Spin Observables of Proton–Deuteron Elastic Scattering at SPD NICA Energies within the Glauber Model and pN Amplitudes

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Abstract—A systematic analysis of nucleon-nucleon scattering amplitudes is available up to a laboratory energy of 3 GeV in case of the \textit{pp} system and up to 1.2 GeV for \textit{pn}. At higher energies there is only incomplete experimental information on \textit{pp} elastic scattering, whereas data for the \textit{pn} system are very scarce. We apply the spin-dependent Glauber theory to calculate spin observables of \textit{pd} elastic scattering at 3–50 GeV/c using \textit{pp} amplitudes available in the literature and parametrized within the Regge formalism. The calculated vector \textit{A}_\textit{v}, \textit{A}_\textit{v}, and tensor \textit{A}_\textit{x}, \textit{A}_\textit{y}, analyzing powers and the spin-correlation coefficients \textit{C}_{\textit{yy,y}}, \textit{C}_{\textit{x,x}}, \textit{C}_{\textit{yy,y}}, \textit{C}_{\textit{x,x},y} can be measured at SPD NICA and, thus, will provide a test of the used \textit{pN} amplitudes.

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INTRODUCTION

The spin amplitudes of \textit{pp} and \textit{pn} elastic scattering contain important information on the dynamics of the \textit{NN} interaction. A systematic reconstruction of these amplitudes from scattering data is provided by the SAID partial-wave analysis [1] and covers laboratory energies up to 3 GeV (\textit{p}_\text{lab} = 3.8 \text{ GeV/c}) for \textit{pp} and 1.2 GeV (\textit{p}_\text{lab} = 1.9 \text{ GeV/c}) for \textit{pn} scattering. At higher energies there is only incomplete experimental information on \textit{pp} scattering, whereas data for the \textit{pn} system are very scarce. In the literature there are some parametrizations for \textit{pN} amplitudes, obtained in the eikonal model [2] for the laboratory momentum 6 GeV/c and within the Regge phenomenology [3] for 3–50 GeV/c (corresponding to 2.77 < \sqrt{s} < 10 \text{ GeV}). Another Regge-type parametrization for values of \textit{s} above 6 GeV\textsuperscript{2} (\textit{p}_\text{lab} \geq 2.2 \text{ GeV/c}) was presented in [4]. A possible way to check existing parametrizations is to study spin effects in proton-deuteron (\textit{pd}) and neutron-deuteron (\textit{nd}) elastic and quasi-elastic scattering. At high energies and small four-momentum transfer \textit{t}, \textit{pd} scattering can be described by the Glauber diffraction theory of multistep scattering, which involves as input on-shell \textit{pN} elastic scattering amplitudes. Applications of this theory with spin-dependent effects included [5] indicate a good agreement with the \textit{pd} scattering data at energies about 1 GeV if the SAID values for the \textit{pN} scattering amplitudes are used as starting point of the calculations [6–8].

In the present work we apply the spin-dependent Glauber theory [5, 6] to calculate spin observables of \textit{pd} elastic scattering at 5–50 GeV/c utilizing the \textit{pp} elastic scattering amplitudes established and parametrized in [3] within the Regge formalism. As a first approximation, for the \textit{pn} amplitudes we use likewise the ones for \textit{pp} from [3]. We should note that, in principle, the Regge approach allows one to construct \textit{pn} (and \overline{\textit{pN}}) amplitudes together with the \textit{pp} amplitudes. However, in view of the scarce experimental information on the spin-dependent \textit{pn} amplitudes and taking into account that the spin-independent parts of the \textit{pp} and \textit{pn} amplitudes at high energies are approximately the same, we assume here that the whole \textit{pn} amplitude is the same as that for \textit{pp}. The calculated vector \textit{A}_\textit{v}, \textit{A}_\textit{v}, and tensor analyzing powers \textit{A}_\textit{x}, \textit{A}_\textit{y}, and the spin-correlation coefficients \textit{C}_{\textit{yy},y}, \textit{C}_{\textit{x},x}, \textit{C}_{\textit{yy},y}, \textit{C}_{\textit{x},x}, \textit{y} can be measured at SPD NICA [9], which will provide a serious test of the used \textit{pN} amplitudes. A knowledge of \textit{pN} helicity amplitudes is required in preparation and subsequent analysis of experiments for search of time-reversal invariance violation effects in double-polarized \textit{pd} scattering [10, 11].
ELEMENTS OF FORMALISM

