Recent results with polarized deuterons and polarimetry at Nuclotron-NICA

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Abstract. Recent results on the deuteron analyzing powers obtained in collisions of polarized deuterons with protons and light nuclei at intermediate and high energies are reported. The obtained results are sensitive to the spin structure of the short range correlations. The prospects of the spin program for hadronic reactions at Nuclotron-NICA facility is discussed. The polarimetry developments are also presented.

1. Introduction

The main activity in the spin studies at the Laboratory of High Energy Physics of the Joint Institute for Nuclear Research (LHEP-JINR) is related to the short range correlations (SRCs) in nuclei, which are the subject of intensive theoretical and experimental works during last years in different scientific centers. Since SRC have densities comparable to the density in the center of a nucleon which is about $\rho \sim 5\rho_0$ ($\rho_0 \approx 0.17$ fm^{-3}), they can be considered as the drops of cold dense nuclear matter [1]. These studies explore a new part of the phase diagram and very essential to understand the evolution of neutron stars. Recent experimental data obtained at BNL [2], SLAC [3] and JLAB [4, 5] and theoretical studies clearly shown that more than 90% all nucleons with momenta $k \geq 300$ MeV/c belong to 2-nucleon SRCs and 3-nucleon SRCs have a significant probability [6]. However, still many open questions persist and further investigations are required both from the experimental and theoretical sides. For instance, the experimental data on the spin structure of 2N (I=1) and 3N SRC are almost absent.

The main tools to study SRCs at hadronic facilities can be the deuteron structure investigations at large internal momenta allowing to explore 2N SRC with $I = 0$; ^{3}He structure to understand the role of 2N SRC with $I = 1$ and 3N SRC; nuclei breakup $A(p,pp)X$, $A(p,pn)X$, $A(p,ppp)X$ etc. with the detection of few nucleons in the final state. The greate importance is the study of the spin effects in these reactions because the data on the SRCs spin structure are scarce. Nuclotron-M and Nuclotron-based Ion Collider fAcility (NICA) [7] 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 0.8 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] and references therein). The contribution of 3NF is found to be up to 30% in the vicinity of so called "cross section minimum" (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] cannot 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 90°. The relativistic multiple scattering calculations [16] 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 $\sim 70°$. 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 [17] 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].

The spin structure of 2N SRCs has been studied at LHEP Accelerator Complex in inclusive deuteron breakup with the emission of protons with large transverse momenta [18]. The data on the tensor analyzing power A_{yy} obtained in the $A(d,p)X$ reaction at different values of x_F are strongly dependent of the transverse momentum of the protons, p_T. Values of A_{yy} are positive at small p_T and monotonously decrease while transverse momentum increasing for all x_F values. On the other hand, A_{yy} values change the sign at $p_T \sim 600$ MeV/c independently on x_F and demonstrate kind of negative asymptotic at large p_T. Such behaviour of A_{yy} contradicts to the theoretical predictions using either standard [19, 20] or covariant [21] deuteron wave functions (DWFs). On the other hand, the A_{yy} data plotted at different values of transverse momenta p_T as a function of x_F demonstrate a weak dependence on x_F. The data obtained at $p_T \sim$550 MeV/c are in a good agreement with the calculations by using covariant DWF [21]. At higher

p_T A_{yy} data have negative values, while the theory predicts a positive sign in the range of measurement.

Therefore, the A_{yy} data sensitive to the 2N SRCs spin structure clearly demonstrate the dependence on two internal variables, x_F and p_T (or their combinations). However, the use of the deuteron structure function that depends on two variables [21] does not allow to describe the data. New data sensitive to the spin structure of short range correlations are certainly required.

2. Experiments at internal target at Nuclotron

The internal target station (ITS) setup is well suited for study of the energy dependence of polarization observables for the deuteron-proton elastic scattering and deuteron breakup reaction with the detection of two protons at large scattering angles [22].

For these purposes the CH_2-target of 10 μm thick is used for the measurements. The yield from carbon content of the CH_2-target is estimated in separate measurements using carbon wire. The monitoring of the intensity is done from the detection of *pp*- quasielastic scattering at 90° in cms by the scintillation counters placed in the horizontal plane. The detection of the *dp*- elastic events is done by the coincidence measurements of the proton and deuteron. The detectors are placed in the 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 [23].

