The $NN$ final-state interaction in the helicity structure of $d(\vec{\gamma}, \pi^-)pp$ reaction

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Abstract

The influence of final-state $NN$-rescattering on the helicity structure of the $\vec{\gamma}d \rightarrow \pi^- pp$ reaction in the energy range from $\pi$-threshold up to 550 MeV has been investigated. The differential polarized cross-section difference for the parallel and antiparallel helicity states is predicted and compared with recent experimental data. It is shown that the effect of $NN$-rescattering is much less important in the polarized differential cross-section difference than in the previously studied unpolarized differential cross section. Furthermore, the contribution of $\vec{\gamma}d \rightarrow \pi^- pp$ to the spin asymmetry of the deuteron is explicitly evaluated over the region of the $\Delta(1232)$-resonance with inclusion of $NN$-rescattering. The effect of $NN$ final-state interaction is found to be much larger in the asymmetry than in the total cross section and leads to an appreciable reduction of the spin asymmetry in the $\Delta$-region.

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1 Introduction

A still very interesting topic in intermediate energy nuclear physics is concerned with the quasifree pion production reaction in nuclei which is governed by three main mechanisms: (i) The elementary amplitudes of the four pion production channels possible on the nucleon, (ii) The Fermi motion of the proton and neutron inside the nucleus, and (iii) The interaction between the final-state hadrons. The investigation of pion photo- and electroproduction has the potential to become an important aspect in meson physics since many important features of the electromagnetic and hadronic reactions can be studied.

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through these processes. Interest in this topic has increased mainly through
the construction of new high-duty continuous electron beam machine such as
MAMI in Mainz or ELSA in Bonn.

The particular interest in pion photoproduction on the deuteron lies in the fact
that the simple and well known deuteron structure allows one to obtain informa-
tion on the production process on the neutron which otherwise is difficult
to obtain in view of the absence of any free neutron targets. The earliest cal-
culations for pion photoproduction on the deuteron were performed using the
impulse approximation (IA) [1,2]. Approximate treatments of final-state in-
teraction (FSI) effects within a diagrammatic approach have been reported in
[3,4,5]. The authors noted that the FSI effects are quite small for the charged-
pion production channels in comparison to the neutral one. Photoproduction
of pions on the deuteron has been investigated in the spectator nucleon model
[6] neglecting all kinds of FSI and two-body processes. The $NN$-FSI has been
considered in [7] and good agreement with experiment was achieved. The influ-
ence of final-state $NN$- and $\pi N$-rescattering on the unpolarized cross sections
has been investigated in [8]. It has been found that $\pi N$-rescattering is much
less important (in general negligible) compared to $NN$-rescattering. Inclusion
of such effects leads to good agreement with experiment. The role of the $N\Delta$
- FSI in the pion photoproduction off the deuteron has been investigated in [9].
It has been shown that full calculations with the off-shell amplitudes of $NN$-
and $N\Delta$-FSI are necessary to obtain a quantitative description of the cross
sections.

Up to now, most of calculations have considered only the unpolarized ob-
servables like differential and total cross sections. These cross sections pro-
vide information only on the sum of the absolute squares of the amplitudes,
whereas polarization observables allow extraction of more information. Ob-
servables with polarized photon beam and/or polarized deuteron target have
been poorly investigated. The particular interest in these observables is based
on the fact that, a series measurements of the polarization observables in pho-
toproduction reactions have been carried out or planned at different laborato-
ries. The GDH collaboration has undertaken a joint effort towards the experi-
mental verification of the Gerasimov-Drell-Hearn (GDH) sum rule, measuring
the difference of the helicity components in total and differential photoabsorp-
tion cross sections. Our goal is to analyze these experimental measurements.

