Possible measurements of the spin one observables in elastic dN, dd collisions at the NICA deuteron beams

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Abstract. The report shows the possibilities of studying the spin one observables in the elastic dN and dd interactions at the NICA collider of the VBLHEP JINR. The use of the colliding deuteron beams would allow us to carry out the measurements of the differential cross sections $I^0(dN, dd)$ and of the differential cross sections $I^{pol}(dN, dd)$ and the vector $A_y(E_d, \theta)$ and tensor $A_{yy}(E_d, \theta)$ and $A_{xx}(E_d, \theta)$ analyzing powers in elastic collisions of the vector and tensor polarized deuterons. The planned luminosity of the colliding polarized deuteron beams will provide sufficiently high elastic events counting rate. The use of the colliding beams of the polarized deuterons for the spin one observable research has a number of significant advantages in comparison with the experiments with the "fixed" target. The angular acceptance of the collider detector covers the full solid angle $4\pi$ radians while the wide ranges of the energies of the dN, dd interactions and the 4-momentum transfer squared are available.

1. Introduction.
Spin physics has been a traditional experimental and theoretical field of fundamental research at JINR. Therefore, one of the main physical tasks for the NICA collider will be research in the particle spin physics [1] as a continuation of the JINR research programme in this field. Obtaining new data on the spin-dependent observables in the elastic NN, dN and dd scattering at the $T_{N,d,Lab}$ energies above 1 GeV could be one of the priority areas of the VBLHEP research at the collider.

In our reports on previous conferences [2, 3] we briefly showed the possibilities of measuring the spin-dependent NN observables with the colliding beams of polarized protons and deuterons at the NICA collider. The requirements to the parameters of colliding beams, detectors and appropriate infrastructure at NICA had been listed. In this report, we will show the opportunities for the spin one dN and dd observables research using the oncoming bunches deuterons of the NICA collider. The use of the colliding beams of the polarized deuterons for the spin one observables research has a number of significant advantages in comparison with the experiments with the "fixed" target.

The angular acceptance of the collider detectors covers the full solid angle $4\pi$ radians while the wide ranges of the energies of the dN, dd interactions and the 4-momentum transfer squared are available. These advantages allow us to obtain simultaneously a complete set of the energy and angular dependencies of the vector $A_y(E_d, \theta)$ and tensor $A_{yy}(E_d, \theta)$, $A_{xx}(E_d, \theta)$ components.
of the analyzing powers for the $dN$, $dd$ reactions in the energy region of the colliding deuteron beams of NICA.

A series of unpolarized experiments on deuteron-deuteron and deuteron-proton elastic scattering have been performed at Dubna, ANL, Serpukhov, CERN, Fermilab and Brookhaven. The investigated kinematical range covers colliding energy from $\sim 1 \text{ GeV}$ to $400 \text{ GeV}$ and 4-momentum transfer squared region from $\sim 0.08 (\text{GeV/c})^2$ to $1.4 (\text{GeV/c})^2$. Data from $dp$ and $dd$ elastic reactions at energy above a few GeV may be used to study aspects of deuteron structure and to probe features of the $2N$ and $3N$ interactions. The most widely used relativistic nuclear scattering model, the relativistic impulse approximation (RIA) and the Glauber multiple-scattering theory have been successfully applied to calculate the differential cross sections up to the ISR energies and spin one observables in $dd$, $dp$ elastic scattering up to a few GeV.

Because of the comparatively simple structure of deuteron, a relatively complete theoretical treatment of the $dp$ and $dd$ scattering processes is feasible. Due to the spin $1-1/2$ structure of the $dp$ system and availability of both polarized proton and polarized deuteron beams and targets, a large number of spin observables may be measured in elastic scattering experiments. A prime objective of the proposed measurements is to obtain a sufficiently large number of independent $dp$ spin observables, measured with sufficient statistical accuracy. These data allow, in a model independent manner, reconstruction of the $dp$ elastic scattering amplitude. At this time, we are still a long way from reaching this objective. Therefore, comparison between the experiment and the theoretical models has to be made on the level of observables rather than the scattering amplitude.

