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Selection of the elastic scattering events in interactions of the NICA colliding proton (deuteron) beams

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Abstract. The features of the kinematics of elastic pp (dd) scattering in the collider system, as well as some issues concerning registration and selection of elastic scattering events in the $NICA$ colliding beams are considered. Equality and the opposite direction of the scattered particle momenta provide a powerful selection criterion for elastic collisions. Variants of the organization of the trigger signal for recording tracks of secondary particles and DAQ system are given. The estimates of the characteristics of elastic NN processes are obtained from available $d\sigma/d\Omega_{CM}$ data for the elastic pp and np scattering. The paper presents examples of simulations using the Monte-Carlo of elastic pp scattering in the colliding proton beams and quasi-elastic np scattering in the colliding deuteron beams and evaluates the outputs of these processes at the $NICA$ collider.

1 Introduction

The $NICA$ collider [1] will provide the colliding beams of polarized protons and deuterons with the energy range of $T_p = 5 \div 12.6\ GeV$ ($\sqrt{s_{pp}} = 12 \div 27\ GeV$) for protons and $T_d = 2 \div 5.5\ GeV$ ($\sqrt{s_{NN}} = 4 \div 13\ GeV$) for deuterons. Obtaining new data on spin-dependent observables in elastic NN and dd scattering at the colliding beams energies $T_{p,d}$ above a few GeV could be the priority area of $VBLHEP$ research at the $NICA$ collider.

In our previous reports and publications [2–4] we have considered opportunities of studying the spin 1/2 and 1 observables in the elastic interactions of the colliding proton and deuteron beams of the $NICA$ collider. It has been shown that in elastic interactions of colliding proton beams one can measure energy and angular dependencies of the analyzing powers of the reactions with one polarized beam A_{oono} or A_{ooon}, and the spin correlation parameters A_{ookk} and A_{oonn} in collisions of both polarized proton beams. In elastic interactions of the colliding deuteron beams it is possible to obtain a complete set of energy and angular dependencies of components of the vector and tensor analyzing powers A_y, A_{yy}, and A_{xx} for the dN and dd reactions. The planned luminosity of the polarized colliding pp and dd beams will allow one to reach a sufficiently high counting rate of the elastic events in these measurements. The use of the colliding polarized pp and dd beams for the spin-dependent observables research will have a number of significant advantages in comparison with the experiments on the "fixed" target. The angular acceptance of the collider detector covers the full solid angle 4π radians when the wide ranges of the energies of the pp, dd interactions and the 4-momentum transfer squared are available.

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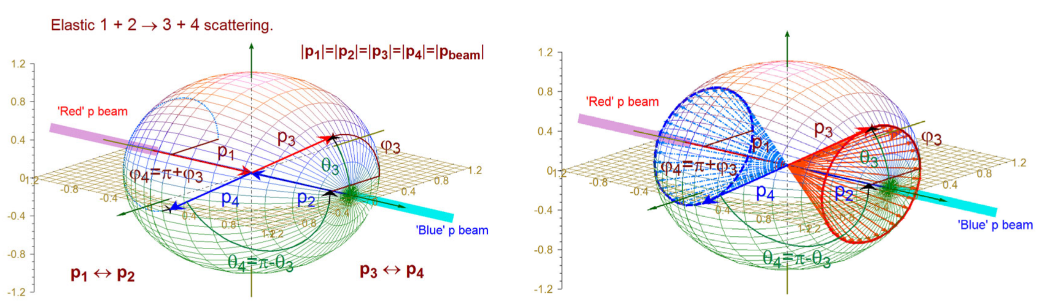
To obtain the values of the spin-dependent pp or dd observables, it is necessary to measure the asymmetry of the outputs of the processes under study, i.e. - the ratio of the difference to the sum of the elastic differential cross sections with opposite signs of polarization of the colliding particles (or right-left asymmetry of the outputs for the same sign of the polarization of the beams).