The reaction amplitude \( pd \rightarrow pd \) can be written as [6]

\[
\langle p' \mu', d' \lambda' | T | p \mu, d \lambda \rangle = \phi_{\mu}^{(\lambda)} \phi_{\mu'}^{(\lambda')} T_{\beta\alpha} (p, p', \sigma) \phi_{\alpha}^{(\lambda)}, \quad (1)
\]

where \( \phi_{\mu}^{(\lambda)} \) (\( \phi_{\mu'}^{(\lambda')} \)) is the Pauli spinor of the initial (final) proton in the state with spin projection \( \mu \) (\( \mu' \)) onto the quantization axis, \( \phi_{\alpha}^{(\lambda)} \) \( (\phi_{\alpha'}^{(\lambda')} \) \) is the polarization vector of the initial \( (\text{final} \ d' \) deuteron in the state with the spin projection \( \lambda \) \( (\lambda' \) \), and \( T_{\beta\alpha} \) is the dynamical tensor

\[
T_{xx} = M_1 + M_2 \sigma_y, \quad T_{xy} = M_3 \sigma_z + M_5 \sigma_y, \quad T_{xz} = M_9 + M_{10} \sigma_y, \quad T_{yx} = M_3 \sigma_z + M_5 \sigma_y, \quad T_{yy} = M_9 + M_{10} \sigma_y, \quad T_{yz} = M_5 + M_{10} \sigma_y, \quad T_{zx} = M_9 + M_{10} \sigma_y, \quad (2)
\]

where \( M_i \) \( (i = 1, \ldots, 18) \) are complex amplitudes determined by the dynamics of the reaction. As was mentioned in [6], under the operation of time reversal this reference frame is rotated around the OY axis on the scattering angle \( \theta \) that is the angle between the vectors \( p \) and \( p' \). This complicates the formulation of the time-reversal (T) invariance conditions as compared to other (non-Madison) reference frames, like in [5] and, therefore, we do not write them explicitly. However, the amplitudes \( M_i \) \( (i = 1, \ldots, 18) \) satisfy T-reversal invariance since they are explicitly expressed as linear combinations of the T-reversal invariant amplitudes \( A_i \) \( (i = 1, \ldots, 12) \) of \( pd \) scattering introduced in [5].

The spin observables \( A_y, A_z \) and \( C_{ijk} \) defined in the notation of [13] and considered in the present work, have the following form in terms of the amplitudes \( M_i \),

\[
\frac{d\sigma}{dt} = \frac{1}{6} \text{Tr} \left[ M M^+ \right]^2, \quad \text{Tr} \left[ M M^+ \right] = 2 \sum_{i=1}^{18} |M_i|^2, \quad (3)
\]

\[
A_y = \text{Tr} M S_y M^+ / \text{Tr} M M^+ = -\frac{2}{18} \text{Im}(M_1 M_9^*),
\]

\[
+ M_2 M_{10}^* + M_{11} M_{12}^* + M_{13} M_{14}^* + M_{15} M_5^* + M_{16} M_6^*, \quad A_y^e = \text{Tr} M S_y M^+ / \text{Tr} M M^+ = \frac{2}{18} \text{Re}(M_1 M_2^*),
\]

\[
+ M_3 M_9^* + M_4 M_5^* + M_6 M_7^* - \text{Im}(M_8 M_7^* + M_9 M_{10}^* + M_{11} M_{12}^* + M_{13} M_{14}^*), \quad A_{yy} = \text{Tr} M P_{yy} M^+ / \text{Tr} M M^+ = 1 - \frac{3}{18} \sum_{i=1}^{18} |M_i|^2
\]

\[
\times (|M_3|^2 + |M_4|^2 + |M_5|^2 + |M_7|^2 + |M_{10}|^2 + |M_{13}|^2),
\]

