Theme - 02-1-1097-2010

Study of the polarization phenomena and spin effects at the JINR Nuclotron-M/NICA Facility.

Project

Probing the Deuteron short-range Spin Structure in the (d,p) reactions using polarized deuteron beam at Nuclotron-M (**DSS project**).

Authors

E.V.Chernykh, Yu.V.Gurchin, A.P.Ierusalimov, A.Yu.Isupov, V.P.Ladygin, N.B.Ladygina, K.S.Legostaeva, A.N.Livanov, S.M.Piyadin, S.G.Reznikov, A.A.Terekhin, A.V.Tishevsky, I.S.Volkov

Joint Institute for Nuclear Research, Dubna, Russia

V.A.Baskov, V.A.Dronov, A.I.Lvov, V.V.Polansky, S.S.Sidorin

Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

V.V.Syschenko, I.E.Vnukov

Belgorod State National Research University, Belgorod, Russia

Yu.N.Filatov, E.D.Tsyplakov

Moscow Physical Technical Institute, Moscow, Russia

A.M.Kondratenko, M.A. Kondratenko

Science and Technique Laboratory Zaryad, Novosibirsk, Russia

M.Janek

Physics Department, University of Zilina, Zilina, Slovak Republic

G.Martinska, J.Urban

P.-J. Safarik University, Kosice, Slovak Republic

Project Leader: V.P.Ladygin

Abstract

The main goals of the DSS experiment is to obtain new and valuable information of the short range spin structure of 2-nucleon and 3-nucleon correlations in the processes with participation of polarized deuterons and protons at Nuclotron. There 2 main tools for that: i) energy scan of the deuteron analyzing powers Ay, Ayy and Axx in deuteron-proton elastic scattering and nucleon analyzing power A_y^p in proton-deuteron elastic scattering at 150-1000 MeV/nucleon at large transverse momenta; ii) study non-mesonic deuteron breakup p(d,pp)n with the detection of 2 final protons in different kinematics (complanar, space-star) at the deuteron kinetic energies of 300-500 MeV. Very important and necessary goal of the DSS project is the development of the efficient polarimetry of the deuteron and proton beams and the navigator for proton spin manipulation, what has the great importance for spin studies at NICA at whole.

1.Introduction

The mail goal of the DSS- 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 ρ=5 ρo (where ρo ∼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 main tools to study SRCs at hadronic facilities can be the deuteron structure investigations at large internal momenta allowing to explore 2N SRC with I=0; 3He 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 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 0.8MeV 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] 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 [9-10]. However, the use of different 3NF models in Faddeev calculations can not reproduce polarization data intensively accumulated during last decade at different facilities [9-15].

On the other hand, *pd*- elastic scattering cross section data obtained already at 250 MeV [12] 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 by new type of short-range 3NF. At higher energies, Faddeev calculations fail to reproduce the cross section at the angles larger than 90o. The relativistic multiple scattering calculations [16,17] give much better agreement with the data at the angles between 60o and 130o. It is shown that the double scattering dominates over the single scattering starting from ∼70o. 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 90o , 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 [18] 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].

At intermediate energies, intensive studies on three-nucleon force effects are proceeded via the deuteron-proton and deuteron-neutron elastic scattering and breakup reactions. At energies Td<300 MeV, Faddeev calculations can provide good description of cross section data, by introducing a three nucleon force, over the whole angular range. However, their reproduction of polarization observables are not as good as that for cross section data, which may be regarded as an insufficiency of our knowledge on spin-dependence of three nucleon force. 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^o – 130^o in the cms. At higher energies, for example, at Td=500 MeV, the Faddeev calculation deviates from the cross section data at backward angles [12]. This may be due to relativistic effects and/or new three-nucleon force other than Fujita-Miyazawa type. Subthreshold pion production may play a role. At higher energies 2N and 3N SRC can manifest. Measurement of energy dependences of polarization observables in the region of cross section minimum can give an irreplaceable clue to the problem.

2. Results of the DSS experiment at ITS

Nuclotron provided no polarized beams in 2022-2023. The DSS setup placed at the internal target station (ITS) [19] has been tested in the commissioning runs in March 2022 and in January 2023 with carbon and xenon beams, respectively.

The scientific activity within the DSS- project in 2022-2023 focused on the following directions.

-Data analysis of the results on the systematic measurements of the Ay, Ayy and Axx analyzing powers in *dp*- elastic scattering at the energies 700-1800 MeV at Internal Target Station (ITS) [20-24] at Nuclotron.

-Data analysis of the cross section in dp- non-mesonic breakup at the energies below 500 MeV for different kinematic configurations of two final protons [25] .

-Data analysis on the angular dependence of the analyzing power in *pp*- quasi-elastic scattering at the deuteron beam energies 200, 500, 550 and 650 MeV/nucleon [26-27].

-Data analysis on the deuteron and proton beam polarization measurements at ITS for the polarized deuteron and proton beams [28-39].

-The simulation and upgrade of the DSS-setup in order to use it as a wide energy range proton polarimeter and for the measurements of the nucleon analyzing power in *pd*- elastic scattering [30-31]. R&D for new polarimeter techniques [32].

-The theoretical analysis of the observables in hadronic reactions with the participation of light nuclei using relativistic multiple scattering model [33].

-New experimental data were obtained for 3 particle correlations in C-C, C-Al, C-Ag and C-W collisions at ITS in March 2022. The measurements for Xe-Ag and Xe-W collisions have been performed in January 2023. The data analysis is in progress.

2.1. DSS setup

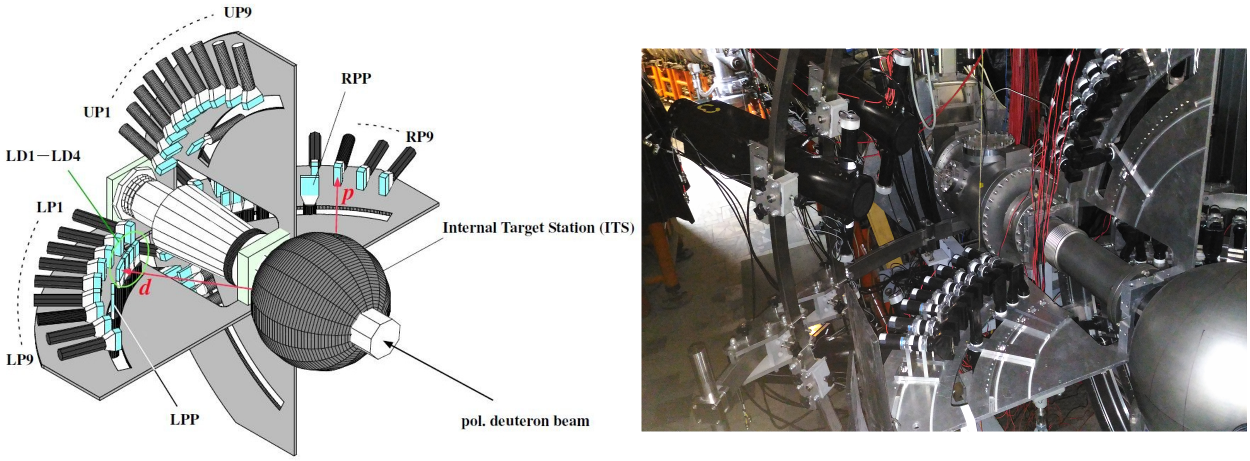

Fig.1. Schematic view of the ITS [19] with the detection system for dp- elastic scattering studies [34] (left panel). Picture of the equipment used in 2016-2017 Nuclotron runs is shown in the right panel.

DSS experiment operates using internal target station (ITS) 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 (see Fig.1).

