POLARIZATION OBSERVABLES OF THE $\gamma d \rightarrow \pi NN$ REACTION IN THE $\Delta(1232)$-RESONANCE REGION

EED M. DARWISH

Physics Department, Faculty of Science, South Valley University, Sohag 85224, Egypt

Received (received date)  
Revised (revised date)

Polarization observables of the three charge states of the pion for the $\gamma d \rightarrow \pi NN$ reaction with polarized photon beam and/or oriented deuteron target are evaluated over the whole $\Delta(1232)$-resonance region adopting a nonrelativistic model based on time-ordered perturbation theory. Results for the $\pi$-meson spectra, linear photon asymmetry, vector and tensor target asymmetries are presented. Particular attention is given, for the first time, to double polarization asymmetries for which we present results for $T_{20}^\ell$ and $T_{2 \pm 2}^\ell$. We found that all other double polarization asymmetries of photon and deuteron target are vanished.

1. Introduction

The study of 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 study of hadron structure. For the following reasons the deuteron plays an outstanding role besides the free nucleon. The first one is that the deuteron is the simplest nucleus on whose structure we have abundant information and a reliable theoretical understanding, i.e., the structure of the deuteron is very well understood in comparison to heavier nuclei. Furthermore, the small binding energy of nucleons in the deuteron, which from the kinematical point of view provides the case of a nearly free neutron target, allows one to compare the contributions of its constituents to the electromagnetic and hadronic reactions to those from free nucleons in order to estimate interaction effects.

Meson photo- and electroproduction on light nuclei is primarily motivated by the following possibilities: (i) study of the elementary neutron amplitude in the absence of a neutron target, (ii) investigation of medium effects, i.e., possible changes of the production operator in the presence of other nucleons, (iii) it provides an interesting means to study nuclear structure, and (iv) it gives information on pion production on off-shell nucleon, as well as on the very important $\Delta N$-interaction in a nuclear medium.

*E-mail address: eeddarwish@yahoo.com
The major reason for studying polarization phenomena lies in the fact that only the use of polarization degrees of freedom allows one to obtain complete information on all possible reaction matrix elements. Without polarization, the cross section is given by the incoherent sum of squares of the reaction matrix elements only. Thus, small amplitudes are masked by the dominant ones. On the other hand, small amplitudes very often contain interesting information on subtle dynamical effects. This is the place where polarization observables enter, because such observables in general contain interference terms of the various matrix elements in different ways. Thus, a small amplitude may be considerably amplified by the interference with a dominant matrix element.

Quasifree $\pi^-$ photoproduction on the deuteron via the $\gamma d \to \pi^- pp$ reaction has been investigated within a diagrammatic approach\textsuperscript{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\textsuperscript{2,3}, the energy dependence of the three charge states of the pion for incoherent pion photoproduction on the deuteron in the $\Delta(1232)$-resonance region has been investigated. We have presented results for differential and total cross sections as well as results for the beam-target spin asymmetry which determines the Gerasimov-Drell-Hearn (GDH) sum rule.

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, one has to measure 23 independent observables, in principle, in order to determine completely the $t$-matrix. Up to present times, only a few observables have been measured and studied in detail, e.g., differential and total cross sections.

In view of the recent technical improvements, e.g., at MAMI in Mainz, ELSA in Bonn and JLab in Newport News, for preparing polarized beams and targets and for polarimeters for the polarization analysis of ejected particles it appears timely to study in detail polarization observables in pion production on the deuteron. The aim will be to see what kind of information is buried in the various polarization observables, in particular, what can be learned about the role of subnuclear degrees of freedom like meson and isobar or even quark-gluon degrees of freedom.

Most recently, we have investigated pion photoproduction on the deuteron in the $\Delta(1232)$-resonance region with special emphasis on single-spin asymmetries\textsuperscript{4}. We have presented results for the linear photon asymmetry $\Sigma$, vector target asymmetry $T_{11}$, and tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$ as functions of the emission pion angle for all the three isospin channels of the reaction $\gamma d \to \pi NN$ with polarized photon beam and/or oriented deuteron target. Our main goal in this paper is to present predictions for the $\pi$-meson spectra, single-spin asymmetries in a different kinematical situation, and, for the first time, double polarization asymmetries of photon and deuteron target. The difference between this paper and the
former one\textsuperscript{4} lies in the fact that here more exclusive polarization observables will be considered.

