Study of polarization effects at Nuclotron

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Abstract. The major goal of the upgraded Nuclotron facility is to obtain the information on the equation-of-state for dense nuclear matter playing a key role in the understanding of the collapse supernovae and neutron stars stability. These studies can be performed either in heavy ion collisions or via the short-range few nucleon correlations. The obtained experimental results and future program with the use of polarized deuteron beam and the internal target station are discussed. The polarization studies for the $NN$, $NA$ and $dA$ reactions with the extracted deuteron beam at the BM@N setup are proposed. The further extension of the polarization program at BM@N is related with the study of the in-medium modification of the polarization for the strange and multi-strange baryons and the spin alignment for vector mesons decaying in hadronic modes.

1. Introduction

The Nuclotron at JINR will provide beams of heavy ions with energies up to 6 A·GeV for isospin symmetric nuclei, and 4.65 A·GeV for $Au$ nuclei. In central heavy-ion collisions at these energies, nuclear densities of about 4 times nuclear matter density can be reached. These conditions are well suited to investigate the equation-of-state (EOS) of dense nuclear matter which plays a central role for the dynamics of core collapse supernovae and for the stability of neutron stars. The observation of multi-strange hyperons or of light hypernuclei at Nuclotron energies would represent a breakthrough in our understanding of strange matter, and would pave the road for the experimental exploration of the 3-rd dimension of the nuclear chart \cite{1}. These studies are complimentary to the CBM experimental program at SIS100 \cite{2}.

Another tool to investigate the EOS at large densities is the study of the short range correlations (SRC) of nucleons in nuclei which 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 \cite{3}. 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 \cite{4}, SLAC \cite{5} and JLAB \cite{6, 7} clearly demonstrate that more than 90\% all nucleons with momenta $k \geq 300$ MeV/c belong to 2N SRC; the probability for a given proton with momenta $300 \lesssim k \lesssim 600$ MeV/c to belong to $pn$ correlation is $\sim 18$ times larger than for $pp$ correlations; the probability for a nucleon to have momentum $\geq 300$ MeV/c in medium nuclei is $\sim 25\%$; 3N SRC are present in nuclei with a significant probability \cite{8}. 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.

**Figure 1.** The dependence of the tensor analyzing power $A_{yy}$ [9, 10, 11, 12, 13] as a function of the proton transverse momentum $p_T$ at four different fixed values of $x_F \sim 0.61$, 0.67, 0.72 and 0.78, are shown in the a), b), c) and d) panels, respectively.

**Figure 2.** $A_{yy}$ data[9, 10, 11, 12, 13] plotted as a function of longitudinal momentum fraction $x_F$ obtained at fixed $p_T$ values of $\sim 550 \text{ MeV/c}$, $\sim 700 \text{ MeV/c}$, $\sim 800 \text{ MeV/c}$ and $\sim 900 \text{ MeV/c}$ are presented in the a), b), c) and d) panels, respectively.

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 $A(p, pp)X, A(p, pm)X, A(p, ppp)X$ etc. with the detection of few nucleons in the final state. The great 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 spin structure of the np SRCs has been investigated at JINR via the measurements of the tensor analyzing power $A_{yy}$ in deuteron inclusive breakup at different energies in the wide regions of the $x_F$ and transverse proton momentum $p_T$ [9, 10, 11, 12, 13]. The data on the tensor analyzing power $A_{yy}$ obtained in the $A(d, p)X$ reaction at different values of $x_F \sim 0.61$, $\sim 0.67$, $\sim 0.72$ and $\sim 0.78$ and plotted as a function of the proton transverse momentum $p_T$ are shown in panels a), b), c) and d) in Fig.1, respectively. The figure is taken from ref.[13]. It is seen that the $A_{yy}$ data for different $x_F$ 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 $p_T \sim 600 \text{ MeV/c}$ independently on $x_F$ and demonstrate kind of negative asymptotic at large $p_T$. The dashed, dash-dotted and solid curves are the results of the calculations using standard [14, 15] and covariant [16] deuteron wave functions (DWFs), respectively. The $A_{yy}$ data obtained at different values of transverse momenta $p_T$ as a function of $x_F$ are plotted in Fig.2. The data shown in panels a), b), c) and d) correspond to the averaged values of $p_T \sim 550 \text{ MeV/c}$, $\sim 700 \text{ MeV/c}$, $\sim 800 \text{ MeV/c}$ and $\sim 900 \text{ MeV/c}$, respectively. The figure is also taken from ref.[13]. The solid curves are the results of the calculations by using covariant DWF [16]. One can see that the $A_{yy}$ data for different values of $p_T$ demonstrate a weak dependence on $x_F$. 
The data obtained at $p_T \sim 550 \sim \text{MeV/c}$ are in a good agreement with the calculations by using covariant DWF [16]. 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 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 [16] does not allow to describe the data.