The target CH2 of 10 mkm thick is used for the measurements at ITS. The yield from the carbon content of the CH2 target is estimated in separate measurements using 10 twisted carbon wires each 8 mkm thick. The monitoring of the intensity is done from the detection of *pp*- quasi-elastic scattering at 90^o in cms by the scintillation counters placed in the horizontal plane. The effect on hydrogen is obtained using CH2-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 [35] and used in the data analysis.

The studies of *dp*- breakup with two final protons detection is based on the use of several dE-E scintillation detectors [20,23]. 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 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.

2.2. Deuteron analyzing powers Ay, Ayy and Axx in dp- elastic scattering

The polarization measurements at ITS has been performed using rather low intensity of polarized deuteron beam. Actually, these measurements were be performed during the commissioning run with new PIS [36] . The priority was given to the measurements of the angular dependence of Ay, Ayy and Axx analyzing powers in *dp*- elastic scattering at the energies between 700 and 1800 MeV.

These measurements were performed using internal target station at Nuclotron [19] with new control and data acquisition system [37]. The existing setup [34] has been upgraded by new VME based DAQ, new MPod based high voltage system, new system of monitors etc.

New SPI [36] has been used to provide polarized deuteron beam. In the current experiment the spin modes with the maximal ideal values of (Pz,Pzz)= (0,0), (1/3,+1) and (1/3, +1) were used. The deuteron beam polarization has been measured at 270 MeV [34]. 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 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 CH2 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 Ay, Ayy and Axx.

The results on the angular dependencies of the vector Ay and tensor Ayy and Axx analyzing powers in dp-elastic scattering at 1300 MeV [20-24] are shown by the solid symbols in the a), b) and c) panels of Fig.2, respectively. Both statistical and systematic errors are indicated. The open symbols are the data obtained earlier at 1200 MeV at ANL and Saclay. One can see good consistency of the

Nuclotron data with the world data. The curves are the results of the relativistic 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 [33,38-39] show by the dash-dotted, dashed and solid lines, respectively. The contribution of the Δ-isobar is significant at backward angles at this energy [33,38-39]. The relativistic multiple scattering model [33,38-39] describes the data on Ay up to 90^o 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 Ayy analyzing power up to 80^o only qualitatively. The double scattering term gives a significant contribution at the angles larger than 40^o, however, its taking into account does not remove the discrepancy of the calculation with the data. The Axx behaviour is not described by the model [33,38-39] over the whole angular range.

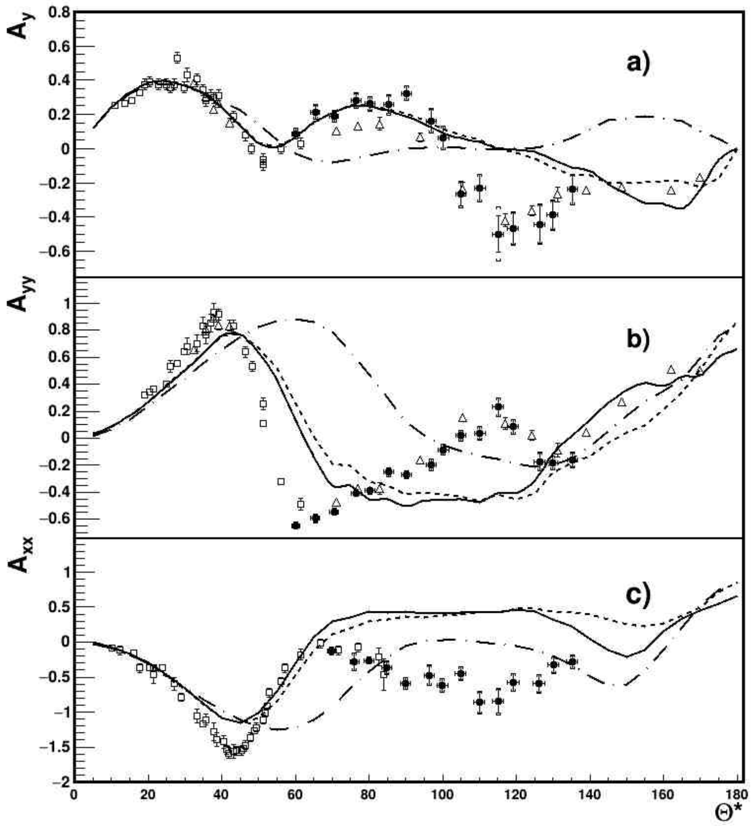

Fig.2. The angular dependencies of the vector Ay and tensor Ayy and Axx analyzing powers in dp-elastic scattering at 1300 MeV [20-24] are shown in the a), b) and c) panels, respectively. The solid symbols are the data obtained by DSS collaboration at Nuclotron, while the open symbols are the data obtained at 1200 MeV at ANL and Saclay. The curves are the results of the relativistic multiple scattering model with different reaction mechanisms included [34,38-39].

One can see also manifestation of the resonant-like structure of the vector Ay and tensor Ayy analyzing powers in the vicinty of 100^o-130^o. Ay reaches -0.4, while Ayy goes to zero. The model cannot describe the unexpected behaviour of Ay and Ayy in the vicinity of 100^o-130^o in the cms. Such behaviour can be due to manifestation of the non-nucleon degrees of freedom like excitation of NN* or dibaryons in the intermediate state. Also the reason of the deviation can be the neglecting by the 3N SRCs.

The energy dependencies of the vector Ay and tensor Ayy analyzing powers at 70^o in the cmsare presented as a function of the transverse momentum P_T in the left and right panels of Fig.3, respectively. The full circles are the results of the present experiment. The full squares are the data obtained at ITS at Nuclotron in 2005[40-41]. Open symbols are the world data. Both Ay and Ayy analyzing powers change the sign at P_T ~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 transverse momenta.

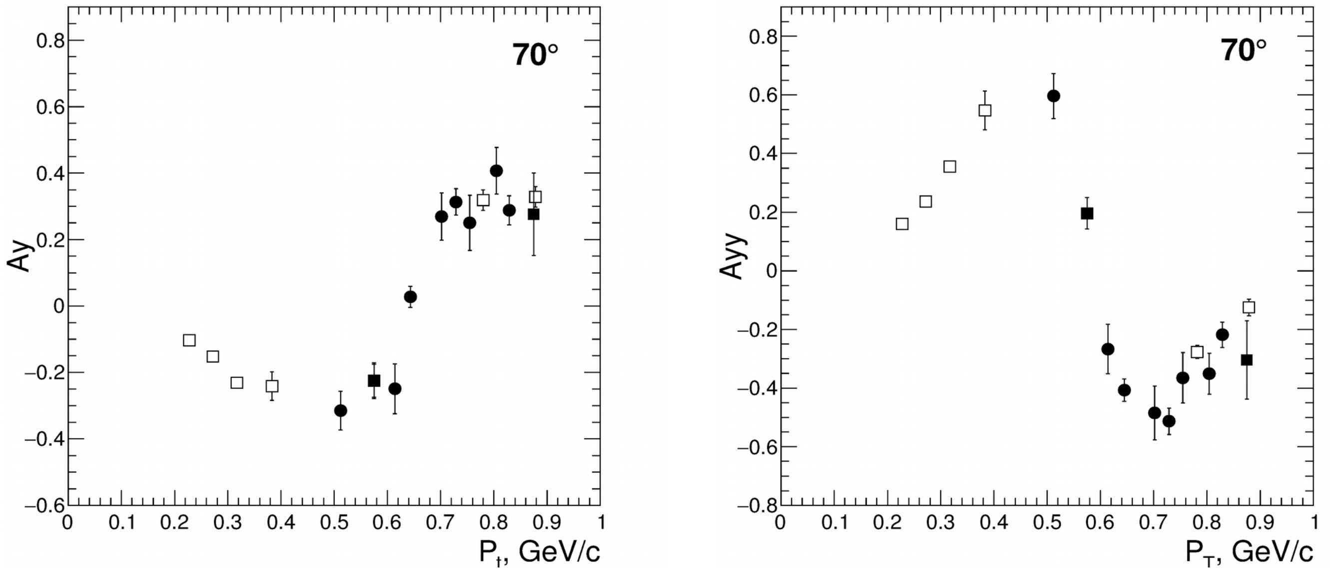

Fig.3. The energy dependence of the vector Ay (left panel) and tensor Ayy (right panel) analyzing powers at 70° in the cms. The full circles are the results of the DSS experiment. The full squares are the data obtained at ITS at Nuclotron in 2005 [40-41]. Open symbols are the world data.

