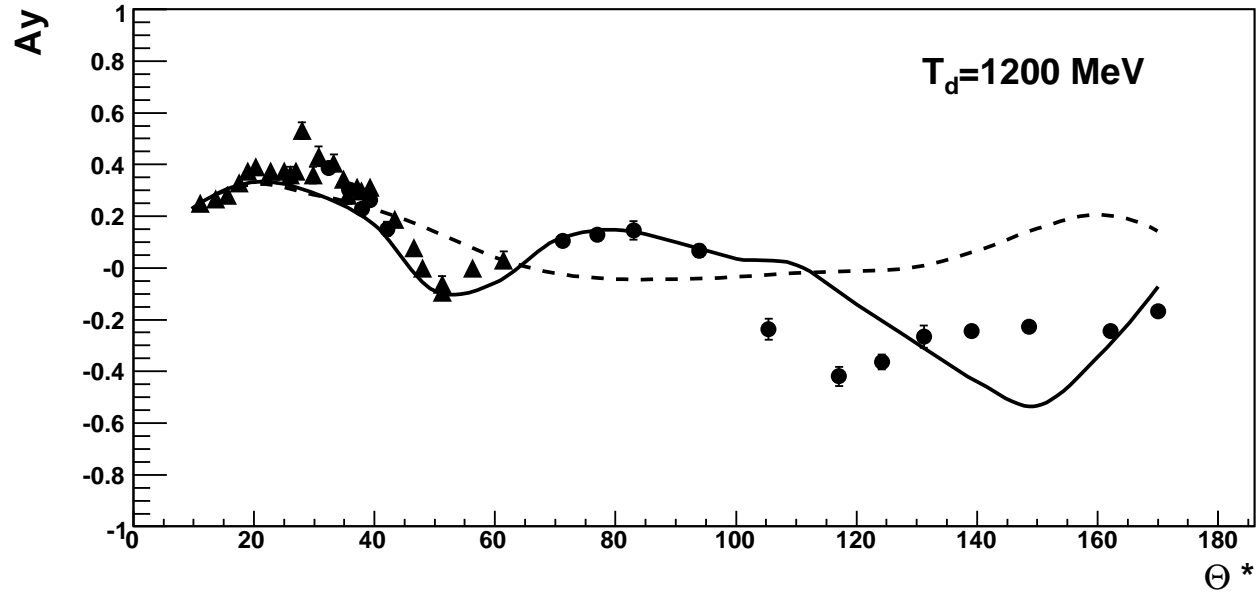
- В настоящее время ведется работа по фитированию коэффициентов в модели Love-Franeu на основе современного фазового анализа.
- Продолжается работа по описанию дифференциальных сечений и поляризационных наблюдаемых при других энергиях. Наряду с A_y и A_{yy} рассматриваются также анализирующая способность протона, передача поляризации от протона к протону, спиновые корреляции.
- Хотелось бы, чтобы были получены новые поляризационные данные на ускорительном комплексе ЛВЭ.