\[
A_{x} = \text{Tr} M P x M^+ / \text{Tr} M M^+ = 1 - \frac{3}{18} \sum_{i=1}^{18} |M_i|^2
\]

\[
\times (|M_3|^2 + |M_4|^2 + |M_5|^2 + |M_7|^2 + |M_{10}|^2 + |M_{13}|^2),
\]

\[
A_{x} = \frac{3}{2} (S_y S_y + S_y S_y) - 2 S_y, \quad \text{and} \quad S_y \quad (j = x, y, z) \quad \text{are} \quad \text{Cartesian components of the spin operator for the system with} \ S = 1.
\]

In [5] (PK) the general spin structure of the transition operator \( pd \rightarrow pd \) is written in a different representation

\[
\text{Im}(M_2 M_5^* + M_{10} M_{15}^* + M_{16} M_6^*) + \text{Re}(M_{14} M_{12}^* - M_{13} M_{11}^*),
\]

\[
C_{xx,y} = \text{Tr} M x x y M^+ / \text{Tr} M M^+ = A_{x}^e - \frac{6}{18} \sum_{i=1}^{18} |M_i|^2
\]

\[
\times \text{Im}(M_8 M_9^* + M_3 M_{11}^* + M_{17} M_5^*),
\]

\[
C_{yy,y} = \text{Tr} M y y y M^+ / \text{Tr} M M^+ = A_{y}^e - \frac{6}{18} \sum_{i=1}^{18} |M_i|^2
\]

\[
\times \text{Re}(M_2 M_1^* + M_{16} M_4^*) - \text{Im}(M_{14} M_{15}^*),
\]

\[
C_{yy,y} = \text{Tr} M y y y M^+ / \text{Tr} M M^+ = A_{y}^e - \frac{6}{18} \sum_{i=1}^{18} |M_i|^2
\]

\[
\times \text{Re}(M_3 M_4^* - \text{Im}(M_{17} M_8^* + M_9 M_7^*)},
\]

where \( \mathcal{P}_y = \frac{3}{2} (S_y S_y + S_y S_y) \).
and in another reference frame with axis $OX' \uparrow \uparrow \hat{q}$, $OZ' \uparrow \uparrow \hat{k}$, $OY' \uparrow \uparrow \hat{n}$, where $\hat{q} = (\mathbf{p} - \mathbf{p}')/|\mathbf{p} - \mathbf{p}'|$, $\hat{k} = (\mathbf{p} + \mathbf{p}')/|\mathbf{p} + \mathbf{p}'|$, $\hat{n} = [\mathbf{k} \times \mathbf{q}]$ forming the right-handed system ($\mathbf{p}$ and $\mathbf{p}'$ being the momenta of the incident and outgoing proton, respectively).

The amplitudes of $pN$ elastic scattering are written as [5]

\begin{equation}
M_N(\mathbf{p}, \mathbf{q}; \sigma, \sigma_N) = A_N + C_N \sigma \hat{n} + C'_N \sigma_N \hat{n} + B_N (\sigma \hat{k}) (\sigma_N \hat{k}) + (G_N + H_N) \times (\sigma \hat{q}) (\sigma_N \hat{q}) + (G_N - H_N) (\sigma \hat{u}) (\sigma_N \hat{u}),
\end{equation}

where the complex numbers $A_N$, $C_N$, $C'_N$, $B_N$, $G_N$, $H_N$ were fixed from the amplitudes of the SAID analysis [1] and parametrized by a sum of Gaussians. For the double scattering term in $pd$ scattering the unit vectors $\hat{k}$, $\hat{q}$, $\hat{u}$ are defined separately for each individual $NN$ collision.

The amplitude (4) is normalized in such a way that the invariant differential cross section has the following form:

\begin{equation}
\frac{d\sigma_N}{dt} = \frac{1}{4} \text{Tr} M_N M_N^*.
\end{equation}

Some additional results of calculations within this approach were reported recently in [8].

