Single-spin asymmetries of $d(\gamma, \pi)NN$ in the first resonance region

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Abstract

Incoherent photoproduction of pions on the deuteron in the first resonance region is investigated with special emphasis on single-spin asymmetries. For the elementary pion production operator an effective Lagrangian model which includes the standard pseudovector Born terms and a resonance contribution from the $\Delta(1232)$-excitation is used. Single-spin asymmetries, both for charged and neutral pion photoproduction on the deuteron, are analyzed and calculated in the first resonance region. The linear photon asymmetry $\Sigma$, vector target asymmetry $T_{11}$ and tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$ for the reaction $d(\gamma, \pi)NN$ with polarized photon beam and/or oriented deuteron target are predicted for forthcoming experiments.

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1 Introduction

It has been known for a long time that the electromagnetic probe belongs to the important tools in investigating the structure and properties of the strongly interacting particles and nuclei. It is not only because its properties are well known but also because it is weak enough, so one can treat it in any reaction perturbatively. Meson production is the primary absorptive process on the nucleon. It proceeds mainly through the intermediate excitation of a nucleon resonance and gives important information on the internal nucleon structure. Therefore, it provides stringent tests of any kind of hadron models.

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During the last years, photo- and electroproduction of pions on a single proton have thoroughly been studied both theoretically and experimentally. Since the deuteron is the simplest nucleus containing a neutron, the process of pion production on the deuteron can be used for examining pion production on a neutron. It can also give information on pion production on off-shell nucleons, as well as on the very important $\Delta N$-interaction in a nuclear medium.

The study of polarization observables in pseudoscalar meson production in electromagnetic reactions on light nuclei has become a very active field of research in medium-energy nuclear physics with respect to the investigation of small but interesting dynamical effects, which normally are buried under the dominant amplitudes in unpolarized total and differential cross sections, but which often may show up significantly in certain polarization observables. The reason for this feature lies in the fact that such small amplitudes or small contributions to large amplitudes may be amplified by interference with dominant amplitudes, or that dominant amplitudes interfere destructively leaving thus more room to the small amplitudes. Polarization observables will also give additional valuable information for checking the spin degrees of freedom of the elementary pion production amplitude of the neutron, provided, and this is very important, that one has under control all interfering interaction effects which prevent a simple extraction of this amplitude.

Recent work in view of continuing technical improvements, such as ELSA in Bonn, LEGS in Brookhaven, CEBAF in Newport News, or MAMI in Mainz, for preparing polarized beams and targets and for polarimeters for the polarization analysis of ejected particles, has motivated the examination of certain aspects of the polarization observables in pion production on the deuteron that are fundamental to the process. Quasifree $\pi^-$ photoproduction on the deuteron via the $\gamma d \rightarrow \pi^- pp$ reaction has been investigated within a diagrammatic approach including $NN$- and $\pi N$-rescattering effects [1]. In that work, the authors reported predictions for the squared moduli of amplitudes $|T_{fi}|^2$, analyzing powers connected to beam polarization $T_{22,00}$, to target polarization $T_{00,20}$, and to polarization of one of the final protons $P_{1y}$. It has been shown, that final state interaction effects play a noticeable role in the behaviour of these observables. In our previous evaluation [2,3], the energy dependence of the three charge states of the pion for the $\gamma d \rightarrow \pi NN$ reaction over the whole $\Delta(1232)$-resonance region has been evaluated. We have presented results for differential and total cross sections as well as the spin asymmetry and the Gerasimov-Drell-Hearn (GDH) sum rule for the deuteron.

Notwithstanding this continuing effort to study this process, the wealth of information contained in it has not yet been fully exploited. Since the $t$-matrix has 12 independent complex amplitudes and in order to determine completely the $t$-matrix, one has to measure 23 independent observables. Up to present times, only a few observables have been measured and studied in details, e.g.,
differential and total cross sections. Therefore, in [4] we have investigated incoherent single pion photoproduction on the deuteron in the ∆(1232)-resonance region with special emphasis on spin-polarization observables. In that work, we have presented some results for the π-meson spectrum with other spin-observables as functions of pion momentum at different values of pion angles for photon energy only at the ∆(1232)-resonance region.

