

# Energy dependence of the vector $A_y$ and tensor $A_{yy}$ and $A_{xx}$ analyzing powers in deuteron-proton elastic scattering at large scattering angles

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**Abstract.** The results on the angular dependencies of the vector  $A_y$  and tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers in deuteron-proton elastic scattering at large scattering angles are presented. These data were obtained at internal target at the JINR Nuclotron in the energy range 400-1800 MeV using polarized deuteron beam from new polarized ion source. New data on the deuteron analyzing powers in the wide energy range demonstrate strong sensitivity to the short-range spin structure of the isoscalar nucleon-nucleon correlations observed earlier. The perspectives of further studies of the short-range correlations using carbon, polarized deuteron and proton beams are discussed.

## 1 Introduction

One of the tools to investigate the equation-of-state (EOS) of dense nuclear matter is the study of the short range correlations (SRC) of nucleons in nuclei which is the subject of intensive theoretical and experimental works during last years. Since SRC have densities comparable to the density in the center of a nucleon which is about  $\rho \sim 5\rho_0$  ( $\rho_0 \approx 0.17 \text{ fm}^{-3}$ ), they can be considered as the drops of cold dense nuclear matter [1]. These studies explore a new part of the phase diagram and very essential to understand the evolution of neutron stars.

The results obtained at BNL [2], SLAC [3] and JLAB [4, 5] clearly demonstrate that more than 90% of all nucleons with momenta  $k \geq 300 \text{ MeV}/c$  belong to 2N SRC; the probability for a given proton with momenta  $300 \leq k \leq 600 \text{ MeV}/c$  to belong to  $pn$ -correlation is about 18 times larger than for  $pp$ -correlations; the probability for a nucleon to have momentum  $\geq 300 \text{ MeV}/c$  in medium nuclei is about 25%; 3N SRC are present in nuclei with a significant probability [6]. However, still a lot of open questions persist and further investigations are

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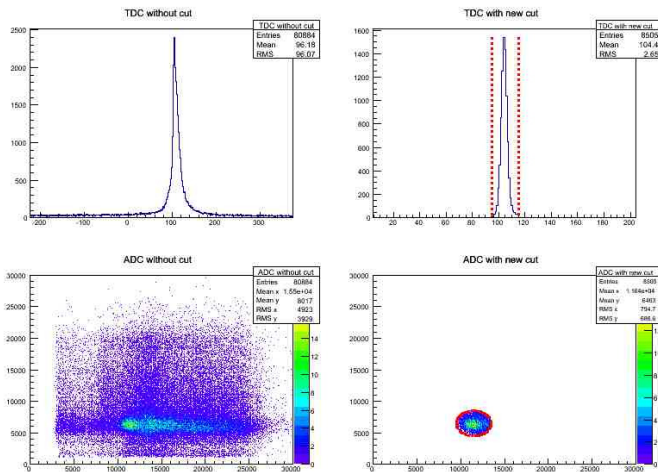
required both from the experimental and theoretical sides. For instance, the experimental data on the spin structure of  $2N$  ( $I=1$ ) and  $3N$  SRC are almost absent.

The main tools to study SRCs at hadronic facilities can be deuteron structure investigations at large internal momenta allowing one to explore  $2N$  SRC with  $I = 0$ ;  ${}^3\text{He}$  structure to understand the role of  $2N$  SRC with  $I = 1$  and  $3N$  SRC; nuclei breakup  $A(p, pp)X$ ,  $A(p, pn)X$ ,  $A(p, ppp)X$  etc. with the detection of few nucleons in the final state. The great importance is the study of the spin effects in these reactions because the data on the SRCs spin structure are scarce. The Nuclotron and NICA will allow one to investigate the spin effects for multi-nucleon correlations in a wide energy range.

The main goal of the Deuteron Spin Structure (DSS) experimental program is to obtain the information on the spin-dependent parts of two-nucleon ( $2N$ ) and three-nucleon ( $3N$ ) forces from two processes:  $dp$ -elastic scattering in a wide energy range and  $dp$ -nonmesonic breakup with two protons detection at energies 300 – 500 MeV [7–9] using the Nuclotron internal target station (ITS) [10]. The motivation of this program at low and intermediate energies is based on theoretical analysis of the experimental results obtained for the deuteron induced reactions (see recent reviews [11, 12] and references therein). Importance of the  $dp$ -elastic scattering studies at high energy is discussed in [13].

