STUDY OF 2N AND 3N SHORT-RANGE CORRELATIONS AT NUCLOTRON-M

V.P.Ladygin[1†], L.S.Azhgirey[1], Yu.V.Gurchin[1], A.Yu.Isupov[1], K.Itoh[3], M.Janek[1,4],
J.-T.Karachuk[1,5], T.Kawabata[2], A.N.Khrenov[1], A.S.Kiselev[1], V.A.Krasnov[1,6],
A.B.Kurepin[6], A.K.Kurilkin[1], P.K.Kurilkin[1], N.B.Ladygina[1], D.Lipchinski[5], A.N.Livanov[1,6],
Y.Maeda[2], A.I.Malakhov[1], G.Martinsky[4], S.Nedev[7], S.M.Piyadin[1], E.B.Plekhanov[1],
J.Popovichi[5], S.Rangelov[7], S.G.Reznikov[1], P.A.Rukoyatkin[1], S.Sakaguchi[2], H.Sakai[2,8],
Y.Sasamoto[2], K.Sekiguchi[9], K.Suda[2,9], A.A.Terekhin[1,10], T.Uesaka[2], J.Urban[4],
T.A.Vasiliev[1], I.E.Vnukov[10]

(1) *Joint Institute for Nuclear Research, Dubna, Russia*
(2) *Center for Nuclear Study, University of Tokyo, Tokyo, Japan*
(3) *Department of Physics, Saitama University, Urawa,Japan*
(4) *P.J.Šafarik University, Košice, Slovakia*
(5) *Advanced Research Institute for Electrical Engineering, Bucharest, Romania*
(6) *Institute for Nuclear Research, Moscow, Russia*
(7) *University of Chemical Technology and Metallurgy, Sofia, Bulgaria*
(8) *University of Tokyo, Tokyo, Japan*
(9) *RIKEN (the Institute for Physical and Chemical Research), Saitama, Japan*
(10) *Belgorod State University, Belgorod, Russia*
† *E-mail: vladygin@jinr.ru*

Abstract

The status and prospects of 2N and 3N short-range correlations studies at Nuclotron-M are presented. This program is focused on the investigations of short-range correlations with polarized deuteron beam. Future experimental program at NICA is also discussed.

1 Introduction

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 $\rho \sim 5\rho_0$ ($\rho_0 \approx 0.17$ 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 momenta $k \geq 300$ MeV/c belong to 2N SRC; (ii) probability for a given proton with momenta $300 \leq k \leq 600$ MeV/c to belong to pn correlation is ∼18 times larger than for pp correlations; (iii) probability for a nucleon to have momentum ≥ 300 MeV/c in medium nuclei is ∼25%; (iv) 3N SRC are present in nuclei with a significant probability [6]. However, still many open questions persist and further investigations are required both from the experimental and theoretical sides.

The main tools to study SRCs at hadronic facilities can be deuteron structure investigations at large internal momenta allowing to explore 2N SRC with $I = 0$; ^{3}He structure to understand the role of 2N SRC with $I = 1$ and 3N SRC; nuclei breakup $A(p, pp)X$, $A(p, pn)X$, $A(p, ppp)X$ etc. with the detection of few nucleons in the final state. The greate importance is the study of the spin effects in these reactions because the data on the SRCs spin structure are scarce. Nuclotron-M 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 0.8 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 [7] 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 [8, 9]. However, the use of different 3NF models in Faddeev calculations can not reproduce polarization data intensively accumulated during last decade at different facilities [8]–[14].

On the other hand, *pd*- elastic scattering cross section data obtained already at 250 MeV [11] 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. These forces can be built within approaches beyond one-boson-exchange. For instance, in the dressed bag model [15] 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 aim of this report is to discuss the possibility to study the spin structure of 2N and 3N SRCs in different processes at Nuclotron-M and NICA.