The measurements of the deuteron analyzing powers in *dp*- elastic scattering have been performed at ITS using polarized beam from polarized ion source POLARIS [24] at the energies 880 and 2000 MeV [25, 26]. The use of large amount of the scintillation counters allowed cover wide angular range. The measurement of the beam polarization has been performed at 270 MeV where the precise data on the tensor and vector analyzing powers based on the absolute calibration of the beam polarization exist [27].

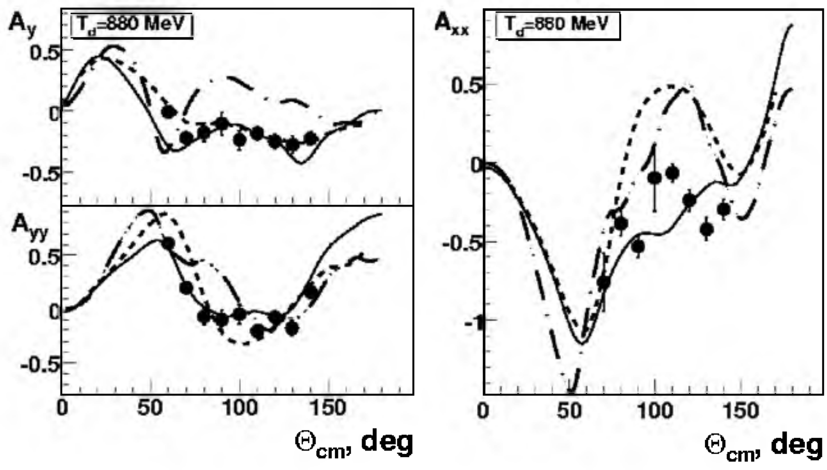

Figure 1. Vector A_y, tensor A_{yy} and A_{xx} analyzing powers in *dp*- elastic scattering at 880 MeV [25, 26]. The lines are the predictions of different models [28, 29, 30] (explained in the text).

The results on the angular dependence of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers obtained at 880 MeV are shown in Fig. 1 by the solid symbols. The solid, dashed and dash-dotted lines are the results of the Faddeev calculations [28] using CD-Bonn nucleon-nucleon potential [19], of the relativistic multiple scattering calculations [29] using CD-Bonn

[19] deuteron wave function (DWF), and the optical potential calculation [30] with the dibaryon DWF [17], respectively. One can see that Faddeev and relativistic multiple scattering models give good description of the data except for A_{xx}. On the other hand, Faddeev calculations [28] fail to reproduce the cross section at the angles larger than 90°, while relativistic multiple scattering calculations [16] give much better agreement with the data at the angles between 60° and 130°.

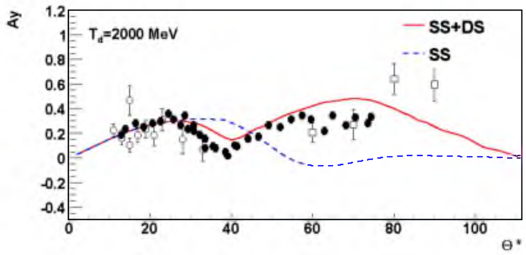

Figure 2. Vector A_y analyzing power in *dp*-elastic scattering at 2000 MeV. The solid symbols represent the data obtained at ANL [31]. Open squares and circles are the data obtained at ITS [26] and at hydrogen bubble chamber at JINR, respectively. The curves are explained in the text.

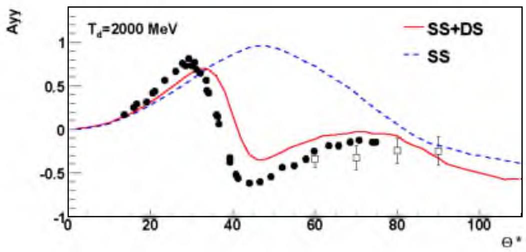

Figure 3. Tensor A_{yy} analyzing power in *dp*-elastic scattering at 2000 MeV. The symbols and curves are the same as in Fig. 2.

