PROCEEDINGS OF SCIENCE

Spin Physics at Nuclotron: Status and Perspectives

Vladimir Ladygin*
Joint Institute for Nuclear Research, Dubna, Russia
E-mail: vladygin@jinr.ru

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], O.Mezhenska[4], S.M. Piyadin[1], S.G. Reznikov[1], Ya.T. Skhomenko[1], A.A. Terekhin[1], A.V. Tishevsky[1], T. Uesaka[5], I.E. Vnukov[6], I.S. Volkov[1] (DSS Collaboration)

[1] *Joint Institute for Nuclear Research, Dubna, Russian Federation*
[2] *National Institute for R&D in Electrical Engineering ICPE-CA, Bukharest, Romania*
[3] *Physics Department, University of Žilina, Žilina, Slovak Republic*
[4] *P.-Ĵ. Shafarik University, Koshiče, Slovak Republic*
[5] *Nishina Center for Accelerator-Based Science, RIKEN, Wako, Japan*
[6] *Belgorod State National Research University, Belgorod, Russian Federation*

Recent results on the spin effects in deuteron-proton elastic scattering, beam and focal polarimetry using polarized deuteron and proton beams from new polarized ion source at Nuclotron-JINR facility are discussed. The vector A_y and tensor A_{yy} and A_{xx} analyzing powers in deuteron-proton elastic scattering at large transverse momenta obtained at internal target at Nuclotron in the energy range 400-1800 MeV are obtained. These data on the deuteron analyzing powers in the wide energy range demonstrate the sensitivity to the short-range spin structure of the isoscalar nucleon-nucleon correlations.

The perspectives of further progress in physics program as well as in the development of the polarimetry and proton spin manipulation techniques are disscussed.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

*Speaker.

PoS(SPIN2023)245

1. Introduction

The main goal of the DSS (Deuteron Spin Structure) experiment is to study the spin structure of two-nucleon (2N) and three nucleon (3N) short-range correlations via the measurements of the polarization observables in the deuteron induced reactions (pd-, dp- and dd- interactions) at Nuclotron. Short range correlations (SRC) of nucleons in nuclei 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 $\rho \sim 5\rho_0$ (where $\rho_0 \approx 0.17$ 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: (i) more than 90% all nucleons with the momenta k larger than 300 MeV/c belong to 2N SRC; (ii) probability for a given proton with momenta 300< k < 600 MeV/c to belong to pn correlation is ~18 times larger than for pp correlations; (iii) probability for a nucleon to have momentum larger than 300 MeV/c in medium nuclei is ~25%; (iv) 3N SRC are present in nuclei with a significant probability [6]. Recently, new data sensitive to SRCs were obtained in the inverse kinematics with carbon beam at Nuclotron [7]. 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 model of 2N and 3N correlations at low and moderate energies (below pion threshold production) can be built from the boson-nucleon picture of strong interaction. During last several years a new generation of nucleon-nucleon potentials are built (Nijmegen, CD-Bonn, AV-18 etc.). These potentials reproduced the NN scattering data up to 350 MeV with very good accuracy. But these potentials cannot reproduce triton binding energy (underbinding is 0.8 MeV for CD-Bonn), deuteron-proton elastic scattering and breakup data. Incorporation of three nucleon forces (3NF), when the interaction depends on the quantum numbers of the all three nucleons, allows to reproduce triton binding energy and unpolarized deuteron-proton elastic scattering and breakup data (see [8, 9] and references therein). The contribution of 3NF in found to be up to 30% in the vicinity of Sagara discrepancy for deuteron-proton elastic scattering at intermediate energies [10, 11]. However, the use of different 3NF models in Faddeev calculations can not reproduce polarization data intensively accumulated during last decade at different facilities [10]-[16].