Such experimental program at the Nuclotron was started by the measurements of the vector  $A_y$  and tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers in  $dp$ -elastic scattering at  $T_d$  of 880 MeV [14] and 2000 MeV [15]. The systematic measurements of the differential cross section have been performed also in recent years [16–18].

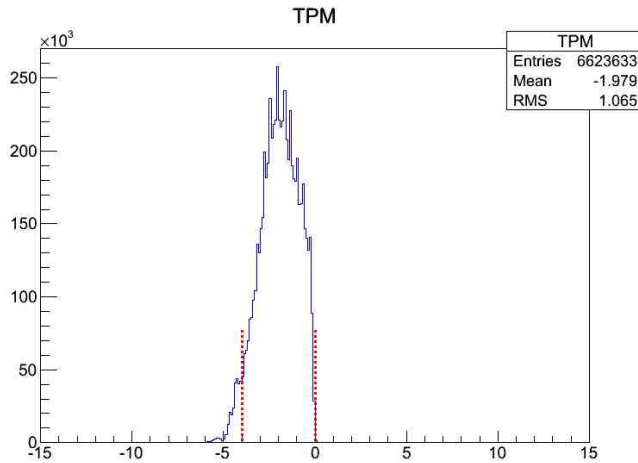
In this paper we report new results of the energy scan of the vector  $A_y$  and tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers in  $dp$ -elastic scattering obtained at the Nuclotron ITS [10] in the energy range of 400-1800 MeV.



**Figure 1.** Selection of the  $dp$ -elastic events at about  $75^\circ$  in c.m.s. at 1000 MeV using time difference and correlation of the energy-losses signals for proton and deuteron counters

## 2 Experimental setup at ITS

The internal target station (ITS) setup is well suited for study of the energy dependence of polarization observables for the deuteron-proton elastic scattering and deuteron breakup

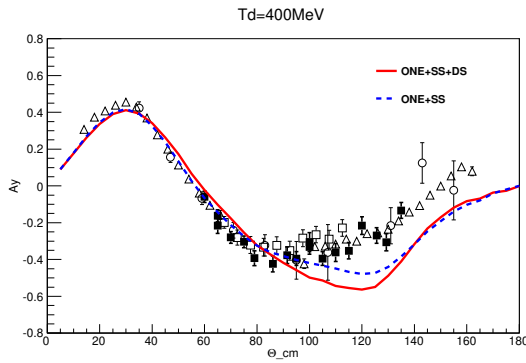


**Figure 2.** Distribution of the beam-target interaction point. The vertical lines represent the criteria to select the  $dp$ -elastic scattering events

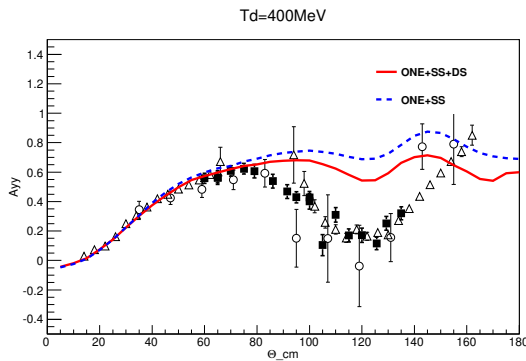
reaction with the detection of two protons at large scattering angles. For these purposes the  $\text{CH}_2$ -target of  $10\ \mu\text{m}$  thick is used for the measurements. The yield from carbon content of the  $\text{CH}_2$ -target is estimated in separate measurements using several twisted  $8\ \mu\text{m}$  carbon wires. The monitoring of the intensity is done from the detection of  $pp$ -quasielastic scattering at  $90^\circ$  in c.m.s. by the scintillation counters placed in the horizontal plane. The detection of the  $dp$ -elastic events is done by the coincidence measurements of the proton and deuteron. The detectors are placed in the both horizontal and vertical planes for the analyzing powers measurements. The selection of the  $dp$ -elastic events is done by the correlation of the energy losses in plastic scintillators for deuteron and proton and their time-of-flight difference. The use of large amount of the scintillation counters allowed one to cover a wide angular range [19]. Such a method has been used to obtain the polarization data in  $dp$ -elastic scattering at  $T_d$  of 880 MeV [14] and 2000 MeV [15].