In this article we discuss the kinematics of the elastic pp and dd scattering processes in the collider system and some of the issues concerning the registration and selection of elastic events. The kinematics features are discussed in the 2-nd section of the paper. The 3-rd section presents the Spin Physics Detector (SPD) elements and Monte Carlo (MC) simulations of scattering events. The fourth section gives the examples of the MC simulations for elastic events in the collider system using the existing experimental data on $d\sigma/d\Omega$ of elastic pp and np collisions.

2 The kinematics of elastic pp and dd scattering in the collider system

To determine possible criteria for the selection of elastic events in interactions of colliding beams, we consider the features of the two-particle $1 + 2 \rightarrow 3 + 4$ kinematics in the collider system. The coordinate system of the collider is simultaneously the laboratory system and Centre-of-Mass system of the colliding particles. The total momentum of the colliding particles and the total momentum of the reaction products are equal to zero. In this case, the momenta of incoming and outgoing particles are equal to each other $|\mathbf{p}_1| = |\mathbf{p}_2| = |\mathbf{p}_3| = |\mathbf{p}_4| = |\mathbf{p}_{beam}|$ and are oriented in the opposite directions $\mathbf{p}_1 \leftrightarrows \mathbf{p}_2$ and $\mathbf{p}_3 \leftrightarrows \mathbf{p}_4$. The equality and opposite direction of the outgoing particle momenta provide a powerful criterion to select elastic pp and dd events in the coordinate system of the collider. A



(a) **(b)**

Figure 1. **(a)** Three-dimensional region of possible values and orientations of the particle momenta in the elastic pp and dd collisions at the $NICA$ collider. **(b)** The distributions of the outgoing particles momenta are isotropic in the azimuthal direction.

three-dimensional range of possible values and orientation of the momentum of the particles in elastic pp and dd collisions in the collider represent a sphere with the radius value of $R = |\mathbf{p}_{beam}|$. Figure 1a. The direction of the momenta of secondary particles is determined by the values of polar θ_3 and θ_4 and azimuthal φ_3 and φ_4 angles of scattering. >From the condition $\mathbf{p}_3 \rightleftarrows \mathbf{p}_4$ it follows that the relation between the polar and azimuthal angles of the outgoing particles should be following: $\theta_4 = \pi - \theta_3$ and $\varphi_4 = \pi - \varphi_3$. The probability of the certain orientation of the $\mathbf{p}_3$ and $\mathbf{p}_4$ vectors is determined by the value of 4-momentum transfer squared $t_{1,3}$ from particle 1 to 3 or from particle 2 to 4. The value of $t_{1,3}$ for pp collisions in the CM system is defined by the following expression: $t_{1.3} = 2m_p^2 - 2E_p^2 + 2p_p^2 cos(\theta_{1,3})$. It is obvious that for the fixed value of $t_{1.3}$, i.e. at the fixed angle θ, the output of the elastic processes will be the same at any value of the azimuthal angle. In the collisions of unpolarized particles the spatial distribution of the outgoing particle momenta is isotropic in azimuthal direction, i.e., for each value of the polar angle θ the value of the azimuthal angle φ is distributed uniformly in the interval $0 \div 2\pi$. See figure 1b.

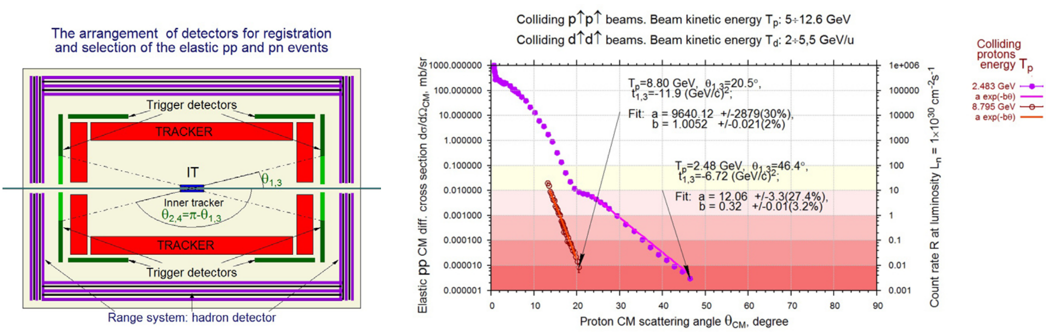
>From the above kinematics, it follows that to select elastic events, you have to register two tracks of secondary particles and be sure that these tracks are oppositely directed. This condition specifies requirements to find the proper detectors for registration and selection of elastic processes in studies with colliding polarized *pp* and *dd* beams of the *NICA* collider.

