The angular distributions of the vector Ay and tensor Ayy, Axx, Axz analyzing powers for the $d\,d \rightarrow {}^3H\,p$ reactions at 200 MeV

A.K. Kurilkin[1†], T. Saito[2], V.P. Ladygin[1], T. Uesaka[3], T.A. Vasiliev[1], M. Janek[1,5], M. Hatano[2], A.Yu. Isupov[1], H. Kato[2], N.B. Ladygina[1], Y. Maeda[3], A.I. Malakhov[1], J. Nishikawa[4], T. Ohnishi[6] H. Okamura[8], S.G. Reznikov[1], H. Sakai[2,3], N. Sakamoto[6], S. Sakoda[2], Y. Satou[7], K. Sekiguchi[6], K. Suda[3], A. Tamii[7] N. Uchigashima[2], K. Yako[2],

(1) *LHE-JINR, 141-980 Dubna, Moscow region, Russia*

(2) *Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*

(3) *Center for Nuclear Study, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*

(4) *Department of Physics, Saitama University, UraWa 338-8570, Japan*

(5) *University of P.J. Safarik, 041-54 Kosice, Slovakia*

(6) *RIKEN, Wako, Saitama 351-0198, Japan*

(7) *Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan*

(8) *CYRIC, Tohoku University, Sendai, Miyagi 980-8578, Japan*

† **E-mail: akuril@sunhe.jinr.ru**

Content

- **Introduction**
  - **Binding energy problem**
  - **Experimental study of tritium**
  - $d\ d \rightarrow {}^3H\ p$ **in the model of one-nucleon exchange**
- **Experiment**
  - **Accelerating complex RARF**
  - **Spectrometer SMART**
- **Data analysis**
  - **Identification of true events for polarization**
  - **Identification of true events for** ${}^3H$
- **Results and discussion**
  - **Angular dependences of the vector and tensor analyzing powers**
- **Conclusions**

Binding energy problem

Binding energy of system is not reproduced by the calculations, which use modern two-particle nucleon-nucleon potentials.

Calculations with the use of local potentials such as Nijm-2, Reid'93, AV18 predict result of approximately 7.62 MeV. The experimental value of 8.48 MeV.

Nonrelativistic calculations of Faddeev equations with the use of non-local CD-Bonn potential gave result of 8.00 MeV. Relativistic corrections gave result of 8.19 MeV.

Because of the fact that binding energy has strong correlation with the value of the spin dependent forces it is possible to expect that an experimental study of the spin structure of the three-nucleon bound system will make it possible to obtain key to understanding of the underestimation of binding energy.

Experimental study of ^3H

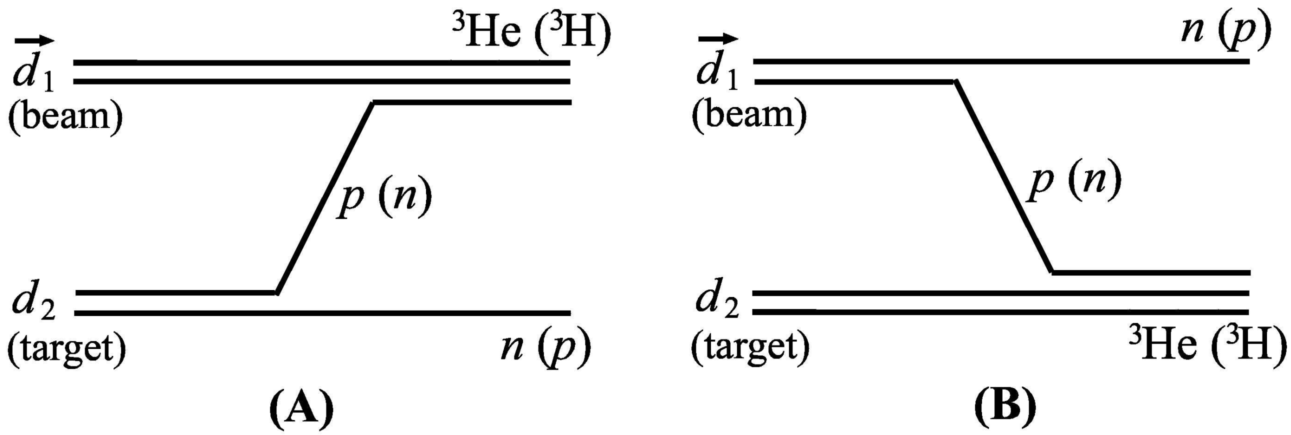
There are only few data, which sensitive to the spin structure three-nucleon bound state, especially, in the connection with polarization studies. The large part of these data is dedicated to the spin structure of ^3He.

An experimental study of ^3H is difficult because of its radioactivity.

The charge and electromagnetic form factors of ^3H were measured in the reaction of the elastic scattering of electrons on tritium target at Saclay. This measurement showed that the region of the second diffraction peak of the three-nucleon form factors still is not understood.

In spite of the sensitivity of the polarization observables to the spin structure of light nuclei, difference from the predictions of model ONE is observed already with the relatively small internal momentum $\approx$ 200 MeV/c.