Breit system

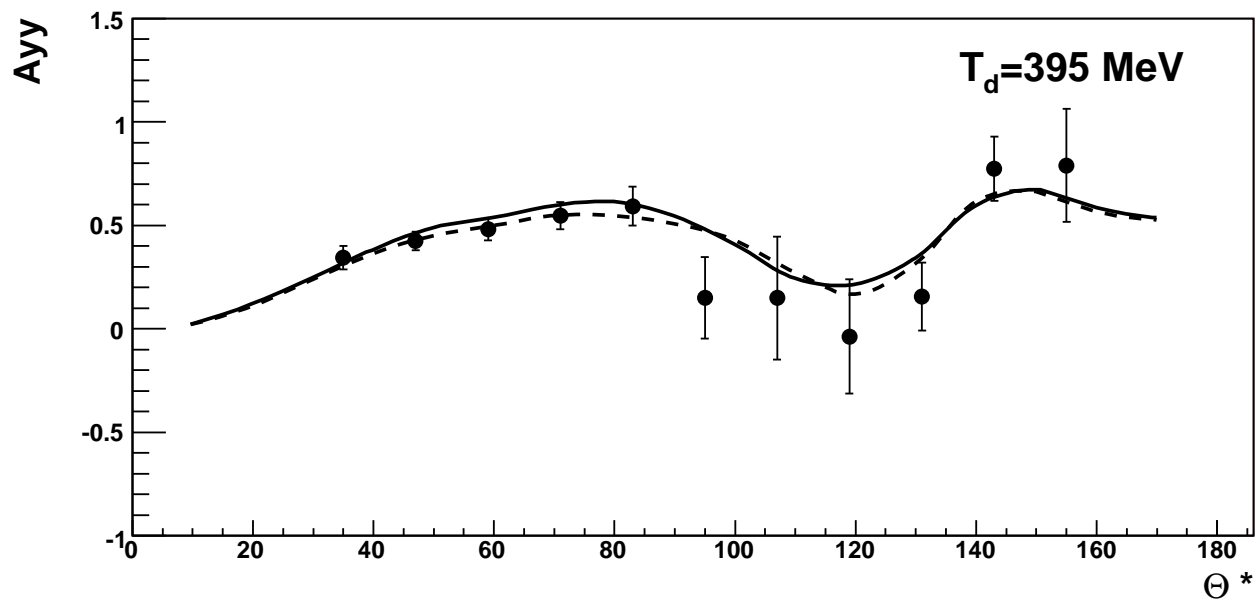
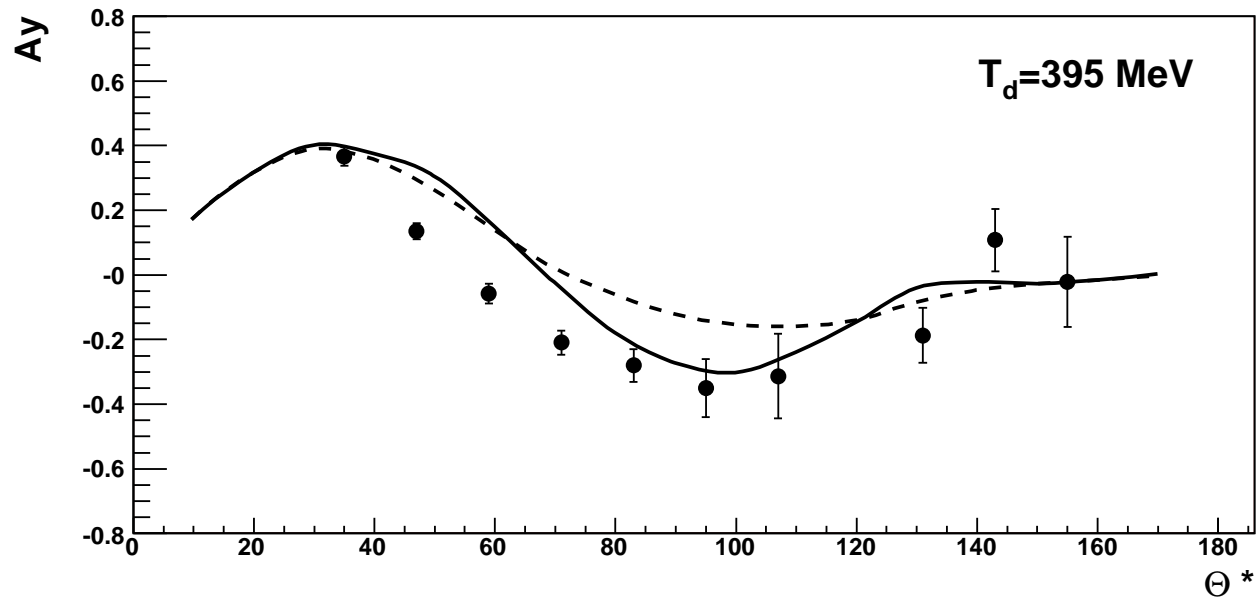
$$E_d = E'_d = \sqrt{M_d^2 + \vec{Q}^2}, \quad E_p = E'_p = \sqrt{m^2 + \vec{p}^2}$$
$$(\vec{p}\vec{Q}) = -\vec{Q}^2$$