3 Spin Physics Detector and Monte Carlo simulations of scattering events

The concept of the detector for spin physics studies at the *NICA* collider has been presented in [5]. The required set of devices for the Spin Physics Detector described in this publication can be also successfully used to register the elastic processes. The scheme of the detectors arrangement to register and select the elastic *pp*, *np* and *dd* events is shown in figure 2a. Two-coordinate detectors - internal (*IT*) and external trackers, determine the tracks of secondary particles, i.e., the directions of the scattered reaction products. Hodoscopes of scintillating counters (*HSC*) and resistive plate chambers (*RPC*) are proposed as trigger detectors for the data acquisition system (*DAQ*).

The use of a solenoid magnet in the *SPD* detector provides another powerful criterion for the selection of elastic events. The magnetic field of this magnet shifts the azimuthal φ coordinates of secondary particles that allows one to carry out off-line data processing to determine and compare their momenta. The solenoid magnetic field does not affect θ polar coordinates of secondary particles and so there are no problems in setting the θ trigger.

To register and select of the elastic *neutron-proton* (*np*) events we can use a Range System (*RS*) (particle range detectors) provided by the concept of *SPD*. The use of these detectors will allow us to estimate the energy value of the scattered *neutrons* and determine its approximate θ and φ coordinates. The signal from the selected part of the range detectors will allow one to select and register the elastic *np* events included in the trigger condition.



(a) **(b)**

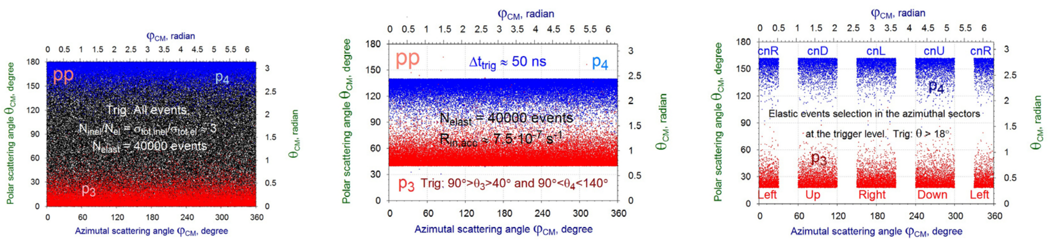
Figure 2. **(a)** The arrangement of detectors in the *SPD* module for registration and selection of the elastic *pp*, *np* and *dd* events. **(b)** Fit of the experimental data sets on the elastic $d\sigma/d\Omega(pp)$ at the *p* beam energies of $T_p = 2.48$ and 8.8 *GeV*.

Angular θ, φ dependencies of the elastic events detected by *SPD* can be visualized by Monte Carlo modeling and used while preparing and carrying out these studies. The values of the parameters required for Monte Carlo simulations can be taken from available sets of experimental data $d\sigma/d\Omega(NN)$ in the Center of Mass (see the compilation [6]). Examples of the experimental $d\sigma/d\Omega(pp)$ and $d\sigma/d\Omega(np)$ data from [6] are shown in figures 2b and 5c.

The scattering events registered by the *SPD* coordinate detectors can be represented by a set of points — the coordinates of particles 3 and 4 in the θ, φ plane. Distributions of elastically scattered particles 3 and 4 in the θ coordinate can be approximated by exponential dependencies taken from the data [6] shown in figures 2b and 5c. The angular φ distribution of the elastic events can be uniform.

