Latest results concerning short range correlations obtained in the dp elastic and dp breakup processes at Nuclotron, JINR

Marian Janek[1⋆], Vladimir P. Ladygin[2], Alexander V. Averyanov[2], Eugene V. Chernykh[2], Dan D. Enache[3], Yuri V. Gurchin[2], Alexandr Yu. Isupov[2], Julia-Tatiana Karachuk[3], Anatoly N. Khrenov[2], Dimitry O. Krivenkov[2], Pavel K. Kurilkin[2], Nadezhda B. Ladygina[2], Alexei N. Livanov[2], Olena Mezhenska[4], Semen M. Piyadin[2], Sergei G. Reznikov[2], Yaroslav T. Skhomenko[2,5], Arkady A. Terekhin[2], Alexei V. Tishevsky[2] and Tomohiro Uesaka[6]

1 Physics Department, University of Zilina, Univerzitna 1, 01001 Zilina, Slovakia,
2 Veksler and Baldin Laboratory of High Energies, Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow region, Russia
3 Advanced Research Institute for Electrical Engineering, Splaiul Unirii 313, Bucharest, Romania
4 Institute of Physics, University of P. J. Shafarik, Park Angelinum 9, 04001 Kosice, Slovakia
5 Belgorod State University, Pobedy 85, 308015 Belgorod, Russia
6 Nishima Center for Accelerator-based Science, RIKEN, 351-0198 Wako, Japan

⋆ janek.marian@gmail.com

Proceedings for the 24th edition of European Few Body Conference, Surrey, UK, 2-6 September 2019
doi:10.21468/SciPostPhysProc.3

Abstract

Deuteron spin structure program is aimed on extraction of two and three nucleon forces information, including their spin dependent parts, from dp elastic and dp breakup processes investigated at intermediate energies. The dp elastic data were obtained at Internal Target Station of Nuclotron (JINR) in the energy range 400-1800 MeV using polarized deuteron beam. Strong sensitivity to the short range spin structure of the isoscalar nucleon-nucleon correlations is observed in deuteron analyzing powers. Preliminary results of the the cross section for the dp breakup reaction have been obtained at 400 MeV of deuteron energy.

Received 14-10-2019
Accepted 05-11-2019
Published 24-02-2020
doi:10.21468/SciPostPhysProc.3.011

1 Introduction

There are many evidences that realistic nucleon-nucleon (NN) potentials such as CD-Bonn [1], AV18 [2] and Nijm I, II and 93 [3] does not describe the NN data above ~ 350 MeV. Binding energies of three [4] and four nucleon systems can not be described using only NN potentials, however theoretical models in which three nucleon forces (3NFs) are included as two pion exchange, e.g. Urbana IX [5] and Tucson-Melbourne [6] give us reasonable agreement. The cross section of reactions with few nucleons involving is in general better described in unpolarized case than in the polarized one. In the vicinity of the Sagara discrepancy the currently known 3NFs contribute by up to 30% to the dp elastic scattering cross section at intermediate energies [7].

The dp breakup reaction at deuteron energy of 270 MeV was investigated at RIKEN [8] and IUCF [9]. It was found that vector analyzing power A_y can be described using NN forces only, but other polarization observables need 3NFs to describe the data. Inclusion of 3NFs improve the description of a part of the data but breaks other. Relativistic effects for the nd elastic scattering cross section at 70 MeV and 250 MeV were investigated in [24]. It was found that relativistic effects contribution is located mainly at backward angles, but their contribution is not large enough to fill discrepancy between experimental data and theory, even in the case when standard three nucleon forces are used.

The main goal of Deuteron Spin Structure program (DSS) is to obtain information about two and three nucleon forces, including their spin dependent parts. For this purpose, dp elastic scattering and dp breakup reaction are investigated in the energy ranges from 300 MeV - 2000 MeV and 300 MeV - 500 MeV of deuteron energy.