On the other hand, pd- elastic scattering cross section data obtained already at 250 MeV [13] can not be reproduced by the Faddeev calculations with the inclusion of modern 3NF. The authors stated that the reason of this discrepancy can be neglecting a new type of short-range 3NF. At higher energies, Faddeev calculations fail to reproduce the cross section at the angles larger than 90°. The relativistic multiple scattering calculations [17, 18] give much better agreement with the data at the angles between 60° and 130°. It is shown that the double scattering dominates over the single scattering starting from ~70°. The deviation of the data on the calculations at backward angles are related with the manifestation of s- type of Fujita-Miyazawa 3NF. Some discrepancy exists around 90°, which can be connected with new type of SR 3NF. These forces can be built within approaches beyond one-boson-exchange. For instance, in the dressed bag model [19] 3NF comes from the interaction between intermediate six-quark state dressed by σ-field and the third nucleon. The description of 2N and 3N correlations at the energies higher than several hundreds

MeV/nucleon should be obtained within QCD [1].

To clarify the situation of the spin-dependence, it is undoubtedly promising to perform systematic study of polarization observables in the region of so called "cross section minimum" which spans angular range 90°-130° in the center of mass system (cms). Measurement of energy dependences of polarization observables in the region of cross section minimum can give an irreplaceable clue to the problem. 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 [20] and 2000 MeV [21]. The systematic measurements of the differential cross section have been performed also in recent years [22]-[25].

In this paper new results on the angular and energy dependencies of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in dp- elastic scattering at 400–1800 MeV as well as developments on the beam and focal polarimetry and proton spin manipulation techniques at Nuclotron will be disscussed.

2. Spin experiments at Internal Target Station at Nuclotron

DSS experiment operates using Internal Target Station (ITS) [26] with up to 6 different targets and beams of polarized deuteron and protons, as well as the light and heavy ions at Nuclotron. The ITS setup is well suited for study of energy dependence of polarization observables for the deuteron-proton elastic scattering and deuteron breakup reaction with the detection of two protons at large angles.

The CH_2 target of 10 μm thick is used for the measurements at ITS. The yield from the carbon content of the CH_2 target is estimated in separate measurements using 10 twisted carbon wires each 8 μm thick. The monitoring of the intensity is done from the detection of pp- quasi-elastic scattering at 90° in cms by the scintillation counters placed in the horizontal plane. The effect on hydrogen is obtained using CH_2-C subtraction procedure.

The detection of the dp- elastic events is done by the coincidence measurements of the proton and deuteron. The detectors are placed in the horizontal plane only for the cross section measurements and 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 interaction point for each event is reconstructed by the target position monitor [27] and used in the data analysis. The use of large amount of the scintillation counters allowed to cover wide angular range [28]. Such a method has been used to obtain the polarization data in dp- elastic scattering at T_d of 880 MeV [20] and 2000 MeV [21].

The studies of dp- breakup with two final protons detection is based on the use of several $\Delta E - E$ scintillation detectors [29]. The measurement of the energies of two protons allow to reconstruct the neutron missing mass. The cross section and analyzing powers for deuteron non-mesonic breakup along the S-curve are obtained using the information on the energies and emission angles of the final particles. The DSS setup with the additional large scintillation detectors placed in the forward direction is able to study the 3 charged particle correlations in the light and heavy ion collisions. The major DSS methodical goal is to provide the efficient polarimetry for the both deuteron and proton polarized beams for the NICA complex at whole.

PoS(SPIN2023)245

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 [30]. These measurements were performed using internal target station at Nuclotron [26] with new control and data acquisition system [31]. The existing setup [28] has been upgraded by new VME based DAQ [32], new MPod based high voltage system [33], 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[28], where precise data on analyzing powers [11, 12, 34] exist, has been developed at ITS at Nuclotron [26]. 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 [34].

New SPI [30] 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 [28]. 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 [35].

3. Deuteron analyzing powers A_y, A_{yy} and A_{xx} in dp- elastic scattering

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. 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 were used to check the correctness of the data analysis procedure. The results obtained at Nuclotron [36] are in good agreement with the data obtained at IUCF [37], [38] and at Saclay [39] earlier. The considering of the contribution of the three-nucleon forces or N^4LO calculations performed within chiral Effective Field Theory (χEFT) [40] 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.