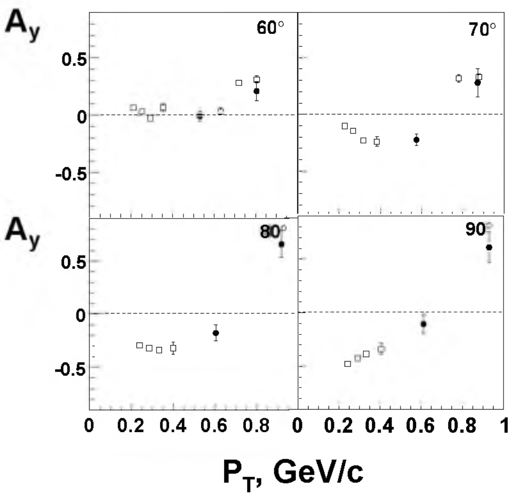

Figure 4. Vector A_y analyzing power in *dp*- elastic scattering obtained at the fixed angles of 60°, 70°, 80° and 90° in the cms as a function of transverse momentum p_T. The open and solid symbols are the data obtained at RIKEN, Saclay, ANL [9, 10, 11, 31, 33, 34] and at Nuclotron [25, 26], respectively.

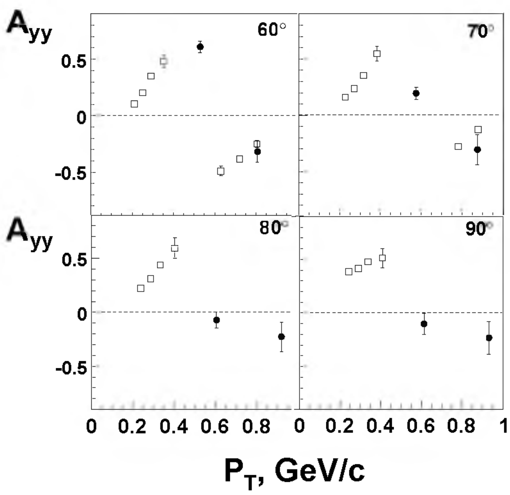

Figure 5. Tensor A_{yy} analyzing power in *dp*- elastic scattering obtained at the fixed angles of 60°, 70°, 80° and 90° in the cms as a function of transverse momentum p_T. The symbols are the same as in Fig. 4.

The results on the vector A_y and tensor A_{yy} analyzing powers obtained at 2000 MeV are shown in Figs. 2 and 3, respectively. The solid symbols represent the data obtained at ANL [31].

Open squares and circles are the data obtained at ITS [26] and at hydrogen bubble chamber [32] at JINR, respectively. The dashed and solid lines are the results of the relativistic multiple scattering model [29] without and with the considering of the double scattering term. One can see that full calculation are in reasonable agreement with the data.

The dependencies of the vector A_y and tensor A_{yy} analyzing powers in *dp*- elastic scattering obtained at the fixed angles of 60°, 70°, 80° and 90° in the cms as a function of transverse momentum p_T are shown in Fig. 4 and in Fig. 5, respectively. The open and solid symbols represent the data obtained at RIKEN, Saclay, ANL [9, 10, 11, 31, 33, 34] and at Nuclotron [25, 26], respectively.

The change of the sign is observed for the vector A_y analyzing power values at p_T ∼600–700 MeV/c at large angles in the cms A_y has small negative values at low p_T, but it achieves large positive values at p_T higher ∼700 MeV/c. It should be noted that large positive values of the single spin asymmetry is observed in *pp*- elastic scattering at high energies and large p_T (so called Krish-effect [35]). The values of A_{yy} are positive at small p_T and change the sign at p_T ∼600–650 MeV/c as in the case of deuteron inclusive breakup [18]. The negative sign of A_{yy} is observed at large p_T. It would be interesting to extend the range of the measurements to larger p_T, where the manifestation of non-nucleonic degrees of freedom is expected.

The study of the energy dependence of the *dp*- elastic scattering analyzing powers at large p_T is one of the tools to study spin effects in cold dense matter.