2 Dp elastic scattering at 400 MeV - 2000 MeV

Polarimetry at Internal Target Station (ITS) [11] is using dp elastic scattering at large scattering angles ($\theta_{cm} \geq 60°$) at 270MeV [12], where precise data on analyzing powers [13] exist. Method gives us determination of deuteron polarization better than 2%. Polarimeter consists of a spherical hull in which up to six targets can be placed. There are 39 scintillation counters placed at the top, bottom, left and right with respect to the deuteron beam, downstream to the ITS of Nuclotron. Scattered deuterons and recoil protons are detected in the coincidence in angular range from $65° - 135°$.Developed multichannel high voltage system power supply system can supply power to 70 Hamamatsu photomultipliers. Polarization measurements were performed with new control and data acquisition system [14]. Developed new polarized ion source (SPI) [15] provided polarization of deuteron beam whose ideal values are: $P_Z, P_{ZZ} = (0,0), (-1/3, -1)$ and $(-1/3, +1)$. The measured values of beam polarization were from $\sim$ 65% to $\sim$ 75% of ideal values. Observed beam polarizations were reasonably stable and demonstrate good reproducibility after interruptions. The selection of dp elastic events are based on correlations of energy losses in scintillators for the proton and deuteron and by difference in theirs time of flight information. Additionally, in order to suppress background cut on interaction point between beam and target was applied, also.

The angular dependence of the cross section at deuteron energy of 1400 MeV is shown in Figure. 1. Curves are predictions based on relativistic-multiple scattering model, e.g. [16] when one nucleon exchange and single scattering term (dashed curve), additional double scattering term (dotted curve) and Δ isobar (solid curve) are included. Nuclotron data are represented by closed symbols, world data at slightly different energies are shown by open symbols. One can see large contribution which comes from double scattering term. It describes the data up to 70°. Δ isobar contribution comes at larger angles above 80° and rises with angle. However the data are described in this angular range only qualitatively.

The angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 400 MeV is shown in Figure.2. Curves are predictions based on relativistic-multiple scattering model when one nucleon exchange and single scattering term (dashed curve) and additional double scattering term (solid curve) are taken into account. Nuclotron data are represented by closed symbols, open ones are world data [17], [18] and [19]. The contribution which comes

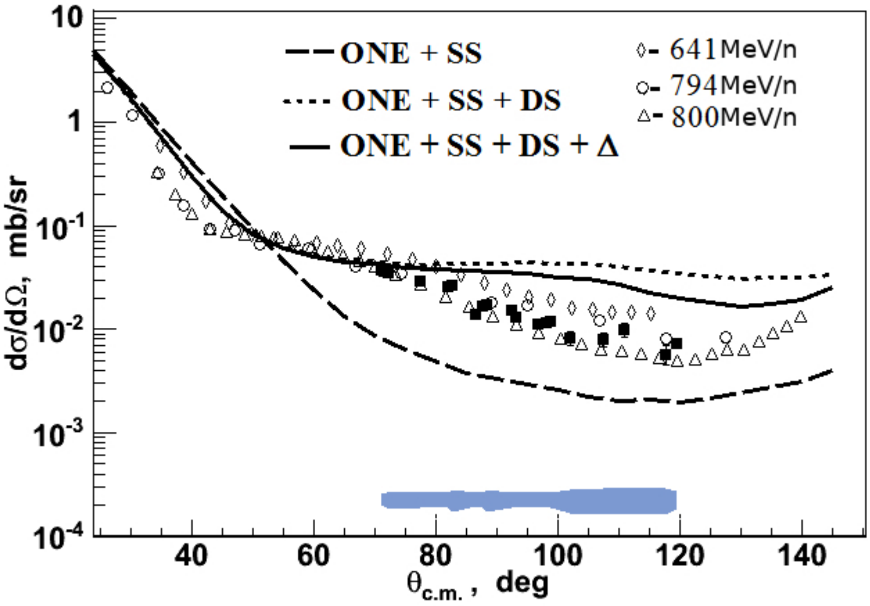

Figure 1: Angular dependence of the cross section at deuteron energy of 1400 MeV. Curves are predictions based on relativistic-multiple scattering model when one nucleon exchange and single scattering term (dashed curve), additional double scattering term (dotted curve) and Δ isobar (solid curve) are included. Nuclotron data are represented by closed symbols, world data at slightly different energies are shown by open symbols.

from double scattering term is rather small at this energy and generally does not improve the description of the data. Vector A_y and tensor A_{yy} analyzing powers are described up to the 70°. Tensor A_{xx} analyzing powers is not described by the model. The reason of the deviation can be neglecting of three nucleon short range correlations.

Angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 700 MeV is shown in Figure.3. Curves are predictions based on relativistic-multiple scattering model when one nucleon exchange and single scattering term (dashed curve), additional double scattering term (dotted curve) and Δ isobar (solid curve) are taken into account. One can see large contribution which comes from double scattering term and small contribution from Δ isobar located in very backward angles. Very good description is obtained in case of tensor analyzing power A_{yy}.

The Angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 1000 MeV is shown in Figure.4. Curves are the same as for the case of 700 MeV. One can see large contribution which comes from double scattering term and moderate to large contribution which comes from Δ isobar, specially at angles larger than 140° . Only part of the A_y data up to 70° is described. Possible reason is that spin structure of the NN interactions and deuteron is missing in relativistic multiple scattering model [16].

3 Dp breakup process at 300 MeV - 500 MeV

Dp breakup data have been accumulated using polarized and unpolarized deuteron beam at 300 MeV, 400 MeV and 500 MeV. Analyzing powers iT_{11} and T_{20} are investigated at deuteron energy of 400 MeV. There are two important settings in which unpolarized data are collected.

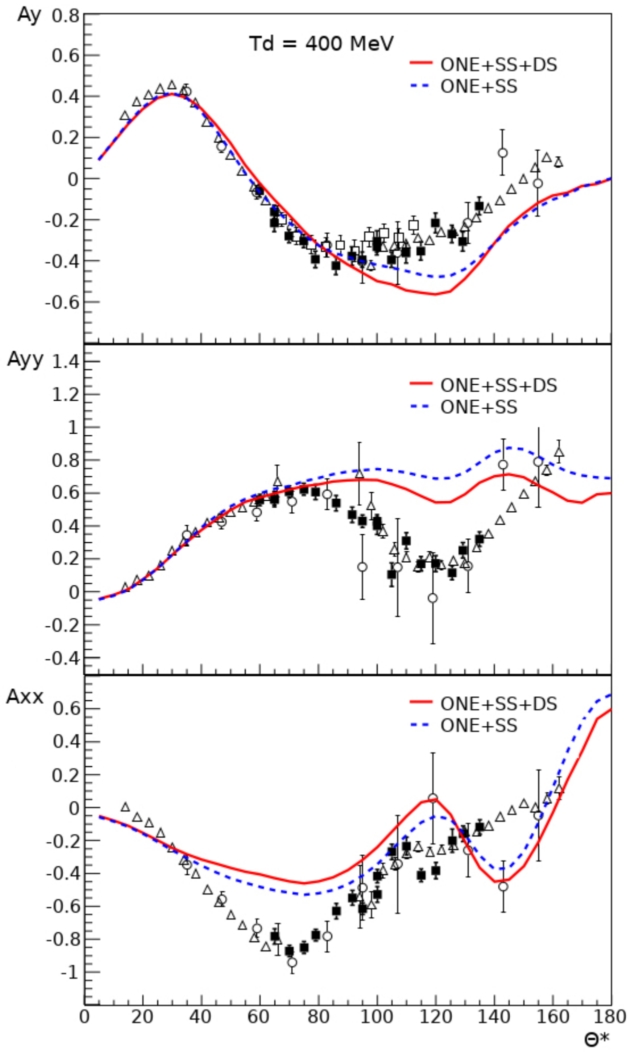

Figure 2: Angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 400 MeV. Curves are predictions based on relativistic-multiple scattering model when one nucleon exchange and single scattering term (dashed curve) and additional double scattering term (solid curve) are taken into account. Nuclotron data are represented by closed symbols, open symbols represent world data.

First settings could give us possibility to investigate two and three nucleon forces, second one could be suitable in searching for relativistic effects. In the first setting, the detectors are placed in configurations in which momentum vectors of outgoing particles have equal momenta in the center of mass system and are separated by 120°. Detectors were placed in various configurations in so called intermediate star. In the second setting, one arm is fixed and second scans angular range.

Analyzing powers iT_{11} and T_{20} were obtained at deuteron energy of 400 MeV at ITS of Nuclotron. Values of polarization of deuteron beam were obtained using polarimetry method described in section 2. Polyethylene and Carbon targets are enclosed in a spherical hull of ITS. Up to six various targets can be placed inside of ITS. Details of the $\Delta E - E$ detector construction can be found in [20]. iT_{11} analyzing power at 72.3° and 76.5° in centre of mass system was measured under pp quasielastic conditions. Obtained values at 72.3° and 76.5° are 0.10 ± 0.02 and 0.11 ± 0.06, respectively. Results are in good agreement with the world pp- quasielastic scattering data within obtained experimental errors. Values of the vector iT_{11} and tensor T_{20}