The paper is organized as follows. In Section 2 we will present the model for the elementary pion production amplitude which will serve as an input for the reaction on the deuteron. Section 3 will introduce the general form of the differential cross section for incoherent pion photoproduction on the deuteron. The treatment of the $\gamma d \rightarrow \pi NN$ amplitude, based on time-ordered perturbation theory, will be described in this section. In Section 4 we will give the complete formal expressions of polarization observables for the $\gamma d \rightarrow \pi NN$ reaction with polarized photon beam and/or oriented deuteron target in terms of the $t$-matrix elements. Details of the actual calculation and the results will be presented and discussed in Section 5. Finally, we close in Section 6 with a summary and an outlook.

2. The $\gamma N \rightarrow \pi N$ Amplitude

The electromagnetic production of pions on the free nucleon, including photoproduction and electroproduction, has long been studied since the pioneering work of Chew \textit{et al.}\textsuperscript{5}. As a result, an enormous amount of knowledge has been accumulated. Recently, theoretical interest in these reactions was revived by the new generation of high-intensity and high duty-cycle electron accelerators. With the developments of these new facilities, it is now possible to obtain accurate data for meson electromagnetic production, including spin-dependent observables. Extensive work during these more than forty years (see for example\textsuperscript{6−19}) indicates that, below 500 MeV incident photon energy, the mechanisms of the $\gamma N \rightarrow \pi N$ reaction are dominated by the Born terms and the $\Delta(1232)$ excitation.

For the elementary pion photoproduction operator, we have taken in this work, as in our previous work\textsuperscript{2,3,4}, the effective Lagrangian model of Schmidt \textit{et al.}\textsuperscript{20}. This model had been constructed to give a realistic description of the $\Delta(1232)$-resonance region. It is given in an arbitrary frame of reference and allows a well defined off-shell continuation as required for studying pion production on nuclei. It 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 the work of Schmidt \textit{et al.}\textsuperscript{20}.

3. Reaction on the Deuteron

The formalism of incoherent pion photoproduction on the deuteron is presented in details in our previous work\textsuperscript{2}. We briefly recall here the necessary notations and definitions.

The general expression of the cross section is given, using the conventions of Bjorken and Drell\textsuperscript{21}, by

$$
\frac{d\sigma}{dE_1 dE_2 d^4 p_1 d^4 p_2} \frac{1}{2 \omega_q} \frac{1}{E_1 E_2} \frac{M^2_q}{4 \omega, E_d} \frac{d^4 q}{|\bar{v}_\gamma - \bar{v}_d|}
$$
\[ \times \frac{1}{6} \sum_{\alpha} |\mathcal{M}^{(\mu)}_{s m m, m_d}|^2, \]

where \( k = (\omega, \vec{k}) \), \( d = (E_d, \vec{d}) \), \( q = (\omega_q, \vec{q}) \), \( p_1 = (E_1, \vec{p}_1) \), and \( p_2 = (E_2, \vec{p}_2) \) are the four-momenta of the initial photon, deuteron, pion, and two nucleons, respectively. Furthermore, \( m_\gamma \) denotes the photon polarization, \( m_d \) the spin projection of the deuteron, \( s \) and \( m_d \) 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. As a shorthand for the quantum numbers we have introduced \( \alpha = (s, m, t, m_\gamma, m_d) \). The states of all particles are covariantly normalized. The reaction amplitude is denoted by \( \mathcal{M}^{(\mu)}_{s m m, m_d} \).

For the evaluation we have chosen the laboratory frame where \( d^\mu = (M_d, \vec{0}) \). 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.

The fully exclusive differential cross section is given by

\[ \frac{d^5 \sigma}{d\Omega_{\pi NN} d\Omega_{\pi NN}} = \rho_s \frac{1}{6} \sum_{\alpha} |\mathcal{M}^{(\mu)}_{s m m, m_d}|^2, \]

where the phase space factor \( \rho_s \) is expressed in terms of relative and total momenta of the two final nucleons, \( \vec{p}_{NN} \) and \( \vec{P}_{NN} \), respectively, as

\[ \rho_s = \frac{1}{(2\pi)^5} \frac{q^2}{\omega_q} \frac{M_d^2}{m_\gamma^2} \frac{p_{NN}^2}{E_2 (p_{NN} + \frac{1}{2} P_{NN} \cos \theta_{P_{NN}}) + E_1 (p_{NN} - \frac{1}{2} P_{NN} \cos \theta_{P_{NN}})} \]

with \( \theta_{P_{NN}} \) is the angle between \( \vec{P}_{NN} \) and \( \vec{p}_{NN} \).