For inelastic scattered particles the θ and φ angular distributions can also be uniform. Under the above assumptions generated by the procedure, the Monte Carlo angular θ, φ distributions of elastic and inelastic events without any selection criteria are shown in figure 3a. Here the black dots represent the inelastic events, red – elastic scattering of the proton from the red oncoming beam, and the blue dots - elastic scattering of the proton from the blue beam.

The counting rate R of scattering events in the collider is proportional to the interaction cross section σ_{int} and luminosity of the collider L: $R = \sigma_{int} \cdot L$. The total pp cross sections in the energy range of the $NICA$ collider are following: $\sigma_{tot} \approx 40\ mb$, $\sigma_{tot,el} \approx 10\ mb$ and $\sigma_{tot,in} \approx 30\ mb$. The estimated luminosity of the colliding beams of polarized protons will reach $L_{pp} \approx 1 \cdot 10^{32}\ cm^{-2}s^{-1}$ at beam energies more than $T_p \approx 11\ GeV$ [7]. At $T_p \approx 3\ GeV$ the luminosity is expected to be equal to $L_{pp} \approx 1 \cdot 10^{30}\ cm^{-2}s^{-1}$. In this paper, we consider the examples of nucleon-nucleon collisions at energies of colliding nucleons $T_p = 2.48\ CeV$, $T_p = 8.8\ GeV$ and $T_n \approx 1.43\ GeV$. Due to these estimates at $T_p = 8.8\ GeV$ we have used the value $L_{pp} \approx 1 \cdot 10^{32}\ cm^{-2}s^{-1}$, and for the other energies the values of $L_{pp} \approx 1 \cdot 10^{30}\ cm^{-2}s^{-1}$. Then the expected counting rates will be $R_{el} \approx 1 \cdot 10^4 s^{-1}$ and



(a) **(b)** **(c)**

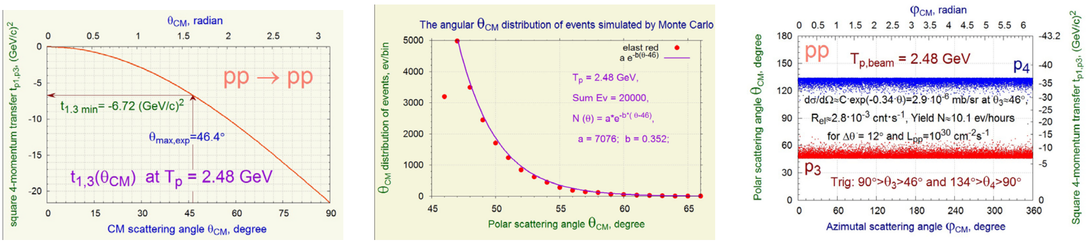
Figure 3. **(a)** Example of a Monte Carlo simulation for all the events without selection. **(b)** Simulation of elastic pp events with two trigger conditions. **(c)** The left-right and up-down events selection in the azimuthal sectors at the trigger level.

$R_{in} \approx 3 \cdot 10^4 s^{-1}$. When the trigger signal duration is $\Delta t \sim 50\ ns$, the probability of the inelastic event presence in this interval is $p_{in} \sim R_{in} \cdot 5 \cdot 10^{-8} = 1.5 \cdot 10^{-3}$ and of the elastic ones is $p_{el} \sim 5 \cdot 10^{-4}$. The counting rate of accidental coincidences, i.e. the probability of detecting the inelastic events along with the elastic ones with trigger conditions for the given scattering angle $C3$: $90^\circ \geq \theta_3 \geq C_3^\circ$ and $90^\circ \leq \theta_4 \leq \pi - C_3^\circ$, will be $R_{acc} \approx p_{el} \cdot R_{in} \approx 7.5 \cdot 10^{-7} s^{-}1$. This level of accidentals leads to almost complete absence of inelastic events in the following figures for the results of the MC simulations.