The fundamental degrees of freedom in the frame of QCD are the quarks and gluons. These degrees (effective ones as $\Delta \Delta, N^*N, NN$ or $6q$ and $9q$ components) begin to play a role at the internucleonic distances comparable with the size of the nucleon. At high energies $s$ and large transverse momenta $p_T$ the constituent counting rules (CCR) [17, 18] are working. These rules predict the dependence of the cross section of the binary reactions at the fixed scattering angle in the cms as a power-law of $s$. The analysis of the experimental data on the cross sections of the $dp \rightarrow pd$ and $dd \rightarrow ^3\text{He}$ reactions [19] has shown that the regime corresponding to CCR can occur already at $T_d \sim 500$ MeV. Therefore, the fundamental degrees of freedom can manifest in the deuteron induced reactions at Nuclotron energies.

2. Recent results and further plans for internal target experiments

The main goal of the Deuteron Spin Structure (DSS) experimental program is to obtain the information on the spin-dependent parts of two-nucleon ($2N$) and three-nucleon ($3N$) forces from two processes: $dp$-elastic scattering in a wide energy range and $dp$-nonmesonic breakup with two protons detection at energies $300 - 500$ MeV [20, 21, 22]. The motivation of this program is based on theoretical analysis of the experimental results obtained at low and intermediate energies for the deuteron induced reactions (see recent reviews [23, 24] and references therein).

Such experimental program at Nuclotron was started by the measurements of the vector $A_y$ and tensor $A_{yy}$ and $A_{xx}$ analyzing powers in $dp$-elastic scattering at $T_d$ of 880 MeV [25] and 2000 MeV [26].

![Figure 3](image-url) Figure 3. The angular dependence of the analyzing powers $A_y$, $A_{yy}$ and $A_{xx}$ of $dp$-elastic scattering at $T_d = 880$ MeV [25].

![Figure 4](image-url) Figure 4. The angular dependence of the differential cross section of $dp$-elastic scattering at $T_d = 940$ MeV [27] and 850 MeV [28], respectively.

The results on the angular dependencies of the analyzing powers $A_y$, $A_{yy}$ and $A_{xx}$ of $dp$-elastic scattering obtained at Nuclotron at 880 MeV [25] are presented in Fig.3. The differential
cross section obtained at 940 MeV [27] and 850 MeV [28] in the earlier experiments are shown in Fig.4 by the open circles and triangles, respectively. The solid, dashed and dot-dashed lines are the results of the non-relativistic Faddeev calculations [23], relativistic multiple scattering model [29, 30] and optical potential approach [31]. The Faddeev calculations without invoking 3N forces reproduce the behaviour of the analyzing powers, however, they fail to describe the cross section data at the scattering angles larger than 70° in the cms. The calculations performed within relativistic multiple scattering model [29, 30] describes the data on the vector analyzing power $A_y$ and cross section. However, there are some problems in the description of the tensor analyzing powers at large angles in the cms. The optical potential approach fails to reproduce both cross section and analyzing powers. The observed deficiencies in the description of the differential cross section and deuteron analyzing powers at $T_d \sim 880$ MeV obtained at quite large transverse momenta require the consideration of the additional mechanisms, for instance, 3N forces. Since present 3N forces models cannot improve the agreement with the data obtained even at lower energies, new models of 3N forces (including their short-range part) should be considered. For instance, the next step in the relativistic multiple scattering model [29, 30] development could be taking into account the explicit $\Delta$- isobar excitation.