![Figure 1](image_url)

**Figure 1.** (a) Vector analyzing power $A_y$ versus $t_{1,3}$ for the elastic $dp$ scattering at $T_d = 0.8 \text{ GeV}$ [4, 5]. (b) Tensor analyzing power $A_{yy}$ versus $t_{1,3}$ for the elastic $dp$ scattering at $T_d = 0.8 \text{ GeV}$ [4, 5]. (c) Tensor analyzing power $T_{20}$ for the elastic $dp$ backward scattering in comparison with the same for $dp- \to pX$ break-up [6, 7, 8].

Experiments on the measurement of the $dp$ and $dd$ spin one observables have been planned and carried out using polarized deuteron beams at Dubna accelerators (Synchrophasotron, Nuclotron), Saclay (SATURNE II) and ANL ZGS. As an example, below we show some experimental results of measurements of the vector and tensor analyzing powers in the elastic $dp$ scattering.

### 2. Formalism of the elastic spin one observables.

For a two-body reaction characterized by the scattering matrix $M$ and initial $\rho_{in}$ and outgoing $\rho_{out}$ spin density matrixes, the intensity $I_{pol}$ of outgoing particles is given by the Cartesian spin
tensors as [9, 10]:

\[
I^{pol} = Tr\rho_{out} = TrM\rho_{in}M^\dagger = I^0[1 + \frac{3}{2}p_yA_y + \frac{1}{2}p_{zz}A_{zz} + \frac{2}{3}p_{xx}A_{xz} + \\
+ \frac{1}{6}(p_{xx} - p_{yy})(A_{xx} - A_{yy})].
\]  
(1)

In this expression both the polarizations \((p_x, p_y)\) and analyzing powers \((A_i, A_{ij})\) are referred to the right-handed coordinate system having \(z\)-axis along the momentum vector \(\vec{k}_{in}\) direction of the input particle, and \(y\)-axis along the vector product \(\vec{k}_{in} \times \vec{k}_{out}\). In the following, this coordinate system will be referred to as \(S\).

The colliding deuteron beams are polarized in a polarized ion source where the quantization axis is oriented vertically along the \(z\) axis of the source system. Denoting the tensor moments which express the beam polarization referred to the spin symmetry axis \(z\) at the polarized ion source by \((p_z, p_{zz})\), the analyzing power moments \((A_i, A_{ij})\) in \(S\) are given by the transformation expression as: \((A_i, A_{ij}) = (p_z, p_{zz})D^i_j(\Phi, \Theta, \Psi)\), where \(\Phi, \Theta\) and \(\Psi\) are the Euler angles rotating coordinate system of the \((p_z, p_{zz})\) into \(S\). The angle between \(z\) and vector \(\vec{k}_{in}\) is \(\beta\), and \(\varphi\) denotes the angle between the projection of \(z\) on the \(xy\)-plane of \(S\) and \(\vec{k}_{in} \times \vec{k}_{out}\). In terms of \(\beta\) and \(\varphi\), the Euler angles which carry the polarized ion source system into \(S\) are \(\Phi = 0\), \(\Theta = -\beta\) and \(\Psi = -(90^\circ + \varphi)\).

Using these Euler angles values we finally obtain

\[
I^{pol} = I^0[1 + 1.5p_zA_y\sin\beta\cos\varphi + 0.25p_{zz}A_{zz}(3\cos^2\beta - 1) - \\
- p_{zz}A_{xx}\sin\beta\cos\varphi - 0.25p_{zz}(A_{xx} - A_{yy})\sin^2\beta\cos2\varphi].
\]  
(2)

We write now the expressions of the particle outputs for specific cases of scattering at the angle \(\theta\) to the left \((L\) direction +\(x\)), right \((R\) direction −\(x\)), up \((U\) direction +\(y\)) and down \((D\) direction −\(y\)) in the coordinate system \(S\). Using the relationship \(A_{xx} + A_{yy} + A_{zz} = 0\) for the Cartesian tensor analyzing forces, we can get the following expressions for the outputs to the right, left, up and down:

\[
I^{Lpol}(\theta_H) = I^{L0}(\theta_H)[1 + 1.5p_zA_y(\theta_H) + 0.5p_{zz}A_{yy}(\theta_H)],
\]  
(3)

\[
I^{Rpol}(\theta_H) = I^{R0}(\theta_H)[1 - 1.5p_zA_y(\theta_H) + 0.5p_{zz}A_{yy}(\theta_H)],
\]  
(4)

\[
I^{Upol}(\theta_V) = I^{U0}(\theta_V)[1 + 0.5p_{zz}A_{xx}(\theta_V)],
\]  
(5)

\[
I^{Dpol}(\theta_V) = I^{D0}(\theta_V)[1 + 0.5p_{zz}A_{xx}(\theta_V)],
\]  
(6)

where \(\theta_H\) is the scattering angle in \(xz\)-plane for right, left cases, and \(\theta_V\) is the scattering angle in \(yz\)-plane for up, down cases.

