Journal of Physics: Conference Series

PAPER • OPEN ACCESS

First results on the energy scan of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in deuteron-proton elastic scattering at Nuclotron[1]

To cite this article: V P Ladygin *et al* 2017 *J. Phys.: Conf. Ser.* **938** 012007

IOP Conf. Series: Journal of Physics: Conf. Series **938** (2017) 012007 doi:10.1088/1742-6596/938/1/012007

First results on the energy scan of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in deuteron-proton elastic scattering at Nuclotron[1]

V P Ladygin[1†], A V Averyanov[1], E V Chernykh[1], D Enache[2] Yu V Gurchin[1], A Yu Isupov[1], M Janek[3], J-T Karachuk[1,2], A N Khrenov[1], D O Krivenkov[1], P K Kurilkin[1], N B Ladygina[1], A N Livanov[1], S M Piyadin[1], S G Reznikov[1], Ya T Skhomenko[1,4], A A Terekhin[1], A V Tishevsky[1], T Uesaka[5]

[1] Joint Institute for Nuclear Research, Dubna, Russia
[2] National Institute for R&D in Electrical Engineering ICPE-CA, Bukharest, Romania
[3] Physics Department, University of Žilina, Žilina, Slovakia
[4] Belgorod State National Research University, Belgorod, Russia
[5] Nishina Center for Accelerator-Based Science, RIKEN, Wako, Japan

E-mail: [†]vladygin@jinr.ru

Abstract. New results on the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in deuteron-proton elastic scattering obtained at Nuclotron in the energy range 400-1800 MeV are presented. These data have been obtained in 2016-2017 at DSS setup at internal target station using polarized deuteron beam from new source of polarized ions. The preliminary data on the deuteron analyzing powers in in the wide energy range demonstrate the sensitivity to the short-range spin structure of the nucleon-nucleon correlations.

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 2N SRC; the probability for a given proton with momenta $300 \leq k \leq 600$ MeV/c to belong to pn correlation is ∼18 times larger than for pp correlations; the probability for a nucleon to have momentum ≥ 300 MeV/c in medium nuclei is ∼25%; 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.

[1] Dedicated to the memory of Prof. L.S.Zolin

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 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, 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. 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 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 8μm 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 monitors etc.

The same setup has been used as a polarimeter based on the use of *dp*- elastic scattering at large angles ($\theta_{\rm cm} \geq 60°$) at 270 MeV[19], where precise data on analyzing powers [24, 25, 26] exist, has been developed at internal target station (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}C$(d, \alpha)^{10}$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.

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 difference. 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}.

4. Discussion of the *dp*- elastic scattering results

A prior of the experiment with polarized deuteron beam DSS collaboration measured the differential cross section of *dp*- elastic scattering in a wide angular range at the energies T_d between 400 and 2000 MeV. The results obtained at ITS at Nuclotron at 1400 MeV [18] given by the full squares are compared with the data obtained earlier at 1283 MeV, 1595 MeV [27] and 1600 MeV [28] shown by the open diamonds, circles and triangles in Fig.1.

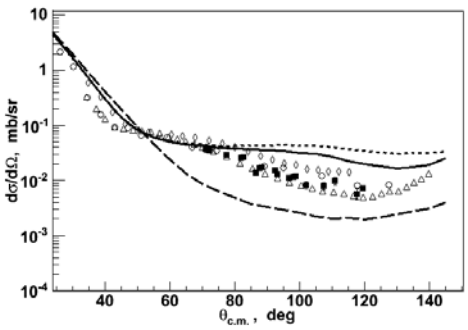

Figure 1. The differential cross section as a function of the cms scattering angle at the deuteron kinetic energy T_d of 1400 MeV [18], 1283 MeV, 1595 MeV [27] and 1600 MeV [28] are shown by the full squares, open diamonds, circles and triangles, respectively. The curves obtained in framework of the relativistic multiple scattering model [29, 30, 31] are explained in the text.