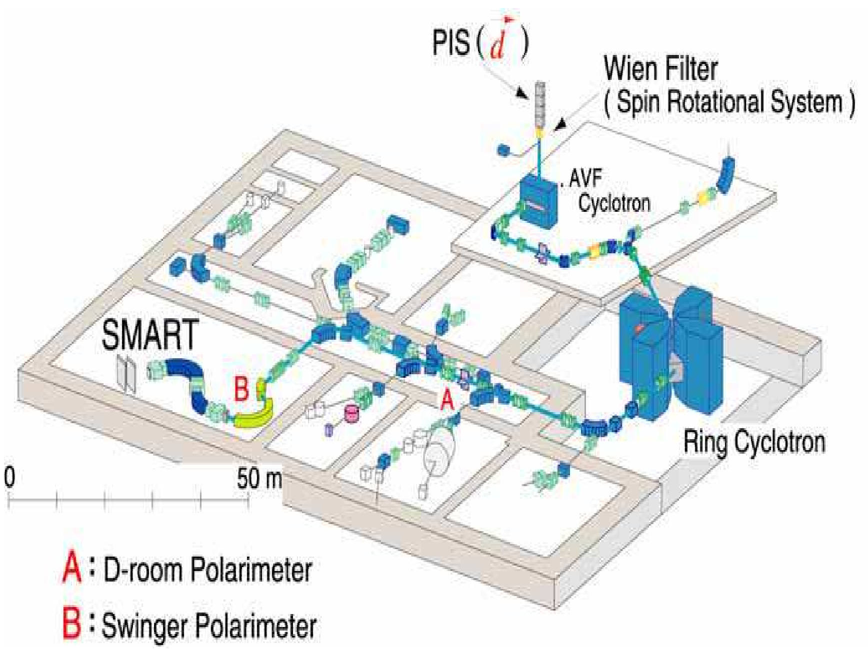
$d\ d\ \rightarrow\ ^3H\ p$ in the model of ONE



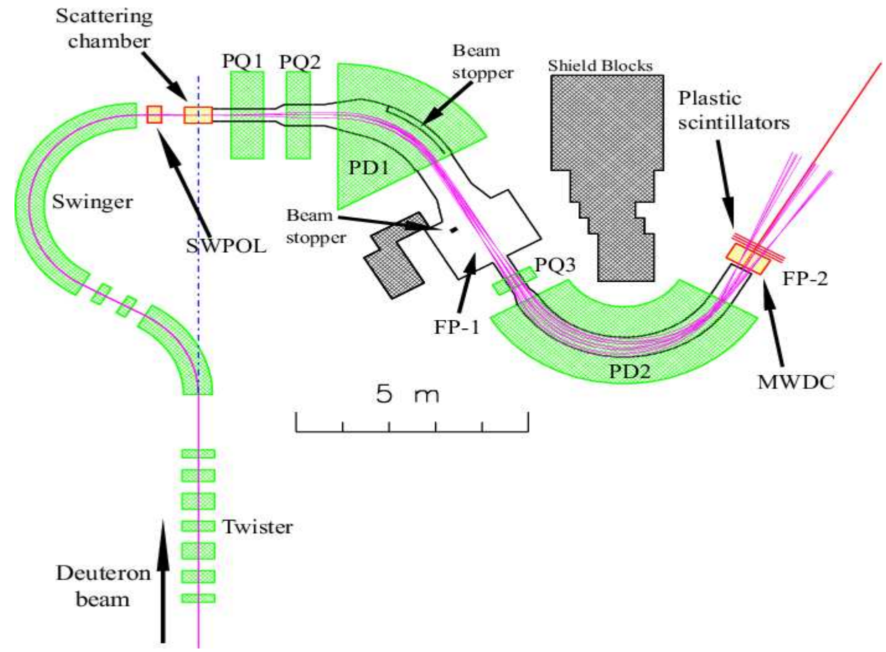
Reactions $\vec{d}\,d\ \rightarrow\ ^3He n$ and $\vec{d}\,d\ \rightarrow\ ^3H p$ can be described within the framework of the model of one-nucleon exchange. Both reactions can be described by the sum of two diagrams, required by the symmetry of the initial state.

The tensor analyzing powers for this reactions at the forward angles is directly connected with the relation of components D/S of wave functions ^3He and ^3H, respectively.

Experiment



RIKEN Accelerator Research Facility



Spectrometer SMART

The polarized beam of deuterons, was ensured by the polarized ion source(PIS), and was accelerated by AVF and Ring Cyclotron up tu energy 200 MeV. The accelerated beam was directed to the target, located in hall E4.

The measurement of the polarization of beam was carried out with help Swinger and Droom polarimeters.

The scattered particles were registered by spectrometer SMART.

Vector (p_z) and tensor polarization (p_{zz}) of deuteron beam

The data set was obtained with the different values of vector (p_z) and tensor polarization (p_{zz}) of deuteron beam. They are determined as follows:

$$p_z = N_+ + N_-$$
$$p_{zz} = N_+ + N_- - 2N_0$$

where N_+, N_-, N_0 designate the population density of particles with the orientation of magnetic moment +1, -1, and 0 respectively.

In this experiment we used four spin modes (0-3), one of which was not polarized. Their ideal values of polarization were:

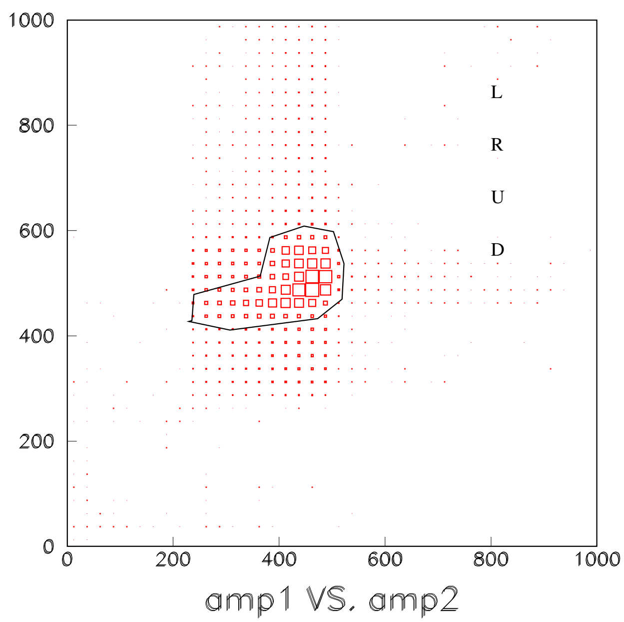
$$Mode(0) : (p_z, p_{zz}) = (0, 0),$$
$$Mode(1) : (p_z, p_{zz}) = (0, -2),$$
$$Mode(2) : (p_z, p_{zz}) = (-2/3, 0),$$
$$Mode(3) : (p_z, p_{zz}) = (1/3, 1).$$