2 Results and plans at Nuclotron-M

Measurement of energy dependences of polarization observables in the region of cross section minimum in *dp*- elastic scattering can give an irreplaceable clue to the problem of 3N SRC. The ITS setup is well suited for the study of energy dependence of polarization observables for the deuteron-proton elastic scattering. Most of the studies so far are conducted at cyclotron facilities, RIKEN[8, 9, 10], RCNP [11], KVI [12, 13, 14], and IUCF. At the facilities, measurement of energy dependence is very expensive because change of beam energy in a cyclotron takes much time (typically more than one day). Nuclotron can accelerate a polarized deuteron beam from several tens of MeV to higher than 1 GeV and can provide us a good opportunity to measure the energy dependence [16].

The polarized deuteron beam has been provided by the polarized ion source (PIS) of atomic beam type POLARIS [17]. The typical intensity of the beam in Nuclotron ring during the experiment was $2 \div 3 \cdot 10^7$ deuterons per spill. The 10 μm CH_2 foil has been used as the target. Also measurements with carbon (wire) target have been performed in order to estimate the background. The data have been accumulated at 270, 880 and 2000 MeV. The measurement of the beam polarization has been performed at 270 MeV, where well established data on analyzing powers exist [8, 9, 10].

The results on the vector A_y and tensor A_{yy}, A_{xx} analyzing powers in *dp*- elastic scattering obtained at 880 MeV [18] are shown in Fig.1. The solid, dashed and dash-dotted lines are the results of the Faddeev calculations [19] using CD-Bonn nucleon-nucleon potential, of the relativistic multiple scattering calculations [20] using CD-Bonn DWF, and the optical potential calculation with the dibaryon DWF [21], respectively. One can see that Faddeev and multiple scattering models give good description of the data except for A_{xx}.

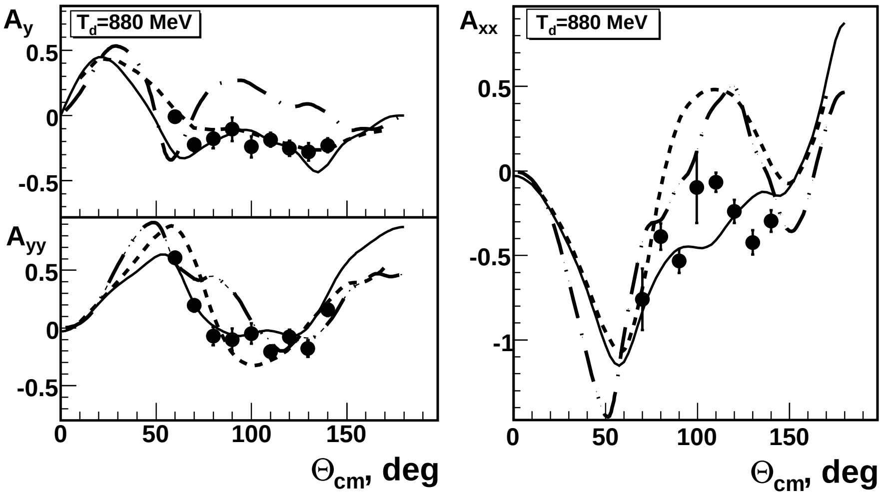

Figure 1: Vector A_y and tensor A_{yy}, A_{xx} analyzing powers in *dp*- elastic scattering at 880 MeV [18]. The curves are explained in the text.

On the other hand, Faddeev calculations [19] fail to reproduce the cross section at the angles larger than 90°, while relativistic multiple scattering calculations [20] give much better agreement with the data at the angles between 30° and 130°. One of the reasons of the discrepancy around 90° can be 3N SRC, which are not included in the calculations. The collaboration is planning to perform the systematic measurements of the *dp*- elastic scattering cross section and analyzing powers at ITS. The status of the experiment preparation is given in the talk at this Conference [22].