As the first stage of the Deuteron Spin Structure (DSS) experimental program [20, 21, 22] the beam energy scan of $dp$- elastic scattering cross section at the deuteron energies 400 – 2000 MeV and measurements of $dp$- non-mesonic breakup at 300, 400 and 500 MeV in different kinematic configurations have been performed at Nuclotron. These measurements were performed using internal target station at Nuclotron [32] with new control and data acquisition system [33]. The continuation of the DSS experimental program at internal target is related with new polarized ion source developed at LHEP-JINR [34].

3. Spin studies with extracted polarized deuteron beam

Spin physics with extracted polarized deuteron beam from new polarized deuteron source [34] can be performed with the start version of the BM@N setup [1]. Since the multiplicity of the secondary particles is small (2 or 3 tracks) the forward and outer trackers only can be used. The BM@N experimental setup will be installed at the renovated 6V beamline [35] in the fixed-target hall of the Nuclotron. The 6V beamline contains the quadrupole lenses doublet, two dipole magnets allowing to correct the beam position in the vertical and horizontal planes, and SP41 dipole magnet with enlarged aperture for the momentum measurements [36].

The transportation line VP1 does not require modification in the sense of the installation or removing of magnetic elements. But spin program realization requires to install the polarimeters (with $CH_2$-C targets) at F3 and F5 focuses for polarimetry of the deuteron (or proton) beam. Also the place at F5 (or F3) is needed to install liquid hydrogen (deuterium) target, polarized $^3$He target [37] and set of nuclear targets. It will be necessary also to have some place for the stop time-of-flight detector.

The spin physics can be divided on 3 part due to position of the target at VP1 transportation beam line. The physics with the target position at F5(or F3) focus is related with the measurements of the polarization observables in the reactions with the emission of the detected particle at forward angles. The solid angle is defined by the lenses doublet 7k100–8k100 of the VP1 transportation beam line. The separation of the primary deuteron and secondary beams is provided by the bending magnet 3SP40. The physics program can include the measurements of the tensor analyzing power $T_{20}$ (and, possibly, vector polarization transfer coefficient $\kappa_0$) in the inclusive deuteron breakup, $A(d, p(0^+))X$, [9, 38, 39] at the highest available energy at Nuclotron; of the tensor analyzing power $T_{20}$ in the inclusive pion production, $A(d, \pi^-(0^0))X$, [40] also at the highest available energy at Nuclotron; of the tensor analyzing power $T_{20}$ (and, possibly, vector polarization transfer coefficient $\kappa_0$) in the inelastic deuteron scattering, $A(d, d')X$, in the vicinity of the baryonic resonances excitation [41]; of the tensor analyzing power $T_{20}$ (and,
possibly, vector polarization transfer coefficient $\kappa_0$ in $p(d,p)d$ [42, 43] and $d(d,p)t$ [44] reactions; of the tensor analyzing power $T_{20}$ and spin correlation $C_{y,y}$ in the $^4\text{He}(d,p)^4\text{He}$ reaction in the kinetic energy range between 1.0 and 1.75 GeV [45, 46]; of the analyzing power $T_{10}$ in the $A(d,^2\text{He})X$ [47] reactions.

The measurements of the $^4\text{He}(d,p)^4\text{He}$ reaction is mostly challenging throughout the above mentioned experiments due to low density of the polarized $^3\text{He}$ target [37]. The goal of the $^3\text{He}(d,p)^4\text{He}$ reaction study at Nuclotron is to understand the reasons of the long staying puzzle, namely, the still unexplained strange structure in the behaviour of the tensor analyzing power $T_{20}$ in $dp$- backward elastic scattering [42, 43] at the internal momentum $k \sim 0.3$–0.5 GeV/c in the vicinity of the D- wave dominance. The experiments performed at RIKEN at the energies below 270 MeV have shown that the polarization correlation coefficient, $C_{y,y} = 1 - \frac{1}{2} T_{20}^{20} + \frac{3}{2} C_{y,y}$, for the $^3\text{He}(d,p)^4\text{He}$ reaction may be a unique probe to the D-state admixture in deuteron [44]. The usefulness of this observable to investigate the D-state admixture is attributed to the strong spin-selectivity in neutron capture process by $^3\text{He}$ nucleus, i.e., spins of transferred neutron and $^3\text{He}$ must be anti-parallel to each other in order to form $^4\text{He}$ in the final state. In the one-nucleon exchange (ONE), the expression for $C_{y,y}$ is proportional to the D-state fraction in deuteron as