The upgraded setup at ITS has been used to measure the vector  $A_y$  and tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers in  $dp$ -elastic scattering between 400 MeV and 1800 MeV using polarized deuteron beam from the new source of polarized ions (SPI) developed at LHEP-JINR [20]. These measurements were performed using internal target station at the Nuclotron [10] with new control and data acquisition system [21]. The existing setup [19] has been upgraded by new VME based DAQ [22], new MPod based high voltage system [23], new system of the luminosity monitors etc.

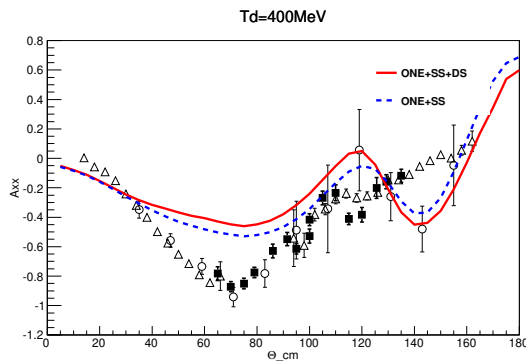
The same setup has been used as a polarimeter based on the use of  $dp$ -elastic scattering at large angles ( $\theta_{\text{cm}} \geq 60^\circ$ ) at 270 MeV [19], where the precise data on analyzing powers [24–26] exist, has been developed at the internal target station at the Nuclotron [10]. The accuracy of the determination of the deuteron beam polarization achieved with this method is better than 2% because of the values of the analyzing powers were obtained for the polarized deuteron beam, which absolute polarization had been calibrated via the  $^{12}\text{C}(d, \alpha)^{10}\text{B}^*[2^+]$  reaction [26].



**Figure 3.** The angular dependence of the vector analyzing power  $A_y$  at the deuteron kinetic energy  $T_d$  of 400 MeV. The full squares are the preliminary results of the DSS experiment at ITS at the Nuclotron. Open symbols are the world data [28, 30]. Curves are explained in the text



**Figure 4.** The angular dependence of the tensor analyzing power  $A_{yy}$  at the deuteron kinetic energy  $T_d$  of 400 MeV. Symbols and lines are the same as in Fig. 3

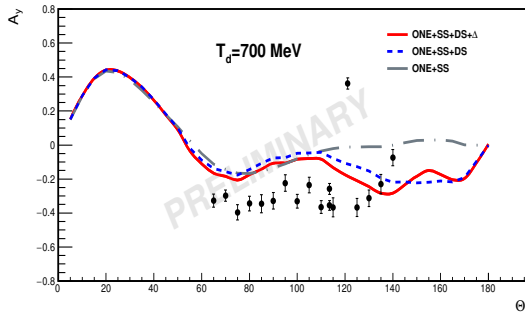


**Figure 5.** The angular dependence of the tensor analyzing power  $A_{xx}$  at the deuteron kinetic energy  $T_d$  of 400 MeV. Symbols and lines are the same as in Fig. 3

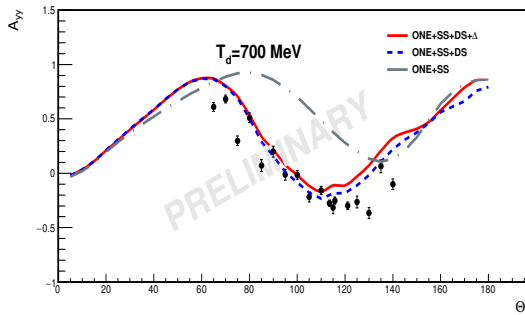
### 3 Measurements of the analyzing power in $dp$ -elastic scattering