We take the orthonormal basis

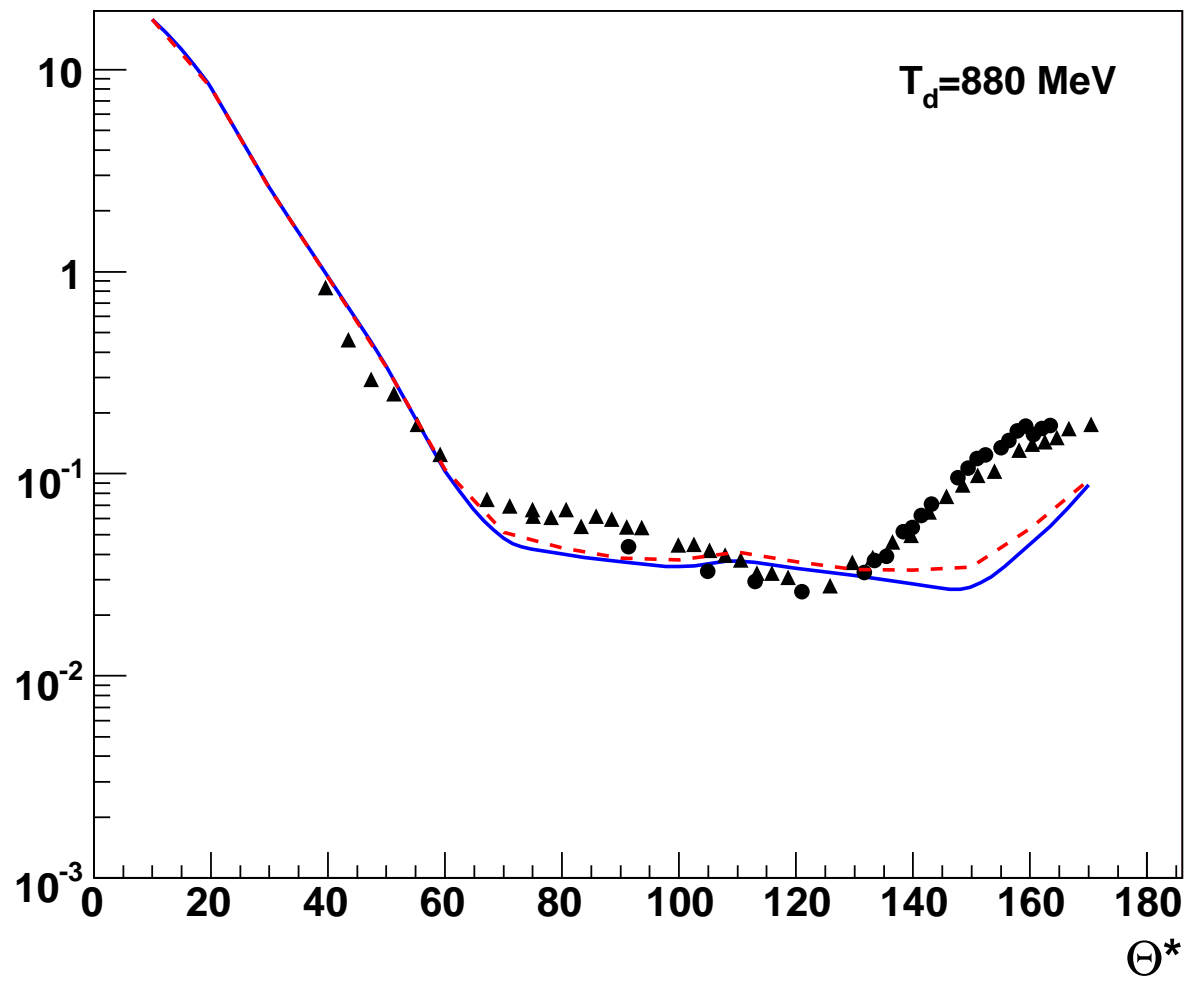
$$\vec{z} = \frac{\vec{p} - \vec{p}'}{|\vec{p} - \vec{p}'|} = -\hat{Q}, \quad \vec{x} = \frac{\vec{p} + \vec{p}'}{|\vec{p} + \vec{p}'|} = \widehat{p + Q}, \quad \vec{y} = \vec{z} \times \vec{x} = \hat{p} \times \hat{Q}$$