The data presented in Figs 2 and 3 clearly demonstrate, on the one hand, the deviation on the predictions of the relativistic scattering model using standard spin structure of the nucleon-nucleon interaction and, on the other hand, resonant-like structures or asymptotic behaviour consistent with the manifestation of the non-nucleonic degrees of freedom. The data also demonstrate that the error bars obtained sometimes are too large to make a definitive conclusions, especially, for the vector analyzing power Ay due small value of the vector component of the deuteron beam polarization. The continuation of the studies are required.

2.3. Analyzing power Ay in pp- quasielastic scattering

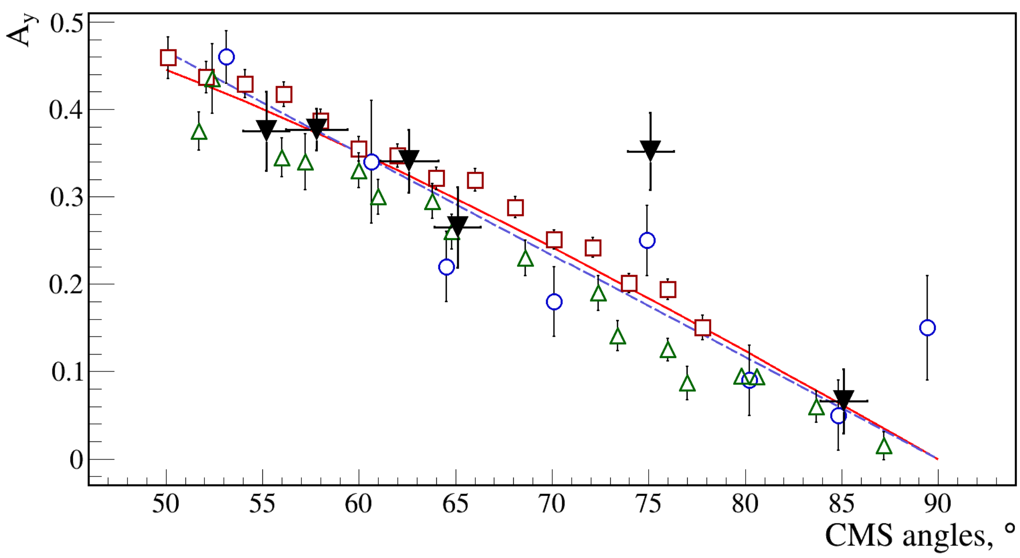

Fig.4. Analyzing power Ay in pp- quasielastic scattering at the energy of 500 MeV/nucleon obtained at Nuclotron (solid symbols) [29]. Open symbols are the world data at close energies. The solid line is the results of SP07 SAID solution [42]. The dashed line is the result of the 2-degree polinom approximation of the shown world data.

The analyzing power Ay 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 [26-29]. The data were taken using the same scintillation detectors as for dp- elastic scattering experiment [34]. The used detectors were placed in the horizontal plane only according to 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 Ay.

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 [42]. See for example Fig.4, 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.

2.4. Deuteron and proton beams polarization measurements

The polarimeter based on the use of dp- elastic scattering at large angles (> 60° in the cms) at 270 MeV [34], where precise data on analyzing powers [10-11] exist, and placed at ITS [19] at Nuclotron has been proposed as the reference deuteron polarimeter at Nuclotron-NICA.The accuracy of the deuteron beam polarization determination 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 [43].

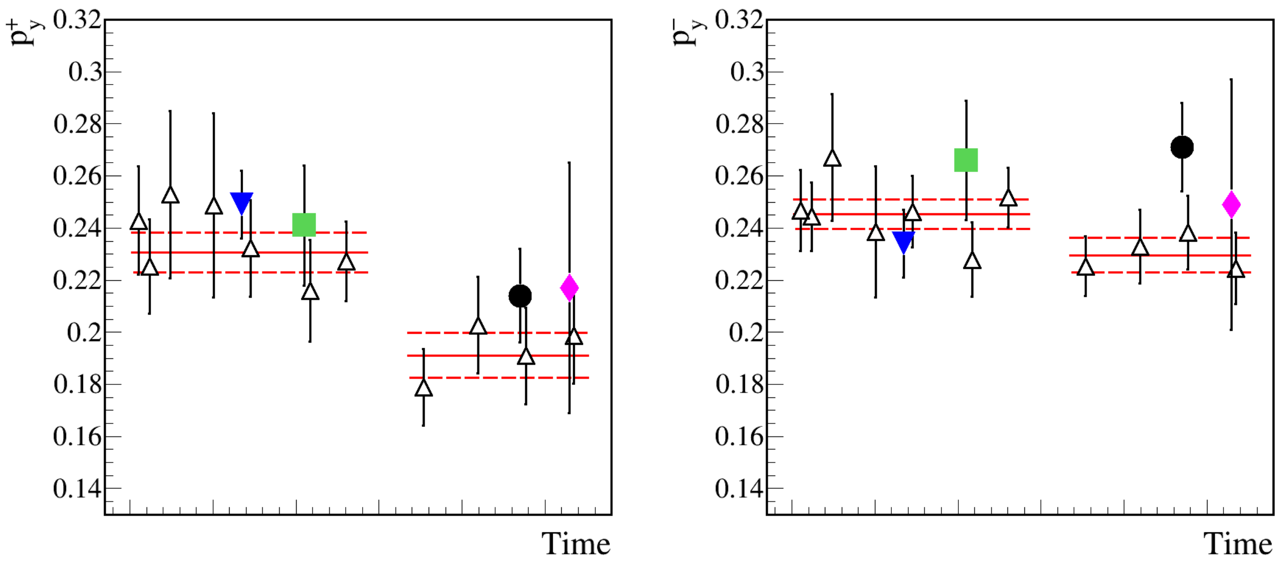

Fig.5. The deuteron beam vector polarization for 2 spin modes as a function of the time measured by 2 different methods. Open symbols represent the results obtained using dp- elastic scattering at 270 MeV [44]. The solid triangles, squares, circles and diamonds are the data obtained using pp- quasi-elastic scattering at 500, 650, 550 and 200 MeV/nucleon, respectively [26-29].

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 [44]. 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.

The vector polarimetry for deuteron and proton beams can be provided with the standard DSS equipment using either dp-elastic scattering at 270 MeV [44], or pp- quasielastic scattering [26-29] in the wide energy range, respectively. The results of the deuteron beam vector polarization measurement for 2 spin modes are presented in Fig.5. 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.