Recently, polarization observables for incoherent pion photoproduction on the
deuteron have been studied in [10,11,12,13,14,15]. $\pi^-$-production channel has
been studied within a diagrammatic approach [10] including $NN$- and $\pi N$-
rescattering. In that work, predictions for analyzing powers connected to beam
and target polarization, and to polarization of one of the final protons are
presented. In our previous evaluation [11], special emphasize is given for the
beam-target spin asymmetry and the GDH sum rule. Single- and double-spin
asymmetries for incoherent pion photoproduction on the deuteron have been predicted in [12,13,14] without any kind of FSI effects. The target tensor analyzing powers of the $d(\gamma, \pi^-)pp$ reaction have been studied in the plane wave impulse approximation [15]. Most recently, our evaluation [11] has been extended to higher energies in [16] with additional inclusion of two-pion and eta production.

As a further step in this study, we investigate in this paper the influence of $NN$ FSI effect on the polarized differential and total cross sections with respect to parallel and antiparallel spins of photon and deuteron for $\gamma d \rightarrow \pi^- pp$. Our second point of interest is to analyze the recent experimental data from the GDH collaboration [17]. With respect to the interactions in the final two-body subsystems, only the $NN$-rescattering is obtained into account since $\pi N$-rescattering has been considered as negligible [7,8].

In Sect. 2 of this paper, the model for the elementary $\gamma N \rightarrow \pi N$ and $NN \rightarrow NN$ reactions which will serve as an input for the reaction on the deuteron is briefly reviewed. Sect. 3 will introduce the general formalism for incoherent pion photoproduction on the deuteron. The separate contributions of the IA and the $NN$-rescattering to the transition matrix are described in this section. Details of the actual calculation and the results are presented and discussed in Sect. 4. Finally, a summary and conclusions are given in Sect. 5.

2 The elementary $\gamma N \rightarrow \pi N$ and $NN \rightarrow NN$ reactions

Pion photoproduction on the deuteron is governed by basic two-body processes, namely pion photoproduction on a nucleon and hadronic two-body scattering reactions. For the latter only nucleon-nucleon scattering is considered in this work. As already mentioned in the introduction, $\pi N$-rescattering is found to be negligible and thus it is not considered in the present calculation.

The starting point of the construction of an operator for pion photoproduction on the two-nucleon space is the elementary pion photoproduction operator on a single nucleon, i.e., $\gamma N \rightarrow \pi N$. In the present work we will examine the various observables for pion photoproduction on the free nucleon using, as in our previous work [8], the effective Lagrangian model developed by Schmidt et al. [6]. The main advantage of this model is that it has been constructed to give a realistic description of the $\Delta(1232)$-resonance region. It is also given in an arbitrary frame of reference and allows a well defined off-shell continuation as required for studying pion production on nuclei. This model consists of the standard pseudovector Born terms and the contribution of the $\Delta(1232)$-resonance. For further details with respect to the elementary pion photoproduction operator we refer to [6]. As shown in Figs. 1-3 in our previ-
ous work [8], the results of our calculations for the elementary process are in
good agreement with recent experimental data as well as with other theoretical
predictions and gave a clear indication that this elementary operator is
quite satisfactory for our purpose, namely to incorporate it into the reaction
on the deuteron.

For the nucleon-nucleon scattering in the $NN$-subsystem we use in this work a
specific class of separable potentials [18] which historically have played and still
play a major role in the development of few-body physics and also fit the phase
shift data for $NN$-scattering. The EST method [19] for constructing separable
representations of modern $NN$ potentials has been applied by the Graz group
[18] to cast the Paris potential [20] in separable form. This separable model
is most widely used in case of the $\pi NN$ system (see for example [21] and
references therein). Therefore, for the present study of the influence of
$NN$-rescattering this model is good enough.