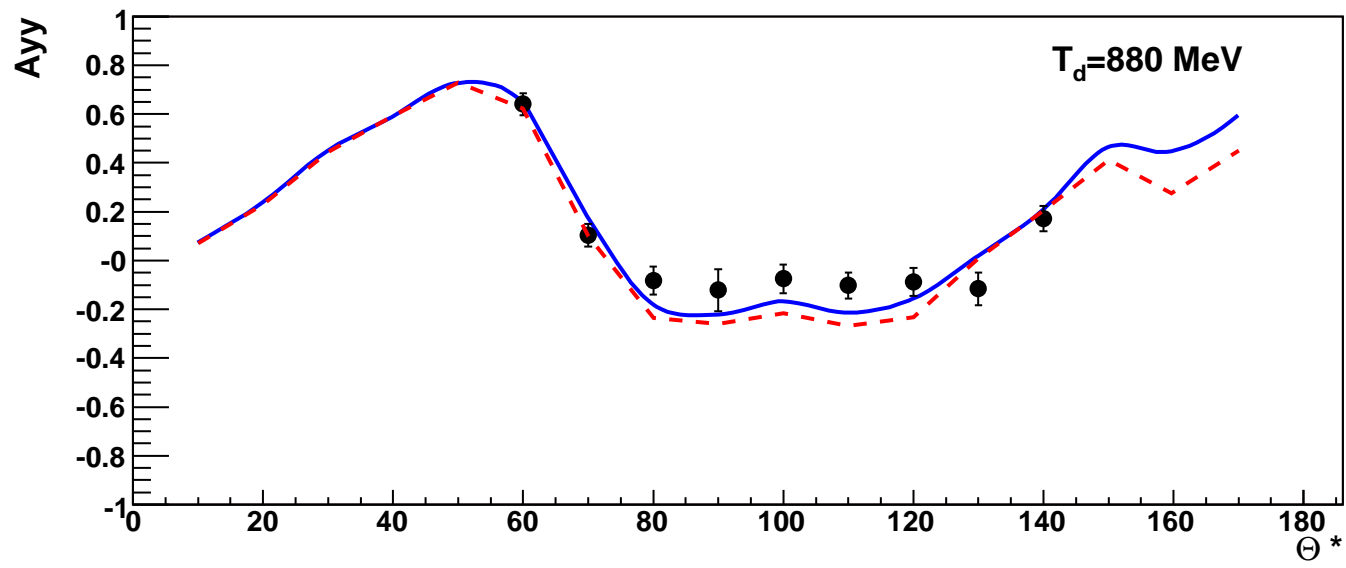
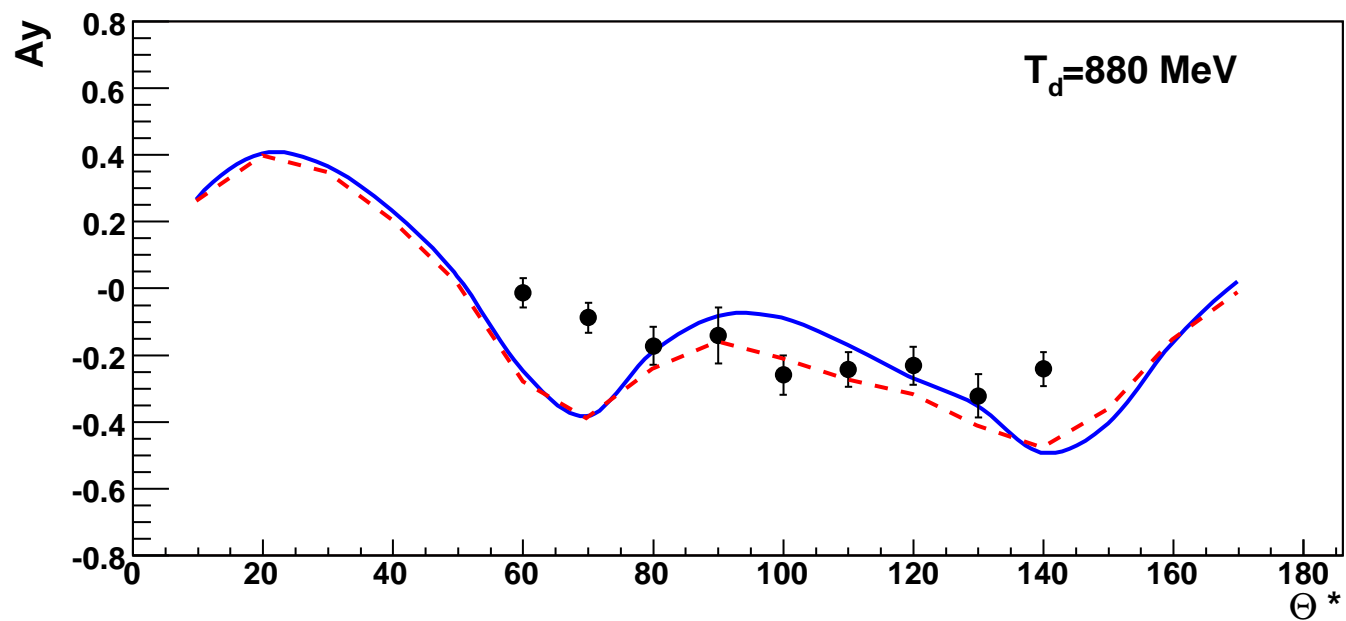
- - J.Arviex et al., Nucl.Phys.A431, p.613 (1984)
- △ - M.Haji-Saied et al., Phys.Rev. C36,p.2010 (1987)