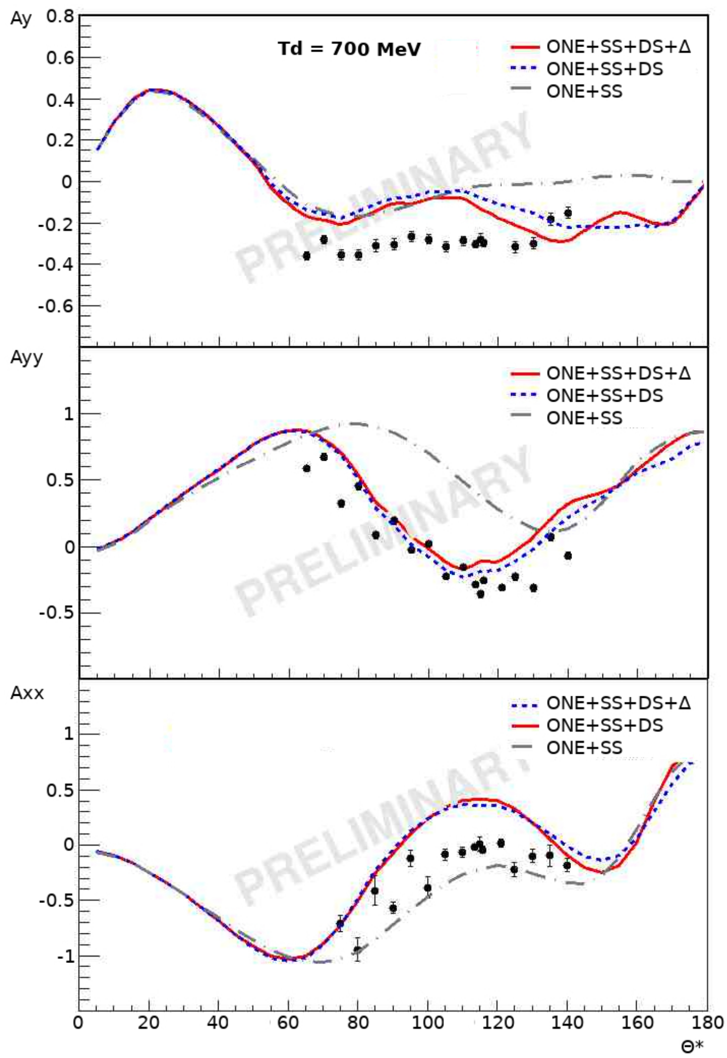

Figure 3: Angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 700 MeV. Curves are predictions based on relativistic-multiple scattering model when one nucleon exchange and single scattering term (dashed curve), additional double scattering term (dotted curve) and Δ isobar (solid curve) are taken into account.

analyzing powers at polar angles of 34.8° and 36.8° and difference between azimuthal angles of 135° are 0.47 ± 0.10 and 0.02 ± 0.20 [21]. Beam luminosity needs to be increase at least of one order in order to substantially decrease errors of analyzing powers.

Dp breakup reaction using unpolarized deuteron beam has been investigated at 300 MeV, 400 MeV and 500 MeV of deuteron energy. ΔE-E correlation of energy losses of charged particles and prediction which comes from GEANT4 simulation is shown in Figure.5. One can see good agreement between reconstructed data and simulation. Reconstructed energy spectra obtained on Polyethylene and Carbon in case of deuteron energy of 400 MeV are shown at the bottom of Figure.5, where left and right panels are related to left and right arms of detector, open and closed histograms represent data obtained on Polyethylene and Carbon targets. Reasonable agreement between experiment and GEANT4 simulation was obtained [22]. One can see clear peak at the value of 100 MeV in both arms which comes from *pp*- quasielastic events. The *pp*- quasielastic reaction at 90° in centre of mass and at the three energies of 300 MeV, 400 MeV and 500 MeV was used to obtain calibration constants. The stability of ampli-