3 $\pi$-photoproduction off the deuteron

The formalism of incoherent pion photoproduction on the deuteron is pre-
sented in detail in our previous work [8]. Here we briefly recall the necessary
notation and definitions. The general expression for the unpolarized cross sec-
tion according to [22] is given by

$$
d\sigma = \frac{\delta^4(k + d - p_1 - p_2 - q) M_N^2 d^3 p_1 d^3 p_2 d^3 q}{96(2\pi)^5 |\vec{v}_\gamma - \vec{v}_d| \omega_\gamma E_d E_1 E_2 \omega_q}
\times \sum_{s m t, m_\gamma, m_d} |\mathcal{M}^{(t \mu)}_{s m m_\gamma, m_d}(\vec{p}_1, \vec{p}_2, \vec{q}, \vec{k}, \vec{d})|^2,
$$

where $k = (\omega_\gamma, \vec{k})$, $d = (E_d, \vec{d})$, $q = (\omega_q, \vec{q})$, $p_1 = (E_1, \vec{p}_1)$ and $p_2 = (E_2, \vec{p}_2)$ de-
ote the 4-momenta of photon, deuteron, pion and two nucleons, respectively.
Furthermore, $m_\gamma$ denotes the photon polarization, $m_d$ the spin projection of
the deuteron, $s$ and $m$ total spin and projection of the two outgoing nucleons,
respectively, $t$ their total isospin, $\mu$ the isospin projection of the pion, and
$\vec{v}_\gamma$ and $\vec{v}_d$ the velocities of photon and deuteron, respectively. The transition
amplitude is denoted by $\mathcal{M}$. Covariant state normalization in the convention
of [22] is assumed.

This expression is evaluated in the lab or deuteron rest frame. A right-handed
coordinate system is chosen where the $z$-axis is defined by the photon momentum
$\vec{k}$ and the $y$-axis by $\vec{k} \times \vec{q}$. The scattering plane is defined by the momenta
of photon $\vec{k}$ and pion $\vec{q}$ whereas the momenta of outgoing nucleons $\vec{p}_1$ and $\vec{p}_2$
define the nucleon plane (see Fig. 1). As independent variables, the pion mo-
mentum $q$, its angles $\theta_\pi$ and $\phi_\pi$, the polar angle $\theta_{p_{NN}}$ and the azimuthal angle $\phi_{p_{NN}}$ of the relative momentum $\vec{p}_{NN}$ of the two outgoing nucleons are chosen. The total and relative momenta of the final $NN$-system are defined by $\vec{P}_{NN} = \vec{p}_1 + \vec{p}_2 = \vec{k} - \vec{q}$ and $\vec{p}_{NN} = \frac{1}{2} (\vec{p}_1 - \vec{p}_2)$, respectively.

Integrating over the pion momentum $q$ and over $\Omega_{p_{NN}}$, one obtains the semi-inclusive differential cross section of pion photoproduction on the deuteron, where only the final pion is detected without analyzing its energy,

$$\frac{d\sigma}{d\Omega_\pi} = \int_0^{q_{\text{max}}} dq \int d\Omega_{p_{NN}} \frac{\rho_s}{6} \sum_{s m t m_d} |\mathcal{M}_{s m t m_d}^{(t \mu)}(\vec{q}, \vec{p}_1, \vec{p}_2)|^2,$$

where $\rho_s$ denotes the phase space factor (see Eq. (7) in [8] for its definition).

The general form of the photoproduction transition matrix is given by

$$\mathcal{M}_{s m t m_d}^{(t \mu)}(\vec{k}, \vec{q}, \vec{p}_1, \vec{p}_2) = (-1)^{s \gamma} \langle \vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu | \epsilon_\mu(m_\gamma) J^\mu(0) | d m_d 00 \rangle,$$

where $J^\mu(0)$ denotes the current operator. The outgoing $\pi NN$ scattering state is approximated in this work by

$$|\vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu \rangle^{(-)} = |\vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu \rangle + G_{0}^{\pi NN(-)} T^{NN} |\vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu \rangle,$$

where $|\vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu \rangle$ denotes the free $\pi NN$ plane wave, $G_{0}^{\pi NN(-)}$ the free $\pi NN$ propagator, and $T^{NN}$ the reaction operator for $NN$-scattering. Thus, the total transition matrix element reads in this approximation
\[ M^{(t\mu)}_{smm',md} = M^{(t\mu)\ IA}_{smm',md} + M^{(t\mu)\ NN}_{smm',md}. \] (5)