$$C_{y,y} = \frac{9}{4} \frac{w^2}{u^2 + w^2},$$

(1)

where $u$ and $w$ are the S- and D-state wave functions of deuteron in momentum space. This is a marked contrast to $T_{20}$ and $\kappa_0$ for $dp$ backward elastic scattering which include S- and D-state interference term ($uw$-term) together with a $u^2$-term. It is thus expected that $C_{y,y}$ may be a candidate to provide an information on the deuteron structure complementary to those from $T_{20}$ and $\kappa_0$ obtained in $dp$- backward elastic scattering [42].

The main goal of the proposed at Nuclotron experiment is to obtain the data on $C_{y,y}$ in the energy region of 1.0–1.75 GeV, 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 and to realize experiment on the full determination of the matrix element of the $^3\text{He}(d,p)^4\text{He}$ 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 PIS [34] and spin-exchange-type polarized $^3\text{He}$ target developed at CNS of Tokyo University [37] and modified for the experiment at Nuclotron can be used.

The simulation has been performed for the initial deuteron kinetic energy $T_d = 1.5$ GeV and the 30 cm $^3\text{He}$ target cell using the GEANT4 toolkit. The initial deuteron beam interacts with 30 cm $^3\text{He}$ target placed in one of the focuses of the V1 beam transportation line, for instance, in F5 focus. The secondary protons and deuterons, as well as primary deuterons pass along V1 transportation beam line with magnetic elements tuned for the optimal momentum of the secondary protons ($\sim$75% from the initial deuteron beam momentum). The identification of the secondary particles (protons and deuterons) in the experiment at extracted beam will be done by the measurements of their time-of-flight (TOF) over a baseline of about 20–30 m. The trigger counter with 1 mm of the quartz radiator and XP2020Q PMTs can be used as the start for TOF system. The other option for the TOF start is the 4 mm scintillation counter viewed from both sides by XP2020 PMT. This counter can be placed in front of the lenses doublet of the 6V beam line [35]. Both start counter options provide similar amount of the additional material. Two cases were considered: $^3\text{He}$ target only and $^3\text{He}$ target + 2 mm of quartz radiator of TOF start counter. Additionally only about 1 m of air was taken into account. Therefore, it was assumed that the pipes of the VP1 and 6V lines will be in vacuum. Only analyzing magnet, GEM tracker and one half of the mRPC-1 wall will be used for the proposed measurements.
The particle momentum will be analyzed using 12 stations GEM tracker placed in the magnetic field. The 1-st and 12-st stations are positioned at the distance of 30 cm and 360 cm from the beginning of the magnetic pole, respectively. The simulation has been performed for magnetic field $B_y$ value of $\sim 0.9$ T. The magnetic field integral $\int Bdl$ is equal to $\sim 3$ T·m at 1900 A with non-linearity of about 5% [36].

![XY profile at 1st GEM station](image1.png)  
**Figure 5.** The XY secondary beam profile at the 1-st GEM station for the magnetic field $B_y$ of $\sim 0.9$ T.

The proton beam spot on the 1-st GEM tracker station is presented in Fig.5. One can see that the X-position of the beam is $\sim 10$ cm from the central axis of the spectrometer. The XZ profile of the secondary beam hits in the GEM tracker stations is shown in Fig.6. The deflection angle is about $\sim 320$ mr. The momentum resolution obtained for the current version of the tracking software is about several per cents. The removing of the additional material as well as the increasing of the space resolution of the tracking detectors (silicon tracker system) will significantly increase the momentum resolution. The time difference between mRPC and start detectors for protons and deuterons for the base line of $\sim 24$ m are separated by $\sim 20$ ns. This allows to have timing resolution of the TOF system at the level of 300–400 ps. Therefore, since the timing resolution of the mRPC wall is about 100 ps, the start counter can have the resolution of about 200–300 ps, what can be easily achieved by using scintillation counter with PMT readout.

The polarization observables in the $p(d,p)d$ [42, 43] and $d(d,p)t$ [44, 48, 49] reactions in the collinear geometry can be measured with the same experimental setup using liquid hydrogen or deuterium target or CH$_2$ and CD$_2$ solid targets with carbon background subtraction.

