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Spin studies of the short-range correlations at Nuclotron

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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 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 in the wide energy range demonstrate the sensitivity to the short-range spin structure of the isoscalar nucleon-nucleon correlations. The perspectives of further studies of the short-range correlations using polarized deuteron and proton beams are discussed.

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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 $\rho \sim 5\rho_0$ ($\rho_0 \approx 0.17$ 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% all nucleons with momenta $k \geq 300$ MeV/c belong to two-nucleon (2N) SRC; the probability for a given proton with momenta $300 \leq k \leq 600$ MeV/c to belong to pn correlation is $\sim$18 times larger than for pp correlations; the probability for a nucleon to have momentum ≥ 300 MeV/c in medium nuclei is $\sim$25%; three-nucleon (3N) SRC are present in nuclei with a significant probability [6]. However, still many open questions persist and further investigations are 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 to explore 2N SRC with $I = 0$; ^{3}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 greate importance is the study of the spin effects in these reactions because the data on the SRCs spin structure are scarce. Nuclotron and NICA will allow 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 2N and 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, 8, 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 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, 17, 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.

2. Experiment at Nuclotron ITS

The ITS setup is well suited for study of the energy dependence of polarization observables for the deuteron-proton elastic scattering and deuteron breakup reaction with the detection of two protons at large scattering angles. For these purposes the CH_2-target of 10 μm thick is used for the measurements. The yield from carbon content of the CH_2-target is estimated in separate measurements using several twisted 8 μm carbon wires. The monitoring of the intensity is done from the detection of pp- quasielastic scattering at 90° in cms 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 to cover wide angular range [19]. Such a metod 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 new Source of Polarized Ions (SPI) developed at LHEP-JINR [20]. These measurements were performed using internal target station at 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 ($\theta_{\rm cm} \geq 60^\circ$) at 270 MeV[19], where precise data on analyzing powers [24, 25, 26] exist, has been developed at ITS at 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 $^{12}{\rm C}(d,\alpha)^{10}{\rm B}^*[2^+]$ reaction [26].

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 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 ∼65-75% from the ideal values [27].

After 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 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 CH_2 target. 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 in Fig. 1, respectively. The right upper panel in Fig. 1 demonstrates the TOF difference for proton and deuterons with 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

(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}.

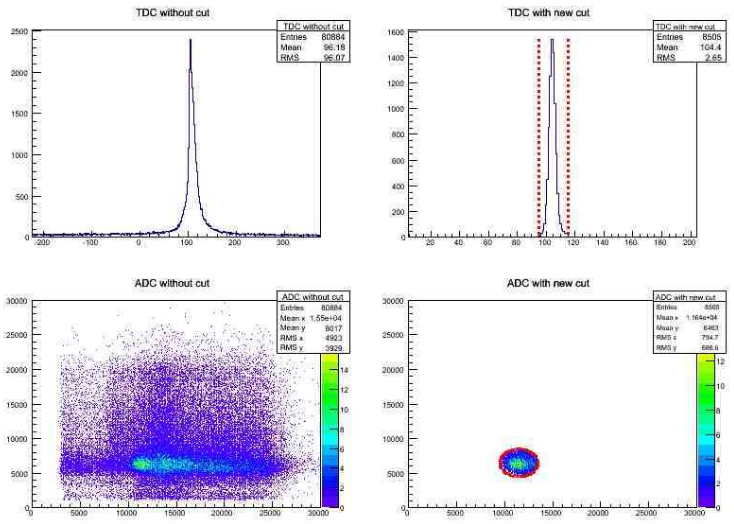

Figure 1: Selection of the dp-elastic events at $\sim 75^\circ$ in cms at 1000 MeV using time difference and correlation of the energy-losses signals signals for proton and deuteron counters.