A graphical representation of the transition matrix is shown in Fig. 2.

\[ \gamma \quad \begin{array}{c} T^N_d \rightarrow N \\ N \rightarrow N \end{array} \quad \gamma \quad \begin{array}{c} T^N_d \rightarrow N \\ N \rightarrow N \end{array} \]

(a) (b)

Figure 2. Diagramatic representation of pion photoproduction on the deuteron including \( NN \)-rescattering in the final state: (a) impulse approximation (IA) and (b) \( NN \)-rescattering.

As shown in [8], the matrix element in the IA has the following expression

\[
M^{(t\mu)\ IA}_{smm',md}(\vec{k}, \vec{q}, \vec{p}_1, \vec{p}_2) = \sqrt{2} \sum_{m'} \langle sm, t - \mu | \left( \vec{p}_1 | t_{\gamma\pi}(\vec{k}, \vec{q}) | -\vec{p}_2 \right) \bar{\Psi}_{m',md}(\vec{p}_2) \\
-(-)^{s+t}(\vec{p}_1 \leftrightarrow \vec{p}_2) |1m', 00\rangle,
\] (6)

where \( t_{\gamma\pi} \) denotes the elementary production amplitude on the nucleon and \( \bar{\Psi}_{m,md}(\vec{p}) \) is given by

\[
\bar{\Psi}_{m,md}(\vec{p}) = (2\pi)^{\frac{3}{2}} \sqrt{2} E_d \sum_{L=0,2} \sum_{mL} i^L C_{mL,mm,d}^{LL} u_L(p) Y_{LmL}(\hat{p}).
\] (7)

For the radial deuteron wave function \( u_L(p) \), the Paris potential [23] is used.

For the \( NN \)-rescattering contribution, one obtains [8]

\[
M^{(t\mu)\ NN}_{smm',md}(\vec{k}, \vec{q}, \vec{p}_1, \vec{p}_2) = \sum_{m'} \int d^3 \vec{p}'_{NN} \sqrt{\frac{E_1 E_2}{E'_1 E'_2}} \tilde{R}^{NN;tm}_{smm',md}(W_{NN}, \vec{p}_{NN}, \vec{p}'_{NN}) \\
\times \frac{M_N}{\vec{p}^2 - \vec{p}'_{NN}^2 + i\epsilon} M^{(t\mu)\ IA}_{sm',m',md}(\vec{k}, \vec{q}, \vec{p}'_1, \vec{p}'_2),
\] (8)

where \( \vec{p}'_{NN} = \frac{1}{2} (\vec{p}'_1 - \vec{p}'_2) \) denotes the relative momentum of the interacting nucleons in the intermediate state, \( W_{NN} \) is the invariant mass of the \( NN \)-subsystem, \( \vec{p}'_{1/2} = \pm \vec{p}'_{NN} + (\vec{k} - \vec{q})/2 \) and \( E'_{1/2} \) are the momenta and the corresponding on-shell energies of the two nucleons in the intermediate state, respectively, and \( \vec{p}^2 = M_N(E_{\gamma d} - \omega_\pi - 2M_N - (\vec{k} - \vec{q})^2/4M_N) \) with \( E_{\gamma d} = M_d + \omega_\gamma \). The conventional \( NN \)-scattering matrix \( \tilde{R}^{NN;tm}_{smm',md} \) is introduced with respect to noncovariantly normalized states. It is expanded in terms of the partial wave contributions \( T^{NN;tm}_{jstll'} \) as follows
\[
\mathcal{R}_{s_{NN}^{t\mu}}^{NN}(W_{NN}, \mathbf{p}_{NN}, \mathbf{p}'_{NN}) = \sum_{J \ell \ell'} \mathcal{F}_{\ell \ell' m m'}^{NN, J \ell \ell'}(\hat{\mathbf{p}}_{NN}, \hat{\mathbf{p}}'_{NN}) \\
\times T_{J \ell \ell'}^{NN, t\mu}(W_{NN}, \mathbf{p}_{NN}, \mathbf{p}'_{NN}),
\]