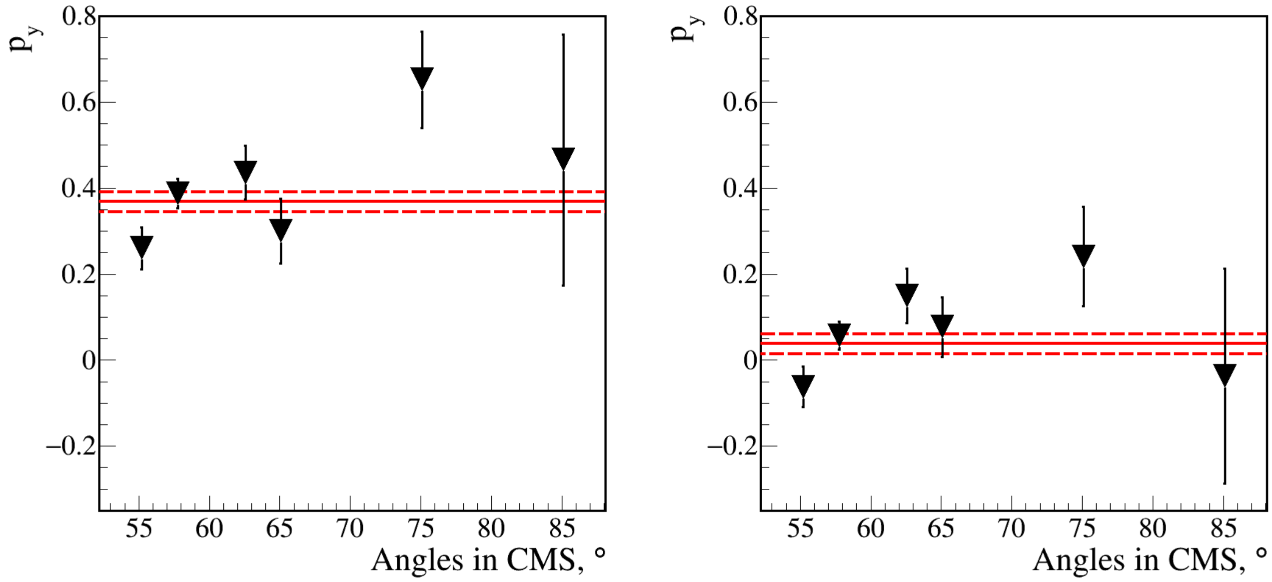

Fig.6. The proton beam polarization at 500 MeV as the function of the scattering angle in the cms. Left and right panels correspond to the polarized (WFT 1→3) and unpolarized proton beams, respectively.

The polarized and unpolarized proton beams provided by SPI [36] have been accelerated up to 500 MeV. The typical beam intensities were $2\text{-}3\cdot10^7$ ppp and $1.5\cdot10^8$ ppp for polarized and unpolarized cases, respectively. SPI provided proton beam polarization using WFT 1→3 with 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 [42]. The results of the proton beam polarization for the polarized proton beam at different angles in the cms are shown in the left panel of Fig.6. The averaged value of the proton beam polarization for WFT 1→3 is 0.368±0.023. The result for the false asymmetry (polarization) for unpolarized proton beam shown in the right panel in Fig.6 is consistent with zero: 0.038 ±0.023.

The classical method to measure the proton beam polarization at intermediate and high energies is the use of the left-right pp- elastic or quasi-elastic scattering (see, for instance, [45] and references therein). The maximal value of the analyzing power at the energies below 2200 MeV/nucleon is close to 40^o in cms [42], that corresponds roughly $14\text{-}15^o$ in the laboratory. Unfortunately, this angle is inaccessible due to design of ITS and detector support. Therefore, the only way to increase figure of merit is to enlarge the acceptance of the polarimeter at ITS by adding new scintillation counters. A simulation has been performed for a polarimeter of protons on an internal target for pp- and pd-elastic scattering reactions in the energy range of 100-1000 MeV. A set of new scintillation detectors for the polarimeter has been manufactured and tested both with RA source and with parasitic beam at Nuclotron in 2022-2023 [30,31]. Also R&D for new type of scintillation counter with SiPM readout has been performed [32].

2.5. DSS setup with light and heavy ions

Work has been carried out to restore the operation of the ITS at Nuclotron and the equipment of the DSS project after Booster construction. Experimental data were obtained for 3 particle correlations in C-C, C-Al, C-Ag and C-W collisions on the internal target in March 2022. The measurements for Xe-Ag and Xe-W collisions have been preformed in January 2023. The data analysis and simulation are in progress.

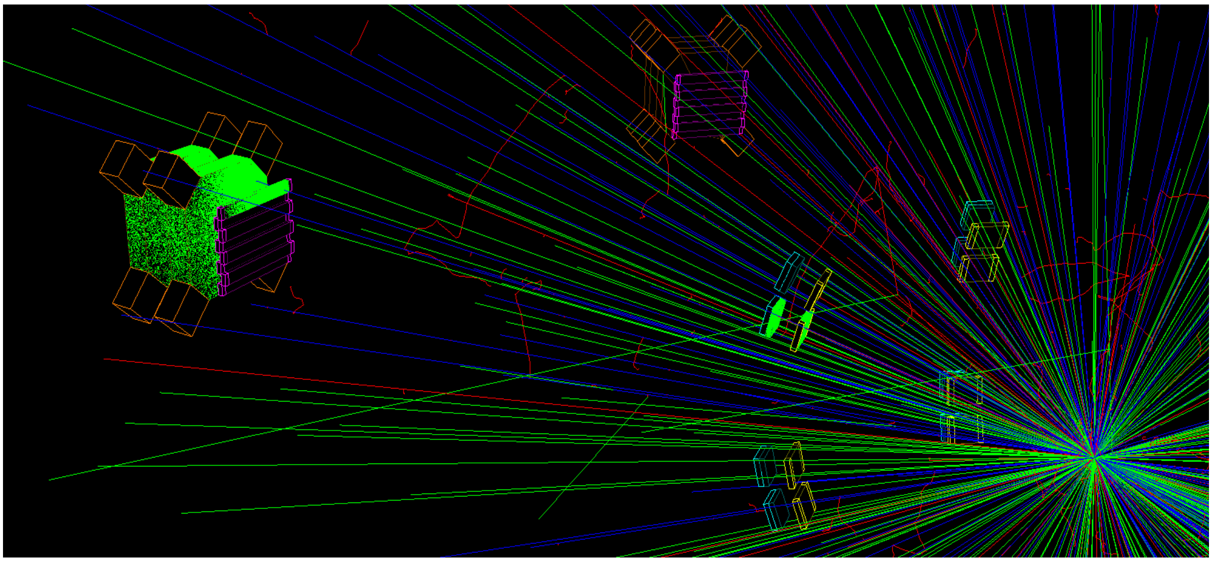

Fig.7. The secondary particles tracks at DSS setup for $^{124}Xe+^{184}W$ central collision at 3 GeV/nucleon obtained with PHQMD model [46].

The equipment used consisted of 2 forward arms. Each of them had 2 large aperture scintillation counters and scintillation hodoscope in front. Each large aperture scintillation counter was viewed by 4 PMTs FEU143. Each hodoscope consisted of 8 scintillators with the size 320x40x4 mm^3 viewed from both sides by PMT FEU85. Also 8 dE-E detectors previously used for dp→ppn reaction studies were used to detect the particles emitted in midrapidity. The trigger required the coincidence of the signals in 2 dE-E detector placed in one scattering plane and in one of the forward arms. Therefore, one can expect the sensitivity of the selected events to the short-range correlations which manifest in the ion-ion collisions. The data analysis is in progress. Fig.7 demonstrates the secondary particles tracks for $^{124}Xe+^{184}W$ central collision at 3 GeV/nucleon obtained with PHQMD model event generator [46] for the DSS experiment.

The forward arms can be used also for the studies of the deuteron induced reactions.

2.6. Analysis of the polarization effects in few-nucleon systems

The relativistic multiple scattering model [16,17] has been developed further for the dp- elastic scattering process by taking into account the explicit Δ- isobar excitation [38] with the ρ- exchange in the Δ- isobar formfactor [39]. It has been applied for the description of the unpolarized and polarized data in the deuteron energy range between 500 MeV and 2000 MeV. This approach has been used to describe the polarization observables in dp- elastic scatting in the wide energy and angular range [33].