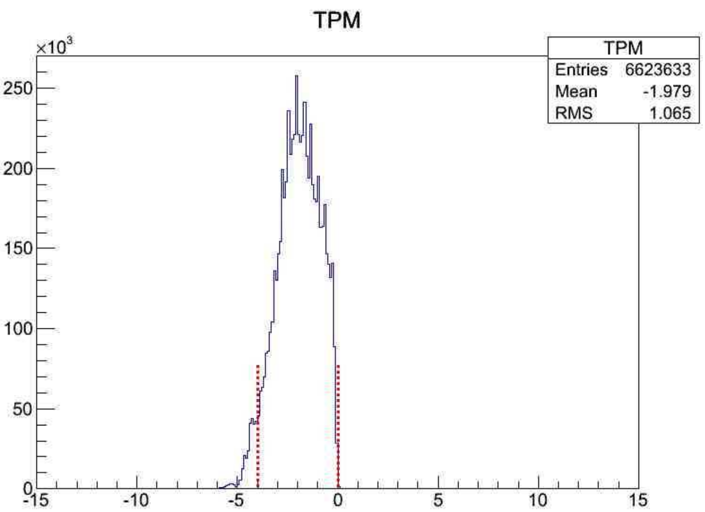

Figure 2: Distribution of the beam-target interaction point. The vertical lines represent the criteria to select the dp-elastic scattering events.

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 Fig. 3, Fig. 4 and Fig. 5, respectively. The full squares are the results of the DSS experiment at ITS at Nuclotron. Open squares, triangles and circles are the data obtained at IUCF [28], [29] and at Saclay [30], respectively. One can see good agreement of new data obtained at Nuclotron with the data from earlier experiments [28]-[30]. The theoretical calculations were performed in the relativistic multiple scattering expansion formalism

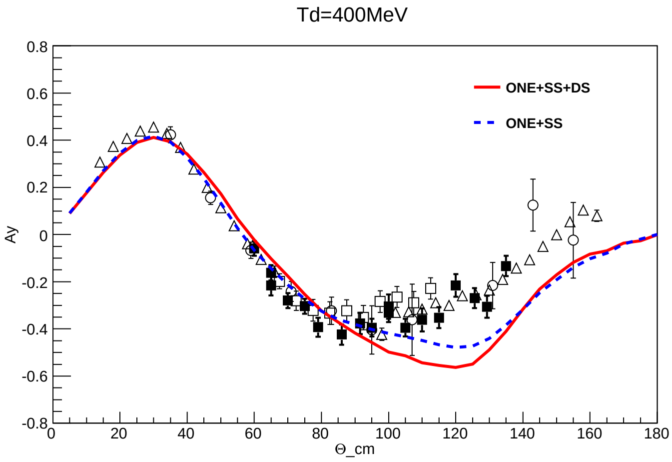

Figure 3: The angular dependence of the vector analyzing power A_y at the deuteron kinetic energy T_d of 400 MeV. The full squares are the preliminary results of the DSS experiment at ITS at Nuclotron. Open symbols are the world data [28, 29, 30]. Curves are explained in the text.

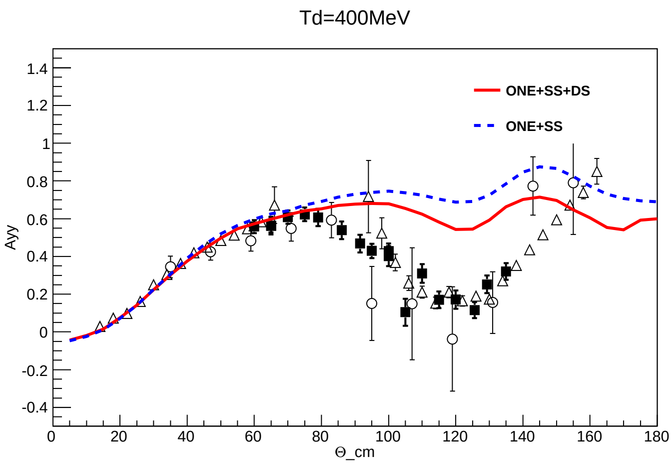

Figure 4: The angular dependence of the tensor analyzing power A_{yy} at the deuteron kinetic energy T_d of 400 MeV. Symbols and lines are the same as in Fig. 3.