**NUMERICAL RESULTS**

The relations between the $pN$ amplitudes $A_N$, $B_N$, $C_N$, $G_N$, $H_N$ and the helicity amplitudes $\phi_1$, $\phi_2$, $\phi_3$, and $\phi_5$, and the corresponding expansion in terms of exponential functions are the following

\begin{align}
A_N(q) &= (\phi_1 + \phi_5)/2 = \sum_j C_{a,j} \exp(-A_{a,j} q^2), \\
B_N(q) &= (\phi_1 - \phi_5)/2 = \sum_j C_{b,j} \exp(-A_{b,j} q^2), \\
C_N(q) &= i \phi_2 = q \sum_j C_{c,j} \exp(-A_{c,j} q^2), \quad (6) \\
G_N(q) &= \phi_3/2 = \sum_j C_{g,j} \exp(-A_{g,j} q^2), \\
H_N(q) &= \phi_4/2 = q^2 \sum_j C_{h,j} \exp(-A_{h,j} q^2),
\end{align}

where $q^2 = -t$. Note that $C'_N$ in Eq. (4) is given by $C'_N(q) = C_N(q) + i(q/2m)A_N(q)$ [5], with $m$ being the nucleon mass.

Numerical values for the parameters of the Gaussians in Eqs. (6) are obtained by fitting to the helicity amplitudes from [3]. Those for $p_{lab} = 45$ GeV/c are summarized in Table 1. Note that the parameters for the real and imaginary parts of the amplitudes are given separately. Also, we would like to mention that $\phi_1 \equiv \phi_3$ in the model by Sibirtsev et al., see Eq. (12) of that
work, and, accordingly, $B_X \equiv 0$. The differential cross section of $pp$ elastic scattering and the vector analyzing power $A_y$ are reproduced with these parameterizations on the same level of accuracy as in [3], in the interval of transferred four momentum $-t < 1.5$ (GeV/c)$^2$. As example, in Fig. 1 we show results for the latter, by the model (dotted line) and by the parameterization (solid line).

In the next step we performed calculations for the $pd$ observables listed in Eqs. (3) at $p_{lab} = 4.68$ and 45 GeV/c, using these Gaussian parameterizations of the $pN$ amplitudes. Results for the differential cross section are shown in Fig. 2 while a selection of spin-dependent observables is presented in Figs. 3 and 4. In the latter figures the results at 4.68 GeV/c are indicated by the dashed lines, those at 45 GeV/c by solid lines. One can see from Fig. 2 that available data on the elastic differential cross section in the forward hemisphere are well described by our calculations. As was mentioned in the Introduction, we assume here that the $A_p$ amplitudes are identical to the $G_p$ amplitudes. Fig. 3 shows that the vector analyzing power $A_y^p$ decreases significantly in absolute value with increasing energy and a similar behaviour is exhibited by $A_y^d$. In contrast, the spin correlation coefficients $C_{s,x}$ and $C_{y,x}$ show the opposite tendency (cf. Fig. 4). Coulomb

### Table 1. Parameters of the $pN$ amplitudes at $p_{lab} = 45$ GeV/c, cf. Eq. (6). The dimension $n$ for the coefficients $C_{\alpha,j}$ depends on the power of the $q$ factor in Eqs. (6) and is $n = 1$ for $A_p$ and $G_p$, $n = 2$ for $C_p$ and $n = 3$ for $H_p$.

| $j$ | $A_y^p$, mb$^{1/2}$/GeV$^2$ | $A_y^d$, GeV$^{-2}$ | $A_y^p$, mb$^{1/2}$/GeV$^2$ | $A_y^d$, GeV$^{-2}$ |
|-----|-----------------|------------------|-----------------|------------------|
| 1   | $-0.10113182E+00$ | $0.26000000E+01$ | $-0.50868385E-01$ | $0.26000000E+01$ |
| 2   | $-0.30272788E+00$ | $0.39000000E+01$ | $0.45135636E+01$ | $0.45000000E+01$ |
| 3   | $0.3625621E-01$   | $0.62769552E+01$ | $0.54701498E+01$ | $0.79740115E+00$ |
| 4   | $0.69044456E+00$  | $0.93549981E+01$ | $-0.10151078E+02$ | $0.12472690E+02$ |
| 5   | $-0.14278735E+01$ | $0.13000000E+02$ | $0.16289509E+02$ | $0.17800000E+02$ |
| 6   | $0.12152644E+01$  | $0.17134442E+02$ | $-0.12268618E+02$ | $0.23842646E+02$ |
| 7   | $-0.14350110E+01$ | $0.21706020E+02$ | $0.46423346E+01$ | $0.30524183E+02$ |