Figures 3b and 3c show examples of using different types of trigger conditions for the elastic pp events selected in the θ, φ plane. Selection of the elastic events in the given range only of the polar angles $\theta_{3,4}$ (fig. 3b) provides the maximum event rate. In $\vec{d}\vec{d}$ collisions to measure all the components of polarization observables, it is required to measure the left-right and up-down asymmetries of the outputs of the elastic process. In this case, the trigger detectors must identify separately $\Delta\varphi$ zones of scattering particles of the "red" beam to the left, right, up and down in the forward hemisphere ($0 < \theta < 90^\circ$) and the corresponding $\Delta\varphi$ areas of conjugated particles of the "blue" beam scattered in the back hemisphere ($90^\circ < \theta < 180^\circ$).

4 Examples of Monte Carlo simulation for pp and np collisions

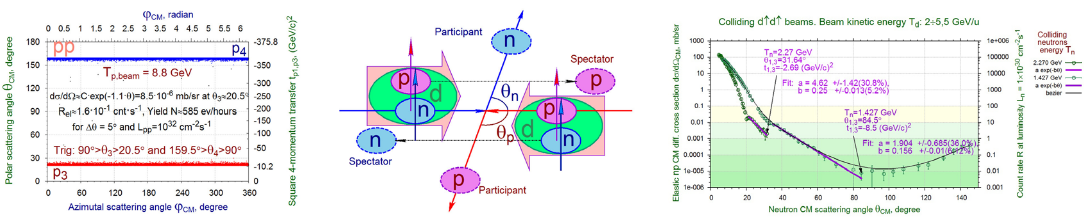
By fitting the experimental θ angular dependencies of $d\sigma/d\Omega(pp)$ and $d\sigma/d\Omega(np)$ [6] from figure 2b and 5c, we get the values of the slope parameters of exponents to use Monte Carlo visualization for these processes. The values of $d\sigma/d\Omega$ from these data at the maximal angle θ_{max} allow us to estimate the event counting rate at this angle. The results of Monte Carlo simulations for the energies of colliding protons of $T_p = 2.48\ GeV$ and $T_p = 8.8\ GeV$ are given in figure 4 and figure 5a. Figure 4a shows the dependence of $t_{1,3}(\theta)$ in the range of $0 \leq \theta \leq 90^\circ$ for $d\sigma/d\Omega(pp)$ data at



(a) **(b)** **(c)**

Figure 4. **(a)** The range of $t_{1,3}(\theta_3)$ values when $0 \leq \theta_3 \leq 90°$ for pp at $T_p = 2.48\ GeV$. **(b)** The θ_{CM} distribution of the events simulated by MC procedure at $T_p = 2.48\ GeV$. **(c)** Results of the MC simulations for pp at $T_p = 2.48\ GeV$.

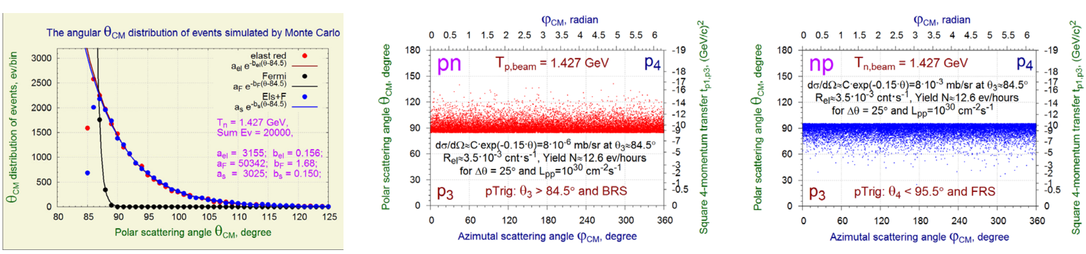
$T_p = 2.48\ GeV$. The maximal angle and the corresponding $t_{1,3}(\theta_{max})$ value are indicated. Generated by the MC procedure the θ distributions of elastic and quasi-elastic events are shown in figure 4b for pp collisions at $T_p = 2.48\ GeV$, and in figure 6a for np collisions at $T_n = 1.427\ GeV$. Figs. 4c, 5a, 6b, and 6c show the MC generated θ, φ distributions of the elastic events and the expected counting rates $R(\theta) = L \int\int d\sigma/d\Omega(\theta)\cdot sin\theta\cdot d\theta d\varphi \simeq 2\pi L d\sigma/d\Omega(\theta)\cdot sin\theta\cdot\Delta\theta\,[s^{-1}]$ and yields $Y(\theta) = R(\theta)\cdot 3.6\cdot 10^3\ [h^{-1}]$ in the specified band $[\theta_{max} \div \theta_{max} + \Delta\theta]$ at the number of T_{beam} values.