The general form of the photoproduction transition matrix is given by

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

where \( J^\mu (0) \) denotes the current operator and \( \epsilon_\mu (m_\gamma) \) the photon polarization vector. The outgoing \( \pi NN \) scattering state is approximated in this work by the free \( \pi NN \) plane wave, i.e.,

\[ \langle \vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu \rangle = \langle \vec{q} \mu, \vec{p}_1 \vec{p}_2 s m t - \mu \rangle^{(-)}. \]

The wave function of the final \( NN \)-state in a coupled spin-isospin basis which satisfies the symmetry rules with respect to a permutation of identical nucleons has the form

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

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
where $t_{\gamma\pi}$ denotes the elementary production amplitude on the nucleon and $\tilde{\Psi}_{m,m_d}(\vec{p})$ is given by
\begin{equation}
\tilde{\Psi}_{m,m_d}(\vec{p}) = (2\pi)^2 \sqrt{2E_d} \sum_{L=0,2} \sum_m i^L C_{LLmm_d}^{(l)} u_L(p) Y_{LM}(\hat{p}),
\end{equation}
denoting with $C_{LLmm_d}^{(l)}$ a Clebsch-Gordan coefficient, $u_L(p)$ the radial deuteron wave function and $Y_{LM}(\hat{p})$ a spherical harmonics. The contribution to the pion production amplitude in (7) is evaluated by taking a realistic $NN$ potential model for the deuteron wave function.

For our calculations we have used the wave function of the Paris potential.

4. Theoretical Calculations of Polarization Observables

The cross section for arbitrary polarized photons and initial deuterons can be computed for a given $M$-matrix by applying the density matrix formalism similar to that given by Arenhövel for deuteron photodisintegration. The most general expression for all possible polarization observables is given by
\begin{equation}
\mathcal{O} = \sum_{\alpha'\alpha} \int d\Omega_{\gamma NN} \rho_s M_{\alpha'\alpha}(t') \tilde{\Omega}_{s'm'sm} \sum_{\mu} M_{\alpha'\alpha}(t') \rho_{m,m'} \rho_{d,m_d},
\end{equation}
where $\rho_{m,m'}$ and $\rho_{d,m_d}$ 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 $\rho_s$ is a phase space factor given in (3). For further details we refer to Ref. 23,24.

As shown in Ref. 4,23 all possible polarization observables for the pion production reaction on the deuteron can be expressed in terms of the quantities
\begin{equation}
V_{LM} = \frac{1}{2\sqrt{3}} \sum_{m_d} \sum_{smt,m_v} (-1)^{1-m_d} \sqrt{2T+1} \left( \begin{array}{cc} 1 & m_d \end{array} \right) \left( \begin{array}{cc} 1 & m_d' \end{array} \right) \mathcal{O}_{\gamma NN} \rho_s M_{\alpha'\alpha}(t') \tilde{\Omega}_{s'm'sm} M_{\alpha'\alpha}(t'),
\end{equation}
and
\begin{equation}
W_{LM} = \frac{1}{2\sqrt{3}} \sum_{m_d} \sum_{smt,m_v} (-1)^{1-m_d} \sqrt{2T+1} \left( \begin{array}{cc} 1 & m_d \end{array} \right) \left( \begin{array}{cc} 1 & m_d' \end{array} \right) \mathcal{O}_{\gamma NN} \rho_s M_{\alpha'\alpha}(t') \tilde{\Omega}_{s'm'sm} M_{\alpha'\alpha}(t'),
\end{equation}
where we use the convention of Edmonds for the Wigner $3j$-symbols.