[31]-[33]. The four contributions are taken into account: One-Nucleon-Exchange (ONE), Single- and Double- Scattering (SS and DS), and Δ- 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 Δ- isobar mechanism is negligible at this energy [33]. The relativistic multiple scattering model [31]-[32] describes the data on A_y and A_{yy} up to $\sim 90^\circ$ 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^4LO calculations performed within chiral Effective Field Theory (χEFT) [34] do not allow to get

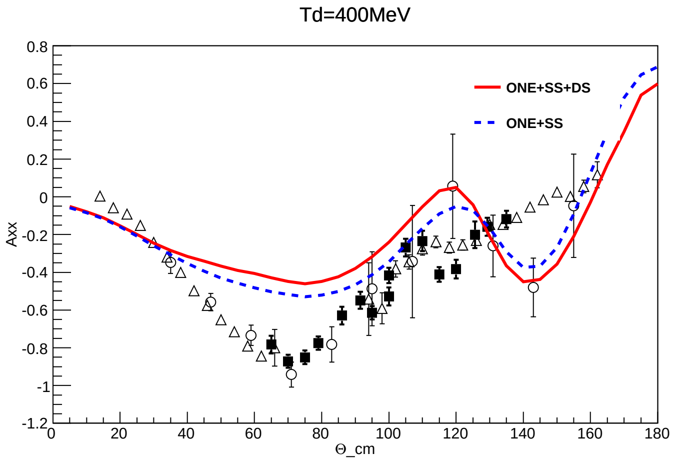

Figure 5: The angular dependence of the tensor analyzing power A_{xx} at the deuteron kinetic energy T_d of 400 MeV. Symbols and lines are the same as in Fig. 3.

an agreement with the data on the tensor analyzing powers. The reason of the deviation can be the neglecting by the 3N SRCs.

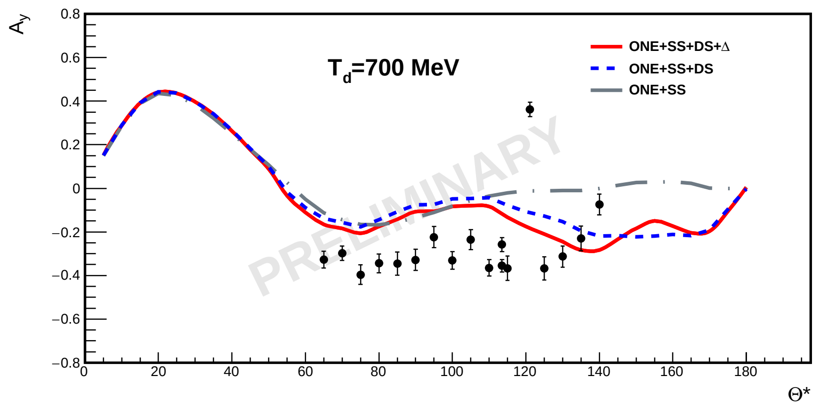

Figure 6: The angular dependence of the vector analyzing power A_y at the deuteron kinetic energy T_d of 800 MeV. The full symbols are the preliminary results of the DSS experiment at ITS at Nuclotron. Curves are explained in the text.

The preliminary results on the vector A_y, tensor A_{yy} and A_{xx} analyzing powers at the deuteron kinetic energy T_d of 800 MeV are presented in Fig. 6, Fig. 7 and Fig. 8, respectively. The data are obtained within angular range of 65°-140° in cms. 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 Δ- isobar excitation term, respectively. One can see, that the DS- term consideration allows to improve the agreement with the data on A_{yy} analyzing power at the angles up to ∼120°. The contribution of Δ- 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 700 MeV.

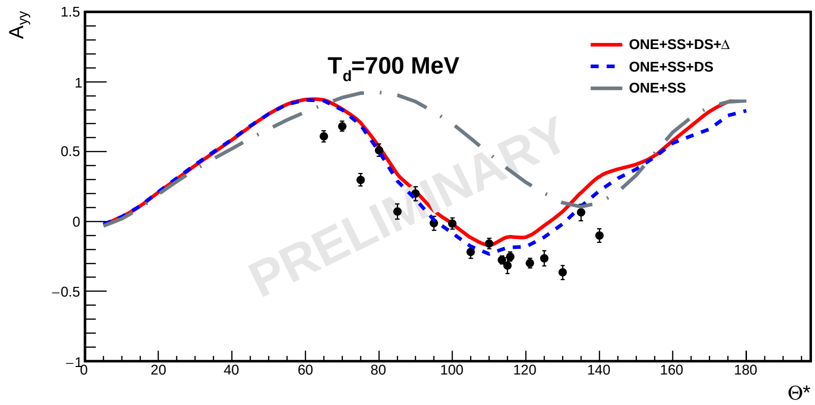

Figure 7: The angular dependence of the tensor analyzing power A_{yy} at the deuteron kinetic energy T_d of 800 MeV. Lines and symbols are the same as in Fig. 6.