| $j$ | $C_{\alpha,j}$, mb$^{1/2}$/GeV$^2$ | $A_{\alpha,j}$, GeV$^{-2}$ |
|-----|-----------------|------------------|
| 1   | $0.74355080E-01$ | $0.26000000E+01$ |
| 2   | $-0.16130899E+01$ | $0.44000000E+01$ |
| 3   | $0.45217973E+01$ | $0.76911688E+01$ |
| 4   | $-0.54780216E+01$ | $0.11953074E+02$ |
| 5   | $0.49683911E+01$ | $0.17000000E+02$ |
| 6   | $0.49231089E+01$ | $0.22724612E+02$ |
| 7   | $0.10015797E+02$ | $0.29054489E+02$ |

| $j$ | $G_{\alpha,j}$, mb$^{1/2}$/GeV$^2$ | $A_{\alpha,j}$, GeV$^{-2}$ |
|-----|-----------------|------------------|
| 1   | $0.31798066E+00$ | $0.26000000E+01$ |
| 2   | $-0.33729009E+01$ | $0.46000000E+01$ |
| 3   | $0.24771736E+02$ | $0.82568542E+01$ |
| 4   | $-0.10758994E+02$ | $0.12992305E+02$ |
| 5   | $0.15394572E+02$ | $0.18600000E+02$ |
| 6   | $-0.13147804E+02$ | $0.24960680E+02$ |
| 7   | $0.45696137E+01$ | $0.31993877E+02$ |

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Fig. 2. Differential cross section for $pd$ elastic scattering. Predictions are shown for $p_{\text{lab}} = 4.8$ (left) and 45 GeV/c (right). Data are taken from [18] (4.8 GeV/c) and [19] (48.9 GeV/c).

Fig. 3. Results for spin-dependent $pd$ observables. Predictions for $p_{\text{lab}} = 4.8$ GeV/c are shown by dashed lines while those at 45 GeV/c correspond to the solid lines. For the latter, the effect of the Coulomb interaction is indicated by the dash-dotted lines.
effects are taken into account here in the \( pp \) amplitude in the same way as in [6] and give a rather small contribution, as can be seen from Figs. 3a, 3b). One should note that the tensor analyzing powers \( A_{xx} \) and \( A_{yy} \), shown in Fig. 4, depend only weakly on the energy. Moreover, these observables do not change qualitatively in forward direction if all spin-dependent amplitudes are excluded and only the spin-independent amplitude \( A_c \) from Eq. (4) is taken into account, cf. the dotted lines. On the hand, the spin correlation parameters \( C_{x,x} \), \( C_{y,y} \) practically vanish in this case (Figs. 4a, 4c).

**CONCLUSIONS**

Nucleon-nucleon elastic scattering is a basic process in the physics of atomic nuclei and the interaction of hadrons with nuclei. Full information about the spin dependent \( pN \) amplitudes can be obtained, in principle, from a complete polarization experiment, which, however, requires to measure twelve independent observables at a given collision energy and, thus, constitutes a too complicated experimental task. On the other hand existing models and corresponding parametrizations of \( pp \) amplitudes in the region of small transferred momenta can be effectively tested by a measurement of spin observables for \( pd \) scattering and a subsequent comparison of the results with corresponding Glauber calculations. The spin observables of \( pd \) elastic scattering studied and evaluated in the present work are found to be not too small and, thus, could be measured at the future SPD NICA facility.

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**CONFLICT OF INTEREST**

The authors declare that they have no conflicts of interest.

Fig. 4. Results for spin-dependent \( pd \) observables. Same description of curves as in Fig. 3. The dotted lines are results where the spin-dependent \( pN \) amplitudes have been omitted in the calculation.
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