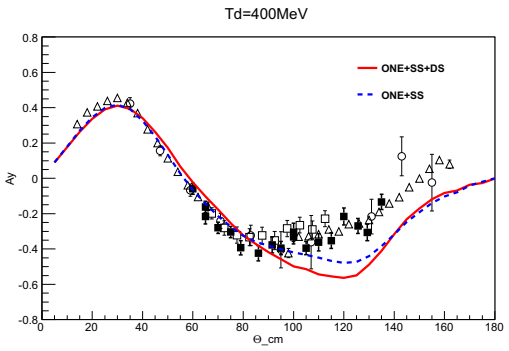

Figure 2. The angular dependence of the deuteron vector analyzing power A_y at the deuteron kinetic energy T_d of 400 MeV. The full squares are the preliminary results of the present experiment at ITS at Nuclotron. Open symbols are the world data [32, 33, 34]. Lines are the calculation within relativistic multiple scattering model [29, 30].

The theoretical calculations were performed in the relativistic multiple scattering expansion formalism [29, 30, 31]. The four contributions are taken into account: one-nucleon-exchange,

single- and double- scattering, 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 [31]. The dashed line in Fig 1 is the result of the calculations taking into account one-nucleon exchange (ONE) and single-scattering (SS) diagrams only, while the dotted line is obtained when double-scattering (DS) term is added into the consideration [29, 30]. The full calculation with Δ- isobar excitation included is given by the solid line [31]. One can see that the differential cross section is described quite well up to the scattering angles of ∼60° taking into account only the ONE and SS terms. If we consider the *dp* -elastic scattering at the angles larger than 60° , it is necessary to include the DS term into consideration. It should be noted the double-scattering contribution into the reaction amplitude increases with the deuteron energy growing and may change the value of the differential cross section on a few orders in comparison with the result obtained without inclusion of the DS-term. The Δ-excitation begins to manifest itself at the angle equal to about 120° and describes the behaviour of the experimental data at the angle above 140° where the differential cross section sharply increases. It has been demonstrated also that the contribution of the Δ- isobar mechanism grows with the initial deuteron energy. It is negligible at $T_d = 500$ MeV and very significant at higher energies [31].

The angular dependence of the deuteron vector analyzing power A_y at the deuteron kinetic energy T_d of 400 MeV is presented in Fig. 2. The full squares are the results of the present experiment at ITS at Nuclotron. Open circles, squares and triangles are the data obtained at Saclay [32] and IUCF [33], [34], respectively. Dashed and solid lines are the calculations performed within relativistic multiple scattering model [29, 30] 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 [31]. One can see good agreement of new data obtained at Nuclotron with the data from earlier experiments [32, 33, 34]. The relativistic multiple scattering model [29, 30] describes the data up to ∼90° only, while it fails to reproduce the data at larger angles. The considering of the DS term does not improve the agreement.

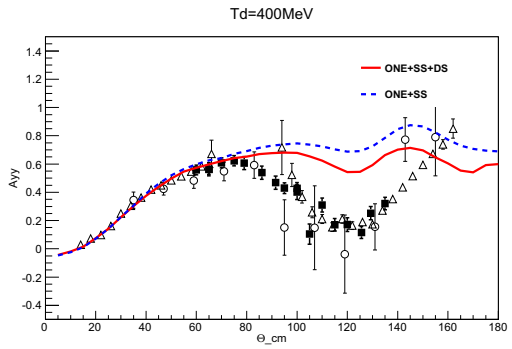

Figure 3. The angular dependence of the tensor analyzing power A_{yy} at the deuteron kinetic energy T_d of 400 MeV. The full squares are the preliminary results of the present experiment at ITS at Nuclotron. Open symbols are the world data [32, 34]. Lines are the same as in Fig. 2.

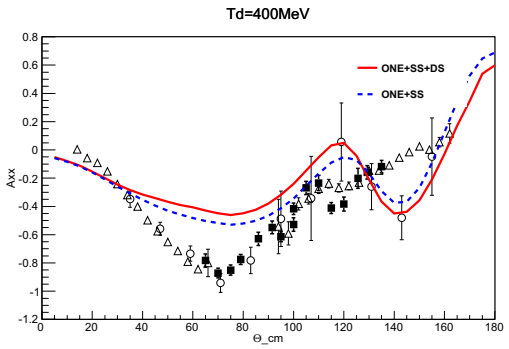

Figure 4. The angular dependence of the tensor analyzing power A_{xx} at the deuteron kinetic energy T_d of 400 MeV. The full squares are the preliminary results of the present experiment at ITS at Nuclotron. Open symbols are the world data [32, 34]. Lines are the same as in Fig. 2.