The results on the angular dependencies of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in dp- elastic scattering at 1300 MeV are shown by the solid symbols in the a), b) and c) panels of Fig.1, respectively. Both statistical and systematic errors are indicated. The open symbols are the data obtained earlier at 1200 MeV at ANL [41] and Saclay [42]. One can see good consistency of the Nuclotron data with the world data. The curves are the results of the relativistic

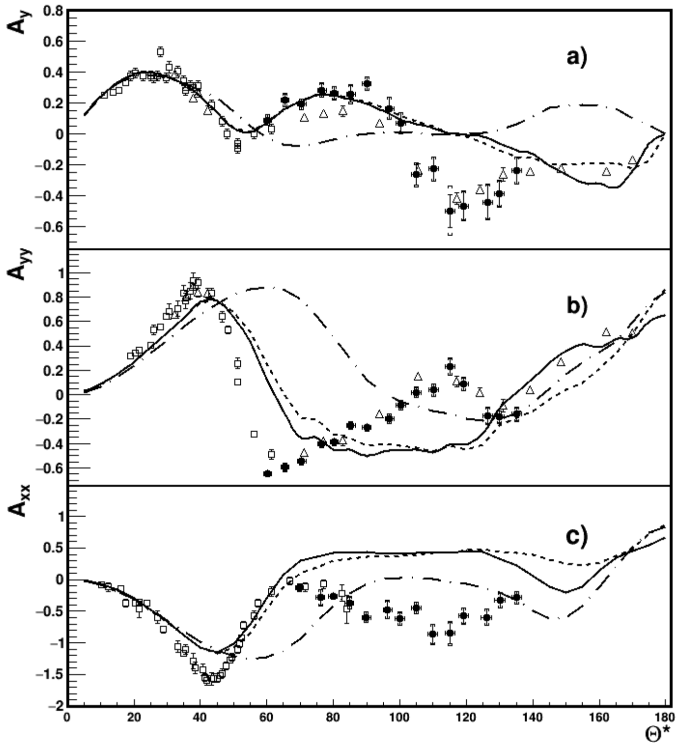

Figure 1: The angular dependencies of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in dp-elastic scattering at 1300 MeV are shown in the a), b) and c) panels, respectively. The solid symbols are the data obtained by DSS collaboration at Nuclotron, while the open squares and triangles are the data obtained at 1200 MeV at ANL [41] and Saclay [42], respectively. The curves are the results of the relativistic multiple scattering model with different reaction mechanisms included [43, 44].

multiple scattering model taking into account one-nucleon exchange and single scattering, double scattering and the excitation of the Δ- isobar in the intermediate state [43, 44] shown by the dash-dotted, dashed and solid lines, respectively. The contribution of the Δ- isobar is significant at backward angles at this energy [43, 44]. The relativistic multiple scattering model describes the data on A_y up to 90° only, while it fails to reproduce the data at larger angles. The considering of neither double scattering term, nor Δ- isobar improves the agreement. The model allows to describe the behaviour of the A_{yy} analyzing power up to 80° only qualitatively. The double scattering term gives a significant contribution at the angles larger than 40°, 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 [43, 44] over the whole angular range.

The energy dependencies of the vector A_y and tensor A_{yy} analyzing powers at the fixed angles in the cms demonstrate the sign change at $P_T \sim 600$ MeV/c and the tendencies to reach the asymptotic values at larger P_T. 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.

4. Analyzing power A_y in pp- quasielastic scattering

The analyzing power A_y in pp- quasielastic scattering has been obtained at the energies of 200, 500, 550 and 650 MeV/nucleon using polarized deuteron beam in the test experiment. The data were taken using the same scintillation detectors as for dp- elastic scattering experiment [28]. The used detectors were placed in the horizontal plane only according to the pp- elastic scattering kinematics. The useful events selection has been done using correlation of the energy losses and time-of-flight difference for the conjugated detectors. The effect on hydrogen has been obtained using CH2-C subtraction procedure. The normalized numbers of pp- quasielastic scattering events for each spin mode were used to calculate the value of the analyzing power A_y.

