Influence of $NN$-rescattering effect on the photon asymmetry of $d(\gamma, \pi^-)pp$ reaction

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Abstract

The influence of final-state $NN$-rescattering on the beam asymmetry $\Sigma$ for linearly polarized photons in $\pi^-$ photoproduction on the deuteron in the energy range from $\pi$-threshold through the $\Delta(1232)$-resonance has been investigated. Numerical results for this spin observable are predicted and compared with recent experimental data from the LEGS Spin collaboration. Final-state $NN$-rescattering is found to be quite important and leads to a better agreement with existing experimental data. Furthermore, the differences with other theoretical models have been discussed.

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1 Introduction

It is a well known fact that polarization observables allow a further and much more detailed analysis of the process under study compared to the differential cross section alone. Because polarization observables contain a much richer information on the dynamics of the system than attainable without beam and/or target polarization and without polarization analysis of the particles in the final state. The reason for this is the fact that in contrast to the differential cross section, which is a sum of the absolute squares of the $t$-matrix elements, these polarization observables contain interference terms of the various reaction amplitudes in different combinations and, therefore, may be more sensitive to small amplitudes and to small contributions of interesting dynamical effects.

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In recent years a great effort, both from theoretical [1,2,3,4,5,6,7] and experimental [8,9,10,11] points of view, has been devoted to the analysis of single-pion photoproduction with polarized beams and/or polarized targets. In [1], $\pi^-$ photoproduction on the deuteron has been studied within a diagrammatic approach including nucleon-nucleon ($NN$) and pion-nucleon ($\pi N$) rescattering in the final state. Special emphasize was given for the analyzing powers connected to beam and target polarization, and to polarization of one of the final protons. First preliminary model calculations for the photon asymmetry $\Sigma$ of the $\vec{\gamma}d \rightarrow \pi^- pp$ reaction have been given in the pure impulse approximation (IA) [2]. The comparison between these predictions for $\Sigma$ and the preliminary experimental data from LEGS Spin collaboration [12] gives a clear indication that the effects of final-state interaction (FSI) may be important. The deuteron tensor analyzing powers of the reaction $d(\gamma, \pi^-)pp$ have been studied in the IA [3] without inclusion of any FSI or two-body exchange current contributions. In our previous papers [4,5,6], various polarization observables in inclusive single-pion photoproduction on the deuteron using a polarized photon beam and/or an oriented deuteron target have been investigated in the pure IA only, i.e., by neglecting any FSI effects and possible two-body contributions to the production operator. In particular, a complete survey on all single- and double-polarization observables like beam and target asymmetries was given. In [7] the influence of final-state $NN$-rescattering on the helicity structure of the inclusive reaction $\vec{\gamma}d \rightarrow \pi^- pp$ has been investigated. The differential polarized cross-section difference for the parallel and antiparallel helicity states has been predicted and compared with recent experimental data from MAMI (Mainz/Pavia) [13]. It has been shown that the effect of $NN$-rescattering is much less important in the polarized differential cross-section difference than in the unpolarized one.

The photon asymmetry $\Sigma$ is very sensitive to the internal mechanisms of the reaction and, therefore, can be a very useful test to impose constraints on the theoretical models. The work has been partly motivated by preliminary experimental results, for the $\vec{\gamma}d \rightarrow \pi^- pp$ channel, with the LEGS Brookhaven National Laboratory [12] which shows strong and not trivial angular dependences of this observable. In agreement with these preliminary data, one can see in [2,6] that the predictions in the pure IA can hardly provide a reasonable description of the data since major discrepancies are found. As already noted in [2,6], the effect of $NN$-rescattering is quite important. This means in particular that the calculation in the spectator nucleon model can only be considered as a first step towards a more realistic description of spin observables.