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

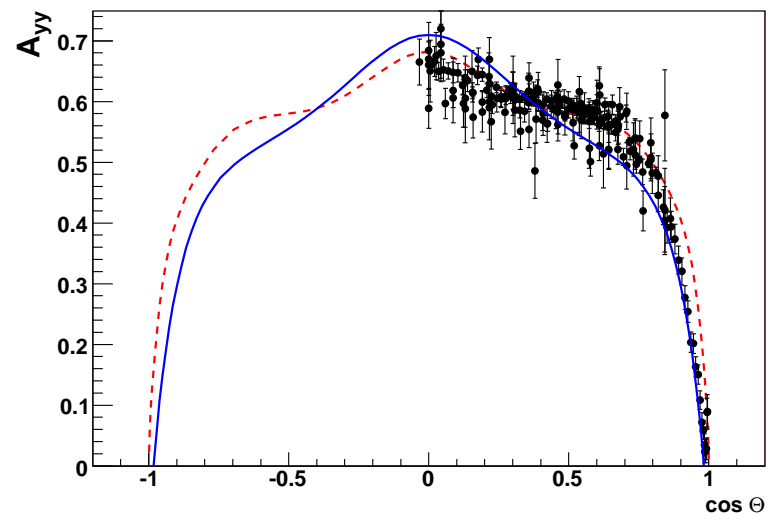
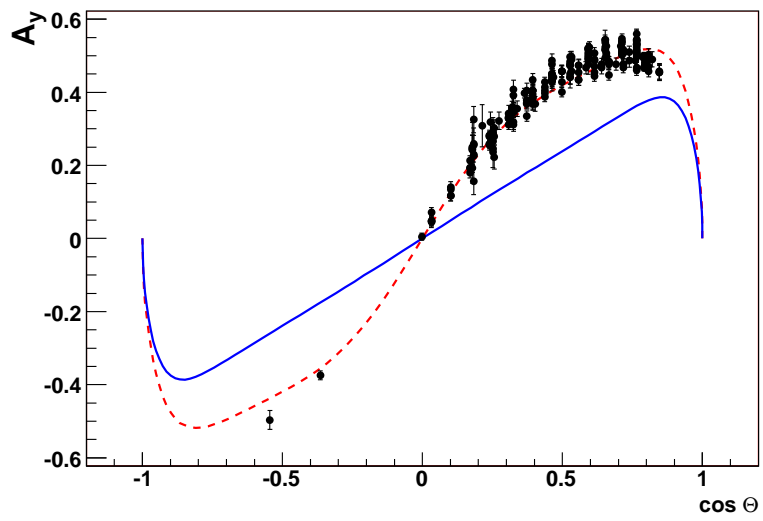


- Δ - N.E.Booth et al., Phys.Rev.D4, p.1261 (1971)
 \bullet - J.C.Alder et al., Phys.Rev.C6, p.2010 (1972)



● NUCLOTRON data

$pp, T_{lab} = 800MeV$



$np, T_{lab} = 800MeV$