Our main aim in this contribution is to investigate incoherent single pion photoproduction on the deuteron in the first resonance region with special emphasis on single-spin asymmetries. Particularly, the scope of this article is to predict some additional polarization observables which are experimentally measured or planned to be measured at different laboratories, for instance, the linear photon asymmetry Σ for the reaction \( \vec{\gamma}d \rightarrow \pi^0np \) which is measured most recently at LEGS Brookhaven National Laboratory [5]. Furthermore, results for all the three isospin channels of the reaction \( d(\gamma, \pi)NN \) with polarized photon beam and/or oriented deuteron target at different photon lab-energies will be reported. The importance of this process comes from the fact that the deuteron, being the simplest nuclear system, plays a similar fundamental role in nuclear physics as the hydrogen atom plays in atomic physics.

The paper is organized as follows. In Section 2 the elementary pion production operator on the free nucleon which we use as input in the calculations on the deuteron is presented. In Section 3 we outline the formalism of incoherent single pion photoproduction on the deuteron. The general form of the differential cross section is also introduced in this section. The treatment of the \( \gamma d \rightarrow \pi NN \) transition matrix elements, based on time-ordered perturbation theory, is described in Section 4. Section 5 is devoted to the central topic of this paper. The complete formal expressions of single-spin asymmetries of the reaction \( \gamma d \rightarrow \pi NN \) with polarized photon beam and/or oriented deuteron target in terms of the transition matrix amplitudes are developed in this section. Details of the actual calculation and the results are presented and discussed in Section 6. Finally, we conclude and summarize our results in Section 7.

2 Elementary process

The most important ingredient of our model is the elementary operator for pion photoproduction on a single nucleon which is the starting point of the construction of an operator for pion photoproduction in the two-nucleon space. In this work we will examine the various observables for pion photoproduction on the free nucleon using, as in our previous work [2,3,4], the effective

\footnote{Data are still preliminary.}
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 contains besides the standard pseudovector Born terms a resonance contribution from the $\Delta(1232)$-excitation. For details with respect to the elementary pion photoproduction operator we refer to [6]. As shown in Figs. 1, 2, and 3 in our previous work [2], 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.

3 Basic formalism

In this section we present the formalism of incoherent single pion photoproduction on the deuteron

$$\gamma(k) + d(d) \rightarrow \pi(q) + N_1(p_1) + N_2(p_2)$$

where $k = (\omega, \vec{k})$ and $d = (E_d, \vec{d})$ denote the initial photon and deuteron four-momenta, respectively. The four-momenta of final meson and two nucleons are denoted by $q = (\omega_q, \vec{q})$ with $\omega_q = \sqrt{m_{\pi}^2 + \vec{q}^2}$, $m_{\pi}$ as pion mass, and $p_j = (E_j, \vec{p}_j)$ ($j = 1, 2$) with $E_j = \sqrt{M_N^2 + \vec{p}_j^2}$, respectively, and $M_N$ as nucleon mass.

The general expression of the cross section is given, using the conventions of Bjorken and Drell [7], by

$$d\sigma = (2\pi)^4 \delta^4 (k + d - q - p_1 - p_2) \frac{1}{|\vec{v}_{\gamma} - \vec{v}_d|} \frac{1}{2\omega_q} \frac{1}{2E_d (2\pi)^3} \frac{1}{2\omega_d} \frac{d^3 q}{2 (2\pi)^3} \frac{1}{2 \omega_{\gamma}}$$

$$\times \frac{1}{2} \frac{d^3 p_1}{2 (2\pi)^3} \frac{M_N}{E_1} \frac{d^3 p_2}{(2\pi)^3} \frac{M_N}{E_2} \frac{1}{6} \sum_{smtm, m_d} |\mathcal{M}_{smtm, m_d}^{(\mu)}(\vec{k}, \vec{d}, \vec{q}, \vec{p}_1, \vec{p}_2)|^2,$$

where $m_{\gamma}$ 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 states of all particles are covariantly normalized. The reaction amplitude is denoted by $\mathcal{M}_{smtm, m_d}^{(\mu)}$. As in [6], we have chosen as independent variables the pion mo-
momentum $q$, its angles $\theta_\pi$ and $\phi_\pi$, the polar angle $\theta_{NN}$ and the azimuthal angle $\phi_{NN}$ of the relative momentum $\vec{p}_{NN}$ of the two outgoing nucleons.