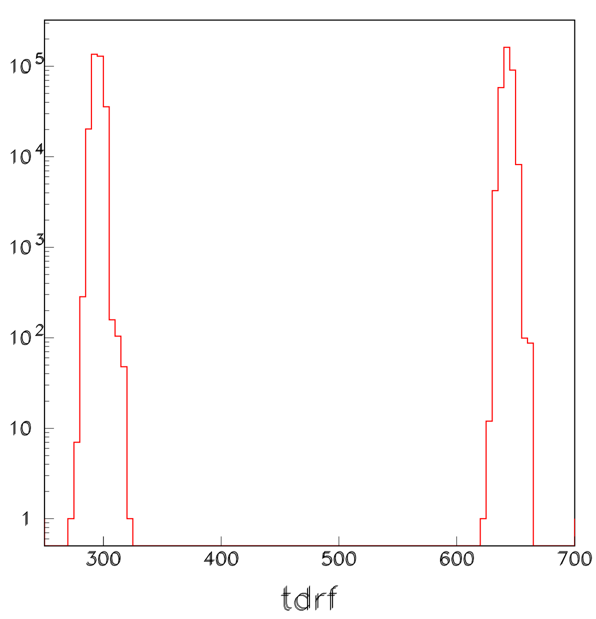
Mode(2), purely vector mode were used only in the case of the A_y measurement.

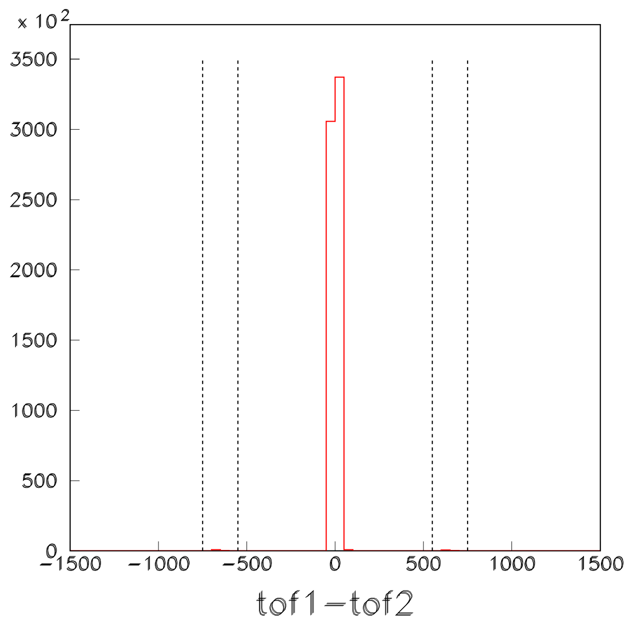
The criteria for true events of polarizations

The criteria used for identification of true events for each mode the polarization of beam are the following:

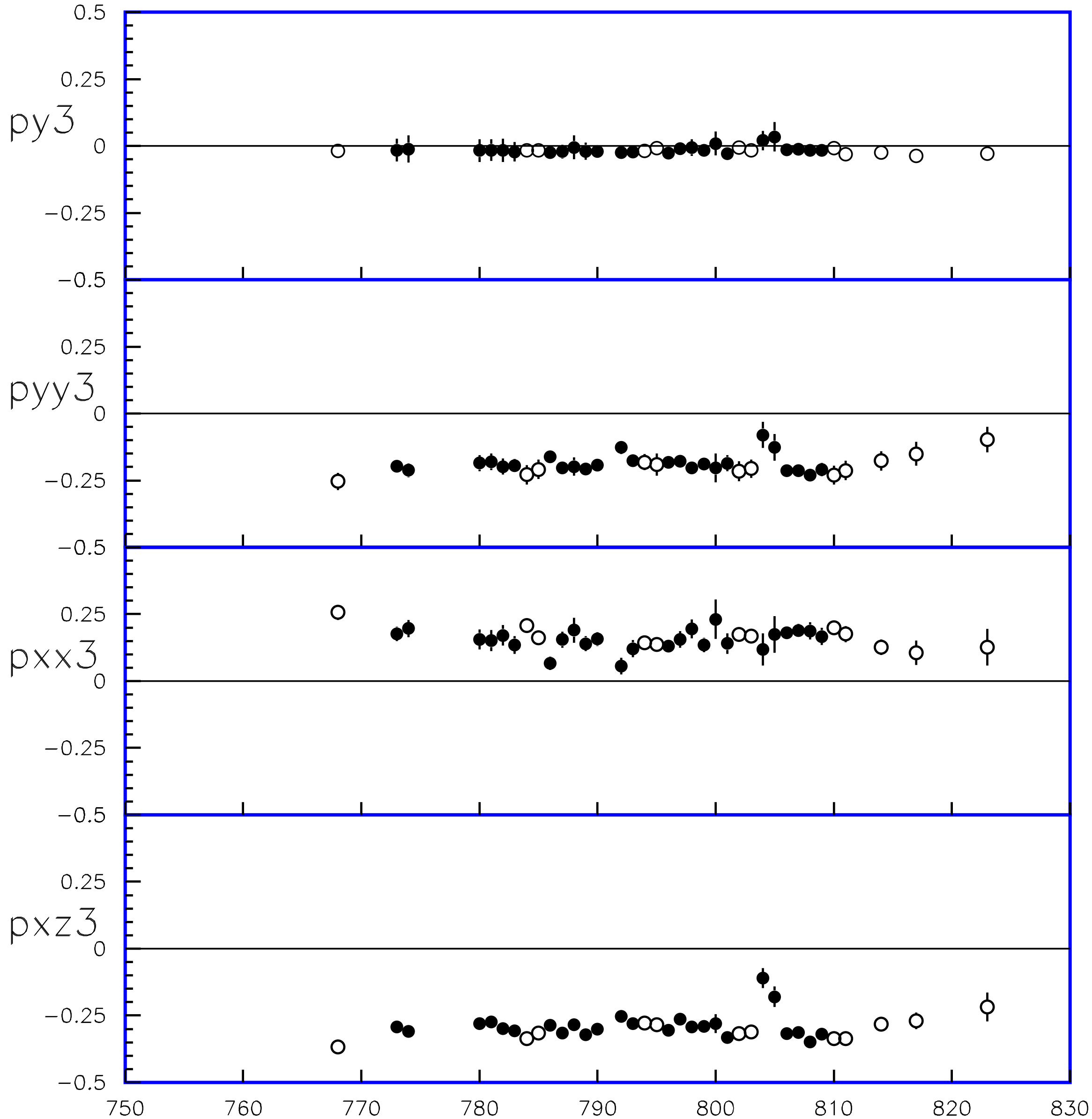
- The Radio Frequency signal of the cyclotron (RF-TDC) must be located in the specific time window.
- The time-of-ligth difference for the deuteron and proton detectors for each pair must be located in the specific time window.
- The amplitudes for each pair detectors must be correlated.