New SPI [20] has been used to provide polarized deuteron beam. In the current experiment the spin modes with the maximal ideal values of  $(P_z, P_{zz}) = (0, 0)$ ,  $(-1/3, +1)$  and  $(-1/3, +1)$  were used. The deuteron beam polarization has been measured at 270 MeV [19]. The  $dp$ -elastic scattering events at 270 MeV were selected using correlation of the energy losses and time-of-flight difference for the deuteron and proton detectors. The values of the beam polarization for different spin have been obtained as weighted averages for 8 scattering angles for  $dp$ -elastic scattering in the horizontal plane only. The typical values of the beam polarization were about 65-75% from the ideal values [27].

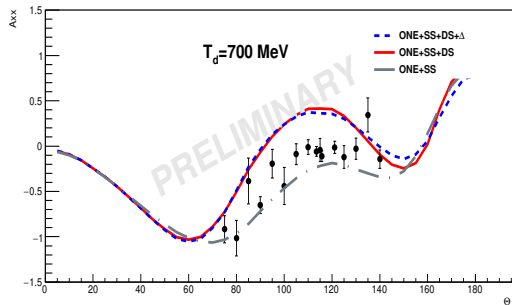
After the deuteron beam polarization measurements at 270 MeV, the beam has been accelerated up to the required energy  $T_d$  between 400 MeV and 1800 MeV. The scintillation



**Figure 6.** The angular dependence of the vector analyzing power  $A_y$  at the deuteron kinetic energy  $T_d$  of 700 MeV. The full symbols are the preliminary results of the DSS experiment at ITS at the Nuclotron. Curves are explained in the text



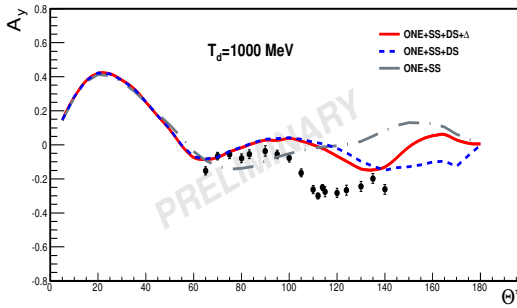
**Figure 7.** The angular dependence of the tensor analyzing power  $A_{yy}$  at the deuteron kinetic energy  $T_d$  of 700 MeV. Lines and symbols are the same as in Fig. 6



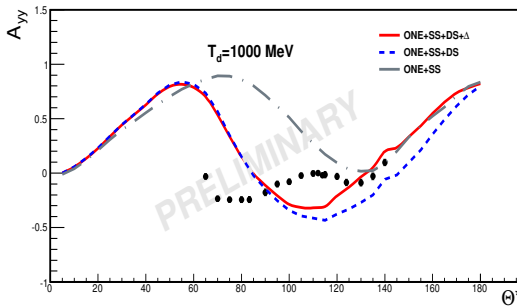
**Figure 8.** The angular dependence of the tensor analyzing power  $A_{xx}$  at the deuteron kinetic energy  $T_d$  of 700 MeV. Lines and symbols are the same as in Fig. 6

detectors were positioned in the horizontal and vertical plane in accordance with the kinematic of  $dp$ -elastic scattering for the investigated energy. The main part of the measurements were performed using  $\text{CH}_2$  target. The carbon target was used to estimate the background. The selection of the  $dp$ -elastic events is done by the correlation of the energy losses in plastic scintillators for deuteron and proton and their time-of-flight (TOF) difference those initial distributions are shown in the left bottom and upper panels of Fig. 1, respectively. The right upper panel of Fig. 1 demonstrates the time-of-flight difference for proton and deuterons with the prompt TOF window, while the final selection of the  $dp$ -elastic events after applying a graphical cut on the correlation of the energy losses is shown in the right bottom panel. Additionally, the criteria on the beam-target interaction point has been applied (see Fig. 2). The normalized numbers of  $dp$ -elastic scattering events for each spin mode were used to calculate the values of the analyzing powers  $A_y$ ,  $A_{yy}$  and  $A_{xx}$ .