The next step in the model development is to consider the N*(1440)- excitation in the intermediate state as well as possible manifestation of the d*(2180) dibaryon. This is very important for the description of the polarization data at large scattering angles, especially, at 100^o-130^o in the cms.

2.7. Proton and deuteron spin manipulation at Nuclotron

The spin transport calculations has been performed for the Nuclotron magnetic optics structure in order to investigate the possibility to manipulate with proton spin in the vicinity of the integer resonances $\gamma G = k$ without introducing of additional magnetic elements [47,48]. These calculations require the experimental check by the measurements of the proton beam polarization by the polarimeters placed at ITS and at the extracted beam line. The final goal is to prove the possibility of Spin- Transparent mode at integer resonances (for SPD at NICA).

First step of this program is the measurements of the integer resonance $\gamma G=k=2$ power (Tkin=108 MeV). For this purpose, one needs to measure the proton beam polarization at 100 and 120 MeV, e.g. below and higher the $\gamma G=2$ resonance. The beam polarization is measured with different speed of the resonance passing dB/dt in T/s. The predictions of the proton beam polarization as a function of the speed of the resonance passing dB/dt is shown in Fig.8. The power of the γG=2 resonance is taken as $\omega=2.5\cdot10^{-4}$.

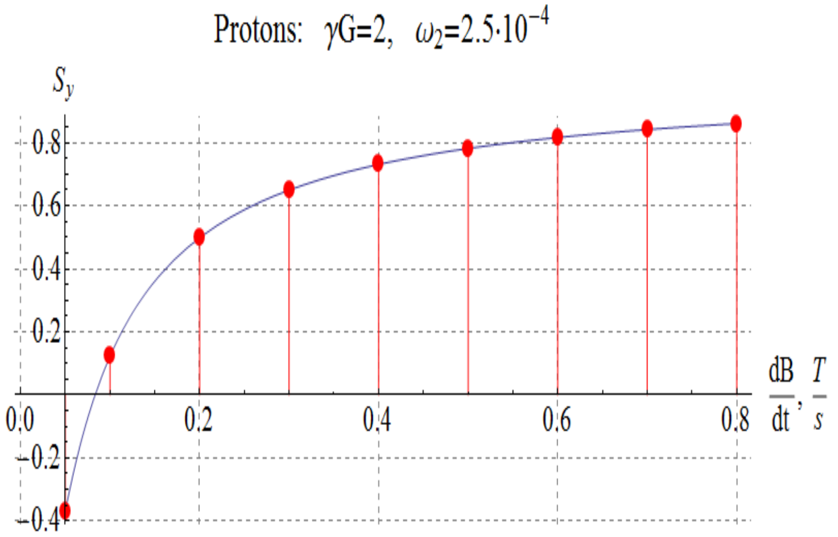

Fig.8. The proton beam polarization as a function of the speed of the resonance passing dB/dt for the power of the γG=2 resonance taken as $\omega=2.5\cdot10^{-4}$.

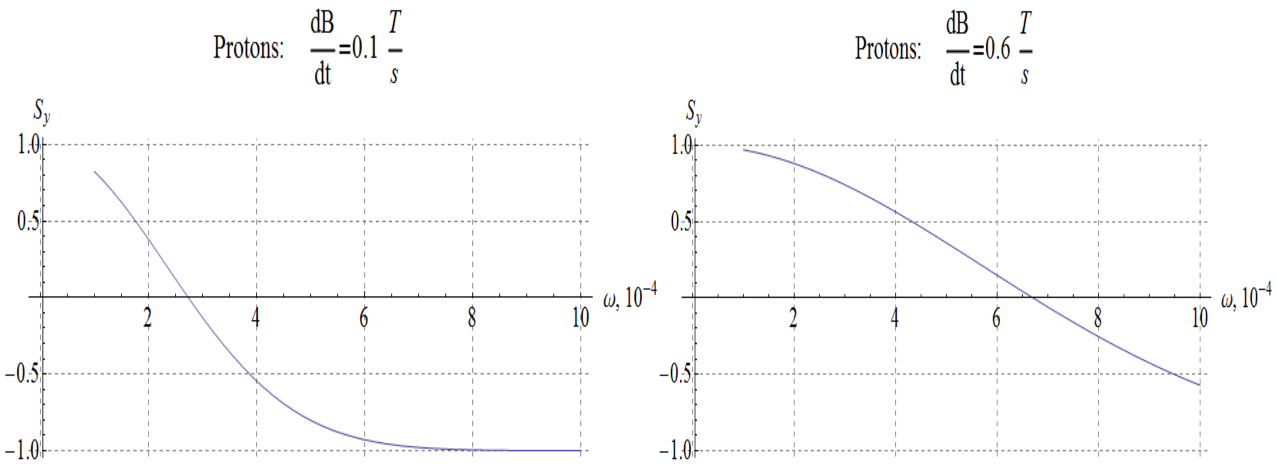

Fig.9. The proton beam polarization as a function of the γG=2 resonance power for the speed of the resonance passing dB/dt =0.1 T/s (left panel) and dB/dt =0.6 T/s (right panel).

The proton beam polarization as a function of the γG=2 resonance power for the speed of the resonance passing dB/dt =0.1 T/s and dB/dt =0.6 T/s is shown in the left and right panels of Fig.9, respectively. The analysis of the dependencies presented in Figs.8 and 9 will allow to obtain the γG=2 resonance power. The similar measurements will be performed for γG=3 resonance at Tkin=631 MeV. For this experiment one needs to perform the proton beam polarimeter calibration at the energies 620 and 640 MeV. The comparison of the proton beam polarization at these energies for different dB/dt will provide the information on the γG=3 resonance power.

Second experiment is the deuteron spin flip crossing the induced internal resonance $\gamma G= \nu_y-8$ using structural quadrupoles at Nuclotron. The measurements will be performed at Tkin=135 MeV/nucleon using ITS polarimeter [44]. Vertical betatron frequency is taken as $\nu_y=7.836$. The resonance crossing is achieved by the changes of the currents in quadrupole magnets of Nuclotron. The degree of polarization before and after resonance crossing is measured. The efficiency of the flip depends on the polarization profile. Experimental data will also provide information on the distribution of amplitudes of betatron oscillations in the beam.

2.8. Papers and talks

In 2022-2024 DSS Collaboration published 16 papers [20-33,47,48].

The results were reported at Nucleus-2022, DSPIN-2023, IBSHEPP-2023, AYSS-2022 and AYSS-2023. DSS had invited talk at International Conference SPIN-2023 in Durham, USA.

3. DSS upgrade plans for 2025-2029

In 2025-2029 DSS experiment mostly will use polarized deuteron and proton beams with upgraded setup. The major goals are to obtain precise data on the analyzing powers in pp-, dp- and pd- elastic scattering. The existig setup demonstrated feasibility to measure 3-charged particle correlation in light and heavy ion collisions- these studies also can be continued with the upgraded setup.

The next steps for the DSS experiment upgrade are:

-the enlargement of the acceptance of the ITS polarimeter for pp- and pd- elastic scattering by installation of about 80 additional scintillation detectors with new mechanics;

-the enlargement of the acceptance and the improvement of the identification for 2 arms, namely, the replace of the scintillation hodoscopes by the straw chambers with the size of 50x50 cm^2, the manufacture of 20 thick scintillation detectors viewed by PMTs from both sides of the scintillator, manufacture of the thin scintillation counters with fast plastic and SiPM light readout; manufacture of 2 small arms equipped by the 20x20 cm^2 straw chambers with dE-E detectors.