where the purely angular function \(\mathcal{F}_{\ell \ell' m m'}^{NN, J \ell \ell'}(\hat{\mathbf{p}}_{NN}, \hat{\mathbf{p}}'_{NN})\) is defined by

\[
\mathcal{F}_{\ell \ell' m m'}^{NN, J \ell \ell'}(\hat{\mathbf{p}}_{NN}, \hat{\mathbf{p}}'_{NN}) = \sum_{M \ell m M} \mathcal{C}_{m m M}^{\ell s J} \mathcal{C}_{m' m' M}^{\ell' s J} Y_{\ell m}(\hat{\mathbf{p}}_{NN}) Y_{\ell' m'}(\hat{\mathbf{p}}'_{NN}).
\]

The necessary half-off-shell \(NN\)-scattering matrix \(T_{J \ell \ell'}^{NN, t\mu}\) was obtained from separable representation of a realistic \(NN\)-interaction [18] which gave a good description of the corresponding phase shifts. Explicitly, all partial waves with total angular momentum \(J \leq 3\) have been included.

4 Results and discussion

The discussion of our results is divided into two parts. First, we will discuss the influence of \(NN\)-FSI effect on the polarized differential cross-section difference \((d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A\) for the parallel and antiparallel helicity states by comparing the pure IA with the inclusion of \(NN\)-rescattering in the final state. Furthermore, we will confront our results with recent experimental data from the GDH collaboration [17]. In the second part, we will then consider the polarized total cross sections for circularly polarized photons on a target with spin parallel \(\sigma^P\) and antiparallel \(\sigma^A\) to the photon spin. The contribution of \(\vec{\gamma}d \rightarrow \pi^- pp\) to the spin response of the deuteron, i.e., the asymmetry of the total photoabsorption cross-section with respect to parallel and antiparallel spins of photon and deuteron, has been explicitly evaluated over the range of the \(\Delta(1232)\)-resonance with inclusion of final-state \(NN\)-rescattering.

4.1 The helicity difference \((d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A\)

We begin the discussion with presenting our results for the differential polarized cross-section difference for the parallel \((d\sigma/d\Omega_\pi)^P\) and antiparallel \((d\sigma/d\Omega_\pi)^A\) helicity states in the pure IA and with \(NN\)-rescattering as shown in Fig. 3 as a function of emission pion angle in the laboratory frame at different values of photon lab-energy. One readily notes, that \(NN\)-rescattering - the difference between the dashed and the solid curves - is quite small, almost completely negligible at pion backward angles. The reason for that stems from the fact that in charged-pion production, the \(^3S_1\)-contribution to the \(NN\) final state is forbidden. In order to give a more detailed and quantitative evaluation of \(NN\)-FSI on the differential polarized cross-section difference, we show in
Figure 3. The differential polarized cross-section difference $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$ for $\vec{\gamma}d \rightarrow \pi^-pp$ for the parallel $(d\sigma/d\Omega_\pi)^P$ and antiparallel $(d\sigma/d\Omega_\pi)^A$ helicity states as a function of pion angle in the laboratory frame in comparison to recent measurement from [17] at different values of photon lab-energy. Notation: dashed curves: IA; solid curves: IA+NN-rescattering; dotted curves: predictions for $\pi^-$ production on the free neutron, i.e., $\vec{\gamma}n \rightarrow \pi^-p$.