3. Future plans at Nuclotron

Future plans of *DSS*(*D*euteron *S*pin *S*tructure)- collaboration in spin studies are related with the construction of new polarized deuteron source [36]. This source will provide the intensity up to $\sim 2 \cdot 10^{10}$ ppp and larger variety of the spin modes than POLARIS [24]. Figure of merit of new source will be increased by a factor $\sim 10^3$ compared with POLARIS [24].

The energy scan of the *dp*- elastic scattering observables and measurements of the analyzing powers in *dp*- nonmesonic breakup will be done using internal target and polarized deuteron beam from new PIS [36].

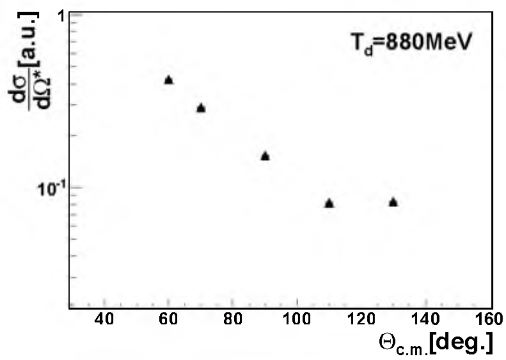

Figure 6. Preliminary results on the angular dependence of the cross section (arbitrary units) in *dp*- elastic scattering obtained at 880 MeV at Nuclotron in March 2010.

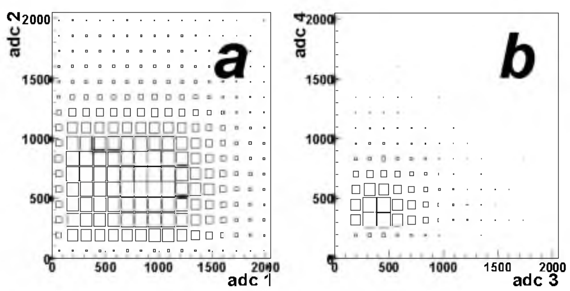

Figure 7. Correlations of the signal amplitudes in *E*-detectors for 2 detected protons from *dp*- nonmesonic breakup at 500 MeV for 2 different kinematic configurations obtained on CH_2 target in March 2010.

The measurements of the cross sections of *dp*- elastic scattering and *dp*- nonmesonic breakup can be done with the current unpolarized ion source as the first step. The preliminary results on the angular dependence of the cross section in *dp*- elastic scattering obtained at 880 MeV at

Nuclotron in March 2010 in arbitrary units are presented in Fig. 6. The *dp*- nonmesonic breakup reaction will be investigated at ITS at Nuclotron using ΔE-E techniques for the detection of two final protons. The results on the correlations of the signal amplitudes in E-detectors for 2 detected protons from *dp*- nonmesonic breakup at 500 MeV for 2 different kinematic configurations obtained on CH_2 target in March 2010 are presented in Fig. 7 a) and b). The simultaneous use of 8 ΔE-E detectors will allow to measure the observables for many kinematic configurations.

The first line experiment with the extracted polarized deuteron beam from new PIS [36] is the study of the spin observables for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction in the energy region of 1.0–1.75 GeV, where the contribution from the deuteron D-state is expected to reach a maximum. The measurements of the tensor analyzing T_{20} and spin correlation $C_{y,y}$ with the use of polarized ^{3}He target developed at CNS of Tokyo University [37] will allow to obtain polarization correlation coefficient $C_{//}$, which is defined by the deuteron D-state probability in the framework of one-nucleon-exchange [38]. The data on the analyzing powers in $d(d,{}^3\mathrm{He})n$ and $d(d,{}^3\mathrm{H})p$ obtained at 270 and 200 MeV [39] demonstrated the sensitivity to the 2N and 3N SRCs spin structure. The measurements of the tensor analyzing power T_{20} in the $d(d,{}^3\mathrm{He})n$ and $d(d,{}^3\mathrm{H})p$ reactions can be performed at Nuclotron with the same setup.