The angular dependencies of the tensor analyzing powers A_{yy} and A_{xx} at the deuteron kinetic energy T_d of 400 MeV are presented in Fig. 3 and Fig. 4, respectively. The full squares are the results of the present experiment at ITS at Nuclotron. Open circles and triangles are the data

obtained at Saclay [32] and IUCF [34], respectively. The lines are the same as in Fig.2. The consideration of the ONE+SS terms allows to describe the behaviour of the A_{yy} analyzing power up to $\sim$80° only. The DS term gives a significant contribution at larger angles, however, its taking into account does not remove the discrepancy of the calculation with the data. The A_{xx} behaviour is not described by the model [29, 30] 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 (χEFT) [35] do not allow 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.

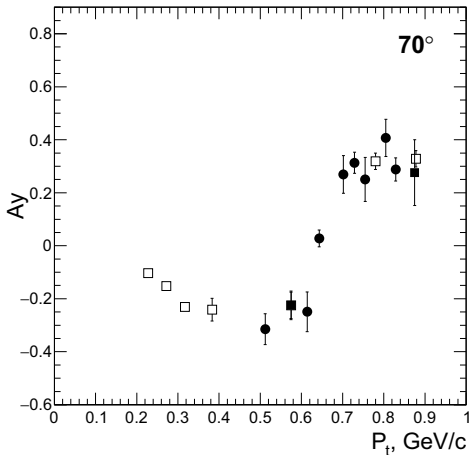

Figure 5. The energy dependence of the vector analyzing power A_y at 70° in the cms. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at Nuclotron in 2005 [14, 15]. Open symbols are the world data [24, 25, 32, 36, 37].

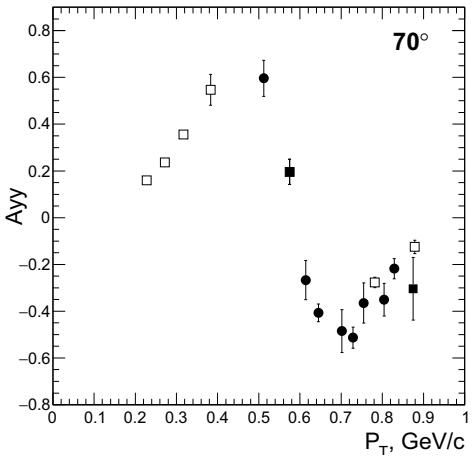

Figure 6. The energy dependence of the tensor analyzing power A_{yy} at 70° in the cms. The full circles are the preliminary results of the present experiment. The full squares are the data obtained at ITS at Nuclotron in 2005 [14, 15]. Open symbols are the world data [24, 25, 32, 36, 37].

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 5 and 6, 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, 32, 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.

5. 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 allows 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.

Next stages of the DSS experiment using polarized deuterons and protons at ITS are the systematic studies of the analyzing powers A_y, A_{yy} and A_{xx} in *dp*- elastic scattering at 270-700 MeV and in *dp*- nonmesonic breakup at 300-500 MeV using new SPI at Nuclotron to study the relativistic effects in 2NFs and manifestation of the short-range 3NFs.

The availability of the polarized proton beam 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, in *pd*- nonmesonic breakup at the energies between 135-250 MeV for different kinematic configurations, in the $pA \to ppX$ reactions etc.

Acknowledgments
The authors thank the Nuclotron staff for providing good conditions of the experiment. They thank A.S. Belov, V.B. Shutov and V.V Fimushkin for the tune of the SPI [20]. They express the gratitude to S.N. Bazylev, V.I. Maximenkova, I.V. Slepnev, V.M. Slepnev and A.V. Shutov for the help during the preparation of the detector and DAQ system. The work has been supported in part by the RFBR under grant $N^0$16-02-00203a, JINR- Slovak Republic and JINR-Romania scientific cooperation programs in 2016-2017.