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. The absolute value of the relative momentum $\vec{p}_{NN}$ is given by

$$p_{NN} = \frac{1}{2} \left( \frac{E_{NN}^2(W_{NN}^2 - 4M_N^2)}{E_{NN}^2 - P_{NN}^2 \cos^2 \theta_{NN}} \right)^{1/2},$$

where $\theta_{NN}$ is the angle between $\vec{P}_{NN}$ and $\vec{p}_{NN}$, $E_{NN}$ and $W_{NN}$ denote total energy and invariant mass of the $NN$-subsystem, respectively.

For the evaluation we have chosen the laboratory frame where $d\mu = (M_d, \vec{0})$ with $M_d$ as deuteron mass. As coordinate system a right-handed one is taken with $z$-axis along the momentum $\vec{k}$ of the incoming photon and $y$-axis along $\vec{k} \times \vec{q}$. Thus, the outgoing pion defines the scattering plane. Another plane is defined by the momenta of the outgoing nucleons which we will call the nucleon plane (see Fig. 4 in [2]).

Finally, we get the differential cross section of incoherent single pion photoproduction on the deuteron as

$$\frac{d^2\sigma}{d\Omega_\pi} = \int_0^{q_{\text{max}}} dq \int d\Omega_{NN} K \frac{1}{6} \sum_{sntm, m_d} |\mathcal{M}_{sntm, m_d}(\vec{k}, \vec{q}, \vec{p}_1, \vec{p}_2)|^2,$$

where the phase space factor $K$ is expressed in terms of relative and total momenta of the two final nucleons as follows

$$K = \frac{1}{(2\pi)^3} \left| \frac{p_{NN}^2 M_N^2}{E_2(p_{NN} + \frac{1}{2}P_{NN} \cos \theta_{NN}) + E_1(p_{NN} - \frac{1}{2}P_{NN} \cos \theta_{NN})} \right| q^2 \times \frac{1}{16 \omega_\gamma M_d \omega_q}.$$  \hspace{1cm} (5)

4 The transition $\mathcal{M}$-matrix

The general form of the photoproduction transition matrix is given by

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

(6)
where $J^{\mu}(0)$ denotes the current operator and $\epsilon_\mu(m_\gamma)$ the photon polarization vector. The electromagnetic interaction consists of the elementary production process on one of the nucleons $T^{(j)}_{\pi\gamma} (j = 1, 2)$ and in principle a possible irreducible two-body production operator $T^{(NN)}_{\pi\gamma}$. The final $\pi NN$ state is then subject to the various hadronic two-body interactions as described by an half-off-shell three-body scattering amplitude $T^{\pi NN}$. In principle, one must take into account all of the possible terms in the calculation of the transition matrix. As an approximation, we neglect the electromagnetic two-body production $T^{(NN)}_{\pi\gamma}$ and then the outgoing $\pi NN$ scattering state is then approximated by the free $\pi NN$ plane wave.

For the spin ($|sm\rangle$) and isospin ($|t - \mu\rangle$) part of the two nucleon wave functions we use a coupled spin-isospin basis $|sm, t - \mu\rangle$. The antisymmetric final $NN$ plane wave function thus has the form

$$|\vec{p}_1, \vec{p}_2, sm, t - \mu\rangle = \frac{1}{\sqrt{2}} \left(|\vec{p}_1(1)\rangle|\vec{p}_2(2)\rangle - (-)^{s+t}|\vec{p}_2(1)\rangle|\vec{p}_1(2)\rangle\right) |sm, t - \mu\rangle ,$$

(7)

where the superscript indicates to which particle the ket refers. In the case of charged pions, only the $t = 1$ channel contributes whereas for $\pi^0$ production both $t = 0$ and $t = 1$ channels have to be taken into account. Then, the matrix element is given by

$$M_{smm, t\mu}^{(t\mu)}(\vec{k}, \vec{q}, \vec{p}_1, \vec{p}_2) = \frac{1}{2} \int \frac{d^3p'_1}{(2\pi)^3} \int \frac{d^3p'_2}{(2\pi)^3} \frac{M_N}{E_1 E_2} \times \sum_{m'} \langle \vec{p}_1\vec{p}_2, sm, t - \mu | t_{\gamma\pi}^{NN}(\vec{k}, \vec{q}) | \vec{p}'_1\vec{p}'_2, 1m', 00 \rangle \times \langle \vec{p}'_1\vec{p}'_2, 1m', 00 | \vec{dm}, 00 \rangle$$

(8)

with

$$t_{\gamma\pi}^{NN}(\vec{k}, \vec{q}) = t_{\gamma\pi}^{NN(1)}(\vec{k}, \vec{q}) + t_{\gamma\pi}^{NN(2)}(\vec{k}, \vec{q}) ,$$