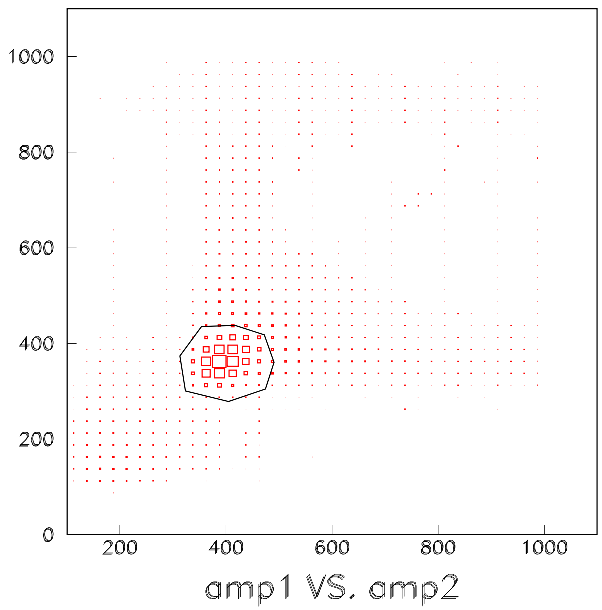
Value polarization for A_{xz}

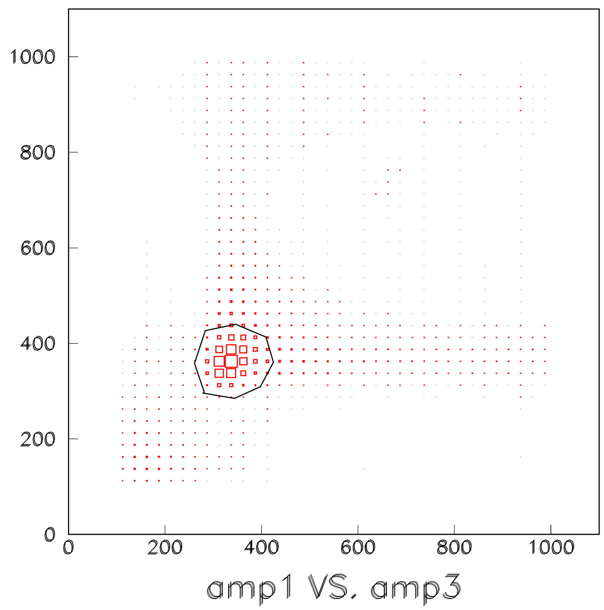


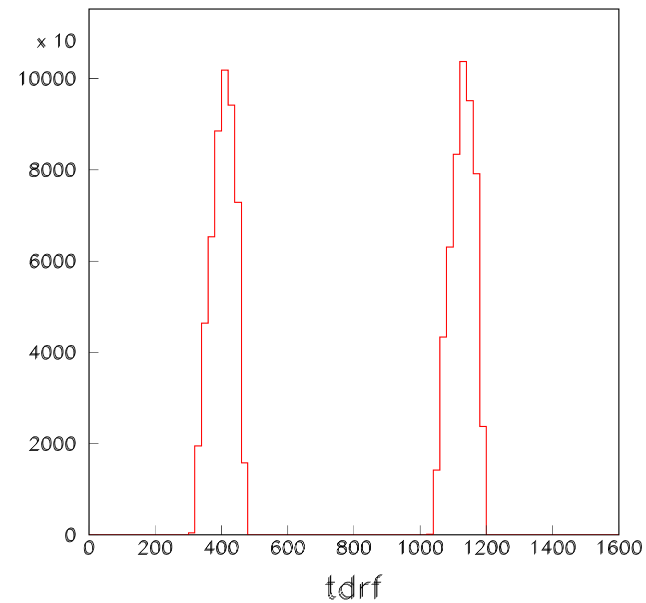
The criteria of true events for ^3H

The criteria used for the identification of the scattered particle ^3H from the $\vec{d}\,d \rightarrow {}^3Hp$ reaction are the following:

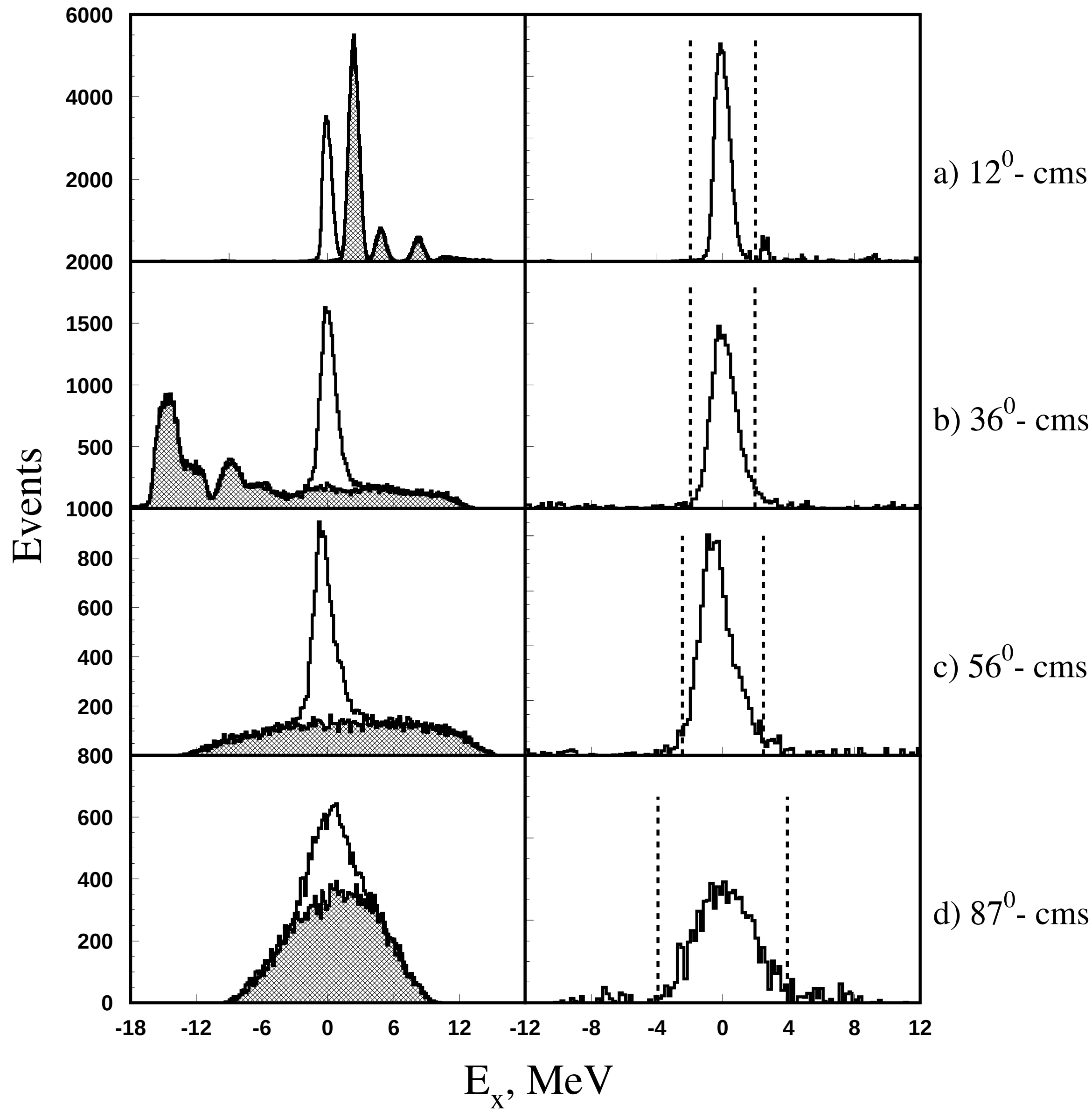
- The particle must be registered in the all three scintillation detectors.
- The amplitudes must be correlated.
- The Radio Frequency signal of the cyclotron (RF-TDC) must be synchronized with the signals from the plastic scintillators.







CD2-C subtraction



The quality of subtraction of the carbon contribution is presented for several angles in the center of mass system.

Equations for analyzing powers

A_y, A_{yy} analyzing powers:

$$N^1_{exp}(\theta_{cm}) = 1 + \frac{1}{2}p^1_{yy}A_{yy}(\theta_{cm}) \tag{1}$$

$$N^2_{exp}(\theta_{cm}) = 1 + \frac{3}{2}p^2_{yy}A_y(\theta_{cm}) \tag{2}$$

$$N^3_{exp}(\theta_{cm}) = 1 + \frac{3}{2}p^3_{yy}A_{yy}(\theta_{cm}) + \frac{1}{2}p^3_{yy}A_{yy}(\theta_{cm}) \tag{3}$$

A_{xx} analyzing power:

$$N^1_{exp}(\theta_{cm}) = 1 + \frac{1}{2}p^1_{xx}A_{xx}(\theta_{cm}) \tag{4}$$

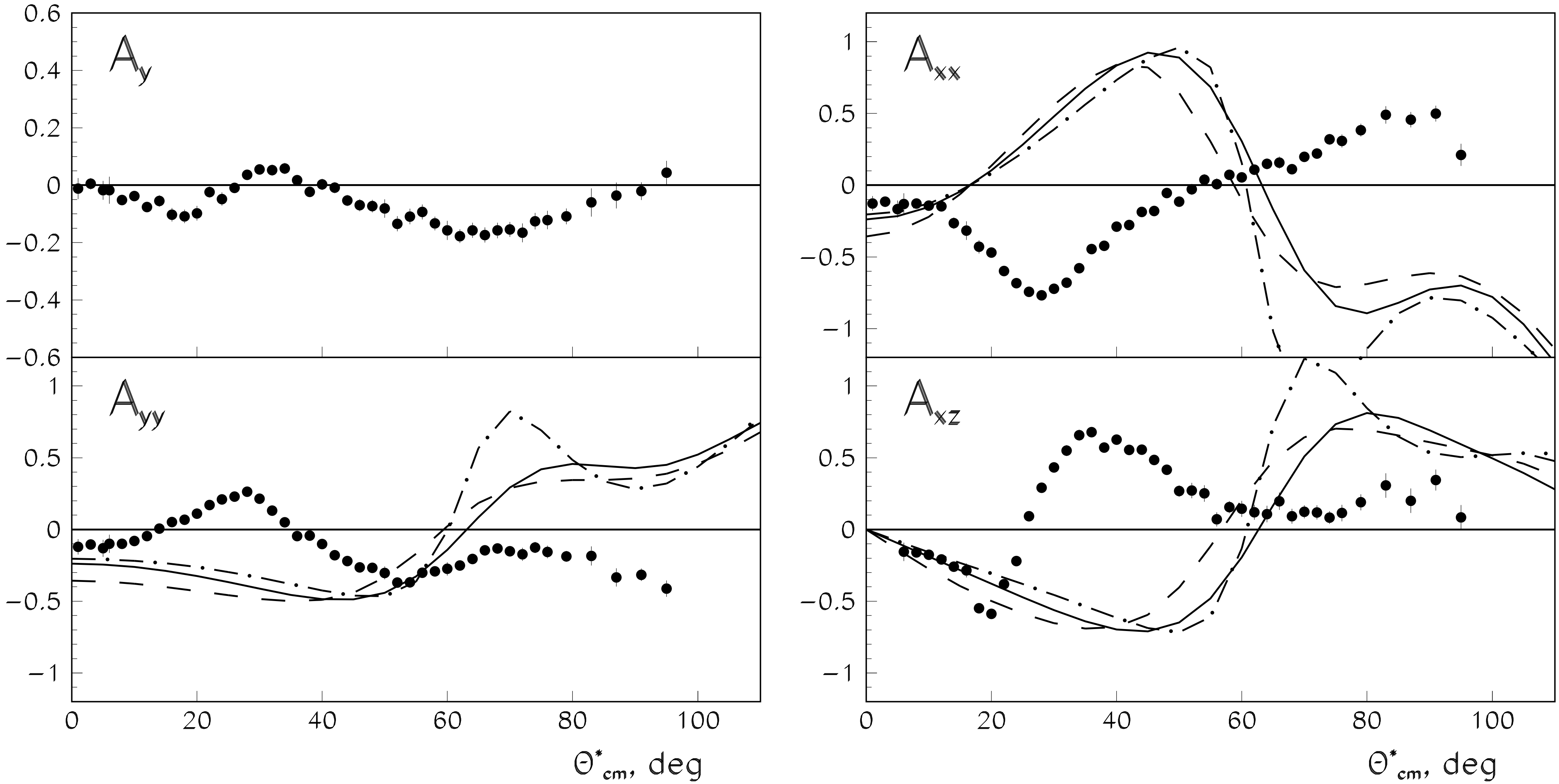
$$N^3_{exp}(\theta_{cm}) = 1 + \frac{1}{2}p^3_{xx}A_{xx}(\theta_{cm}) \tag{5}$$

A_{xz} analyzing power:

$$N^i_{exp}(\theta_{cm}) = 1 + \frac{2}{3}p^i_{xz}A_{xz}(\theta_{cm}) + C^i, (i = 1, 3) \tag{6}$$

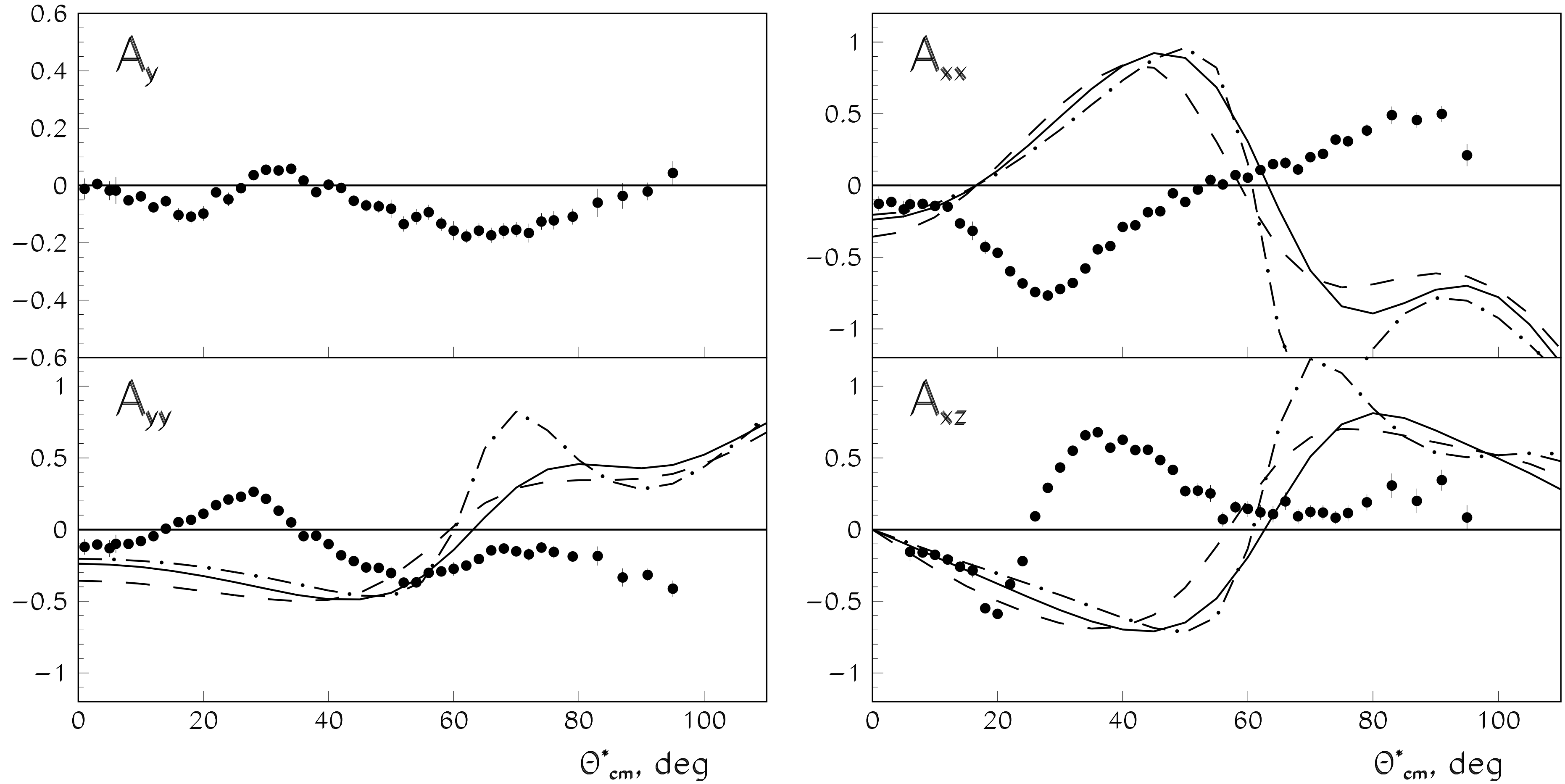
$$C^i = \frac{3}{2}p^i_yA_y(\theta_{cm}) + \frac{1}{2}p^i_{yy}A_{yy}(\theta_{cm}) + \frac{1}{6}(2p^i_{xx} + p^i_{yy})2A_{xx}(\theta_{cm}) + A_{yy}(\theta_{cm}) \tag{7}$$