(a) **(b)** **(c)**

Figure 5. **(a)** Results of the Monte Carlo simulations for pp collisions at $T_p = 8.8\ GeV$. **(b)** The quasi-elastic $\vec{N}\vec{N}$ scattering in the polarized deuteron $\vec{d}\vec{d}$ collisions. **(c)** Fit of the experimental data sets on $d\sigma/d\Omega$ for elastic np scattering at the energies of the colliding dd beams at $T_d = 2.85$ and $4.54\ GeV$.

Assuming that the deuteron is a weakly bounded system, one can apply the formalism of elastic pp scattering to describe a quasi-elastic NN scattering independently on each nucleon in the deuteron. See figure 5b. The nucleons in the deuteron have the same value and orientation of polarization as the



(a) **(b)** **(c)**

Figure 6. **(a)** The θ_{CM} distribution of events simulated by the MC procedure at $T_n = 1.427\ GeV$. **(b)** Results of the MC simulations for pn collisions at $T_n = 1.427\ GeV$. **(c)** The same but for np collisions.

deuteron itself $\vec{P}_N = \vec{P}_d$ and half deuteron kinetic energy $T_N = 0.5\ T_d$. The Fermi motion of nucleons in the deuteron influences weakly on the angular distribution of scattering products $\Delta\theta_{Fm} < 22\ mrad$ at $p_p \sim 2.2\ GeV/c$. The Gaussian momentum spread of the nucleon in the deuteron is also small $\sigma_p \approx 2.5\%$. Results of the MC simulations for pn and np collisions at $T_n = 1.427\ GeV$ are presented in figure 6. Figure 6a shows the θ distributions simulated by the MC procedure at $T_n = 1.427\ GeV$

for: - elastic *np* scattering (red dots and curve); - due to the Fermi motion of the nucleons in the deuteron (black dots and curve); and - elastic scattering + Fermi motion (blue dots and curve). The effect of Fermi motion is noticeable only within the limits of its θ distribution. Trigger conditions for the distributions of figure 6b and 6c include HSC or/and RPC signal $\theta_3 > 84.5°$ from the *pn* scattered proton and the signal of the scattered neutron from the corresponding backward part of the RS detectors - BRS and vice versa for the *np* scattering.

5 Conclusion

The features of the kinematics of the processes of elastic *pp* and *dd* scattering in the collider system have been considered. The equality and opposite direction of the momenta of the scattered particles provide a powerful selection criterion for elastic collisions in this system. Possible choices of the trigger signal to register the tracks of secondary particles and data acquisition system have been given.

According to available $d\sigma/d\Omega_{CM}(pp)$ and $d\sigma/d\Omega_{CM}(np)$ data in the energy range of the $NICA$ collider we have estimated the parameters of the angular distributions for the Monte Carlo simulations of these processes. The results of MC simulations of the elastic and quasi-elastic *pp* and *np* processes and estimations of counting rates and outputs of these reactions at specified scattering angles have been given. The presented examples of the MC simulations of elastic events can be used in the research of elastic *pp*, *np*, and *dd* interactions in the colliding beams at the $NICA$ collider. The obtained results have shown that in the colliding *pp* and *dd* beams at the $NICA$ collider can obtain a sufficiently high counting rate and outputs of the elastic collision events.

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