Another tool to study 2N and 3N SRCs spin structure is the non-mesonic *dp*- breakup at intermediate energies. The measurements of *dp*- breakup in different parts of the phase space give the possibility to separate the contribution of 2N and 3N SRCs. The first results of the beam test with the $\Delta E - E$ detectors for the experiment at ITS is reported in the talk at this Conference [23].

The mail goal of PHe3-CUPID3 experiment is to measure polarization observables for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction at E_d = 1.0–1.75 GeV by using polarized deuteron beam from Nuclotron and polarized ^{3}He target developed at CNS [24] shown in the left panel of Fig.2. The experiments performed at RIKEN at the energies below 270 MeV have shown that the polarization correlation coefficient, $C_{//} = 1 - \frac{1}{2\sqrt{2}}T_{20} + \frac{3}{2}C_{y,y}$, for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction may be a unique probe to the D-state admixture in deuteron [25]. The usefulness of this observable to investigate the D-state admixture is attributed to the strong spin-selectivity in neutron capture process by ^{3}He nucleus, i.e., spins of transfered neutron and ^{3}He must be anti-parallel to each other in order to form ^{4}He in the final state.

The aim of the experiment is to obtain the data on $C_{//}$ in the energy region, where the contribution from the deuteron D-state is expected to reach a maximum in one-nucleon exchange approximation, to obtain new information on the strange structure observed in the behaviour of T_{20} in the *dp*- backward elastic scattering [26] and to realize experiment on the full determination of the matrix element of the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction in the model independent way. These data will help us also to understand the short-range spin structure of deuteron and effects of non-nucleonic degrees of freedom. For these purposes polarized deuteron beam from new high intensity PIS [27] must be used. The full symbols in the right panel of Fig.2 are the data obtained at RIKEN [25]. The open squares show the expected precision for the data at Nuclotron-M. The lines are the prediction of the one-nucleon exchange (ONE) approach.

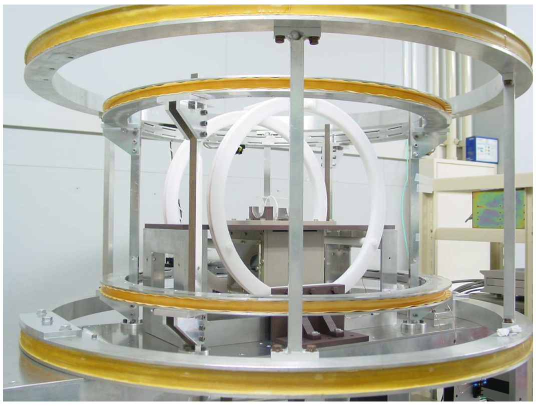

Figure 2: View of CNS polarized ^{3}He target [24] prepared for the experiment at Nuclotron-M.

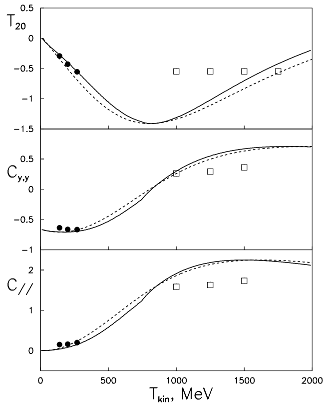

Figure 3: Tensor analyzing power T_{20}, spin correlation $C_{y,y}$ and correlation coefficient $C_{//}$ in the $d^3\mathrm{He} \to p^4\mathrm{He}$ reaction. The full circles are the data obtained at RIKEN [25], the open symbols reproduce the expected precision for the data at Nuclotron-M.