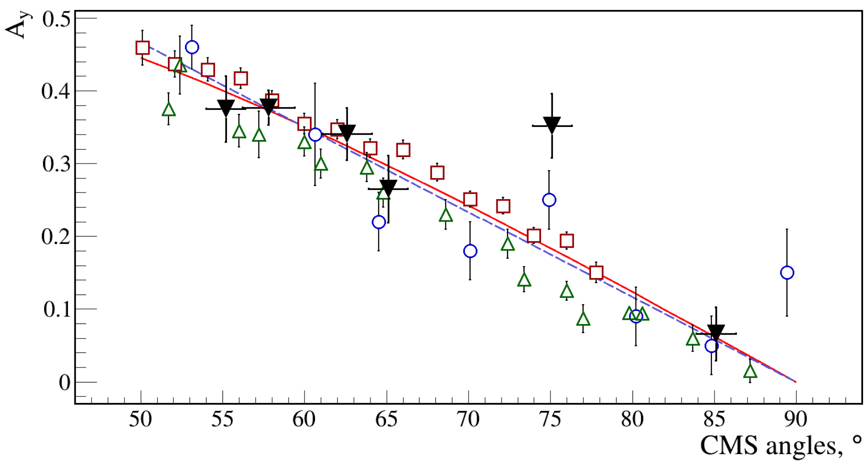

Figure 2: Analyzing power A_y in pp- quasielastic scattering at the energy of 500 MeV/nucleon obtained at Nuclotron (solid symbols). Open symbols are the world data at close energies. The solid line is the results of the SAID SP07 solution [45].

The Nuclotron data are in good agreement with the world data taken at close energies as well as with the SP07 solution of partial wave analysis SAID [45]. See for example Fig.2, where the data obtained at 500 MeV/nucleon are presented. The error bars achieved in the experiment are large enough due to small value of the vector component of the deuteron beam polarization. Nevertheless, the obtained data can be used for the evaluation of the polarized deuteron beam vector component.

5. Deuteron and proton beams polarization measurements

The vector and tensor polarizations were measured several times in the Nuclotron runs performed in 2016-2017. The values had small statistical and systematics errors. They were rather stable within each part of the experiment as well as within more than 200 hours of the SPI operation [35]. On the other hand, SPI demonstrated good reproducibility of the polarization values for different sets of the data after long interruptions. It was found also the value of the β- angle, which defines the direction of polarization vector in the space, is about -90°, e.g. normal to the Nuclotron orbit plane.

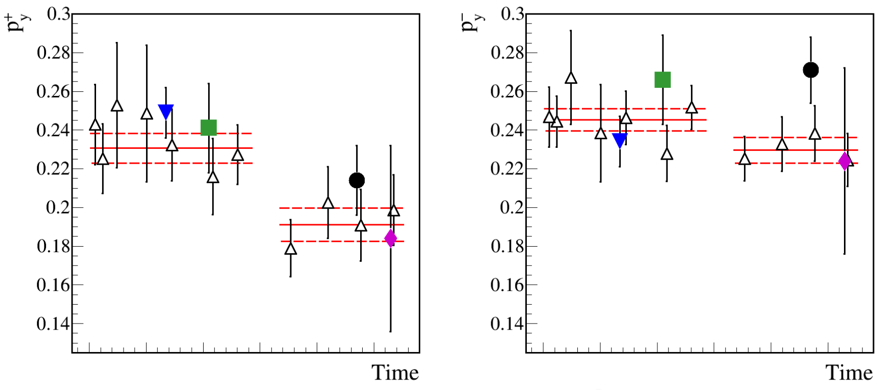

Figure 3: The deuteron beam vector polarization for 2 spin modes as a function of the time measured by 2 different methods. Open symbols represent the results obtained using dp- elastic scattering at 270 MeV [35]. The solid triangles, squares, circles and diamonds are the data obtained using pp- quasi-elastic scattering at 500, 650, 550 and 200 MeV/nucleon, respectively.

The vector polarimetry for deuteron and proton beams can be provided with the standard DSS equipment using either dp- elastic scattering at 270 MeV [35], or pp- quasielastic scattering in the wide energy range, respectively. The results of the deuteron beam vector polarization measurement for 2 spin modes are presented in Fig.3. One can see good agreement between the data obtained by these different methods. The error bars for the beam polarization values obtained at 200 MeV/nucleon (full diamonds) are large due to small value of the analyzing power at this energy. Therefore, the method using pp- quasielastic scattering at large scattering angles can be used for the deuteron/proton beam polarization measurement at least up to 650 MeV/nucleon.