The unpolarized differential cross section is then given by

$$\frac{d^3\sigma}{d\Omega_\pi dq} = V_{00}. \quad (12)$$

The photon asymmetry for linearly polarized photons is given by

$$\Sigma \frac{d^3\sigma}{d\Omega_\pi dq} = -W_{00}. \quad (13)$$

The vector target asymmetry is given by

$$T_{11} \frac{d^3\sigma}{d\Omega_\pi dq} = 2 \Im m V_{11}. \quad (14)$$

The tensor target asymmetries are given by

$$T_{2M} \frac{d^3\sigma}{d\Omega_\pi dq} = (2 - \delta_{M0}) \Re e V_{2M}, \quad (M = 0, 1, 2). \quad (15)$$

The photon and target double polarization asymmetries are given by

(i) Circular asymmetries

$$T_{1M}^c \frac{d^3\sigma}{d\Omega_\pi dq} = (2 - \delta_{M0}) \Re e V_{1M}, \quad (M = 0, 1), \quad (16)$$

$$T_{2M}^c \frac{d^3\sigma}{d\Omega_\pi dq} = 2 \Im m V_{2M}, \quad (M = 0, 1, 2), \quad (17)$$

(ii) Longitudinal asymmetries

$$T_{1M}^\ell \frac{d^3\sigma}{d\Omega_\pi dq} = i W_{1M}, \quad (M = 0, \pm 1), \quad (18)$$

$$T_{2M}^\ell \frac{d^3\sigma}{d\Omega_\pi dq} = -W_{2M}, \quad (M = 0, \pm 1, \pm 2). \quad (19)$$

5. Results and Discussion

The discussion of our results is divided into three parts. First, we will discuss the $\pi$-meson spectra as a function of the absolute value of pion momentum $q$ at two different emission pion angles $\theta_\pi = 10^\circ$ and $120^\circ$ for photon energy at the $\Delta(1232)$-resonance region, i.e. $\omega_{\gamma}^{\text{lab}} = 330$ MeV. In the second part, we will consider the single-spin asymmetries, i.e., the linear photon asymmetry $\Sigma$, the vector target asymmetry $T_{11}$, and the tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$. In the last part, we will present and discuss our results for the double polarization asymmetries. In all parts, we will give calculations for the three isospin channels of the $d(\gamma, \pi)NN$ reaction.
5.1. The $\pi$-Meson Spectra

We start the discussion with the $\pi$-meson spectra $d^3\sigma/(d\Omega_\pi dq)$ depicted in Fig. 1 as a function of the absolute value of pion momentum $q$ at two different values of emission pion angle $\theta_\pi$ for each isospin channel of the $\gamma d \rightarrow \pi NN$ reaction for $\omega_{\gamma}^{lab} = 330$ MeV. One sees, that when the absolute value of pion momentum $q$

reaches its maximum, the absolute value of the relative momentum $p_{NN}$ of the two outgoing nucleons vanishes, and thus a narrow peak is appears in the forward emission pion angles for charged as well as for neutral pion photoproduction channels. In the lower part of Fig. 1 we see, that the unpolarized differential cross section is small and the narrow peak which appears at forward emission pion angles is disappears. The same effect appears in the coherent process of charged pion phot-and electroproduction on the deuteron$^{15,26}$, in deuteron electrodisintegration$^{27}$ as well as in $\eta$-photoproduction$^{28}$. It is also clear that the maximum value of $q$ (when $p_{NN} \rightarrow 0$) is decreases with increasing the emission pion angle. In principle, the
experimental observation of this peak in the high $\pi$-momentum spectrum may serve as another evidence for the understanding of the $\pi$-meson spectra.

In conclusion, one notes that the contributions from Born terms are important for charged pion production channels but these are much less important in the case of neutral pion production.

5.2. Single-Spin Asymmetries

5.2.1. Linear Photon Asymmetry

Here we discuss our results for the photon asymmetry $\Sigma$ for linearly polarized photons for all the different charge states of the pion of $d(\vec{\gamma}, \pi)NN$. The $\gamma$-asymmetry for fixed pion angles of $10^\circ$ and $120^\circ$ are plotted in Fig. 2 as a function of the absolute value of pion momentum $q$ at $\omega_{lab} = 330$ MeV. The dotted curves show the contribution of the $\Delta(1232)$-resonance alone in order to clarify the importance of the Born terms. We see that the photon asymmetry has always negative values at forward and backward emission pion angles for charged as well as for neutral pion channels. One notes qualitatively a similar behaviour for charged pion channels whereas a totally different behaviour is seen for the neutral pion channel.