The solid nuclear target can be placed inside the pole of the 3SP40 magnet. It can be varied from the beginning to the middle of the pole of the 3SP40 magnet. The target position in the middle of the switched off magnet corresponds to $\sim 100$ mr. This configuration can be used for the measurements of the tensor $A_{yy}$ and vector $A_y$ analyzing powers (and, possibly, vector polarization transfer coefficient $C_y^v$) in inclusive deuteron breakup, $A(d,p)X$, at large transverse proton momenta [9, 10, 11, 12, 13] at the highest available energy at Nuclotron; of the tensor $A_{yy}$ and vector $A_y$ analyzing powers [50, 51, 52] (and, possibly, vector polarization transfer coefficient $C_y^v$ [53]) in the inelastic deuteron scattering, $A(d,d')X$, in the vicinity of the baryonic resonances excitation; of the tensor $A_{yy}$ and vector $A_y$ analyzing powers in the inclusive pion production, $A(d,\pi^-)X$, [54] also at the highest available energy at Nuclotron. The measurements of the analyzing powers in inclusive deuteron breakup and the inelastic deuteron scattering in the vicinity of the baryonic resonances excitation can be performed simultaneously. All these experiments require the additional TOF detector placed between F5 and F6 focuses.

The third part of the measurements is the spin physics with the target position at F6 focus. The position of the F6 focus can be change by the magnetic optics of the 6V beam line. The
target position for this part of the experiments can be varied depending on the readiness of the inner tracker. For the low multiplicity events (2 or 3 tracks) one can use the same forward tracker as for the discussed above experiments. The separation of the primary deuteron and secondary beams is provided by the modernized analyzing magnet SP41 [36]. The physics is related with the baryonic resonances spin properties studies at the energies between 2 and 6 GeV of the deuteron kinetic energy and includes the measurements of the tensor $A_{yy}$ and vector $A_y$ analyzing powers in quasi-elastic and inelastic $A(d, pp)X$ reaction; of the tensor $A_{yy}$ and vector $A_y$ analyzing powers in the inelastic deuteron scattering $A(d, d')X$ [53] and $A(d, d')\pi^\pm X$ reactions; investigation of the vector analyzing power in neutron induced reactions (with the proton spectator detection) like $np \rightarrow pn$, $np \rightarrow pp\pi^-$, $np \rightarrow n\pi^+\pi^-$ [55, 56] etc. For the these experiments the full size RPC wall is required. In parallel, the measurement of the $dp$- elastic scattering [25, 26], $dd \rightarrow ^3He$ [57, 58, 59] and $dA \rightarrow ^3HeX$ [47] processes can be performed.

The spin studies with BM@N requires also the advanced deuteron beam polarimetry at Nuclotron discussed in [60, 61].

4. Polarization effects in heavy ion collisions at Nuclotron

The change of the polarization properties of the secondary particles in the nucleus-nucleus collisions compared to the nucleon-nucleon collisions can be investigated at BM@N. A number of polarization observables have been proposed as a possible signature of phase transition, namely, decreasing of the $Λ^0$ transverse polarization in central collisions non-zero $Λ^0$ longitudinal polarization, non-zero $J/Ψ$ polarization at low $p_T$, anisotropy in dielectron production from vector mesons decay, global hyperon polarization and spin-alignment of vector mesons in non-central events, vorticity and hydrodynamical helicity in noncentral heavy-ion collisions etc.

5. Conclusions

New data on the analyzing powers $A_y$, $A_{yy}$ and $A_{xx}$ in $dp$- elastic scattering at various energies up to 2000 MeV and well as for the $dp$- nonmesonic breakup at the energies between 300 and 500 MeV for different kinematic configurations can be measured at ITS at the Nuclotron using new PIS [34].

First stage of the BM@N setup (without or with reduced version of the inner tracker) is well suited for the physics with polarized deuterons confirmed by the feasibility studies for the measurements of the polarization observables in the $^3He(d, p)^4He$ reaction at 1.5 GeV.

Measurements of the polarization effects in the heavy ion collisions can significantly enrich the physics at BM@N.

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