The polarized and unpolarized proton beams provided by SPI [30] have been accelerated up to 500 MeV. The typical beam intensities were 2-3$\cdot 10^7$ ppp and 1.5$\cdot 10^8$ ppp for polarized and unpolarized cases, respectively. SPI provided proton beam polarization using WFT $1 \rightarrow 3$ transition with the ideal value of the polarization +1. The polarization of the proton beam has been obtained using the data from 12 pairs of the detectors placed in the kinematic coincidences on the left and right. The values of the analyzing power for pp- elastic scattering were taken from SP07 solution of SAID partial wave analysis [45]. The averaged value of the proton beam polarization for WFT $1 \rightarrow 3$ transition is 0.368$\pm$0.023. The result for the false asymmetry (polarization) for unpolarized proton beam is 0.038$\pm$0.023.

The perspectives of further spin studies at Nuclotron are related with the polarized beams intensity increasing up to at least 5$\cdot 10^9$ (due to CH_2 target limitation) and 10^{10} ppp for the internal and extracted beams, respectively. The main goals of the experiments at ITS is the measurements of the deuteron analyzing powers in dp- elastic scattering at large tranverse momenta, nucleon analyzing power A_y^p in pd- elastic scattering at 100-1000 MeV, dp- and pd- non-mesonic breakup at the energies between 135-250 MeV/nucleon, development of the deuteron and proton beams polarimetry. The special attention will be paid to the deuteron and proton spin manipulation techniques at Nuclotron [46, 47]. The first experiments with polarized protons can be the measurement of the $\gamma G = 2$ and $\gamma G = 3$ integer resonances powers [46]. The main experiment at the extracted beam is the studies devoted to the high energy neutron and proton focal polarimetry [48].

6. Conclusions

- Upgraded Nuclotron with new SPI [30] provides quite unique opportunity for the studies of the spin effects and polarization phenomena in few body systems using polarized deuteron and proton beams, for the focal and beam polarimetry development.
- The results obtained at Nuclotron demonstrate the asymptotic values for the A_y and A_{yy} analyzing powers in dp- elastic scattering at large tranverse momenta ($\geq$600 MeV/c). This can be due to the manifestation of the fundamental degrees of freedom.
- The nearest goals are to reach $5{\cdot}10^9$ and 10^{10} deuterons/spill for the ITS and extracted beam experiments, respectively; to start the experiments with polarized proton beam.

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 [30]. 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. Authors thanks Yu.N. Filatov and A.M. Kondratenko for the discussions on the deuteron and proton spin manipulation techniques at Nuclotron.

References

[1] L. Frankfurt, M. Sargsian, M. Strikman, *Recent observation of short range nucleon correlations in nuclei and their implications for the structure of nuclei and neutron stars*, *Int. J. Mod. Phys.* **A23** (2008) 2991.

[2] E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, J. W. Watson, *Evidence for the strong dominance of proton-neutron correlations in nuclei*, *Phys. Rev. Lett.* **97** (2006) 162504.

[3] L. L. Frankfurt, M. I. Strikman, D. B. Day, M. M. Sargsian, *Evidence for short range correlations from high $Q^2(e,e')$ reactions*, *Phys. Rev.* **C48** (1993) 2451.

[4] K. Sh. Egiyan et al., *Observation of nuclear scaling in the $A(e,e')$ reaction at x(B) greater than 1*, *Phys. Rev.* **C68** (2003) 014313.

[5] K. S. Egiyan et al., *Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei*, *Phys. Rev. Lett.* **96** (2006) 082501.

[6] L. Frankfurt, M. Sargsian, and M. Strikman, *Future directions for probing two and three nucleon short-range correlations at high energies*, *AIP Conf. Proc.* **1056** (2008) 322.

[7] M. Patsyuk et al., *Unperturbed inverse kinematics nucleon knockout measurements with a 48 GeV/c carbon beam*, *Nature Phys.* **17** (2021) 693.

[8] W. Glöckle, H. Witala, D. Hüber, H. Kamada, J. Golak, *The Three nucleon continuum: achievements, challenges and applications*, *Phys. Rep.* **274** (1996) 107.

[9] N. Kalantar-Nayestanaki, E. Epelbaum, J. G. Messchendorp and A. Nogga, *Signatures of three-nucleon interactions in few-nucleon systems*, *Rep. Prog. Phys.* **75** (2012) 016301.