![Fig. 2. Linear photon asymmetry $\Sigma$ of $d(\vec{\gamma}, \pi)NN$. Notation of the curves as in Fig. 1.](image-url)
It is also clear, that the contributions from Born terms are much important, in particular at \( q \simeq 200 \text{ MeV} \) which is very clear for charged pion channels. We observe that the interference of the Born terms with the \( \Delta(1232) \)-resonance contribution causes considerable changes in the photon asymmetry. Experimental measurements as well as other theoretical predictions will give us more valuable information on the photon asymmetry.

5.2.2. Vector Target Asymmetry

Fig. 3 shows our results for the vector target asymmetry \( T_{11} \) as a function of \( q \) at two different values of \( \theta_\pi \) for \( \omega^\text{lab} = 330 \text{ MeV} \). The asymmetry \( T_{11} \) clearly differs in size between charged and neutral pion production channels, being even opposite in phase. For charged pion production channels we see from the left and middle panels of Fig. 3, that the vector target asymmetry has always negative values. At forward pion angles these values come mainly from the Born terms since a small contribution from the \( \Delta \)-resonance was found. At backward angles, the negative values come from an interference of the Born terms with the \( \Delta(1232) \)-resonance contribution since the \( \Delta \)-contribution is large in this case.

![Graph showing vector target asymmetry](image-url)
With respect to the neutral pion production channel, we see from the solid curves of the right panel of Fig. 3, that the vector target asymmetry $T_{11}$ has a very small negative values at smaller pion momentum and relatively large positive values at higher pion momentum. 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. The sensitivity of $T_{11}$ to the Born terms has also been discussed by Blaazer et al.\textsuperscript{29} and Wilhelm and Arenhövel\textsuperscript{30} 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 (10) and (14). 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.

5.2.3. **Tensor Target Asymmetries**

Let us present and discuss now the results of the tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$ for $d(\gamma, \pi)NN$. We start from the tensor asymmetry $T_{20}$. 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. Results for $T_{20}$ are plotted in Fig. 4 at two different values of pion angles as a function of $q$ for
Polarization observables of the $\gamma d \rightarrow \pi NN$ reaction in the $\Delta(1232)$-resonance region

$\omega^{lab} = 330$ MeV. In general, one notes again the importance of Born terms in the case of charged pion production channels. In the case of neutral pion production channel one sees, that the Born terms are important only at extreme forward pion angles. One sees also that the contribution of Born terms is very small for backward pion angles and higher pion momentum, but it is relatively large for small pion momentum.

Fig. 5 shows our results for the tensor target asymmetry $T_{21}$ as a function of $q$ for two fixed pion angles $\theta_{\pi} = 10^\circ$ and $120^\circ$ at $\omega^{lab} = 330$ MeV. One notices that the $T_{21}$ asymmetry is sensitive to Born terms, in particular at forward pion angles. Also in this case one notes the importance of Born terms in the case of charged pion photoproduction reactions, in particular at smaller pion momentum. In the case of $\pi^0$ channel one sees that the contribution of Born terms is much less important at all angles.

In Fig. 6 we depict our results for the tensor target asymmetry $T_{22}$ as a function of $q$. We have used here the same two values of pion angle $\theta_{\pi}$ as in the previous figures. Like the results of Figs. 4 and 5, the $T_{22}$ asymmetry is sensitive to the values of pion angle $\theta_{\pi}$. We notice that the $T_{22}$ asymmetry changes dramatically if only the $\Delta$-contribution is taken into account.
5.3. Double Polarization Asymmetries

In this subsection we present and discuss our results, obtained with the deuteron wave function of the Paris potential \(^{22}\) and the pion production operator on the free nucleon of Schmidt \textit{et al.} \(^{20}\), for the circular and longitudinal double polarization asymmetries. The results of this section are presented as functions of pion angle \(\theta_\pi\) at different values of photon lab-energy, i.e., we integrated over \(q\) from 0 to \(q_{\text{max}}\) in Eqs. (9, 10, 11).