3.1. Upgrade of the ITS polarimeter

First priority task is to develop the proton polarimeter which uses both pp- and pd- elastic scattering at 100-1000 MeV. The simulation has been performed to maximize figure of merit [30-31]. According the simulation results the size of the scintillation detectors has been choosen. The production and testing with RA source of 80 scintillation detectors based on Hamamatsu PMTs H7415 is finished. The results of the amplitude measurements from RA source for one of the detectors are shown in the left panel of Fig. 10. Part of the produced scintillation counters has been tested in 2022-2023 using parasitic beam at ITS.

The design of new mechanics for the proton polarimeter is shown in the right panel of Fig.10. New polarimeter has to be able perform the measurements of both deuteron and proton beams polarizations.

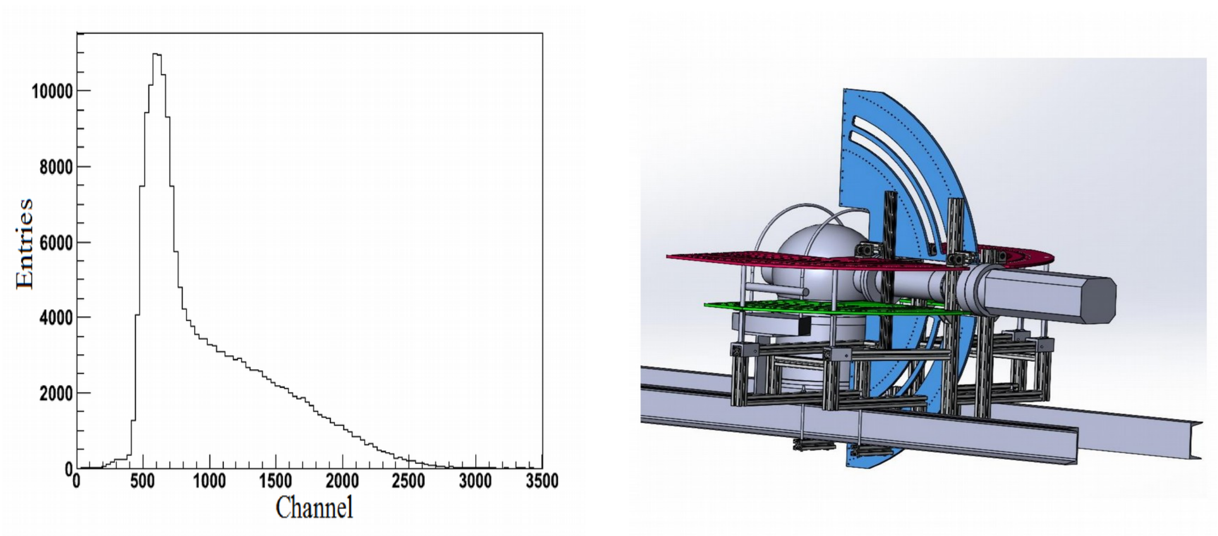

Fig.10. Left panel: the amplitude signal from RA- source for new scintillation detector. Right panel: new mechanics for the upgraded deuteron-proton polarimeter.

The parts of new polarimeter mechanics are contracted. We expect the commissioning of new polarimeter with RA source and cosmics in the middle of 2024 to be ready for the polarized beam run at Nuclotron.

R&D for new type of the scintillation counters with SiPM readout [32] will be continued for the deuteron and proton polarimetry.

3.2. Forward arms upgrade

Two forward arms consisting of 2 large scintillation counters and hodoscope will be upgraded. The hodoscopes will be replaced by the set of 50x50 cm^2 straw chambers. Also 10 new scintillation counters with the size of 50x10x10 cm^3 viewed by PMT from both sides will be produced to replace existing large scintillation counters.

4 straw chambers intially prepared for the CBM experiment at FAIR by JINR group are exist and fully equipped by FEE based on the AST1-1 ASIC. The picture of the 50x50 cm^2 straw chamber is shown in the left panel of Fig.11. VME TDCs based on the use of HPTDC chip with the total number of 640 channels are ready. 20 PMTs ETE-9821B with 78mm photocathode diameter are delivered. Therefore, it is feasible to manufacture one arm within 2024-2025. Initially, this arm will be equipped and tested in the SPD testbeam zone.

The equipment of the second arm can be done using the same technologies. There is difficulty with the additional TDCs for straw detectors due to lack of HPTDC chips. Also, PMTs ETE-9821 B are quite expensive, therefore, it is planned to use PMTs CR119 with the similar photocathode diameter. R&D for the scintillation detectors is required.

Two small arms equipped by the 20x20 cm^2 straw chambers will be produced in order extend the energy range of the Ay and Ayy analyzing powers measurements in dp- elastic scattering as well as for the dp- nonmesonic breakup in the complanar geometry. The technology developed for SPD testbeam zone tracking detectors will be used. At the first stage of the DSS experiment the existing 20x20 cm^2 straw chambers shown in the right panel of Fig.11 will be used. The dE and E scintillation detectors will be produced using SiPMs or PMTs, respectively.

Fig.11. Left panel: existing 50x50 cm^2 straw chambers. Right panel: test of the one plane 20x20 cm^2 straw chamber for SPD test zone.

The track reconstruction with straw detectors will be done using the algorithm based on the solve of the H.Schubert problem for 4 straight lines [47] successfully adopted at HADES.

4. Physics program for 2025-2029

The following major physics goals will be studied within DSS project.

1. Study of the energy dependence the deuteron analyzing powers Ay,Ayy and Axx in dp- elastic scattering in the vicinity of the structure observed at 100^o-130^o in the cms.
2. Precise measurements of the analyzing power Ay in pp- quasi-elastic and elastic scattering at the energies 100-1000 MeV.
3.Measurements of the nucleon analyzing power A_y^p in pd- elastic scattering at the energies 100-1000 MeV.
4. Study of dp- non-mesonic breakup in the complanar geometry using straw detectors.
5. Study of the 3 particles correlations in ion-ion collisions using DSS installation with tracking.

DSS project will solve also the following methodical goals.

1. Measurements of the integer resonances $\gamma G = 2$ and $\gamma G = 3$ powers for polarized proton beam using ITS polarimeter.
2. Study of the polarized beam parameters using deuteron spin flip at 135 MeV/nucleon.
3. Preparation of the ITS polarimetry for the study of the higher integer resonances up to $\gamma G = 7$.
4. R&D for the effective beam polarimetry at Nuclotron and local polarimetry at SPD at collider.

5. Beam time and resources request

New SPI [36] will allow to have a variety of spin modes. In the experiment we are planning to use the spin modes with the following ideal values of (Pz,Pzz): (0,0), (0,-2), (+1,+1) and (-1,+1) (or an alternative set: (0,0), (0,-2), (-2/3,0) and (1/3,+1)) .

Unfortunately, due to rather low intensity of the polarized deuteron beam, the estimated error bars in the analyzing powers in dp- elastic scattering obtained during 2016-2017 were only about 0.05 (not 0.02 as it was expected). On the other hand, low energy part (300 MeV -700 MeV) was not measured. Therefore, during next term the calibration data at the energies of 300 MeV -700 MeV will be obtained with an interval of 50 MeV. These data are very important to study the short-range 3NF spin structure. The systematic studies of Ay and Ayy at high energies will be performed with straws detectors. The energy step is also 50 MeV at the energies 1100 MeV-1500 MeV.