For the left-right scattering case we get the asymmetry expression \(a = 3p_zA_y(\theta_H) = I^{Lpol}/I^{L0} - I^{Rpol}/I^{R0}\) and can obtain value of the vector analyzing power \(A_y(\theta_H) = a/(3p_z)\) or the vector component of the deuteron beam polarization \(p_z = a/(3A_y(\theta_H))\). For the sum of the left-right yields we get \(I^{Lpol}/I^{L0} + I^{Rpol}/I^{R0} = 2 + p_{zz}A_{yy}(\theta_H)\), and can obtain value of the tensor component of analyzing power \(A_{yy}(\theta_H)\) or value of the tensor component of the deuteron beam polarization \(p_{zz}\). For the case of up-down scattering the sum of the yields gives \(I^{Upol}/I^{U0} + I^{Dpol}/I^{D0} = 2 = p_{zz}A_{xx}(\theta_V)\), and we can obtain value of the tensor component \(A_{xx}(\theta_V)\) of the analyzing power.

Assuming the deuteron is a loosely coupled system, one can apply the above formalism to describe the elastic \(dd\) and quasi-elastic \(dN - deuteron\) scattering on individual nucleon in the deuteron (See Fig.2a). To measure the elastic \(dp, dd\) differential cross section we have to select
these elastic events among all inelastic ones. The parameters of the NICA detectors have to provide selection of the elastic dp and dd events.

The polarimetry of the polarized colliding dd beams at the NICA was previously discussed in [2, 3]. Here we only note that the detection of the elastic dp, dd scattering events by the NICA detectors provide the ability to determine the left-right asymmetries of the reaction yields. This will enable us to estimate the polarization values of the colliding beams directly at the interaction point. This could be done both for proton and deuteron colliding beams.

3. Kinematics of the dp and dd elastic collisions.

Before proceeding to the yield evaluations for the elastic dp, dd collisions at the NICA deuteron beams we briefly recall features of the elastic scattering kinematics:
- for experiments with the ”fixed” target, in Lab. system \( (p_2^{\text{Lab}} = 0, E_2^{\text{Lab}} = m_2) \),
- for the system of the colliding beams \( (m_1 \neq m_2, \beta_1 = \beta_2, p_p = 0.5 \cdot p_d, E_p = 0.5 \cdot E_d \)
  when neutron in deuteron is spectator), and
- for the colliding particles center-of-mass \( (\vec{p}_p + \vec{p}_d = 0) \).

Figure 2b shows the dependencies of the proton and deuteron Lab. kinetic energies \( T_{p,d}^{\text{Lab}} \) from the kinetic energy \( T_{p,d}^{\text{Col}} \) in the collider.

![Figure 2](image)

**Figure 2.** (a) Schematic view of the quasi-elastic dp scattering in the colliding beams of deuterons. (b) Dependencies of \( T_{p,d}^{\text{Lab}} \) from \( T_{p,d}^{\text{Col}} \). (c) Elastic \( d_1 + N_1 \rightarrow d_2 + N_2 \) collision at Lab. system.

![Figure 3](image)

**Figure 3.** (a) Elastic \( d_1 + d_2 \rightarrow d_3 + d_4 \) collision at Lab. system. (b) Elastic \( d_1 + N_1 \rightarrow d_2 + N_2 \) collision at the NICA collider. (c) Elastic \( d_1 + d_2 \rightarrow d_3 + d_4 \) collision at the NICA collider (CM system).

The kinematic characteristic ranges for the elastic dp and dd collisions at the Lab, SM, and Col. systems are shown in figures 2c, 3a \( \div 3c \). The dependencies of the four-momentum transfer squared \( t_{1,3} \) from the beam deuteron energy \( T_{d,\text{Lab,CM}} \) and from deuteron scattering angle \( \theta_{d,\text{Lab,CM}} \) in the Lab, CM, and Col. coordinate systems are shown by the three-dimensional figures.