First of all, we would like to mention here that all the circular double polarization asymmetries are vanished in the region of the \(\Delta(1232)\)-resonance. With respect to the longitudinal double polarization asymmetries, we found that only the \(T_{20}^f\) and \(T_{2+2}^f\) asymmetries are not vanished. All other longitudinal double polarization asymmetries are vanished in the region of our interest. However, it is difficult to measure these asymmetries in the \(\Delta(1232)\)-resonance region. We found also that the values of the \(T_{2+2}^f\) asymmetry are identical with the values of \(T_{2-2}^f\). Therefore, in the following we present and discuss our results for only \(T_{20}^f\) and \(T_{2+2}^f\).
5.3.1. The Double Polarization Asymmetry $T_{20}^\ell$

Fig. 7 shows our results for the longitudinal double polarization asymmetry $T_{20}^\ell$ (see Eqs. (11) and (19) for its definition) as a function of emission pion angle $\theta_\pi$ for fixed values of photon lab-energies of $\omega_{\gamma_{\text{lab}}} = 285, 330, \text{ and } 450 \text{ MeV}$ for all the three charge states of the pion for the reaction $\gamma d \rightarrow \pi NN$. For neutral pion production (see the right panels of Fig. 7), we see that $T_{20}^\ell$ has always positive values for all photon lab-energies and emission pion angles. For energies below and above the $\Delta(1232)$-resonance, the double polarization asymmetry $T_{20}^\ell$ shows sensitivity

![Graph showing the double polarization asymmetry $T_{20}^\ell$ for different photon lab-energies and emission pion angles]

Fig. 7. The double polarization asymmetry $T_{20}^\ell$ of $\gamma d \rightarrow \pi NN$ as a function of emission pion angle $\theta_\pi$ at three different values of photon lab-energies. Notation of the curves as in Fig. 1.
on the Born terms, in particular for angles between 60° and 120°. Furthermore, it is apparent that at extreme forward and backward emission pion angles the asymmetry $T_{20}^\ell$ is very small in comparison to other angles. At $\omega_{\text{lab}}^{\gamma} = 450$ MeV the dominant contribution comes from the resonance term.

For the calculations of charged pion production channels (see the left and middle panels of Fig. 7), we see that $T_{20}^\ell$ has negative values at forward pion angles which is not the case at backward angles. It is also noticeable that the contributions of Born terms are large, in particular at energies above the resonance region. At extreme backward angles, we see that $T_{20}^\ell$ has small positive values.

5.3.2. The Double Polarization Asymmetry $T_{2+2}^\ell$

First of all, we would like to point out that the values of $T_{2+2}^\ell$ asymmetry are identical with the values of $T_{2-2}^\ell$ (see Eqs. (11) and (19) for their definition). Therefore, the results of the $T_{2-2}^\ell$ asymmetry are not presented here. Our results for the longitudinal double polarization asymmetry $T_{2+2}^\ell$ are plotted in Fig. 8 for the photon lab-energies $\omega_{\text{lab}}^{\gamma} = 285, 330, \text{ and } 450$ MeV as a function of emission pion angle for all the three charge states of the pion for the reaction $\gamma d \rightarrow \pi NN$. The solid curves show the results of the full calculations while the dotted curves represent the results when only the $\Delta(1232)$-resonance is taken into account.

In general, one readily notes that the longitudinal asymmetry $T_{2+2}^\ell$ has negative values at all photon energies and pion angles. For neutral pion production channel (see the right panels of Fig. 8), we noticed that the contributions of Born terms are negligible, even at energies below and above the resonance. For charged pion production channels (see the left and middle panels of Fig. 8), it is apparent that the contributions of Born terms reduce the $T_{2+2}^\ell$ asymmetry. It is very interesting to examine these spin observables experimentally.

6. Conclusions and Outlook

In this paper we have presented results for $\pi$-meson spectra, single and double polarization asymmetries for incoherent single pion photoproduction reaction on the deuteron in the $\Delta(1232)$-resonance region. The $\gamma d \rightarrow \pi NN$ scattering amplitude is given as a linear combination of the on-shell matrix elements of pion photoproduction on the two nucleons. 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.

Predictions for unpolarized differential cross section $d^3\sigma/d\Omega_{\pi} dq$, single polarization asymmetries (linear photon asymmetry $\Sigma$, vector target asymmetry $T_{11}$ and tensor target asymmetries $T_{20}$, $T_{21}$, and $T_{22}$) as well as for double polarization asymmetries (circular and longitudinal double polarization asymmetries for photon and deuteron target) are given. We found that all the circular double polarization asymmetries are vanished. Concerning the longitudinal double polarization asymmetries,
we found that only $T_{20}^d$ and $T_{2+2}^d$ are not vanished. All other double polarization asymmetries are vanished in the region of our interest. As already noticed in the discussion above, we found also that interference of Born terms and the $\Delta(1232)$-contribution plays a significant role. Unfortunately, there are no experimental data available to be compared to the observables we computed.