(9)

where $t_{\gamma\pi}^{NN(j)}$ denotes the elementary production amplitude on nucleon “$j$”. The deuteron wave function has the form

$$\langle \vec{p}_1\vec{p}_2, 1m, 00 | \vec{dm}, 00 \rangle = (2\pi)^3 \delta^3(\vec{d} - \vec{p}_1 - \vec{p}_2) \frac{\sqrt{2E_1E_2}}{M_N} \tilde{\Psi}_{m,m_d}(\vec{p}_{NN})$$

(10)

with

$$\tilde{\Psi}_{m,m_d}(\vec{p}) = (2\pi)^3 \sqrt{2E_d} \sum_{L=0,2} \sum_{m_L} i^L C_{m_Lmm_d}^{L11} u_L(p) Y_{LM}(\vec{p}) .$$

(11)
Using (9) one finds in the laboratory system for the matrix element the following expression

\[ M_{smm',md}^{(t\mu)}(k, q, p_1, p_2) = \sqrt{2} \sum_{m'} \langle sm, t - \mu | \left( (\vec{p}_1 | t^{N(1)}_{\gamma \pi}(k, q) | - \vec{p}_2) \tilde{\Psi}_{m',md} \right) - (-)^{s+t}(\vec{p}_1 \leftrightarrow \vec{p}_2) | 1m', 00 \rangle. \] (12)

Note, that in (12) the elementary production operator acts on nucleon “1” only. This matrix element possesses the obvious symmetry under the interchange of the nucleon momenta

\[ M_{smm',md}^{(t\mu)}(k, q, p_2, p_1) = (-)^{s+t+1} M_{smm',md}^{(t\mu)}(k, q, p_1, p_2). \] (13)

5 Definition of a general polarization observable

In this section the expressions for single-spin asymmetries are derived. For a given \( M \)-matrix we compute the cross section for arbitrary polarized photons and initial deuterons by applying the density matrix formalism similar to that given by Arenhövel [8] for deuteron photodisintegration. The most general expression for all possible polarization observables in the reaction \( d(\gamma, \pi)NN \) is given in terms of the transition \( M \)-matrix by

\[ \mathcal{O} = \sum_{smtm'\gamma m'd_d} \int_0^{q_{max}} dq \int d\Omega_{pNN} K \mathcal{M}_{s'm',m' \gamma m_d}^{(t\mu')} \tilde{\Omega}_{s'm'sm} M_{smm',md}^{(t\mu)} \rho_{\gamma m_d} \rho_{m_d m_d}^{d_d}, \] (14)

where \( \rho_{\gamma m_d} \) and \( \rho_{m_d m_d}^{d_d} \) denote the density matrices of initial photon polarization and deuteron orientation, respectively, \( \tilde{\Omega}_{s'm'sm} \) is an operator associated with the observable, which acts in the two-nucleon spin space and \( K \) is a phase space factor given in (5). For further details we refer to [8].

As shown in [8], that all possible polarization observables for the reaction \( \gamma d \rightarrow \pi NN \) with polarized photon beam and/or oriented deuteron target can be expressed in terms of the quantities
\[ V_{IM} = \frac{(-)^{M} \sqrt{2I+1}}{2\sqrt{15}} \sum_{m'_d m_d} (-)^{1-m'_d} C_{m_d m'_d M}^{112} \]
\[ \times \sum_{smtm_{\gamma}} q_{\max} \int dq \int d\Omega_{p\pi} K M_{s_{m\gamma} m_d}^{(t\mu)} * M_{s_{m\gamma} m_d}^{(t\mu)}, \] (15)

and

\[ W_{IM} = \frac{(-)^{M} \sqrt{2I+1}}{2\sqrt{15}} \sum_{m'_d m_d} (-)^{1-m'_d} C_{m_d m'_d M}^{112} \]
\[ \times \sum_{smtm_{\gamma}} q_{\max} \int dq \int d\Omega_{p\pi} K M_{s_{m\gamma} m_d}^{(t\mu)} * M_{s_{m\gamma} m'_d}^{(t\mu)} \] (16)

A quantity of great interest is the photon asymmetry \( \Sigma \) for linearly polarized photons, which is defined as

\[ \Sigma = \frac{d^2 \sigma}{d\Omega_{\pi}} = -W_{00}. \] (17)