References

[1] Frankfurt L, Sargsian M and Strikman M 2008 *Int.J.Mod.Phys. A* **23** 2991.
[2] Piasetzky E, Sargsian M, Frankfurt L, Strikman M and Watson J W 2006 *Phys.Rev.Lett.* **97** 162504.
[3] Frankfurt L L, Strikman M I, Day D B and Sargsian M M 1993 *Phys.Rev. C* **48** 2451.
[4] Egiyan K Sh *et al.* 2003 *Phys.Rev. C* **68** 014313.
[5] Egiyan K Sh *et al.* 2006 *Phys.Rev.Lett.* **96** 082501.
[6] Frankfurt L, Sargsian M and Strikman M 2008 *AIP Conf.Proc.* **1056** p.322.
[7] Ladygin V P *et al.* 2014 *Phys.Part.Nucl.* **45** 327.
[8] Ladygin V P *et al.* 2014 *Few Body Syst.* **55** 709.
[9] Janek M *et al.* 2017 *Few Body Syst.* **58** 40.
[10] Malakhov A I *et al.* 2000 *Nucl.Instrum.Meth. in Phys.Res. A* **440** 320.
[11] Glöckle W, Witala H, Hüber D, Kamada H and Golak J 1996 *Phys.Rept.* **274** 107.
[12] Kalantar-Nayestanaki N, Epelbaum E, Messchendorp J G and Nogga A 2012 *Rept.Prog.Phys.* **75** 016301.
[13] Ladygin V P *et al.* 2016 *Int. J. Mod. Phys. Conf. Ser.* **40** 1660074.
[14] Kurilkin P K *et al.* 2012 *Phys.Lett. B* **715** 61.
[15] Kurilkin P K *et al.* 2011 *Phys.Part.Nucl.Lett.* **8** 1081.
[16] Gurchin Yu V *et al.* 2013 *Phys.Part.Nucl.Lett.* **10** 243.
[17] Terekhin A A *et al.* 2015 *Phys.Part.Nucl.Lett.* **12** 695.
[18] Terekhin A A *et al.* 2017 *JINR preprint R1-2017-33 (in Russian)*, to be published in *Phys.Atom.Nucl.*.
[19] Kurilkin P K *et al.* 2011 *Nucl.Instr.Meth. in Phys.Res. A* **642** 45.
[20] Fimushkin V V *et al.* 2016 *J.Phys.Conf.Ser.* **678** 012058.
[21] Isupov A Yu *et al.* 2013 *Nucl.Instrum.Meth. in Phys.Res. A* **698** 127.
[22] Isupov A Yu *talk at this Conference.*
[23] Skhomenko Ya T *et al. talk at this Conference.*
[24] Sekiguchi K *et al.* 2002 *Phys.Rev.* C **65** 034003.
[25] Sekiguchi K *et al.* 2004 *Phys.Rev.* C **70** 014001
[26] Suda K *et al.* 2007 *Nucl.Instr.Meth. in Phys.Res.* A **572** 745.
[27] Gülmez E *et al.* 1991 *Phys.Rev.* C **43** 2067.
[28] Winkelmann E *et al.* 1980 *Phys.Rev.* C **421** 2535.
[29] Ladygina N B 2008 *Phys.Atom.Nucl.* **71** 2039.
[30] Ladygina N B 2009 *Eur.Phys.J.* A **42** 91.
[31] Ladygina N B 2016 *Eur.Phys.J.* A **52** 199.
[32] Garçon M *et al.* 1986 *Nucl.Phys.* A **458** 287.
[33] Cadman R V *et al.* 2001 *Phys.Rev.Lett.* **86** 967.
[34] Przewoski B v *et al.* 2006 *Phys.Rev.* C **74** 064003.
[35] Binder S *et al.* 2016 Phys.Rev. C **93** 044002.
[36] Haji-Saied M *et al.* 1987 *Phys.Rev.* C **36** 2010.
[37] Ghazikhanian V *et al.* 1991 *Phys.Rev.* C **43** 1532.