In this letter we investigate, therefore, the influence of final-state $NN$ interaction on the photon asymmetry for the reaction $d(\vec{\gamma}, \pi^-)pp$ in the energy region from $\pi$-threshold through the $\Delta(1232)$-resonance. To our knowledge, the influence of $NN$-FSI effect on this spin observable has never been studied before. The $\pi N$-rescattering contribution has been considered as negligible in
the region of the $\Delta(1232)$-resonance $[14,15]$ and thus it is not considered in the present work. Our main goal is to analyze the recent experimental data from LEGS $[12]$. Furthermore, it was an open question whether the inclusion of rescattering contributions would lead to a good description of the available data.

In the next section we will define the photon asymmetry $\Sigma$ in terms of the transition matrix amplitude. In section 3 we will present and discuss the numerical results of our calculations and compare them with the experimental data and other predictions. Finally, we summarize our conclusions in section 4.

2 Linear photon asymmetry

The beam asymmetry $\Sigma$ for linearly polarized photons is defined in analogy to deuteron photodisintegration $[16]$ writing the differential cross section for linearly polarized photons and unpolarized deuterons in the form

$$
\frac{d\sigma}{d\Omega_\pi}(\theta_\pi, \phi_\pi) = \frac{d\sigma_0}{d\Omega_\pi}(\theta_\pi) \left[ 1 + P_\ell^\gamma \Sigma(\theta_\pi) \cos 2\phi_\pi \right],
$$

where $d\sigma_0/d\Omega_\pi$ denotes the semi-inclusive unpolarized differential cross section of incoherent pion photoproduction on the deuteron, where only the final pion is detected without analyzing its energy $[14]$, $P_\ell^\gamma$ is the degree of linearly polarized photons $[16]$, $\theta_\pi$ and $\phi_\pi$ represent the polar and azimuthal pion angles and $\Sigma$ is the photon asymmetry for linearly polarized photons. Then one has $[4,16]$

$$
\Sigma \frac{d\sigma_0}{d\Omega_\pi} = -W_{00},
$$

with

$$
W_{00} = \frac{1}{2\sqrt{3}} \sum_{smt,m_d,m_d'} (-)^{1-m_d'} C_{m_d-m_d'}^{110} \int_{q_{\text{max}}} dq \int d\Omega_{pNN} \rho_s (\mathcal{M}_{sm,m,m_d}^{(tw)})^* \mathcal{M}_{s-m,m,m_d'}^{(tw)}.
$$

denoting with $C_{m_1m_2m}^{ij}$ a Clebsch-Gordan coefficient, $m_\gamma$ the photon polarization, $m_d$ the spin projection of the deuteron, $s$ and $m$ total spin and its projection of the two outgoing nucleons, respectively, $t$ their total isospin, $\mu$
the isospin projection of the pion, \( q_{\text{max}} \) the maximum value of pion momentum, \( \Omega_{p_{NN}} \) the solid angle of the relative momentum \( \vec{p}_{NN} \) of the final \( NN \) system and \( \rho_s \) the phase space factor. For further details with respect to the kinematical variables and quantum numbers we refer to our previous work [14].

For the transition \( M \)-matrix we include, in this work, besides the pure IA, the driving term from \( NN \)-rescattering, so that the total transition matrix reads

\[
M^{(t\mu)}_{s m m', m_d} = M^{(t\mu)}_{s m m', m_d} + M^{(t\mu)}_{s m m', m_d} \quad \text{(4)},
\]

where the first term represents the transition amplitude in the pure IA and the second is the corresponding one for \( NN \)-rescattering in the final state. Further details with respect to the matrix elements are not discussed here and can be found in [14].

### 3 Results and discussion

Here we present and discuss our results for the photon asymmetry \( \Sigma \) for linearly polarized photons of \( \pi^- \) photoproduction on the deuteron with inclusion of \( NN \)-rescattering in the final state. These results are also compared to the preliminary experimental data of LEGS [12] and the preliminary IA calculations of Lee [2]. The results presented here are calculated by using the elementary photoproduction operator of Schmidt et al. [17] and the deuteron wave function of Paris potential [18]. For the half-off-shell \( NN \)-scattering amplitude, the separable representation [19] of the realistic Paris potential has been used. All partial waves with total angular momentum \( J \leq 3 \) are included.