The required beam time for the calibration was evaluated for the solid angle of each detector of 2.2 msr. The cross section decreases with a beam energy by a factor of 20 from 270 MeV to 2.0 GeV. Since we are limited by the use of thin CH2 target the maximal available intensity is $5\cdot10^9$ ppp. For determination of the analyzing power with a statistical uncertainty of $\Delta A = 0.02$, one needs 10^4 countsfor one detector. This takes about 12 hours for 4 polarization modes including the time for tuning of the beam, changing of the detector position etc. Low energy part can be performed with the existing equipment, while the high energy part will require the installation of the straw detectors. The estimated beam time is **300** hours.

The proton beam polarization was measured as 0.368±0.023 [26-29]. This value can be increased by the tuning of the spin precessor of SPI [36]. We are planning to perform the measurements of the nucleon analyzing power A_y^p pd- elastic scattering in the energy range between 100 MeV/n and 1000 MeV/n using the coincidence techniques. We expect the error bar of $\Delta A_y^p\sim 0.02$ in the measurements at 14 proton energies: 100, 150, 200, 250, 300, 350, 400, 440, 500, 600, 700, 800, 900 and 1000 MeV. The estimated beam time request is **150** hours for the intensity of $5\cdot10^9$ ppp. For this task we need to prepare CD2 target, new mechanics and part of new scintillation counters. This task is strongly overlap with the goal of the proton beam polarimetry based on pp- quasielastic scattering, which will require additionally **100** hours.

The studies of dp- non-mesonic breakup will be performed after the measurements of dp- elastic scattering. For these purposes we need the maximal available intensity of $5\cdot10^9$ ppp. The major goal is to perform the measurements in the complanar geometry at 400 MeV using straw detectors for tracking. The estimated beam time is **200** hours.

The R&D for the beam polarimetry (local SPD and NICA) and spin manipulation experiments will require about **100** hours/year.

The experiments with light and heavy ions will be performed in the USER-2 mode, and, therefore, will not require pilot beam.

Upgrade of the setup will include the purchase of new HV system(CAEN), the manufacture of new straw tube detectors, gas system (Ar+CO2), scintillation detectors, mechanics and electronics.

The required resources are indicated in the tables presented below. The required pilot beam time with polarized deuterons and protons is about 240 hours/year.

Conclusions

During 2025-2029 we expect to obtain the following results.
1. Study of the energy dependence the deuteron analyzing powers Ay,Ayy and Axx in dp- elastic scattering in the vicinity of the structure observed at 100^o-130^o in the cms.
2. Precise measurements of the analyzing power Ay in pp- quasi-elastic and elastic scattering at the energies 100-1000 MeV significant for partial wave analysis and beam polarimetry at NICA.
3.Measurements of the nucleon analyzing power A_y^p in pd- elastic scattering at the energies 100-1000 MeV.
4. The theoretical analysis of the observables in hadronic reactions with the participation of light nuclei will be continued.
5. Study of dp- non-mesonic breakup in the complanar geometry using straw detectors.
6. Study of the 3 particles correlations in ion-ion collisions using DSS installation with tracking.
7. Measurements of the integer resonances $\gamma G = 2$ and $\gamma G = 3$ powers for polarized proton beam using ITS polarimeter.
8. Study of the polarized beam parameters using deuteron spin flip at 135 MeV/nucleon.
9. Preparation of the ITS polarimetry for the study of the higher integer resonances up to $\gamma G = 7$.
10. R&D for the effective beam polarimetry at Nuclotron and local polarimetry at SPD at collider.

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, 2991 (2008).
[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, 162504 (2006).
[3] L.L.Frankfurt, M.I.Strikman, D.B.Day, M.M.Sargsian, Evidence for short range correlations from high *Q*2 in *(e, e')* reactions, Phys.Rev. C48, 2451 (1993) .
[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, 014313 (2003).
[5] K.S. Egiyan et al., Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei, Phys. Rev. Lett. 96, 082501 (2006).
[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, 322 (2008).
[7] M.Patsyuk et al., Unperturbed inverse kinematics nucleon knockout measurements with a 48 GeV/c carbon beam, Nature Phys. 17, 693 (2021).
[8] W.Gloeckle, H.Witala, D.Hueber, H.Kamada, J.Golak, The Three nucleon continuum: achievements, challenges and applications, Phys.Rep. 274, 107 (1996).
[9] 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, 60 (1996).
[10] K.Sekiguchi et al., Complete set of precise deuteron analyzing powers at intermediate energies: comparison with modern nuclear force predictions, Phys.Rev. C65, 034003 (2002).
[11] K.Sekiguchi et al., Polarization transfer measurement for 1H(d↑,p↑)2H elastic scattering at 135-MeV/u and three nucleon force effects, Phys.Rev. C70, 014001 (2004).

[12] K.Hatanaka, Y.Shimizu et al., Cross-section and complete set of proton spin observables in p↑d elastic scattering at 250-MeV, Phys.Rev. C66, 044002 (2002).
[13] R.Bieber et al., Three-Nucleon Force and the Ay Puzzle in Intermediate Energy p↑+d and d↑+p Elastic Scattering, Phys. Rev. Lett. 84, 606 (2000).
[14] K.Ermisch et al., Search for Three-Nucleon Force Effects in Analyzing Powers for p↑d Elastic Scattering, Phys. Rev. Lett. 86, 5862 (2001).
[15] K.Ermisch et al., Systematic investigation of the elastic proton deuteron differential cross-section at intermediate-energies, Phys. Rev. C68, 051001 (2003).
[16] N.B.Ladygina, Deuteron-proton elastic scattering at intermediate energies, Phys.Atom.Nucl. 71, 2039 (2008).
[17] N.B.Ladygina, Differential Cross Section of dp- Elastic Scattering at Intermediate Energies, Eur.Phys.J.A42, 91 (2009).
[18] 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, 287 (2004).
[19] A.I.Malakhov et al., Potentialities of the internal target station at the Nuclotron, Nucl.Instr.Meth. in Phys.Res. A440, 320 (2000).
[20] 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, 3 (2022).
[21] 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, 251 (2022).
[22] V.P.Ladygin et al. (DSS Collaboration), Deuteron analyzing powers Ay, Ayy and Axx in dp-elastic scattering at large transverse momenta, JPS Conf.Proc. 37, 020902 (2022) .
[23] M.Janek et al. (DSS Collaboration), Short Range Correlations Investigated by DSS Collaboration in Reactions Involving Deuterons, Phys.Part.Nucl. 54(4), 595 (2023).
[24] V.P.Ladygin et al. (DSS Collaboration), Measurements of the Deuteron Analyzing Powers Ay, Ayy and Axx in dp- Elastic Scattering at Nuclotron, Yad.Fiz.86(6), 681 (2023) [in Russian].
[25] O.Mezhenska et al. (DSS Collaboration), Investigation of the dp-Breakup Reaction at Intermediate Energies at Nuclotron, Phys.Part.Nucl. 54(3), 393 (2023).
[26] I.S.Volkov et al. (DSS Collaboration), Analyzing power of quasi-elastic proton-proton scattering at the energies from 200 to 650 MeV/nucleon, Bull.Russ.Acad.Sci.Phys. 86(9), 1074 (2022).
[27] I.S.Volkov et al. (DSS Collaboration), Analyzing power of quasi-elastic proton-proton scattering at the energy of 550 MeV, Phys.Part.Nucl. Lett. 20(5), 1191 (2023).
[28] I.S.Volkov et al. (DSS Collaboration), Deuteron Beam Vector Polarization Measurement Using Proton- Proton Quasielastic Scattering at the Energies 500 and 650 MeV/nucleon, Yad.Fiz. 86(6), 686 (2023) [in Russian].
[29] I.S.Volkov et al. (DSS Collaboration), Vector analyzing power of quasi-elastic proton-proton scattering at the energy of 500 MeV/nucleon, Phys.Part.Nucl. Lett. 21(1), 32 (2024) [in Russian].
[30] A.A.Terekhin et al. (DSS Collaboration), Proton and Deuteron Polarimetry at the NICA Nuclotron Accelerator Complex, Bull.Russ.Acad.Sci.Phys. 87(7), 1166 (2023).
[31] A.A.Terekhin et al. (DSS Collaboration), Proton Polarimeter at the Internal Target Station of the Nuclotron at the Joint Institute for Nuclear Research, Phys.Part.Nucl. 54 (4), 634 (2023).
[32] A.V.Tishevsky et al. (DSS Collaboration), Study of the scintillation detector prototype for the upgraded polarimeter at the internal target station at the Nuclotron, Phys.Part.Nucl. Lett. 20(5), 1165 (2023).
[33] N.B.Ladygina, Study of deuteron-proton elastic scattering at intermediate energies, Phys.Atom.Nucl. 86(6), (2023).
[34] P.K.Kurilkin et al. (DSS Collaboration), The 270 MeV deuteron beam polarimeter at the Nuclotron Internal Target Station, Nucl. Instrum. Methods in Phys. Res., A642, 45 (2011).
[35] Yu.V.Gurchin et al., Target position monitor for internal target station at the Nuclotron, Phys.Part.Nucl. Lett. 4, 263 (2007).
[36] V.V.Fimushkin et al., Development of polarized ion source for the JINR accelerator complex, J.Phys.Conf.Ser. 678, 012058 (2016) ;
A.S.Belov et al., Source of polarized ions for the JINR accelerator complex, J.Phys.Conf.Ser. 938, 012017 (2017).