Experimental results



The vector A_y and tensor A_{yy}, A_{xx} and A_{xz} analyzing powers for $\overrightarrow{d}\,d \rightarrow {}^3Hp$ reactions. The solid, long-dashed, and dash-dotted curves are the results of ONE calculations using Urbana, Paris and Reid soft core ^3He wave function, respectively.

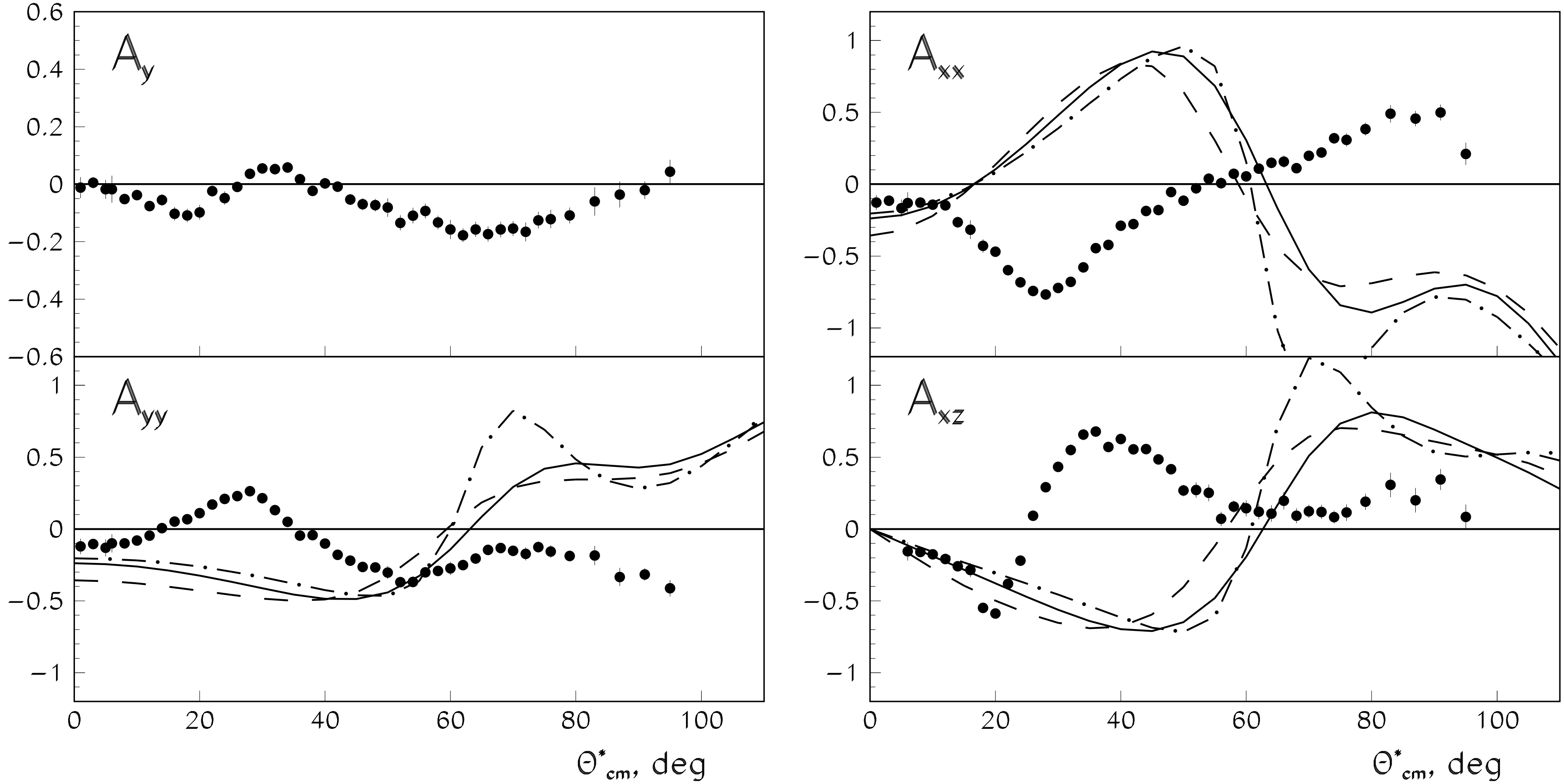
Discussion



One can see strong sensetivity to the ^3H spin structure when ^3H is emitted in the forward angle in the center of mass system and strong variation of analyzing powers versus an angle.

ONE calculation predicts that the tensor analyzing powers at the forward scattering are sensitive to the spin structure ^3H.