4. Deuteron beam polarimetry at Nuclotron-NICA

The spin studies require the high precision polarimetry to obtain reliable values of beam polarization. Since deuteron is a spin-1 particle, the polarimetry should have a capability to determine simultaneously both vector and tensor components of the beam polarization. For these purposes, the polarimeter based on the use of *dp*- elastic scattering at large angles ($\theta_{\mathrm{cm}} \geq 60°$) at 270 MeV, where precise data on analyzing powers [10, 11] exist, has been developed at ITS at Nuclotron [40]. 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, whose absolute polarization had been calibrated via the $^{12}\mathrm{C}(d,\alpha)^{10}\mathrm{B}^*[2^+]$ reaction [27].

The asymmetry measurements at several scattering angles were used to increase the polarimeter figure of merit. The values of the analyzing powers A_y, A_{yy}, A_{xx} and A_{xz} at these angles were obtained by the cubic spline interpolation of the data taken from Refs. [10, 11] (see Fig. 8). Fig. 9 displays the values of the tensor p_{yy} and vector p_y polarizations of the beam for "2-6" and "3-5" spin modes of POLARIS [24] as function of the deuteron scattering angle in the cms. One can see good agreement of the polarization values obtained at different scattering angles in the cms. The estimated figures of merit values for ITS polarimeter [40] are comparable with the figures of merit for the deuteron polarimeter used at the extracted beam at RIKEN [27].

Figs. 10 and 11 illustrate the polarization values for the spin modes "2-6" and "3-5" of POLARIS [24], respectively, as functions of the measurement time in hours. One can see rather good time stability of the beam polarization values during ~220 hours of the beam.

The current polarimeter [40] is proposed as the main deuteron polarimeter at Nuclotron-NICA. The *dp*- elastic and quasi-elastic scattering analyzing powers obtained at 880 and 2000 MeV [25, 26] are large enough to provide the efficient beam polarization measurements. Therefore, the ITS polarimeter should be calibrated in the energy domain of 300–2000 MeV. The feasibility of the *dp*- elastic scattering events selection using information on the energy losses in the scintillator and timing information has been demonstrated [41] at $\theta^d_{lab} \sim 8°$ at the energies 1600 and 2000 MeV [41]. Such polarimeter can be installed at the Nuclotron extracted beam. In the first run with polarized deuterons from new PIS [36] the measurements of the beam polarization at 270 MeV at ITS polarimeter [40] will be performed, after that the ITS polarimeter will be calibrated in the energy domain of 300–2000 MeV. The external beam

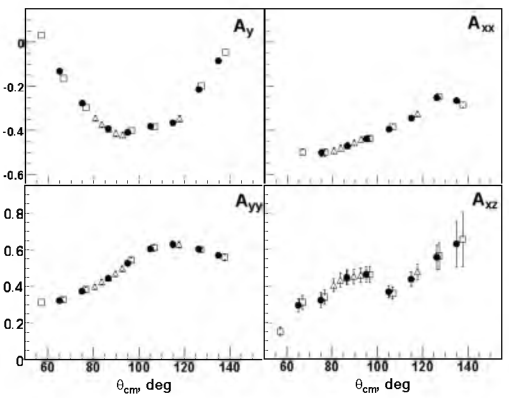

Figure 8. Analyzing powers A_y, A_{yy}, A_{xx} and A_{xz} of dp- elastic scattering at 270 MeV as function of the scattering angle in the c.m. The open symbols are the RIKEN data [10, 11]. The extrapolated values of the analyzing powers used to determine the deuteron beam polarization are shown with the solid circles.

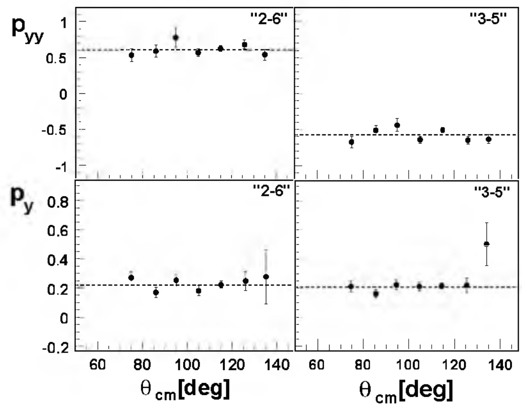

Figure 9. Tensor p_{yy} and vector p_y polarizations of the beam for ”2-6” and ”3-5” spin modes of POLARIS [24] as function of the deuteron scattering angle in the cms.