It can be expressed in terms of the transition \( M \)-matrix elements as follows

\[ \Sigma = \frac{2}{F} \text{Re} \sum_{smtm_{\gamma}} q_{\max} \int dq \int d\Omega_{p\pi} K M_{s_{m\gamma} m_d}^{(t\mu)} * M_{s_{m\gamma} m_d}^{(t\mu)} \] (18)

with

\[ F = \sum_{smtm_{\gamma} m_d} q_{\max} \int dq \int d\Omega_{p\pi} K |M_{s_{m\gamma} m_d}^{(t\mu)}|^2. \] (19)

The vector target asymmetry \( T_{11} \) is defined as

\[ T_{11} = \frac{d^2 \sigma}{d\Omega_{\pi}} = 2 \Im m V_{11}. \] (20)

It can be expressed in terms of the transition \( M \)-matrix as follows

\[ T_{11} = \frac{\sqrt{6}}{F} \Im m \sum_{smtm_{\gamma}} q_{\max} \int dq \int d\Omega_{p\pi} K \left[ M_{s_{m\gamma} m_d -1}^{(t\mu)} - M_{s_{m\gamma} m_d +1}^{(t\mu)} \right] M_{s_{m\gamma} m_d 0}^{(t\mu)} * \] (21)
The tensor target asymmetries $T_{2M}$ with $M = 0, 1, 2$ are defined as

$$T_{2M} \left( \frac{d^2 \sigma}{d\Omega} \right) = (2 - \delta_{M0}) \Re \nu_{2M}, \quad M = 0, 1, 2. \quad (22)$$

These asymmetries can also be expressed in terms of the transition $\mathcal{M}$-matrix as follows

$$T_{20} = \frac{1}{\sqrt{2} \mathcal{F}} \sum_{smtm, \gamma} q_{\text{max}} \int dq \int d\Omega_{NN} \mathcal{K} \left[ |\mathcal{M}_{smm, \gamma+1}^{(t\mu)}|^2 + |\mathcal{M}_{smm, \gamma-1}^{(t\mu)}|^2 - 2 |\mathcal{M}_{smm, \gamma}^{(t\mu)}|^2 \right], \quad (23)$$

$$T_{21} = \frac{\sqrt{6} \mathcal{F}}{\mathcal{F}} \Re \sum_{smtm, \gamma} q_{\text{max}} \int dq \int d\Omega_{NN} \mathcal{K} \left[ \mathcal{M}_{smm, \gamma-1}^{(t\mu)} - \mathcal{M}_{smm, \gamma+1}^{(t\mu)} \right] \mathcal{M}_{smm, \gamma}^{(t\mu)*}, \quad (24)$$

$$T_{22} = \frac{2\sqrt{3} \mathcal{F}}{\mathcal{F}} \Re \sum_{smtm, \gamma} q_{\text{max}} \int dq \int d\Omega_{NN} \mathcal{K} \mathcal{M}_{smm, \gamma-1}^{(t\mu)} \mathcal{M}_{smm, \gamma+1}^{(t\mu)*}. \quad (25)$$

6 Results and discussion

Here we present and discuss the numerical results of the formalism developed before in calculating the single-spin asymmetries of all the three isospin channels of pion photoproduction on the deuteron in the $\Delta(1232)$-resonance region. The contribution to the pion production amplitude in (12) is evaluated by taking the realistic $NN$ potential model for the deuteron wave function. For our calculations we used the wave function of the Paris potential [9], which is in good agreement with $NN$ scattering data [10]. We would like to remark, that as we see from the discussion below we have obtained essentially the same results for the linear photon and vector target asymmetries if we take the deuteron wave function of the Bonn r-space potential [11] instead of the Paris one while small changes in the results are found for the tensor target asymmetries.

The discussion of our results is divided into three parts. The first part contains the discussion of the results for the photon asymmetry $\Sigma$ for linearly
polarized photons as a function of pion angle $\theta_\pi$ in the laboratory frame at four different photon lab-energies. In the second part we discuss the results for the vector target asymmetry $T_{11}$. The results for the tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$ are discussed in the third part. In all parts, we give the calculations for all the three isospin channels of the reaction $d(\gamma, \pi)NN$. In order to investigate qualitatively the separate role of the contributions, the effect of various contributions of the single-nucleon operator, i.e., Born terms and $\Delta(1232)$-resonance term, is shown.