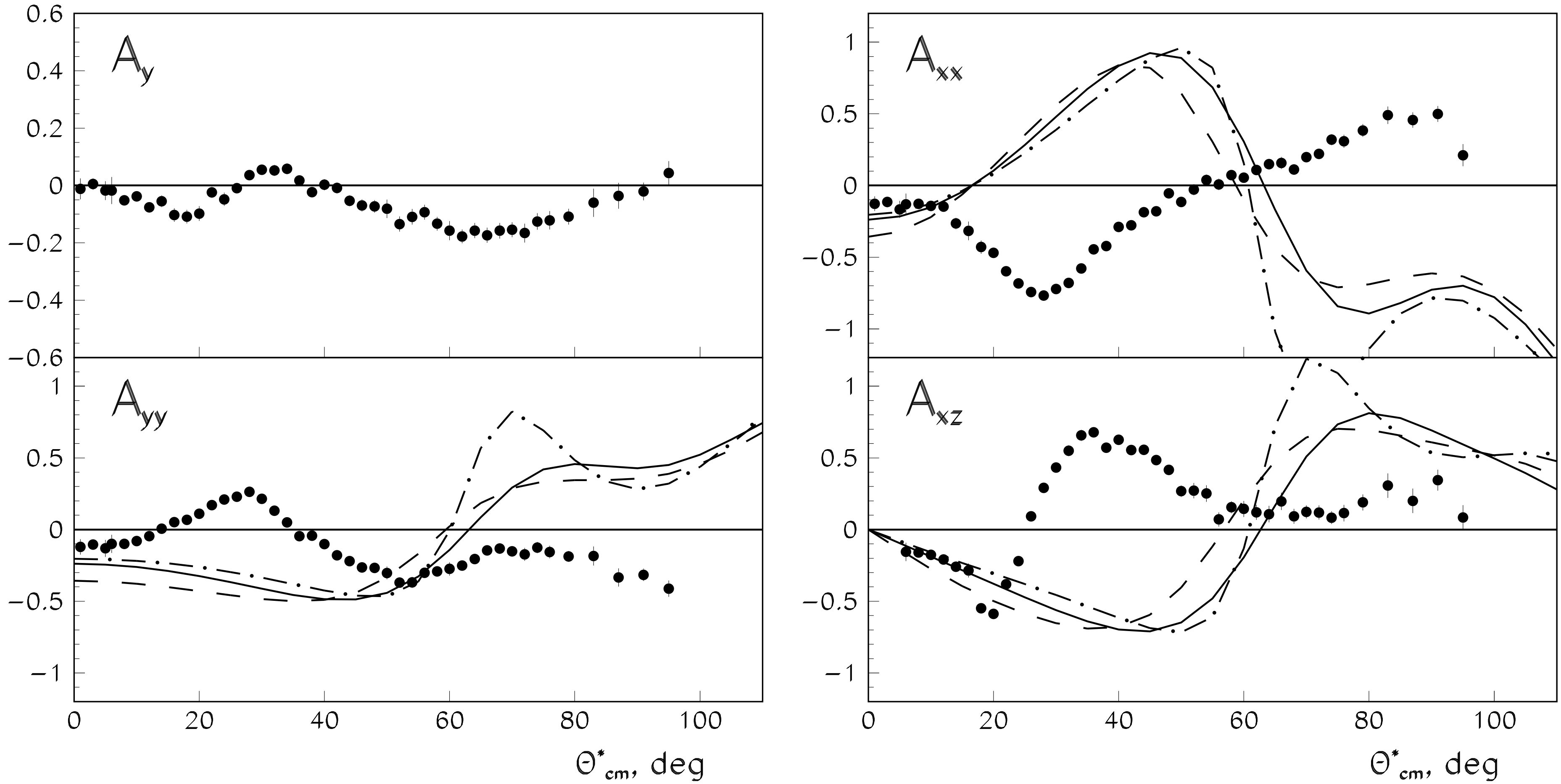
Discussion



As can be seen, the experimental data for A_{yy}, A_{xx}, A_{xz} analyzing powers strongly disagree with the predictions of ONE model calculations.

The predictions of ONE model calculations qualitatively reproduce the angular distributions of the tensor analyzing powers at small angles only.

Discussion



ONE calculation predicts a zero value of the vector analyzing power, but a some structure in the angular distribution of the vector analyzing power is observed.

This result will be a clue to investigate of the reaction mechanism beyond the ONE model.

Conclusion

- **The results of the vector A_y and tensor A_{yy}, A_{xx}, A_{xz} analyzing powers in the $\overrightarrow{d}d \rightarrow {}^3Hp$ reactions at the energy of deuterons 200 MeV in the angular range of 0 - 95 degrees in the center-of-mass system have been obtained. The data demonstrate large values of the analyzing powers.**

- **The experimental data were compared with theoretical predictions of ONE calculations based on Urbana, Paris and RSC ${}^3He$ wave functions. The predictions of ONE model calculations qualitatively reproduce the angular distributions of the tensor analyzing powers at small angles only. However, the ONE calculations cannot reproduce the data in the whole angular range of the measurements.**

- **The obtained experimental data require further development in theoretical approaches either for adequate description of the structure of light nuclei at short distances or taking into account mechanisms in addition to ONE.**

Thank you for the attention!

Method of obtaining the analyzing powers.

The differential cross section for the spin mode M is expressed as:

$$(\frac{\partial\sigma}{\partial\Omega})^M = (\frac{Y^M}{\rho(Q^M/e)\Delta\Omega\varepsilon^M})$$

were Y^M : yield of the true events;ρ: thickness of the targets; Q^M : integrated beam charge; e : deuteron charge; $\Delta\Omega$: solid angle; ε^M : (MWDC detection efficiency)$\times$(live-time ratio of the data aquisition).

To obtain the analyzing powers for the $\overrightarrow{d}d \rightarrow {}^3Hp$ and $\overrightarrow{d}d \rightarrow {}^3Hen$ reactions, the normalized cross sections for the spin mode M (M=1,2,3) a defined as:

$$N^M_{exp} = (\frac{\partial\sigma}{\partial\Omega})^M / (\frac{\partial\sigma}{\partial\Omega})^{M=0}$$

Excitation Energy is expressed as:

$$E_x = \sqrt{(E_0 - E_{3N})^2 - (P_0 - P_{3N})^2} - M_N$$

where P_0 is the incident momentum; $E_0 = 2M_d + T_d$ is the total initial energy; E_{3N} and P_{3N} are the energy and the momentum of the three-nucleon system, respectively; M_N is the nucleon mass.