Fig. 4 the relative effect by plotting the ratio of the corresponding cross-section difference to the ones for the IA, i.e.,
\[
\frac{(\Delta d\sigma)^{IA+NN}}{(\Delta d\sigma)^{IA}} = \left[ \frac{\left( \frac{d\sigma}{d\Omega_\pi} \right)^{P} - \left( \frac{d\sigma}{d\Omega_\pi} \right)^{A}}{\left( \frac{d\sigma}{d\Omega_\pi} \right)^{P} - \left( \frac{d\sigma}{d\Omega_\pi} \right)^{A}} \right]^{IA+NN}. \tag{11}
\]

One sees that the major contribution from \(NN\)-FSI appears at forward pion angles. This contribution is much less important in the differential polarized cross-section difference than in the previously studied unpolarized differential cross sections (compare with Fig. 13 in [8]). It has been found that \(NN\)-FSI reduces the unpolarized differential cross section by about 15% at \(\theta_\pi = 0^\circ\) [8]. This reduction decreasing rapidly with increasing pion angle.

By comparing the results of the difference \(\left( \frac{d\sigma}{d\Omega_\pi} \right)^{P} - \left( \frac{d\sigma}{d\Omega_\pi} \right)^{A}\) for \(\vec{\gamma}\vec{d} \rightarrow \pi^- pp\) (solid curves in Fig. 3) with those for the free \(\vec{\gamma}\vec{n} \rightarrow \pi^- p\) case (dotted curves in Fig. 3), we see that a large amount of correction is needed to go from the bound deuteron to the free neutron case. The difference between both results decreases to a tiny effect at backward angles. Fig. 3 shows also a comparison of our results for the helicity difference with the experimental data from the GDH collaboration [17]. It is obvious that a quite satisfactory agreement with experiment is achieved. An experimental check of the helicity difference at extreme forward and backward pion angles is needed. Also, an independent check in the framework of effective field theory would be very interesting.

\subsection{4.2 Polarized total cross sections}

Here the results for the polarized total cross sections in IA alone and with \(NN\)-FSI effect are presented as shown in Fig. 5, where the left top panel shows the total photoabsorption cross section \(\sigma^P\) for circularly polarized photons on a target with spin parallel to the photon spin, the right top panel shows the one for antiparallel spins of photon and target \(\sigma^A\), the left bottom panel shows the spin asymmetry \(\sigma^P - \sigma^A\) and the right bottom panel shows the results for the unpolarized total cross section in comparison with the experimental data from [24] (ABHHM), [25] (Frascati) and [26] (Asai). For comparison, we also show in the same figure the results for \(\pi^- \) production on the free neutron by the dotted curves. In order to see more clearly the relative size of the interaction effect, we have plotted in Fig. 6 the ratios with respect to the IA.

One notes for the cross sections \(\sigma^P\) and \(\sigma^A\), the spin asymmetry \(\sigma^P - \sigma^A\) as well as for the unpolarized total cross section of the nucleon and the deuteron qualitatively a similar behaviour, although for the deuteron the maxima and minima are smaller and also slightly shifted towards higher energies. Furthermore, in the case of \(\sigma^P\) a large deviation between the IA and the elementary one - the difference between the dashed and the dotted curves - is seen because of the Fermi motion and FSI, whereas for \(\sigma^A\) the difference is smaller. \(NN\)-
FSI effect appears mainly in $\sigma^P$. The left bottom panel in Fig. 5 shows that the helicity difference of the total cross section ($\sigma^P - \sigma^A$) starts out negative due to the $E_{0+}$ multipole which is dominant in the threshold region and has a strong positive contribution due to the $M_{1+}$ multipole which is dominant in the $\Delta(1232)$-resonance region. It is also clear that FSI leads to a strong reduction of the spin asymmetry in the energy region of the $\Delta(1232)$-resonance. This reduction becomes about 35 $\mu$b in the maximum. Thus, the IA is not a reasonable approximation as it is for the unpolarized total cross section.
Figure 5. The total photoabsorption cross-sections for circularly polarized photons on a target with spin parallel $\sigma^P$ (upper part: left) and antiparallel $\sigma^A$ (upper part: right) to the photon spin for $\vec{\gamma}\vec{d} \rightarrow \pi^-pp$ as functions of photon lab-energy. The lower part shows the difference $\sigma^P - \sigma^A$ (lower part: left) and the unpolarized total cross section (lower part: right). The experimental data are from [24] (ABHHM), [25] (Frascati) and [26] (Asai). Notation of the curves as in Fig. 3.