[10] N. Sakamoto et al., *Measurement of the vector and tensor analyzing powers for the d-p elastic scattering at Ed = 270 MeV*, *Phys.Lett.* **B367** (1996) 60.

[11] K. Sekiguchi et al., *Complete set of precise deuteron analyzing powers at intermediate energies: comparison with modern nuclear force predictions*, *Phys. Rev.* **C65** (2002) 034003.

[12] K. Sekiguchi et al., *Polarization transfer measurement for* $^1H(\vec{d},\vec{p})^2H$ *elastic scattering at 135-MeV/u and three nucleon force effects*, *Phys. Rev.* **C70** (2004) 014001.

[13] K. Hatanaka, Y. Shimizu et al., *Cross-section and complete set of proton spin observables in pâĘŚd elastic scattering at 250-MeV*, *Phys.Rev.* **C66** (2002) 044002.

[14] R. Bieber et al., *Three-Nucleon Force and the* A_y *Puzzle in Intermediate Energy* $\vec{p}+d$ *and* $\vec{d}+p$ *Elastic Scattering*, *Phys. Rev. Lett.* **84** (2000) 606.

[15] K. Ermisch et al., *Search for Three-Nucleon Force Effects in Analyzing Powers for pâĘŚd Elastic Scattering*, *Phys. Rev. Lett.* **86** (2001) 5862.

[16] K. Ermisch et al., *Systematic investigation of the elastic proton deuteron differential cross-section at intermediate-energies*, *Phys. Rev.* **C68** (2003) 051001.

[17] N. B. Ladygina, *Deuteron-proton elastic scattering at intermediate energies*, *Phys. Atom. Nucl.* **71** (2008) 2039.

[18] N. B. Ladygina, *Differential Cross Section of dp- Elastic Scattering at Intermediate Energies*, *Eur. Phys. J.* **A42** (2009) 91.

[19] V. I. Kukulin et al., *The properties of the three-nucleon system with dressed-bag model for NN interactions: 1. New scalar three-body force*, *J. Phys. G: Nucl. Part. Phys.* **30** (2004) 287.

[20] P. K. Kurilkin et al., *Measurement of the vector and tensor analyzing powers for* dp*- elastic scattering at 880 MeV*, *Phys. Lett.* **B715** (2012) 61.

[21] P. K. Kurilkin et al., *Investigation of the angular dependence of the analyzing powers in the deuteron-proton elastic scattering at the nuclotron*, *Phys. Part. Nucl. Lett.* **8** (2011) 1081.

[22] Yu. V. Gurchin et al., *The cross-section in* dp*- elastic scattering at the energies of 500 MeV, 700 MeV and 880 MeV obtained at the internal target station of Nuclotron*, *Phys. Part. Nucl. Lett.* **10** (2013) 243.

[23] A. A. Terekhin et al., *Study of the dp-elastic scattering at 2 GeV*, *Phys. Part. Nucl. Lett.* **12** (2015) 695.

[24] A. A. Terekhin et al., *Differential cross section for elastic deuteron - proton scattering at the energy of 700 MeV per nucleon*, *Phys. Atom. Nucl.* **80** (2017) 106.

[25] A. A. Terekhin et al., *The differential cross section in deuteron-proton elastic scattering at 500, 750 and 900 MeV/nucleon*, *Eur. Phys. J.* **A55** (2019) 129.

[26] A. I. Malakhov et al., *Potentialities of the internal target station at the Nuclotron*, *Nucl. Instrum. Meth. in Phys. Res.* **A440** (2000) 320.

[27] Yu. V. Gurchin et al., *Target position monitor for internal target station at the Nuclotron*, *Phys. Part. Nucl. Lett.* **4** (2007) 263.

[28] P. K. Kurilkin et al., *The 270 MeV deuteron beam polarimeter at the Nuclotron Internal Target Station*, *Nucl. Instr. Meth. in Phys. Res.* **A642** (2011) 45.

[29] M. Janek et al. (DSS Collaboration), *Study of the dp Elastic and dp Breakup Complementary Processes Using Polarized and Unpolarized Beam of Nuclotron*, *Few-Body Syst* **63** (2022) 3.