All the above mentioned single-spin asymmetries are calculated by integrating over the pion momentum $q$ and the polar angle $\theta_{pNN}$ and the azimuthal angle $\phi_{pNN}$ of the relative momentum $\vec{p}_{NN}$ of the two outgoing nucleons. These integrations are carried out numerically. The number of integration Gauss-points was being increased until the accuracy of calculated observable becomes good to 1%.

6.1 Photon asymmetry

Here we discuss our results for the photon asymmetry $\Sigma$ for linearly polarized photons for all the three different charge states of the pion of the reaction $d(\vec{\gamma}, \pi)NN$. The $\gamma$-asymmetry at four different values of the photon lab-energies are plotted in Fig. 1 for $\vec{\gamma}d \rightarrow \pi^-pp$ (left panels), $\pi^+nn$ (middle panels), and $\pi^0np$ (right panels) as a function of pion angle $\theta_\pi$ in the laboratory frame. The solid curves show the results of the full calculation while the dotted ones show the contribution of the $\Delta(1232)$-resonance alone in order to clarify the importance of the Born terms. First of all, we see that the photon asymmetry has always a negative values at forward and backward emission pion angles for charged as well as for neutral pion channels. Only a very small positive value is found for $\pi^+$ production at 450 MeV. One notes qualitatively a similar behaviour for charged pion channels whereas a totally different behaviour is seen for the neutral pion channel.

For extreme forward and backward pion angles one sees, that the effect of Born contributions is relatively small in comparison to the results when $\theta_\pi$ changes from $60^\circ$ to $120^\circ$. One notices also, that the contribution from Born terms are much important in this region, in particular for charged pion channels. In the energy range of the $\Delta(1232)$-resonance, one sees that the contribution from Born terms are important in the case of charged pion channels. For the neutral pion channel we see, that this contribution is very small at 330 MeV. Since these calculations were done at 330 MeV, it is not surprising that the $\Delta$-contribution is dominant. For lower and higher energies, one sees again the sizeable effect from Born terms which arise from the Kroll-Rudermann term since it contributes only to the photoproduction of charged pions. One sees
also, that $\Sigma$ is sensitive to the energy of the incoming photon.

We would like to remark here, that we have obtained essentially the same results for the linear photon asymmetry if we take the deuteron wave function of the Bonn r-space potential [11] instead of the deuteron wave function of the Paris one [9]. We would also like to mention, that the curves in both cases are identical and therefore the results using the deuteron wave function of the Bonn potential are not shown in Fig. 1. Finally, we observe that the interference of the Born terms with the $\Delta(1232)$-resonance contribution causes considerable changes in the linear photon asymmetry. Experimental measurements will give us more valuable information on this asymmetry.

6.2 Vector target asymmetry

In this subsection we discuss our results for the vector target asymmetry $T_{11}$. Fig. 2 shows these results as a function of pion angle $\theta_\pi$ in the laboratory frame at four different values of photon lab-energies for $\gamma \vec{d} \rightarrow \pi^- pp$ (left panels), $\pi^+ nn$ (middle panels), and $\pi^0 np$ (right panels), respectively. The asymmetry $T_{11}$ clearly differs in size between charged and neutral pion photoproduction channels, being even opposite in phase. For charged pion photoproduction reactions we see from the left and middle panels of Fig. 2, that the vector target asymmetry has always a negative values which mainly come from the Born terms. A small positive contribution from the $\Delta$-resonance is found only at pion forward angles. At backward angles, the negative values for $T_{11}$ come from an interference of the Born terms with the $\Delta(1232)$-resonance contribution. For all energies one observes at forward angle the strongest effect of the Born terms.

With respect to the neutral pion photoproduction channel, we see from the right panels of Fig. 2, that the vector target asymmetry is always positive. For energies below the $\Delta$-resonance, a very small negative value is found at extreme backward pion angles while a relatively large positive value at forward angles is found. It is interesting to point out the importance of the Born terms in the charged pion production reactions in comparison to the contribution of the $\Delta(1232)$-resonance. This means, that $T_{11}$ is sensitive to the Born terms. The same effect was found by Blaazer et al. [12] and Wilhelm and Arenhövel [13] for the coherent pion photoproduction reaction on the deuteron. The reason is that $T_{11}$ depends on the relative phase of the matrix elements as can be seen from (15) and (20). It would vanish for a constant overall phase of the $t$-matrix, a case which is approximately realized if only the $\Delta(1232)$-amplitude is considered. Finally, we notice that $T_{11}$ vanishes at $\theta_\pi = 0$ and $\theta_\pi = \pi$ which is not the case for the linear photon asymmetry.
As discussed above in the case of photon asymmetry we obtained the same results for the vector target asymmetry if we take the deuteron wave function of the Bonn potential instead of the one of the Paris potential. Therefore, the results with the Bonn potential are not shown in Fig. 2.