We start with presenting our results for the linear photon asymmetry \( \Sigma \) at different photon lab-energies \( \omega_\gamma = 200, 270, 330, 370, 420 \) and \( 500 \) MeV in Fig. 1 as a function of emission pion angle \( \theta_\pi \) in the laboratory frame. The solid curves show the results of the full calculation, i.e., when \( NN \)-rescattering is included, while the dashed curves show the contribution of the IA alone in order to clarify the importance of \( NN \)-FSI effect. In order to show in greater detail the relative influence of \( NN \)-rescattering effect on the linear photon asymmetry, we show in Fig. 2 the effect of \( NN \)-rescattering relative to the IA by the ratio \( \Sigma^{IA+NN}/\Sigma^{IA} \), where \( \Sigma^{IA} \) denotes the photon asymmetry in the IA and \( \Sigma^{IA+NN} \) the one including the contribution of \( NN \)-rescattering.

In the photon energy domain of this work, the magnetic multipoles dominate over the electric ones, due to the excitation of the \( \Delta \)-resonance. This is clear from the dominately negative values of \( \Sigma \) as shown in Fig. 1. On the contrary, the left-top and right-bottom panels in Fig. 1 show that small positive values
are found at $\omega_\gamma = 200$ and 500 MeV. We see also that the asymmetry $\Sigma$ is sensitive to the energy of the incoming photon. It is noticeable, that the photon asymmetry $\Sigma$ vanish at $\theta_\pi = 0^\circ$ which is not the case at $180^\circ$. At extreme forward and backward emission pion angles one sees, that the photon asymmetry is relatively small in comparison to the results when $\theta_\pi$ changes from about $30^\circ$ to $120^\circ$. One notices also, that the contribution from $NN$-rescattering is much important in this region, in particular in the peak position. For lower and higher photon energies, one finds the strongest effect by $NN$-rescattering.

Fig. 3 shows the sensitivity of our results for the linear photon asymmetry $\Sigma$ to the photon lab-energy $\omega_\gamma$ at three fixed values of pion angle $\theta_\pi = 0^\circ$, $90^\circ$ and $180^\circ$ for photon lab-energies between 200 and 500 MeV. In order to show the relative influence of $NN$-rescattering effect on the linear photon asymmetry, we show in the bottom panels of Fig. 2 the effect of $NN$-rescattering relative to the IA by the ratio $\Sigma^{IA+NN}/\Sigma^{IA}$, where $\Sigma^{IA}$ denotes the photon asymmetry in the IA and $\Sigma^{IA+NN}$ the one including the contribution of $NN$-rescattering. In view of these results, one notes that $NN$-rescattering - the difference between the solid and the dashed curves - is quite small, almost completely negligible at extreme forward and backward angles.
Fig. 4 shows a comparison of our numerical results for the linear photon asymmetry $\Sigma$ in the pure IA (dashed curves) and with $NN$-rescattering (solid curves) with experimental data. In view of the fact that experimental data for this spin observable are not available in a final form, we compare our predictions with the preliminary experimental data from the LEGS Spin collaboration [12] as depicted in Fig. 4. We see that the general feature of the data is reproduced. However, the discrepancy is rather significant in the region where the photon energy close to the $\Delta$-resonance. This could be due to the higher order rescattering mechanisms which are neglected in this work. In the same figure, we also show the results from the IA only (dashed curves). It is seen that the $NN$-rescattering yields an about 10% effect in the region of the peak position. We found that this is mainly due to the interference between the IA amplitude and the $NN$-FSI amplitude. In agreement with our previous results [6], one notes that the pure IA (dashed curves in Fig. 4) cannot describe the experimental data. The inclusion of $NN$-FSI leads at $\omega_\gamma = 270$ MeV to a quite satisfactory description of the data, whereas at $330$ MeV $NN$-FSI effect is small and therefore differences between theory and experiment are still evident. It is appear that our model is still not capable of describing the measured photon asymmetry, even if $NN$-FSI is included. Future efforts must be made to remove the remaining discrepancies such as a complete three-body
Figure 3. Linear photon asymmetry $\Sigma$ for $d(\gamma, \pi^-)pp$ as a function of the photon lab-energy $\omega_\gamma$ at fixed values of pion angle $\theta_\pi$ in the laboratory frame with $NN$-rescattering (top panels) and their ratios with respect to the pure IA (bottom panels). Notation as in Fig. 1.