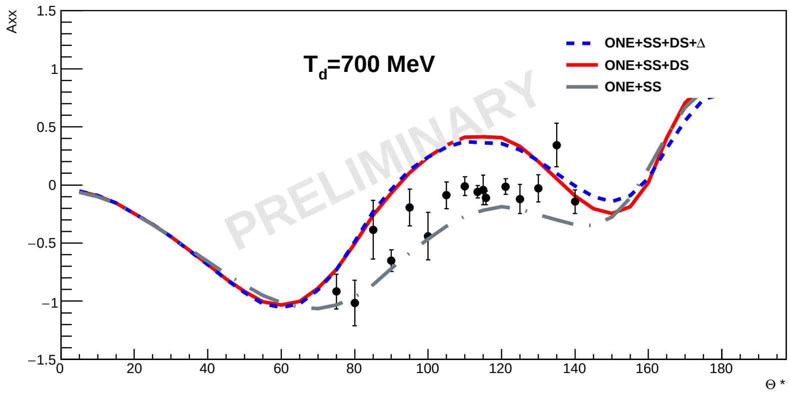

Figure 8: The angular dependence of the tensor analyzing power A_{xx} at the deuteron kinetic energy T_d of 800 MeV. Lines and symbols are the same as in Fig. 6.

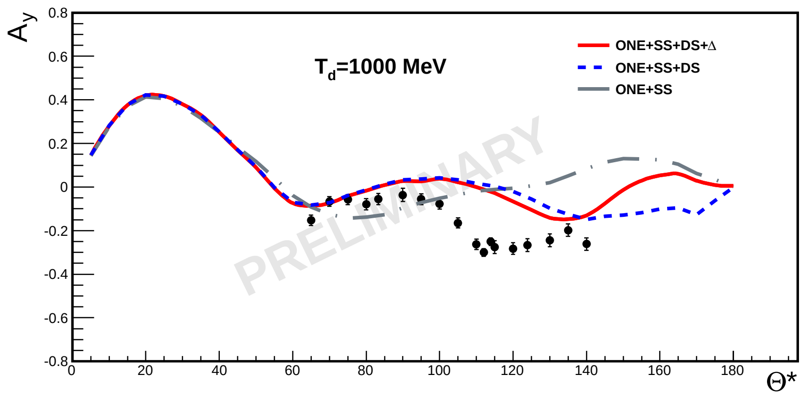

Figure 9: The angular dependence of the vector analyzing power A_y at the deuteron kinetic energy T_d of 1000 MeV. The full symbols are the preliminary results of the DSS experiment at ITS at Nuclotron. Lines are the same as in Fig. 6.

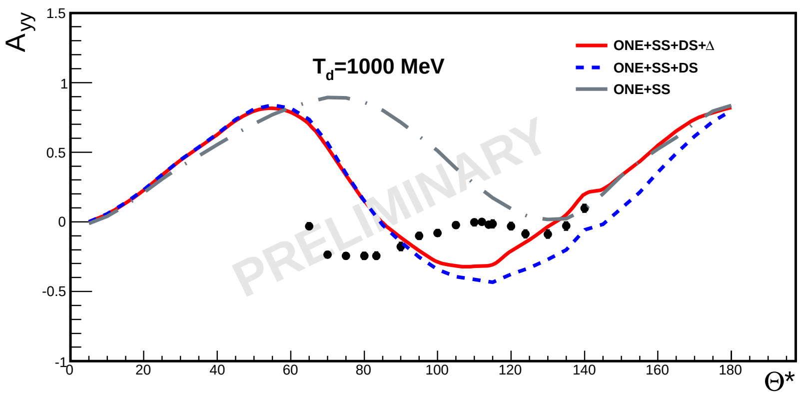

Figure 10: The angular dependence of the tensor analyzing power A_{yy} at the deuteron kinetic energy T_d of 1000 MeV. Lines and symbols are the same as in Fig. 6.