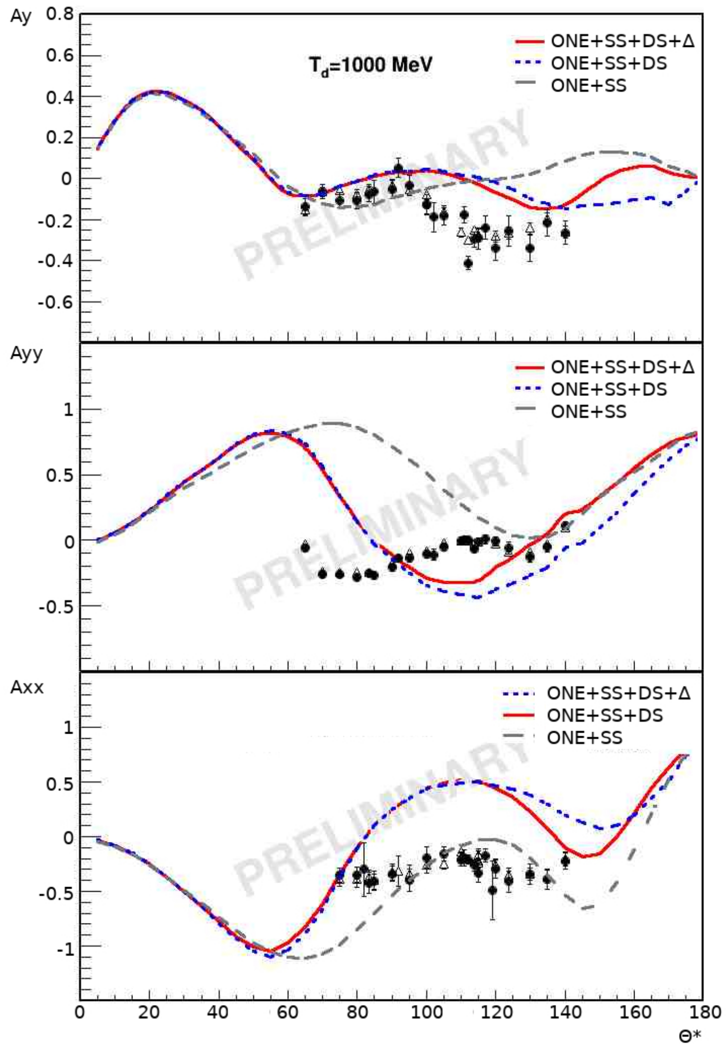

Figure 4: Angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 1000 MeV. Curves are predictions based on relativistic-multiple scattering model when one nucleon exchange and single scattering term (dashed curve), additional double scattering term (dotted curve) and Δ isobar (solid curve) are taken into account.

tude of all photomultiplier tubes (PMTs) were monitored during all data acquisition. Detailed description of LED system of PMTs can be found in [20]. Calibration procedure is described in [23].

Relativistic effects have been found to be important in nd breakup reaction at 200 MeV in special kinematics in which one arm is fixed and second scans angular interval [24]. It was found specific pattern in differential cross section as a function of scattering angle. Relativistic contribution varies from no contribution to very large one. We performed the measurement of dp breakup reaction in inverse kinematics at deuteron energy of 400 MeV. First arm is fixed at angle of 43° and second one scans the angular range. Second arm takes the following angular values: 27°, 31°, 35° and 39°.

Preliminary results of the five fold differential cross section of dp breakup reaction investigated at 400 MeV for the case of detector arms placed at the angles of 31° and 43°, 35° and 43°, 39° and 43° are shown in Figure.6. Only statistical errors are shown. $S-$ variable repre-