Moreover, already the IA deviates significantly from the corresponding nucleon quantities. It is also obvious that $\sigma^P$ is much larger than $\sigma^A$ because of the $\Delta$-excitation.

For the unpolarized total cross section in the right bottom panel of Fig. 5, one also notes that $NN$-FSI effect is small, not more than about 5 percent. This effect comes mainly from the change in the radial wave function of the final NN partial waves by the interaction. Therefore, it reduces the cross section. The charged final state $p\pi^-$ had been investigated 30 years ago in a bubble chamber measurement of the $\gamma d \rightarrow pp\pi^-$ reaction by the ABHHM collaboration [24], at Frascatti [25], and later at higher energies by the TAGX-collaboration.
Figure 6. The ratios $\sigma_{P A+NN}/\sigma_{PA}$ (upper part: left), $\sigma_{A+NN}/\sigma_{IA}$ (upper part: right), $(\sigma^P - \sigma^A)_{IA+NN}/(\sigma^A - \sigma^A)_{IA}$ (lower part: left) and $\sigma_{IA+NN}/\sigma_{IA}$ (lower part: right) as functions of photon lab-energy.

[26]. The right bottom panel of Fig. 5 shows a comparison between our results and this set of experimental data. One readily notes, that the inclusion of $NN$-rescattering improves the agreement between experimental data and theoretical predictions considerably.

5 Summary and conclusions

The influence of $NN$-FSI effect on the polarized differential and total cross-section differences $(d\sigma/d\Omega_\pi)^P - (d\sigma/d\Omega_\pi)^A$ and $\sigma^P - \sigma^A$, respectively, for the parallel and antiparallel helicity states for the $\vec{\gamma}d \to \pi^- p$ reaction is investigated. These helicity asymmetries give valuable information on the nucleon spin structure and allow a test of the GDH sum rule. For the elementary
production operator on the nucleon, an effective Lagrangian model is used. As model for the interaction of the $NN$-subsystem we used separable representation of realistic $NN$ interaction which give a good description of the corresponding phase shifts.

The study of the polarized differential cross-section difference revealed that the reduction by inclusion of $NN$-rescattering appears predominantly at pion forward angles by about 15 percent. For pions emitted in the backward direction the $NN$-rescattering effect is completely negligible. In comparison with experiment, a quite satisfactory agreement is obtained. The polarized total cross sections for circularly polarized photons on a target with spin parallel $\sigma^P$ and antiparallel $\sigma^A$ to the photon spin are also investigated. The contribution of $\vec{\gamma}d \rightarrow \pi^- pp$ to the spin response of the deuteron has been explicitly evaluated over the range of the $\Delta(1232)$-resonance with inclusion of $NN$-rescattering. In the case of $\sigma^P$, we obtained a significant difference between the IA and the elementary one, whereas for $\sigma^A$ the difference is smaller. We found that $NN$-FSI effect appears mainly in $\sigma^P$. It leads to a strong reduction of the spin asymmetry in the energy region of the $\Delta(1232)$-resonance. This reduction becomes about 35 $\mu$b in the maximum. For the unpolarized total cross section, we found that $NN$-rescattering reduces the total cross section in the $\Delta(1232)$-resonance region by about 5 percent. In comparison with experiment, the inclusion of such effect leads to an improved agreement with experimental data.