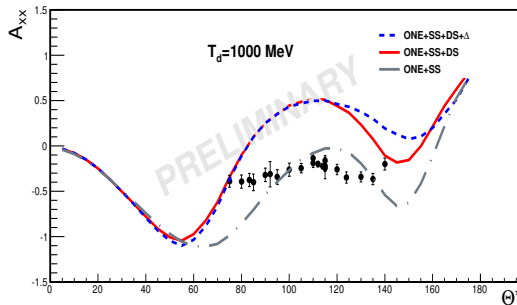
The angular dependencies of the vector  $A_y$ , tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers at the deuteron kinetic energy  $T_d$  of 400 MeV are presented in Figs. 3, 4 and 5, respectively. The



**Figure 9.** The angular dependence of the vector analyzing power  $A_y$  at the deuteron kinetic energy  $T_d$  of 1000 MeV. The full symbols are the preliminary results of the DSS experiment at ITS at the Nuclotron. Lines are the same as in Fig. 6



**Figure 10.** The angular dependence of the tensor analyzing power  $A_{yy}$  at the deuteron kinetic energy  $T_d$  of 1000 MeV. Lines and symbols are the same as in Fig. 6

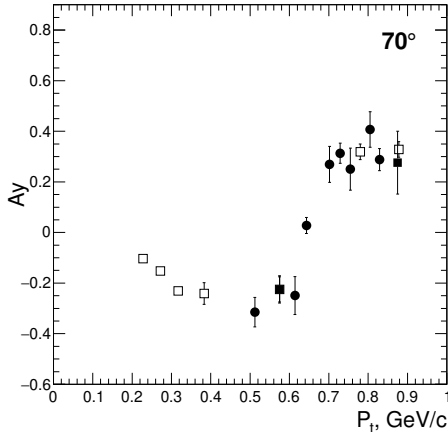


**Figure 11.** The angular dependence of the tensor analyzing power  $A_{xx}$  at the deuteron kinetic energy  $T_d$  of 1000 MeV. Lines and symbols are the same as in Fig. 6

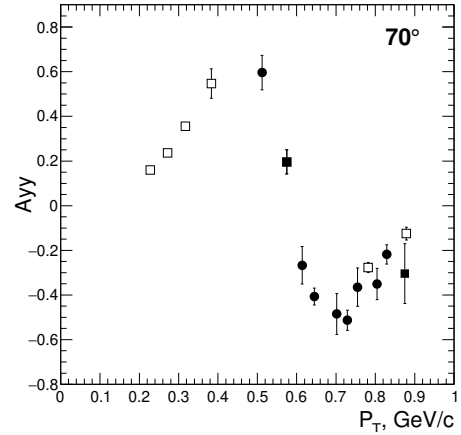
full squares are the results of the DSS experiment at ITS at the Nuclotron. Open circles, squares and triangles are the data obtained at Saclay [28] and IUCF [29], [30], respectively. One can see a good agreement of the new data obtained at the Nuclotron with the data from earlier experiments [28–30].

The theoretical calculations were performed in the relativistic multiple scattering expansion formalism [31–33]. The four contributions are taken into account: one-nucleon-exchange (ONE), single- and double-scattering (SS and DS), and  $\Delta$ -isobar excitation. The presented approach was applied earlier to describe the differential cross sections at deuteron energies between 500 and 1300 MeV in a whole angular range [33]. Dashed and solid lines are the calculations performed within relativistic multiple scattering model [31, 32] considering ONE+SS terms only and with the DS contribution added, respectively. Note that the contribution of the  $\Delta$ -isobar mechanism is negligible at this energy [33]. The relativistic multiple scattering model [31, 32] describes the data on  $A_y$  and  $A_{yy}$  to about  $90^\circ$  only, while it fails to reproduce the data at larger angles. The considering of the DS term does not improve the

agreement. The  $A_{xx}$  behaviour is not described by the model [31, 32] over the whole angular range. The considering of the contribution of the three-nucleon forces or  $N^4$ LO calculations performed within chiral effective field theory ( $\chi$ EFT) [34] do not allow one to get an agreement with the data on the tensor analyzing powers. The reason of the deviation can be the neglecting by the 3N SRCs.