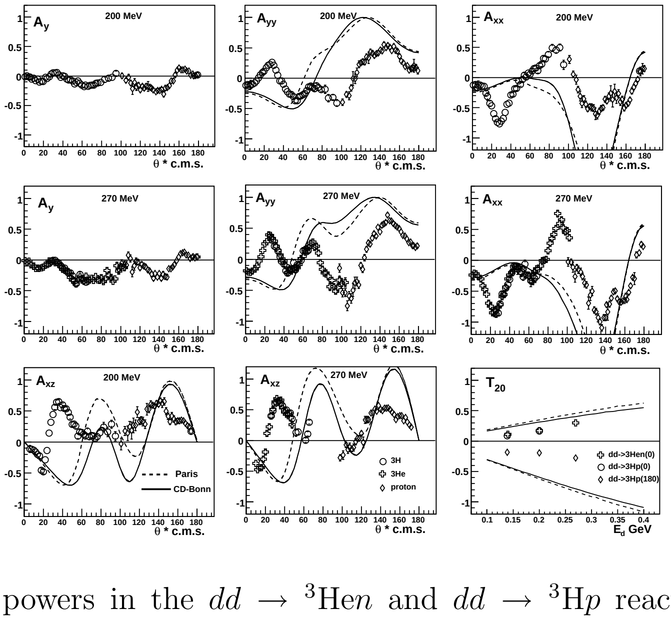

Figure 4: Analyzing powers in the $dd \to {}^3\mathrm{He}n$ and $dd \to {}^3\mathrm{H}p$ reactions at intermediate energies [28, 29, 30]. The curves are explained in the text.

The studies of the SRC can be performed also in the $dd \to {}^3\mathrm{He}n$ and $dd \to {}^3\mathrm{H}p$ reactions. The results on the analyzing powers for these reactions obtained at intermediate energies at RIKEN [28, 29, 30] are shown in Fig.3. The tensor analyzing powers are sensitive to the spin structure of 2N and 3N SRCs. The lines are the ONE predictions with the use of the standard NN potentials. The measurements of the energy dependence of T_{20} in the $dd \to {}^3\mathrm{He}n$ reaction can be continued at Nuclotron-M with new PIS [27].

3 Future for NICA

New heavy ion and polarized particles collider NICA is planned for the energies $\sqrt{s_{NN}}$ ~4–12 GeV and up to $\sqrt{s}$ ~27 GeV for $\vec{d}\vec{d}$- abd $\vec{p}\vec{p}$- collisions, respectively. The serious advantage of this facility is the availability of polarized deuterons (neutrons). The main topics of the spin studies at NICA can be spin content of nucleon, nuclear and color transparency in spin observables, polarization effects in hyperon production, single and double asymmetries in meson production, NN and light nuclei short-range spin structure [31].

Deuteron and ^{3}He(^{3}H) spin structure can be studied using two-arms magnetic spectrometer from $\vec{d}d \to pX$ [32], $\vec{d}d \to {}^3\mathrm{He}n({}^3\mathrm{H}p)$ [28, 29, 30] and $^3\vec{\mathrm{He}}{}^3\vec{\mathrm{He}} \to ppX$ reactions. The deuteron internal structure in the $\vec{d}N \to pX$ process can be probed at NICA energies up to p_T ~2–3 GeV/c, where different models predict significantly different behaviour of the observables [33]. These data will be sensitive to the problem of hidden color in nuclei.

The collider mode gives very serious advantage to study 2N and 3N SRCs in nuclei from the $A(p,pp)X$ and $A(p,pn)X$ processes because of large coverage of the phase space for the correlated nucleon pairs in lab.

Color transparency can be studied in $p(\vec{d},pp)n$ and $A(\vec{d},pp)X$ collisions [34] by the detection of two protons at large transverse momenta.

4 Conclusions

The spin structure of 2N and 3N short-range correlations can be studied at Nuclotron-M both at internal and extracted beams in the few-nucleons interaction.

The putting into operation new PIS will significantly increase the potentialities of these studies at Nuclotron-M.

The collider mode and availability of polarized beams give serious advantages to study 2N and 3N SRCs at NICA.

The authors thanks Yu.S.Anisimov, J.Kliman, V.Matousek, M.Morhach and I.Turzo for the help in the preparation of ITS for the experiment. The investigation has been supported in part by the Russian Foundation for Basic Research (grant No.07-02-00102-a).