[37] A.Yu.Isupov et al., The Nuclotron internal target control and data acquisition system, Nucl.Instrum.Meth. in Phys. Res., A698, 127 (2013).
[38] N.B.Ladygina, Delta excitation in deuteron-proton elastic scattering, Eur.Phys.J.A52 (7), 199 (2016).
[39] N.B.Ladygina, On reaction mechanisms in deuteron–proton elastic scattering, Eur.Phys.J.A56 (5), 133 (2020).
[40] P.K. Kurilkin et al., Measurement of the vector and tensor analyzing powers for dp- elastic scattering at 880 MeV, Phys.Lett. B715, 61 (2012).
[41] 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, 1081 (2011).
[42] R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, R.L.Workman, Updated Analysis of NN Elastic Scattering to 3 GeV, Phys. Rev. C76, 025209 (2007).
[43] K.Suda et al., Absolute calibration of the deuteron beam polarization at intermediate energies via the $^{12}C(\vec{d},\alpha)^{10}B^*(2+)$ reaction, AIP Conf.Proc. 570(1), 806 (2001).
[44] Ya.T. Skhomenko et al. (DSS Collaboration), Deuteron Beam Polarimeter at Nuclotron Internal Target, Eur. Phys. J. Web Conf. 204, 10002 (2019).
[45] L.S.Azhgirey et al., Intermediate- energy polarimeter for measurement of the deuteron and proton beam polarization at the JINR synchrophasotron, Nucl. Instrum. Methods Phys. Res. A497, 340 (2003).
[46] J.Aichelin et al., Parton-hadron-quantum-molecular dynamics: A novel microscopic nn -body transport approach for heavy-ion collisions, dynamical cluster formation, and hypernuclei production, Phys.Rev.C 101 (4), 044905 (2020).
[47] Yu.N.Filatov et al., Spin Navigator on the Base of the Correcting Dipoles at Nuclotron/JINR, JETP Lett. 116(7), 413 (2022).
[48] Yu.N.Filatov et al., Proton-Spin-Flipping System Based on Orbit-Steerer Dipoles in the Nuclotron/JINR Operating at the $\gamma G = 7$ Spin Resonance, JETP Letters 118(6), 387 (2023).
[49] A.V.Belyaev et al., On the initial approximation of charged particle tracks in detectors with linear sensing elements, Nucl.Instrum.Meth.A 938, 1 (2019).

SWOT analysis for the DSS- project

Strengths: The strong points of the DSS- project are the unique physics related with the studies of the short-range correlations spin structure, development of the efficient polarimetry for the deuteron and proton beams, contribution to the first stage physics program at SPD. The project is an inevitable step for spin program at NICA.

Weaknesses: Very high competition for the beam at Nuclotron due to higher priority of the heavy ion program.

Opportunities: Project provides visible role for young scientists, real possibility to defense the thesis (6 PhD thesis and more than 15 Master thesis).

Threats: Sanctions impact on the availability and the cost of the necessary equipment. Also they reflect on the limitation of the scientific contacts and the absence of the exchanges with European and Japanese collaborators.

Participating countries, scientific and educational organizations

Organization	Country	City	Participants	Type of agreement
LPI of RAS	Russian Federation	Moscow	A.I.Lvov + 4	Collaboration
Belgorod SNRU	Russian Federation	Belgorod	I.E.Vnukov + 1	Collaboration
MPTI	Russian Federation	Moscow	Yu.N.Filatov+1	Collaboration
STL Zaryad	Russian Federation	Novosibirsk	A.M.Kondratenko+1	Collaboration
ARIEE	Romania	Bukharest	3	Suspended in 2022
Zilina University	Slovak Republic	Zilina	1	Collaboration
P.J.Shafarik Univer.	Slovak Republic	Koshice	2	Collaboration
Miyazaki University	Japan	Miyazaki	1	Suspended in 2022
Tohoku University	Japan	Sendai	5	Suspended in 2022
CNS, University of Tokyo	Japan	Tokyo	1	Suspended in 2022
RIKEN Nishina Center	Japan	Saitama	1	Suspended in 2022

Manpower needs in the first year of implementation

№№ n/a	Category of personnel	JINR staff, amount of FTE	JINR Associated Personnel, amount of FTE
1.	research scientists	6.80	
2.	engineers	3.20	
3.	specialists		
4.	office workers		
5.	technicians		
	Total:	**10.00**	

Available manpower from JINR staff

No.	Category of personnel	Full name	Division	Position	Amount of FTE
1.	research scientists	V.P. Ladygin A.Yu.Isupov Yu.V. Gurchin S.G.Reznikov N.B.Ladygina A.A.Terekhin E.V.Chernykh A.P.Ierusalimov	VBLHEP VBLHEP VBLHEP VBLHEP VBLHEP VBLHEP VBLHEP VBLHEP		0.70 0.80 1.00 0.80 1.00 0.80 0.50 0.50
					6.10
2.	engineers	I.S.Volkov A.V.Tishevsky K.S.Legostaeva A.N.Livanov	VBLHEP VBLHEP VBLHEP VBLHEP		0.80 0.80 0.50 0.10
					2.20
3.	specialists				
4.	technicians				
	Total:				**8.30**

Proposed schedule and resource request for the DSS project

Expenditures, resources, funding sources			Cost (thousands of US dollars)/ Resource requirements	Cost/Resources, distribution by years				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation	50	10	10	10	10	10
		Materials	115	25	25	25	20	20
		Equipment, Third-party company services	180	34	34	34	39	39
		Commissioning						
		R&D contracts with other research organizations	200	40	40	40	40	40
		Software purchasing	5	1	1	1	1	1
		Design/construction	50	10	10	10	10	10
		Service costs (*planned in case of direct project affiliation)*						
Required resources	**Standard hours**	Resources						
		- the amount of FTE,		10	10	10	10	10
		- accelerator/installation,	1320*	300*	300*	240*	240*	240*
		- reactor,…						
Sources of funding	**JINR Budget**	JINR budget *(budget items)*	600	120	120	120	120	120
	Extra funding (supplementary estimates)	Contributions by partners Funds under contracts with customers						

* The beam time can be shared in part with other users

Extra funding sources are not expected.