**Figure 12.** The energy dependence of the vector analyzing power  $A_y$  at  $70^\circ$  in the c.m.s. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at the Nuclotron in 2005 [14, 15]. Open symbols are the data [24, 25, 28, 36, 37] obtained in the previous experiments



**Figure 13.** The energy dependence of the tensor analyzing power  $A_{yy}$  at  $70^\circ$  in the c.m.s. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at the Nuclotron in 2005 [14, 15]. Open symbols are the same as in Fig. 12

The preliminary results on the vector  $A_y$ , tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers at the deuteron kinetic energy  $T_d$  of 700 MeV are presented in Figs. 6, 7 and 8, respectively. The data are obtained within angular range of  $65^\circ$ - $140^\circ$  in c.m.s. The dash-dotted, dashed and solid lines are the predictions obtained within relativistic multiple scattering model [33] considering ONE+SS terms only, with the DS contribution and with  $\Delta$ -isobar excitation term, respectively. One can see, that the DS-term consideration allows one to improve the agreement with the data on  $A_{yy}$  analyzing power at the angles to about  $120^\circ$ . The contribution of  $\Delta$ -isobar excitation is small even at backward angles. Analyzing power  $A_y$  and  $A_{xx}$  are not described by the calculations. The similar picture in the description of the data on the analyzing power is observed at 800 MeV [35].

The preliminary results on the vector  $A_y$ , tensor  $A_{yy}$  and  $A_{xx}$  analyzing powers at the deuteron kinetic energy  $T_d$  of 1000 MeV are presented in Figs. 9, 10 11, respectively. The lines are the predictions obtained within relativistic multiple scattering model [33] considering ONE, SS, DS and  $\Delta$ -isobar excitation terms. They are the same as in Fig. 6. One can see that the model describes the behavior of the vector analyzing power  $A_y$  to about  $100^\circ$  in c.m.s., while the tensor analyzing powers  $A_{yy}$  and  $A_{xx}$  are not described over the whole range of measurements. The  $\Delta$ -isobar excitation term gives a significant contribution at the angles larger than  $140^\circ$  in c.m.s. Apparently, spin structure of the nucleon-nucleon interactions and deuteron at short distances is missed in the standard description used in the relativistic multiple scattering model [31–33].

The energy dependencies of the vector  $A_y$  and tensor  $A_{yy}$  analyzing powers at  $70^\circ$  in the c.m.s. are presented as a function of the transverse momentum  $P_T$  in Figs 12 and 13, respectively. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at the Nuclotron in 2005 [14, 15]. Open symbols are the world data [24, 25, 28, 36, 37]. Both  $A_y$  and  $A_{yy}$  analyzing powers change the sign at  $P_T \sim 600$  MeV/c and have the tendencies at larger  $P_T$  to reach the positive and negative constant values, respectively. These features of the data indicate the serious deviation of the spin structure of the 2N SRCs on the standard description of the nucleon-nucleon interaction. Further theoretical investigations are required to understand the behaviour of the data at large  $P_T$ .

The availability of the polarized proton beam at the Nuclotron [38] allows one to extend the DSS physics program at ITS [13], namely, to perform the experiments on the measurements of the nucleon analyzing power  $A_y^p$  in  $pd$ -elastic scattering at 135-1000 MeV and in  $pd$ -nonmesonic breakup at the energies between 135-250 MeV for different kinematic configurations etc.

## 4 Conclusions

- The upgraded Nuclotron with the new SPI [20] provides quite unique opportunity for the studies of the spin effects and polarization phenomena in few body systems.
- The realization of the DSS program at the ITS will allow one to obtain the crucial data on the spin structure of 2-nucleon and 3-nucleon short range correlations. The first natural step in these studies, namely, the energy scan of the deuteron analyzing powers in  $dp$ -elastic scattering has been performed in 2016-2017. The data demonstrate the sensitivity to the short-range spin structure of the deuteron.
- Next experiments using polarized deuterons and protons at ITS are in preparation.
- The extension of the studies to the high energies is possible with the extracted polarized deuteron and proton beams.

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