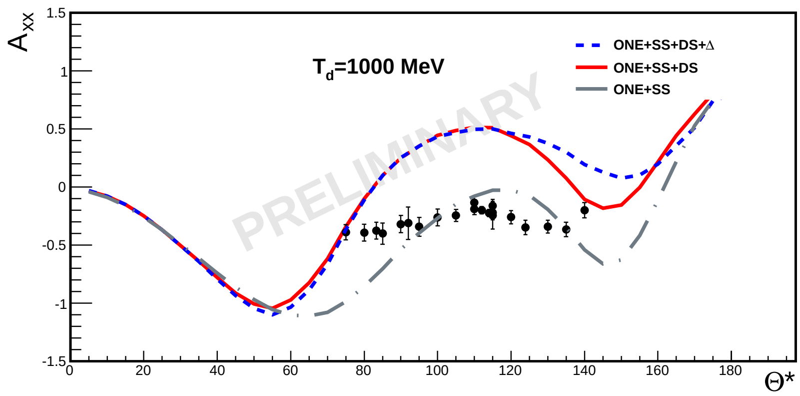

Figure 11: The angular dependence of the tensor analyzing power A_{xx} at the deuteron kinetic energy T_d of 1000 MeV. Lines and symbols are the same as in Fig. 6.

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 Fig. 9, Fig. 10 and Fig. 11, respectively. The lines are the predictions obtained within relativistic multiple scattering model [33] considering ONE, SS, DS and Δ- 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 up to $\sim$100° in cms, while the tensor analyzing powers A_{yy} and A_{xx} are not described over whole range of measurements. The Δ- isobar excitation term gives a significant contribution at the angles larger than 140° in cms. 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° in the cms 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 Nuclotron in 2005 [14]-[15]. Open symbols are the world data [24, 25, 30, 35, 36]. Both A_y and A_{yy} analyzing powers change the sign at $P_T \sim$ 600 MeV/c and have the tendencies at

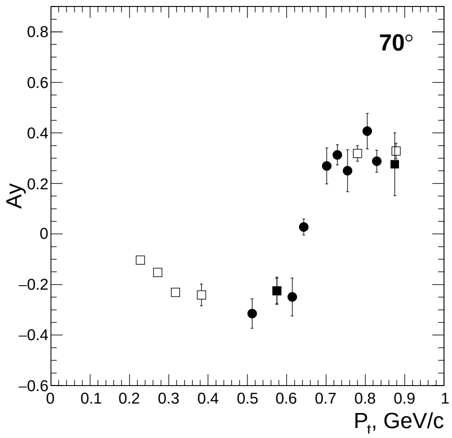

Figure 12: The energy dependence of the vector analyzing power A_y at 70° in the cms. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at Nuclotron in 2005 [14]-[15]. Open symbols are the data [24, 25, 30, 35, 36] obtained in the previous experiments.

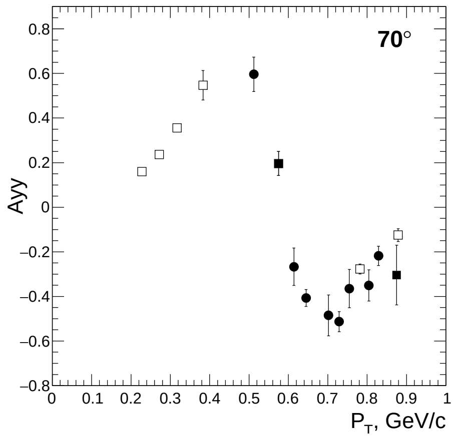

Figure 13: The energy dependence of the tensor analyzing power A_{yy} at 70° in the cms. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at Nuclotron in 2005 [14]-[15]. Open symbols are the same as in Fig.12.

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 Nuclotron [37] allows 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- non-mesonic breakup at the energies between 135-250 MeV for different kinematic configurations etc.

4. Conclusions

- Upgraded Nuclotron with 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 ITS will allow 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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