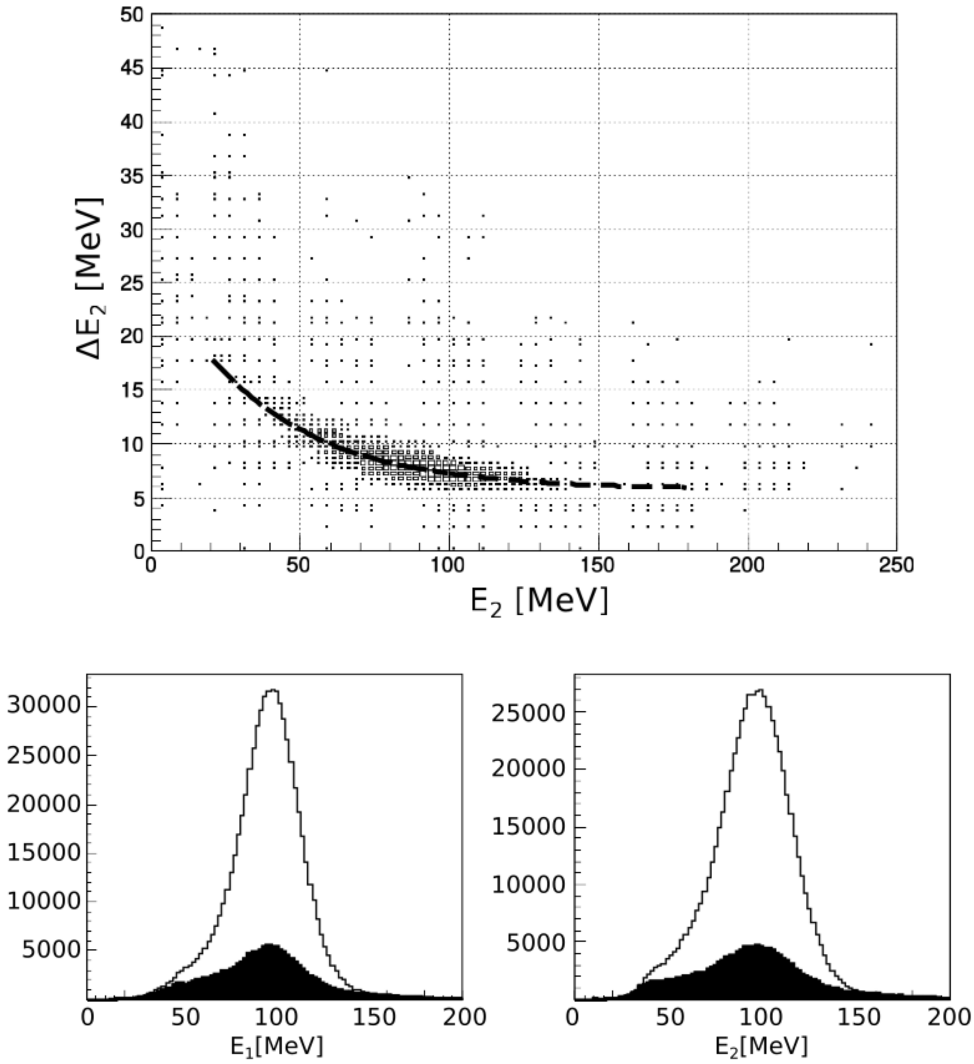

Figure 5: Top: ΔE-E correlation of energy losses of charged particles (mainly protons) and prediction which comes from GEANT4 simulation (dashed line). Bottom: Energy spectra obtained on Polyethylene and Carbon in case of deuteron energy of 400 MeV. Left and right panels are related to left and right arms of detector. Open and closed histograms represent data obtained on Polyethylene and Carbon targets.

sents arc-length of kinematic curve in the plot of two registered protons. $S-$ variable interval is cut due to detector acceptance. Preliminary data show some structures at the vicinity of ≈ 100 MeV and ≈ 260 MeV.

4 Conclusion

Cross section of dp elastic scattering and predictions of relativistic-multiple scattering model at 1400 MeV is presented. Good agreement is observed up to 70°. Angular dependence of the vector A_y, tensor A_{yy} and A_{xx} at deuteron energy of 400, 700 and 1000 MeV is presented along with the predictions based on relativistic multiple scattering model. Large contribution which comes from double scattering term is observed, but it does not improve the description of analyzing powers in all cases, rather at small angles. Moderate contribution which comes