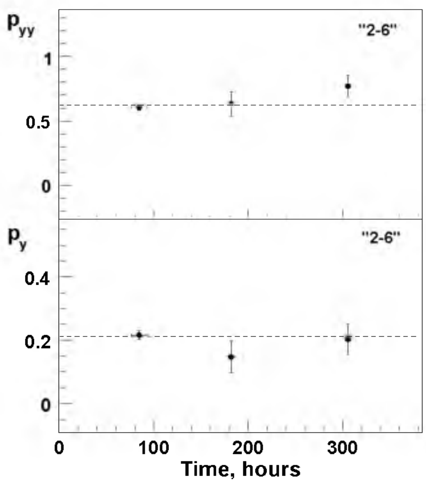

Figure 10. Tensor p_{yy} and vector p_y polarizations of the beam for the spin mode ”2-6” of POLARIS [24] versus the measuring time in hours.

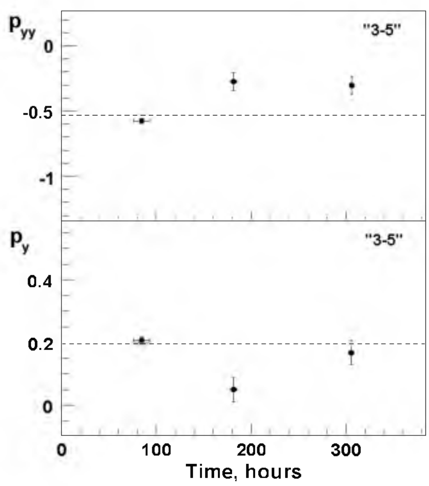

Figure 11. Tensor p_{yy} and vector p_y polarizations of the beam for the spin mode ”3-5” of POLARIS [24] versus the measurement time in hours.

polarimeters will be calibrated at 1600 MeV. Therefore, the polarization standard for Nuclotron will be established. This procedure will provide the error in the beam polarization measurements of ∼3% at the energies of 300–2000 MeV and better than ∼ 5% at higher energies.

The mostly suitable candidates for the deuteron beam polarimetry at NICA are the dC-elastic scattering in the CNI region and quasi-elastic $NN \to \pi^0 X$ reaction with the spectator tagging. However, further theoretical and experimental studies are required.

5. Conclusions

The important data on the SRCs spin structure are already obtained at Nuclotron.

Future plans of such investigations at internal and extracted beams in the few-nucleon interactions at Nuclotron are based on the use of new PIS [36]. The collider mode and availability of polarized beams could give serious advantages to study 2N and 3N SRCs at NICA.

The conception of the deuteron beam polarimetry for Nuclotron-NICA is formulated. Polarimetry developments are started.