Now we compare our results for the linear photon asymmetry with the preliminary model predictions of Lee [2] as shown in Fig. 5. The solid curves show the results of the present calculations when $NN$-rescattering is included and the dashed ones show our results in the IA alone. The preliminary IA results of Lee [2] are represented in this figure by the dotted curves. It is very clear that the results for the IA of the present work showed certain significant differences to the preliminary IA results [2] which cannot be attributed to the use of different elementary pion photoproduction operators and/or from different realistic $NN$ potential models used for the deuteron wave function. It is clear from the right panel of Fig. 5 that the discrepancy is rather significant in the region of the $\Delta(1232)$-resonance, in particular in the peak position.

As already mentioned in the beginning of this section, our results are calculated using the effective Lagrangian model developed by Schmidt et al. [17]. The main advantage of this model is that it has been constructed to give a realistic description of the $\Delta$-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. As shown in Figs. 1-3 in [14], the results for this model are in good agreement with recent experimental data as well as with other theoretical predictions. On the other hand, the well-known dynamical model of Sato and Lee [20] has been used in [2]. This model has given also a successful description of the pion photoproduction data. Therefore, the big difference between both predictions in the IA results cannot be attributed to the use of different elementary operators. This can be interpreted as lack of understanding of the nonresonant background, which in dynamical models is related to the pion cloud. It seems that pion cloud effects are not yet consistently included in dynamical models. An independent evaluation for $\Sigma$ in the pure IA as well as with the 'totally neglected' rescattering mechanisms in [2] would be very interesting to understand the origin of this discrepancy.

4 Summary

In this letter we have investigated the influence of final-state $NN$-rescattering effect on the linear photon asymmetry $\Sigma$ for the $\gamma d \rightarrow \pi^- pp$ reaction in the photon energy range from $\pi$-threshold to 500 MeV. We have found that the effect due to the final two-nucleon interaction to be small, but it can has significant contribution to the photon asymmetry through its interference with the dominant term from the impulse approximation. Furthermore, the linear photon asymmetry is found to be sensitive to the energy of the incident photon. In comparison with the preliminary experimental data from LEGS [12], the
Figure 5. Photon polarization asymmetry $\Sigma$ for $d(\vec{\gamma}, \pi^-)pp$ reaction at two photon lab-energies. Dashed curves: IA of present calculations; solid curves: IA plus $NN$-FSI of present calculations; dotted curves: preliminary IA calculations of Lee [2].

Inclusion of $NN$-FSI effect leads to a better agreement with experimental data. With respect to the comparison with the preliminary results of [2] in the IA, we found a large difference between both calculations in the peak position. The origin of this difference is still not clear.

We would like to conclude that the results presented here for linear photon asymmetry of $d(\vec{\gamma}, \pi^-)pp$ can be used as a basis for the simulation of the behaviour of this asymmetry and for an optimal planning of new experiments of this reaction with polarized photon beams. An experimental check of these predictions for the linear photon asymmetry covering a large range for the pion angle would provide an additional significant test of our present understanding of this spin observable. Furthermore, an independent evaluation in the framework of effective field theory would be very interesting. Future improvements should include further investigations including FSI as well as two-body effects.

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