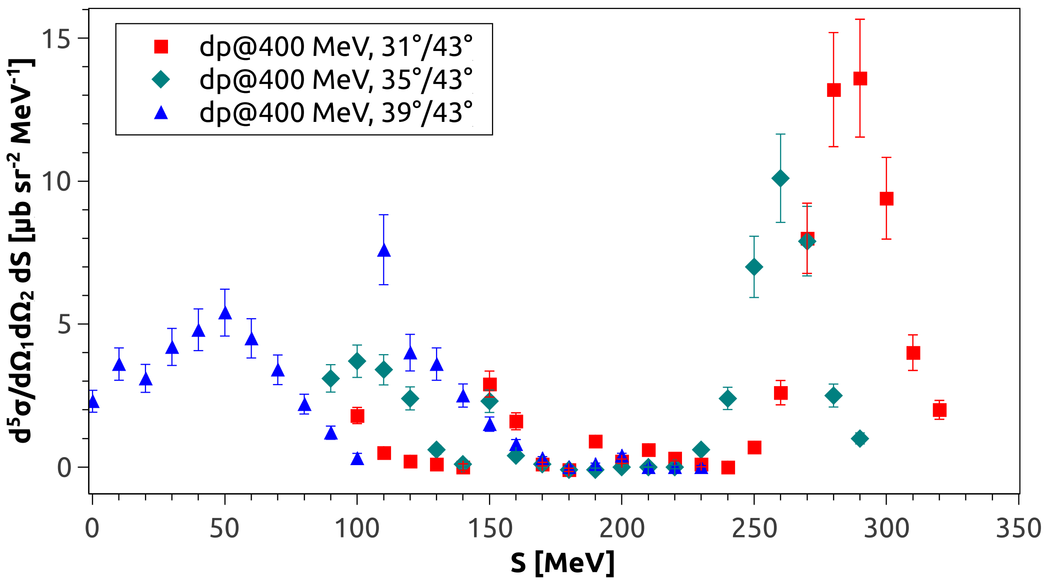

Figure 6: Preliminary results of the five fold differential cross section of dp breakup reaction investigated at 400 MeV for the case of detector arms placed at the angles of 31° and 43° (red symbols), 35° and 43° (green symbols), 39° and 43° (blue symbols), respectively. Only statistical errors are shown.

from Δ isobar is found at higher energies. Δ isobar contribution improves the qualitative description of the cross section at 1400 MeV.

Preliminary results of the five fold differential cross section of dp breakup reaction investigated at 400 MeV for the case of detector arms placed at the angles of 31° and 43°, 35° and 43°, 39° and 43° are presented. One can see some structures in kinematic $S-$ curve at the vicinity of $\approx$ 100 MeV and $\approx$ 260 MeV. The next step is to obtain results at other angles to investigate observed structure in recent data.

Acknowledgements

The authors thank the Nuclotron staff for providing good conditions of the experiment and for the tune of the polarized ion source SPI [15].

Funding information The work has been supported in part by the Ministry of Education, Science, Research and Sport of the Slovak Republic VEGA Grant No. 1/0113/18 (M.J.), by the RFBR under grant No.19-02-00079a (V. P. L.) and by JINR- Slovak Republic cooperation programs (M. J. and V. P .L.) in 2019.

References

[1] S. A. Coon and W. Glöckle, *Two-pion-exchange three-nucleon potential: Partial wave analysis in momentum space*, Phys. Rev. C **23**, 1790 (1981), doi:10.1103/PhysRevC.23.1790.

[2] S. A. Coon, M. D. Scadron, P. C. McNamee, B. R. Barrett, D. W. E. Blatt and B. H. J. McKellar, *The two-pion-exchange three-nucleon potential and nuclear matter*, Nucl. Phys.

A **317**, 242 (1979), doi:10.1016/0375-9474(79)90462-7.

[3] V. G. J. Stoks, R. A. M. Klomp, C. P. F. Terheggen and J. J. de Swart, *Construction of high-quality NN potential models*, Phys. Rev. C **49**, 2950 (1994), doi:10.1103/PhysRevC.49.2950.

[4] H. R. Setze et al., *Cross-section measurements of the space-star configuration in N-D breakup at 13.0 MeV*, AIP Conf. Proc. **334**, 463 (1995), doi:10.1063/1.48131.

[5] G. Rauprich, S. Lemaître, P. Niessen, K. R. Nyga, R. Reckenfelderbaumer, L. Sydow, H. Paetz Gen. Schieck, H. Witała and W. Glöckle, *Study of the kinematically complete breakup reaction* $^2H(p,pp)n$ *at* $E_p = 3$ *MeV with polarized protons*, Nucl. Phys. A **535**, 313 (1991), doi:10.1016/0375-9474(91)90451-B.

[6] H. Patberg et al., *Deuteron breakup reaction* $^2H(\vec{p},pp)n$ *induced by polarized protons at* $E_p = 19.0 MeV$, Phys. Rev. C **53**, 1497 (1996), doi:10.1103/PhysRevC.53.1497.

[7] N. Sakamoto et al., *Measurement of the vector and tensor analyzing powers for the d-p elastic scattering at* $E_d = 270 MeV$, Phys. Lett. B **367**, 60 (1996), doi:10.1016/0370-2693(95)01398-9.

[8] K. Sekiguchi et al., *Three-nucleon force effects in the* $^1H(\vec{d},\vec{p}p)n$ *reaction at 135 MeV/nucleon*, Phys. Rev. C **79**, 054008 (2009), doi:10.1103/PhysRevC.79.054008.