References

[1] L. Frankfurt, M. Sargsian, M. Strikman, Int.J.Mod.Phys.**A23**, 2991 (2008).

[2] E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, J.W. Watson, Phys.Rev.Lett. **97**, 162504 (2006).

[3] L.L. Frankfurt, M.I. Strikman, D.B. Day, M.M. Sargsian, Phys.Rev. **C48**, 2451 (1993).

[4] K.Sh. Egiyan et al., Phys.Rev. **C68**, 014313 (2003).

[5] K.S. Egiyan et al., Phys.Rev.Lett. **96**, 082501 (2006).

[6] M.I. Strikman, in *Proc. of the VI-th Int.Conf. on Perspectives in Hadronic Physics*, 12-16 May 2008, Trieste, Italy; to be published in AIP Conf.Proc.

[7] W. Glöckle, H. Witala, D. Hüber, H. Kamada, J. Golak, Phys.Rep. **274**, 107 (1996).

[8] N. Sakamoto et al., Phys.Lett. **B367**, 60 (1996).

[9] K. Sekiguchi et al., Phys.Rev. **C65**, 034003 (2002).

[10] K. Sekiguchi et al., Phys.Rev. **C70**, 014001 (2004).

[11] K. Hatanaka, Y. Shimizu et al., Phys.Rev. **C66**, 044002 (2002).

[12] R. Bieber et al., Phys. Rev. Lett. **84**, 606 (2000).

[13] K. Ermisch et al., Phys. Rev. Lett. **86**, 5862 (2001).

[14] K. Ermisch et al., Phys. Rev. **C68**, 051001 (2003).

[15] V.I. Kukulin et al., J. Phys. G: Nucl. Part. Phys. **30**, 287 (2004).

[16] T. Uesaka, V.P. Ladygin et al., Phys.Part.Nucl.Lett.**3**, 305 (2006).

[17] N.G. Anishchenko et al., AIP Conf.Proc. **95**, 445 (1983).

[18] P.K. Kurilkin et al., Eur.Phys.J. ST **162**, 137 (2008); *talk at this Conference.*

[19] H. Witala, *private communication.*

[20] N.B. Ladygina, *a*rXiv:0705.3149 [nucl-th]; Phys.Atom.Nucl. **71**, 2039 (2008); *talk at this Conference.*

[21] M.A. Shikhalev, *a*rXiv:0710.4040 [nucl-th], Phys.Atom.Nucl., *in press.*

[22] Yu.V. Gurchin et al., *talk at this Conference.*

[23] S.M. Piyadin et al., *talk at this Conference.*

[24] T. Uesaka et al.,Nucl.Instr. and Meth. in Phys.Res. **A402**, 212 (1998).

[25] T. Uesaka et al., Phys. Lett. **B533**, 1 (2002).

[26] V. Punjabi et al., Phys.Lett. **B350**, 178 (1995).

[27] V.V. Fimushkin et al., Eur.Phys.J. ST **162**, 275 (2008).

[28] V.P. Ladygin et al., Phys.Lett. **B598**, 47 (2004).

[29] M. Janek et al., Eur.Phys.J. **A33**, 39 (2007).

[30] A.K. Kurilkin et al., Eur.Phys.J. ST **162**, 133 (2008); *talk at this Conference.*

[31] V.P. Ladygin et al., in *Proc. of the VI-th Int.Conf. on Perspectives in Hadronic Physics*, 12-16 May 2008, Trieste, Italy; to be published in AIP Conf.Proc.

[32] S.V. Afanasiev et al., Phys.Lett. **B434**, 21 (1998); V.P. Ladygin et al., Few-Body Systems **32**, 127 (2002); L.S. Azhgirey et al., Phys.Lett. **B595**, 151 (2004); V.P. Ladygin et al., Phys.Lett. **B629**, 60 (2005).

[33] L.S. Azhgirey et al., Phys.Part.Nucl.Lett. **4**, 497 (2007).

[34] L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, Phys.Rev. **C56**, 2752 (1997).