Acknowledgments

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References

[1] Frankfurt L, Sargsian M and Strikman M 2008 *Int.J.Mod.Phys.* A **23** 2991
[2] Piasetzky E, Sargsian M, Frankfurt L, Strikman M and Watson J W 2006 *Phys.Rev.Lett.* **97** 162504
[3] Frankfurt L L, Strikman M I, Day D B and Sargsian M M 1993 *Phys.Rev.* C **48** 2451
[4] Egiyan K Sh *et al.* 2003 *Phys.Rev.* C **68** 014313
[5] Egiyan K S *et al.* 2006 *Phys.Rev.Lett.* **96** 082501
[6] Frankfurt L, Sargsian M and Strikman M 2008 *AIP Conf.Proc.* **1056** 322
[7] Sissakian A N, Kekelidze V D and Sorin A S (for the NICA collaboration) 2009 *Nucl. Phys.* A **827** 630
[8] Glöckle W, Witala H, Hüber D, Kamada H and Golak J 1996 *Phys.Rep.* **274** 107
[9] Sakamoto N *et al.* 1996 *Phys.Lett.* B **367** 60
[10] Sekiguchi K *et al.* 2002 *Phys.Rev.* C **65** 034003
[11] Sekiguchi K *et al.* 2004 *Phys.Rev.* C **70** 014001
[12] Hatanaka K *et al.* 2002 *Phys.Rev.* C **66** 044002
[13] Bieber R *et al.* 2000 *Phys.Rev.Lett.* **84** 606
[14] Ermisch K *et al.* 2001 *Phys.Rev.Lett.* **86** 5862
[15] Ermisch K *et al.* 2003 *Phys.Rev.* C **68** 051001
[16] Ladygina N B 2009 *Eur.Phys.J.* A **42** 91
[17] Kukulin V I *et al.* 2004 *J.Phys.G: Nucl.Part.Phys.* **30** 287
[18] Ladygin V P *et al.* 2005 *Phys.Lett.* B **629** 60; Azhgirey L S *et al.* 2008 *Phys.Atom.Nucl.* **71** 279
[19] Machleidt R 2001 *Phys. Rev.* C **63** 024001
[20] Lacombe M, Loiseau B, Vinh Mau R, Cote J, Pires P and de Tourreil R, 1981 *Phys.Lett.* B **101** 139
[21] Karmanov V A and Smirnov A V 1992 *Nucl.Phys.* A **546** 691; 1994 *Nucl.Phys.* A **575** 520; Carbonell J and Karmanov V A 1995 *Nucl.Phys.* A **581** 625; 1995 *Nucl.Phys.* A **589** 713; Carbonell J, Desplanques B, Karmanov V A and Mathiot J F 1998 *Phys.Rep.* **300** 125
[22] Uesaka T *et al.* 2006 *Phys.Part.Nucl.Lett* **3** 305
[23] Gurchin Yu V *et al.* 2007 *Phys.Part.Nucl.Lett.* **4** 263
[24] Anishchenko N G *et al.* 1983 *AIP Conf.Proc.* **95** 445
[25] Suda K *et al.* 2007 *AIP Conf.Proc.* **915** 920; 2008 *AIP Conf.Proc.* **1011** 241.
[26] Kurilkin P K *et al.* 2008 *Eur.Phys.J.* ST **162** 137; 2009 *Int.J.Mod.Phys.* A **24** 530
[27] Suda K *et al.* 2007 *Nucl.Instr.Meth. in Phys.Res.* A **572** 745
[28] Witala H, private communication
[29] Ladygina N B 2008 *Phys.Atom.Nucl.* **71** 2039; Ladygina N B *e-Print* arXiv:0805.3021[nucl-th]
[30] Shikhalev M A 2009 *Phys.Atom.Nucl.* **72** 588
[31] Bleszynski M *et al.* 1979 *Phys.Lett.* B **87** 178; Haji-Saied M *et al.* 1987 *Phys.Rev.* C **36** 2010
[32] Glagolev V V *et al.* *Proc.* of *ISHEPP-XX*, 4-9 Oct. 2010, Dubna, Russia, to be published
[33] Ghazikhanian V *et al.* 1987 *Phys.Rev.* C **43** 1532
[34] Garçon M *et al.* 1986 *Nucl.Phys.* A **458** 287
[35] Krisch A D 2007 *Eur.Phys.J.* A **31** 423
[36] Fimushkin V V *et al.* 2008 *Eur.Phys.J.* ST **162** 275
[37] Uesaka T *et al.* 1998 *Nucl.Instr. and Meth. in Phys.Res.* A **402** 212
[38] Uesaka T *et al.* 2002 *Phys.Lett.* B **533** 1
[39] Kurilkin A K *et al.* 2008 *Eur.Phys.J.* ST **162** 133; Ladygin V P *et al.* 2004 *Phys.Lett.* B **589** 47; Janek M *et al.* 2007 *Eur.Phys.J.* A **33** 39
[40] Kurilkin P K *et al.* *e-Print* arXiv:1005.0525 [nucl-ex], submitted to *Nucl.Instr. and Meth. in Phys.Res.* A
[41] Gurchin Yu V *et al.* *JINR preprint* E1-2010-122, submitted to *Phys.Part.Nucl.Lett.*