[9] H. O. Meyer et al., *Axial observables in* $\vec{d}\vec{p}$ *breakup and the three-nucleon force*, Phys. Rev. Lett. **93**, 112502 (2004), doi:10.1103/PhysRevLett.93.112502.

[10] H. Witała, J. Golak, R. Skibiński, W. Glöckle, W. N. Polyzou and H. Kamada, *Relativistic effects in neutron–deuteron elastic scattering and breakup*, Few-Body Syst. **49**, 61 (2010), doi:10.1007/s00601-010-0098-4.

[11] A. I. Malakhov et al., *Potentialities of the internal target station at the Nuclotron*, Nucl. Instr. Meth. in Phys. Res. Sec. A **440**, 320 (2000), doi:10.1016/S0168-9002(99)00966-3.

[12] P. K. Kurilkin et al., *The 270MeV deuteron beam polarimeter at the Nuclotron Internal Target Station*, Nucl. Instr. Meth. in Phys. Res. Sec. A **642**, 45 (2011), doi:10.1016/j.nima.2011.03.054.

[13] K. Sekiguchi et al., *Complete set of precise deuteron analyzing powers at intermediate energies: Comparison with modern nuclear force predictions*, Phys. Rev. C **65**, 034003 (2002), doi:10.1103/PhysRevC.65.034003.

[14] A. Yu. Isupov, V. A. Krasnov, V. P. Ladygin, S. M. Piyadin and S. G. Reznikov, *The Nuclotron internal target control and data acquisition system*, Nucl. Instr. Meth. in Phys. Res. Sec. A **698**, 127 (2013), doi:10.1016/j.nima.2012.09.057.

[15] V. V. Fimushkin, A. D. Kovalenko, L. V. Kutuzova, Y. V. Prokofichev, B. Shutov, A. S. Belov, V. N. Zubets and A. V. Turbabin, *Development of polarized ion source for the JINR accelerator complex*, J. Phys.: Conf. Ser. **678**, 012058 (2016), doi:10.1088/1742-6596/678/1/012058.

[16] N. B. Ladygina, *Delta excitation in deuteron-proton elastic scattering*, Eur. Phys. J. A **52**, 199 (2016), doi:10.1140/epja/i2016-16199-5.

[17] M. Garcon et al., *Measurements of vector and tensor analysing powers for 191 and 395 MeV deuteron scattering*, Nucl. Phys. A **458**, 287 (1986), doi:10.1016/0375-9474(86)90358-1.

[18] R. V. Cadman et al., *Evidence for a three-nucleon-force effect in proton-deuteron elastic scattering*, Phys. Rev. Lett. **86**, 967 (2001), doi:10.1103/PhysRevLett.86.967.

[19] B. v. Przewoski et al., *Analyzing powers and spin correlation coefficients for $p + d$ elastic scattering at 135 and 200 MeV*, Phys. Rev. C **74**, 064003 (2006), doi:10.1103/PhysRevC.74.064003.

[20] S. M. Piyadin et al. [DSS collaboration], *ΔE-E detector for proton registration in non-mesonic deuteron breakup at the Nuclotron internal target*, Phys. Part. Nuclei Lett. **8**, 107 (2011), doi:10.1134/S1547477111020105.

[21] M. Janek et al., *Analyzing powers iT_{11} and T_{20} of $dp \to ppn$ reaction at 400 MeV investigated at Nuclotron* Communications: Scientific letters of the University of Zilina, **3**, 62 (2017).

[22] M. Janek, B. Trpišová, S. M. Piyadin and V. P. Ladygin, *GEANT4 simulation of dp non-mesonic breakup reaction at 300 and 500 MeV*, Phys. Part. Nuclei Lett. **11**, 552 (2014), doi:10.1134/S1547477114040219.

[23] M. Janek et al., *Calibration procedure of the ΔE–E detectors for dp breakup investigation at nuclotron*, Phys. Part. Nuclei Lett. **15**, 76 (2018), doi:10.1134/S1547477118010090.

[24] H. Witała, J. Golak, R. Skibiński, W. Glöckle, W. N. Polyzou and H. Kamada *Relativistic effects in neutron–deuteron elastic scattering and breakup*, Few-Body Syst. **49**, 61 (2011), doi:10.1007/s00601-010-0098-4.