[30] V. V. Fimushkin et al., *Development of polarized ion source for the JINR accelerator complex*, *J. Phys. Conf. Ser.* **678** (2016) 012058;

A. S. Belov et al., *Source of polarized ions for the JINR accelerator complex*, *J. Phys. Conf. Ser.* **938** (2017) 012017.

[31] A. Yu. Isupov, V. A. Krasnov, V. P. Ladygin, S. M. Piyadin, S. G. Reznikov, *The Nuclotron internal target control and data acquisition system*, *Nucl. Instrum. Meth. in Phys. Res.* **A698** (2013) 127.

[32] A. Yu. Isupov, *Online polarimetry of the Nuclotron internal deuteron and proton beams*, *J. Phys. Conf. Ser.* **938** (2017) 012019.

[33] Ya. T. Skhomenko et al., *Software development for multi-channel LV/HV supply system based on Wiener MPod*, *BSU Sci. Bull. Math.& Phys.* **234** (2016) 126.

[34] K. Suda et al., *Absolute calibration of the deuteron beam polarization at intermediate energies via the* $^{12}\mathrm{C}(d,\alpha)^{10}\mathrm{B}^{*}[2^{+}]$ *reaction*, *Nucl. Instr. Meth. in Phys. Res.* **A572** (2007) 745.

[35] Ya. T. Skhomenko et al., *Measurement of the deuteron beam polarization at internal target at Nuclotron for DSS experiment* , *J. Phys. Conf. Ser.* **938** (2017) 012022.

[36] V. P. Ladygin et al. (DSS Collaboration), *Angular Dependencies of the Deuteron Analyzing Powers in Elastic dp Scattering at Large Transverse Momenta*, *Phys. Part. Nucl.* **53** (2022) 251.

[37] R. V. Cadman et al., *Evidence for a three nucleon force effect in proton - deuteron elastic scattering*, *Phys. Rev. Lett.* **86** (2001) 967.

[38] B. v Przewoski et al., *Analyzing powers and spin correlation coefficients for* $p+d$ *elastic scattering at 135 MeV and 200 MeV*, *Phys. Rev.* **C74** (2006) 064003.

[39] M. Garçon *et al.*, *Measurements of vector and tensor analysing powers for 191 and 395 MeV deuteron scattering*, *Nucl. Phys.* **A458** (1986) 287.

[40] S. Binder *et al.*, *Few-nucleon systems with state-of-the-art chiral nucleon-nucleon forces*, *Phys. Rev.* **C93** (2016) 044002.

[41] M. Haji-Saied et al., *Tensor and vector spin observables in pd elastic scattering at 600 MeV, 800 MeV, and 1000 MeV*, *Phys. Rev.* **C36** (1987) 2010.

[42] V. Ghazikhanian et al., *Vector and tensor spin observables in the reaction* $^{1}\vec{H}(\vec{d},d)^{1}\vec{H}$ *at 1.6 GeV*, *Phys. Rev.* **C43** (1991) 1532.

[43] N. B. Ladygina, *Delta excitation in deuteron- proton elastic scattering*, *Eur. Phys. J.* **A52** (2016) 199.

[44] N. B. Ladygina, *On reaction mechanisms in deuteron-proton elastic scattering*, *Eur. Phys. J.* **A56** (2020) 133.

[45] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, R. L. Workman, *Updated Analysis of NN Elastic Scattering to 3 GeV*, *Phys. Rev.* **C76** (2007) 025209.

[46] Yu. N. Filatov et al., *Spin Navigator on the Base of the Correcting Dipoles at Nuclotron/JINR*, *JETP Lett.* **116(7)** (2022) 413.

[47] Yu. N. Filatov et al., *Proton-Spin-Flipping System Based on Orbit-Steerer Dipoles in the Nuclotron/JINR Operating at the* γG *= 7 Spin Resonance*, *JETP Lett.* **118(6)** (2023) 387.

[48] S. N. Basilev et al., *Measurement of neutron and proton analyzing powers on C, CH,* CH_2 *and Cu targets in the momentum region 3–4.2 GeV/c*, *Eur. Phys. J.* **A56** (2020) 26.