### 6.3 Tensor target asymmetries

Let us present and discuss now the results of the tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$ as shown in Figs. 3, 4, and 5 for $\gamma \vec{d} \rightarrow \pi^- pp$, $\pi^+ nn$, and $\pi^0 np$, respectively. We start from the tensor asymmetry $T_{20}$ which is plotted in the left panels of Figs. 3, 4, and 5 for $\gamma \vec{d} \rightarrow \pi^- pp$, $\pi^+ nn$, and $\pi^0 np$, respectively, as a function of pion angle $\theta_\pi$ in the laboratory frame at four different values of photon lab-energies. The dotted curves represent the results for the contribution of the $\Delta(1232)$-resonance and the solid ones show the results when the Born terms are included. For $\gamma d \rightarrow \pi NN$ at forward and backward emission pion angles, the asymmetry $T_{20}$ allows one to draw specific conclusions about details of the reaction mechanism. In comparison to the results for photon and vector target asymmetries we found here, that the contribution from the Born terms is very small both for charged and neutral pion production channels. It is also noticeable, that for charged channels the asymmetry $T_{20}$ has a relatively large positive values at pion forward angles while a small negative ones at backward angles are found. For the neutral pion production channel we see, that $T_{20}$ has a negative values at forward angles and a positive ones at backward angles. Only for energies above the $\Delta$-resonance we note, that it has a small negative values at extreme backward angles.

The tensor target asymmetry $T_{21}$ of $\gamma \vec{d} \rightarrow \pi^- pp$, $\pi^+ nn$, and $\pi^0 np$ is plotted in the middle panels of Figs. 3, 4, and 5, respectively. It is clear that $T_{21}$ differs in size between charged and neutral pion production channels. One notices, that for charged pion channels $T_{21}$ asymmetry is sensitive to the Born terms, in particular at forward pion angles. In the case of $\pi^0$ channel one sees, that the contribution of the Born terms is much less important at all energies. In comparison to the results for photon and vector target asymmetries we found also here, that the contribution from the Born terms is small both for charged and neutral pion production channels. It is also noticeable, that in the case of charged pion channels the asymmetry $T_{21}$ has a relatively large positive values at pion forward angles. For the neutral pion channel we see, that $T_{21}$ has a negative values at forward angles. Furthermore, as in the case of vector target asymmetry, we found that $T_{21}$ is vanishes at $\theta_\pi = 0$ and $\theta_\pi = \pi$.

In the right panels of Figs. 3, 4, and 5 we depict our results for the tensor target asymmetry $T_{22}$ for the reactions $\gamma \vec{d} \rightarrow \pi^- pp$, $\pi^+ nn$, and $\pi^0 np$, respectively. One readily notes the importance of Born terms, in particular for charged pion
channels at extreme forward pion angles. Like the results of the $T_{20}$ and $T_{21}$ asymmetries, the $T_{22}$ asymmetry is sensitive to the values of pion angle $\theta_{\pi}$. At $\theta_{\pi} = 60^\circ$ we see, that the Born terms are important for $\pi^0$ production channel while these terms are very important for charged pion channels at extreme forward angles. Moreover, we found that $T_{22}$ is also vanishes at $\theta_{\pi} = 0$ and $\theta_{\pi} = \pi$.

Finally, we would like to remark that we have obtained a different results for the tensor target asymmetries if we take the deuteron wave function of the Bonn potential instead of the one of the Paris potential. This difference is very clear in the case of neutral pion production channel as seen in the right panels of Fig. 5.

7 Conclusions

In this paper we have studied incoherent single pion photoproduction on the deuteron in the first resonance region with special emphasis on single-spin asymmetries. For the elementary pion photoproduction operator an effective Lagrangian model is used which is based on time-ordered perturbation theory and describes well the elementary $\gamma N \rightarrow \pi N$ reaction. Particular attention was paid to the single-spin asymmetries. We have presented results for the linear photon asymmetry $\Sigma$, vector target asymmetry $T_{11}$ and tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$. In particular, we have studied in detail the interference of the nonresonant background amplitudes with the dominant $\Delta$-excitation amplitude. The vector target asymmetry $T_{11}$ has been found to be very sensitive to this interference. As already mentioned in the discussion above, interference of Born terms and the $\Delta(1232)$-contribution plays a significant role in the calculations. Unfortunately, there are no experimental data available to be compared to the spin observables we computed.