It remains as a task for further theoretical research to investigate the reaction $\gamma d \rightarrow \pi NN$ including a three-body treatment in the final $\pi NN$ system. This extension is desirable for the calculation of such rescattering for further developments. Instead of a separable potential, a more realistic potential for the $NN$-scattering should be considered. A further interesting topic concerns the study of polarization observables with the inclusion of rescattering effects. These studies give more detailed information on the $\pi NN$ dynamics and thus providing more stringent tests for theoretical models. As future refinements we consider also the use of a more sophisticated elementary production operator, which will allow one to extend the present results to higher energies. A measurement of the spin asymmetry for the deuteron is needed.

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References

[1] G.F. Chew, H.W. Lewis, Phys. Rev. 84 (1951) 779.
[2] M. Lax, H. Feshbach, Phys. Rev. 88 (1952) 509.
[3] I. Blomqvist, J.M. Laget, Nucl. Phys. A 280 (1977) 405.
[4] J.M. Laget, Nucl. Phys. A 296 (1978) 388.
[5] J.M. Laget, Phys. Rep. 69 (1981) 1.
[6] R. Schmidt, H. Arenhövel, P. Wilhelm, Z. Phys. A 355 (1996) 421.
[7] M.I. Levchuk, M. Schumacher, F. Wissmann, nucl-th/0011041.
[8] E.M. Darwish, H. Arenhövel, M. Schwamb, Eur. Phys. J. A 16 (2003) 111.
[9] I.T. Obukhovsky et al., J. Phys. G 29 (2003) 2207.
[10] A.Yu. Loginov, A.A. Sidorov, V.N. Stibunov, Phys. Atom. Nucl. 63 (2000) 391.
[11] E.M. Darwish, H. Arenhövel, M. Schwamb, Eur. Phys. J. A 17 (2003) 513.
[12] E.M. Darwish, Nucl. Phys. A 735 (2004) 200.
[13] E.M. Darwish, Int. J. Mod. Phys. E 13 (2004) (in press).
[14] E.M. Darwish, J. Phys. G: Nucl. Part. Phys. G 31 (2005) (in press).
[15] A.Yu. Loginov, A.V. Osipov, A.A. Sidorov, V.N. Stibunov, nucl-th/0407045.
[16] H. Arenhövel, A. Fix, M. Schwamb, Phys. Rev. Lett. 93 (2004) 202301; H. Arenhövel, A. Fix, M. Schwamb, in Proceedings of the 3rd International Symposium on the Gerasimov-Drell-Hearn Sum Rule and its Extensions (GDH 2004), Norfolk, Virginia, June 1-5, 2004, nucl-th/0409015.
[17] P. Pedroni, private communication; C.A. Rovelli, Diploma Thesis, University of Pavia, Italy, 2002.
[18] J. Haidenbauer, W. Plessas, Phys. Rev. C 30 (1984) 1822; ibid C 32 (1985) 1424.
[19] D.J. Ernst, C.M. Shakin, R.M. Thaler, Phys. Rev. C 8 (1973) 46; ibid C 9 (1974) 1780.
[20] M. Lacombe et al., Phys. Rev. C 21 (1980) 861.
[21] H. Garcilazo, T. Mizutani, πNN Systems, World Scientific, Singapore, 1990.
[22] J.D. Bjorken, S.D. Drell, Relativistic Quantum Mechanics, McGraw-Hill, New York, 1964.
[23] M. Lacombe et al., Phys. Lett. B 101 (1981) 139.
[24] P. Benz et al., Nucl. Phys. B 65 (1973) 158.

[25] G. Chiefari, E. Drago, M. Napolitano, C. Sciacca, Lett. Nuovo Cim. 13 (1975) 129.

[26] M. Asai et al., Phys. Rev. C 42 (1990) 837.