We would like to conclude that the results presented here for polarization observables in the $d(\gamma, \pi)NN$ reaction in the $\Delta$-resonance region 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.

Finally, we would like to point out that future improvements of the present approach should include further investigations including final state interactions. This approach is necessary for the problem at hand since polarization observables are sensitive to dynamical effects. As future refinements we consider also the use of a more sophisticated elementary production operator, which will allow one to extend the present approach to higher energies, and the role of irreducible two-body contributions to the electromagnetic pion production operator.

Acknowledgements

I would like to thank H. Arenhövel as well as many scientists of the Institut für Kernphysik of the J. Gutenberg-Universität, Mainz for fruitful discussions.

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. **A16**, 111 (2003).
3. E. M. Darwish, H. Arenhövel, and M. Schwamb, Eur. Phys. J. **A17**, 513 (2003).
4. E. M. Darwish, Nucl. Phys. **A735**, 200 (2004).
5. G. F. Chew, M. L. Goldberger, E. E. Low, and Y. Nambu, Phys. Rev. **106**, 1345 (1957).
6. N. M. Kroll and M. A. Rudermann, Phys. Rev. **93**, 233 (1954).
7. S. Fubini, G. Furlan, and C. Rossetti, *Il Nuovo Cim.* **40**, 1171 (1965).
8. F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. **B4**, 1 (1967); F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. **B4**, 54 (1967); F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. **B4**, 103 (1967).
9. M. G. Olsson and E. T. Osypowski, Nucl. Phys. **B87**, 399 (1975).
10. M. G. Olsson and E. T. Osypowski, Phys. Rev. **D17**, 174 (1978).
11. H. Tanabe and K. Ohta, Phys. Rev. **C31**, 1876 (1985).
12. A. Donnachie, in *High Energy Physics* Vol. 5, edited by E. H. S. Burhop, (Academic Press, New York, 1972).
13. I. Blomqvist and J. M. Laget, Nucl. Phys. **A280**, 405 (1977).
14. J. M. Laget, Phys. Rep. **69**, 1 (1981).
15. J. M. Laget, Nucl. Phys. **A296**, 388 (1978).
16. P. Bosted and J. M. Laget, Nucl. Phys. **A296**, 413 (1978).
17. S. Nozawa, B. Blankleider, and T.-S. H. Lee, Nucl. Phys. **A513**, 459 (1990).
18. H. García-Lázaro and E. Moya de Guerra, Nucl. Phys. **A562**, 521 (1993).
19. D. Drechsel, O. Hanstein, S. S. Kamalov, and L. Tiator, MAID Program, Institut für Kernphysik, J. Gutenberg-Universität, www.kph.uni-mainz.de/de/MAID/.
20. R. Schmidt, H. Arenhövel, and P. Wilhelm, Z. Phys. **A355**, 421 (1996).
21. J. D. Bjorken and S. D. Drell, *Relativistic Quantum Mechanics* (McGraw-Hill, New York, 1964).
22. M. Lacombe et al., Phys. Lett. **B101**, 139 (1981).
23. H. Arenhövel, Few-Body Syst. **4**, 55 (1988).
24. B. A. Robson, *The Theory of Polarization Phenomena* (Clarendon Press, Oxford, 1974).
25. A. R. Edmonds, *Angular Momentum in Quantum Mechanics* (Princeton University Press, New Jersey, 1957).
26. G. Köhler et al., Nucl. Phys. **A466**, 612 (1987).
Polarization observables of the $\gamma d \rightarrow \pi NN$ reaction in the $\Delta(1232)$-resonance region

27. W. Fabian and H. Arenhövel, *Nucl. Phys.* A258, 461 (1976).
28. A. Fix and H. Arenhövel, *Z. Phys.* A359, 427 (1997).
29. F. Blaazer, B. L. G. Bakker, and H. J. Boersma, *Nucl. Phys.* A568, 681 (1994).
30. P. Wilhelm and H. Arenhövel, *Nucl. Phys.* A593, 435 (1995).