We would like to conclude that the results presented here for spin observables of $d(\gamma, \pi)NN$ can be used as a basis for the simulation of the behaviour of polarization observables and for an optimal planning of new polarization experiments of this reaction. It would be very interesting to examine our predictions experimentally.

As future refinements of the present model we consider the use of a more sophisticated elementary production operator, which will allow one to extend the present approach to higher energies. Future improvements should also include further investigations including final state interaction as well as two-body effects.
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References

[1] A.Yu. Loginov, A.A. Sidorov, and V.N. Stibunov, Phys. Atom. Nucl. 63, 391 (2000).

[2] E.M. Darwish, H. Arenhövel, and M. Schwamb, Eur. Phys. J. A 16, 111 (2003).

[3] E.M. Darwish, H. Arenhövel, and M. Schwamb, Eur. Phys. J. A 17, 513 (2003).

[4] E.M. Darwish and Kh. Gad, [nucl-th/0309031]

[5] M. Lucas and A. Sandorfi, private communication; M. Lucas, talk given at the LOWq workshop on Electromagnetic Nuclear Reactions at Low Momentum Transfer, August 23-25, 2001, Halifax, Nova Scotia, Canada.

[6] R. Schmidt, H. Arenhövel, and P. Wilhelm, Z. Phys. A 355, 421 (1996).

[7] J.D. Bjorken and S.D. Drell, Relativistic Quantum Mechanics (McGraw-Hill, New York, 1964).

[8] H. Arenhövel, Few-Body Syst. 4, 55 (1988).

[9] M. Lacombe et al., Phys. Lett. B 101, 139 (1981).

[10] E.M. Darwish, PhD thesis (Mainz, 2002), [nucl-th/0303056]

[11] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. 149, 1 (1987); R. Machleidt, Adv. Nucl. Phys. 19, 189 (1989).

[12] F. Blaazer, B.L.G. Bakker, and H.J. Boersma, Nucl. Phys. A 568, 681 (1994).

[13] P. Wilhelm and H. Arenhövel, Nucl. Phys. A 593, 435 (1995).
Figure 1. Linear photon asymmetry $\Sigma$ of $\bar{\gamma} d \rightarrow \pi^- pp$ (left panels), $\pi^+ nn$ (middle panels), and $\pi^0 np$ (right panels) as a function of pion angle $\theta_\pi$ in the laboratory frame at different photon lab-energies. Solid curves: full calculation; dashed curves: contribution of $\Delta(1232)$-resonance, i.e., without the Born terms.
Figure 2. Vector target asymmetry $T_{11}$ of $\gamma d \rightarrow \pi^- pp$ (left panels), $\pi^+ nn$ (middle panels), and $\pi^0 np$ (right panels) as a function of pion angle $\theta_{\pi}$ in the laboratory frame at different photon lab-energies. Notation of the curves as in Fig. 1.
Figure 3. Tensor target asymmetries $T_{20}$ (left panels), $T_{21}$ (middle panels), and $T_{22}$ (right panels) of $\gamma d \rightarrow \pi^- pp$ as a function of pion angle $\theta_\pi$ in the laboratory frame at different photon lab-energies. Solid (dash-dotted) curves: full calculation using the deuteron wave function of Paris [9] (Bonn [11]) potential model; dotted (long-dashed) curves: contribution of $\Delta(1232)$-resonance using the deuteron wave function of Paris [9] (Bonn [11]) potential model.
Figure 4. Tensor target asymmetries $T_{20}$ (left panels), $T_{21}$ (middle panels), and $T_{22}$ (right panels) of $\gamma d \rightarrow \pi^+ nn$ as a function of pion angle $\theta_\pi$ in the laboratory frame at different photon lab-energies. Notation of the curves as in Fig. 3.
Figure 5. Tensor target asymmetries $T_{20}$ (left panels), $T_{21}$ (middle panels), and $T_{22}$ (right panels) of $\gamma d \rightarrow \pi^0 np$ as a function of pion angle $\theta_\pi$ in the laboratory frame at different photon lab-energies. Notation of the curves as in Fig. 3.