Note a significant benefit of the collisions research in center-of-mass in comparison with experiments with ”fixed” targets.
4. The elastic event yields in the \(dd\) and \(dp\) collisions.
Unfortunately, the existing \(dN\) and \(dd\) data are quite poor, however they will provide a realistic assessment of the outputs of the elastic \(dp\) and \(dd\) scattering processes. In Fig. 4 we present the existing data on differential \(dp\), \(pd\), and \(dd\) cross-sections at the Center-of-Mass system or/and at the Collider system.

![Colliding \(d\) beams. Beam kinetic energy \(T_d\): 2\(\sim\)5.5 GeV/u](image)

Figure 4. Available experimental data set on the differential cross sections for the elastic \(dp\) [11–13] (blue symbols), \(dd\) [14, 15] (magenta symbols), and \(pd\) [16–21] (green symbols) collisions in the \(CM\) and Collider systems.

The \(x\)-axis represents the deuteron scattering angle \(\theta_d\) in the \(CM\) or \(Col\). systems of the colliding deuterons. The left logarithmic scale represents values of the differential cross sections \(d\sigma/d\Omega_{CM,Col}(dd, dp, pd)\) in the \(CM\) or \(Col\). systems of the colliding deuterons. The legend indicating the symbols representing the \(d\sigma/d\Omega_{CM,Col}(dd, dp, pd)\) values obtained at a given kinetic energy \(T_d\), \(CM\), \(Col\) of the colliding deuterons is shown on the right edge of the Fig. 4. The presented \(dp, dd, pd\) data sets are approximated with the Bezier curves of degree \(n\) (the number of data points) that connect the endpoints.

The kinematic characteristics of the boundary points of multiple data sets are shown in Fig. 4 by the arrows. There the values of the deuteron kinetic energy \(T_d\), \(CM\), \(Col\) of the colliding deuterons and the squared four-momentum transfer \(t_{d1}, t_{d3}\) are specified. These data will facilitate the estimations of the outputs of the elastic \(dp\) and \(dd\) processes in the \(CM\) or \(Col\) systems of the interacting particles.

Right logarithmic scale in Fig. 4 shows the values of the count rate \(R\) of the elastic \(dp, dd\) events expected for appropriate values of the cross sections \(d\sigma/d\Omega_{CM,Col}\) when the luminosity of the colliding deuteron beams is equal to \(L_d = 1 \times 10^{30} cm^{-2}s^{-1}\). The use of this scale allows us to quickly get reasonable estimation of the expected counting rates for the elastic events.

5. Conclusion.
The possibilities of measuring the spin-one observables in the elastic \(dd\) and quasi-elastic \(dp\) interactions at the colliding \(\vec{d}\) beams of the \(NICA\) collider were considered. The formalism [9, 10] that specifies the spin-one observables in the elastic \(dp\) and \(dd\) scattering was briefly considered.
The kinematic characteristics of the $dp$ and $dd$ scattering processes at the Laboratory system and in the Center of mass system of the colliding particles were analyzed. It is shown that in the elastic $dp$ and $dd$ scattering at the colliding $d$ beams the broader ranges both the energy values of the interacting particles and the square of the four-momentum transfer are achieved in comparison with the experiment using the "fixed" target. Other significant advantages of the measurements at the collider compared with the experiments with the "fixed" targets are the following: the angular acceptance of the collider detector extends to the full solid angle $4\pi$ rad and the so-called "target" in such measurements does not contain background impurities, which complicate the processing of the accumulated data. These advantages allow as to obtain simultaneously a complete set of the energy and angular dependencies of the vector and tensor analyzing power $A_y(E_d, \theta)$, $A_{yy}(E_d, \theta)$ and $A_{xx}(E_d, \theta)$ components for the $dN$, $dd$ reactions in the energy region of the colliding deuteron beams of NICA.

Available existing data set [11–21] on the differential elastic $dp$, $dd$, and $pd$ cross sections in the collider system or in the CM of the colliding particles were shown. The output estimations of the elastic $dp$, $dd$ events were presented

The spin one observables data planned to be obtained in the measurements of the elastic $dN$ and $dd$ scattering will promote a creation of an adequate phenomenological and theoretical description of the $dN$ and $dd$ interaction over the $T_{col}$ energy region of $4 \div 11\, GeV$ ($T_{lab} \sim 30 \div 170\, GeV$).

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