π^0-MESON PHOTOPRODUCTION ON A POLARIZED DEUTERON

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(Received April 17, 1990)

The asymmetry T of the angular distribution of π^0-mesons produced in the $\gamma d \to d\pi^0$ reaction, if photons are unpolarized and the deuteron target is vector-polarized, is studied. The calculations take into account the contributions of the impulse approximation and of possibly existing wide dibaryon resonances with $J^P = 2^+$ and $J^P = 3^-$. The energy dependence of the asymmetry T is investigated for fixed 4-momentum transfer squared or at fixed θ (θ is the angle of π^0 production in the centre-of-mass system of $\gamma d \to d\pi^0$). The θ-dependence of the asymmetry T at fixed E_γ is also considered. The computed asymmetries T are found to be sensitive to the choice of the Fermi momentum of the nucleon in the deuteron and to the quantum numbers of dibaryon resonances. The asymmetry T values are as a rule large and can be measured experimentally.

PACS numbers: 25.20.Lj

1. Introduction

In modern practice, the polarized deuteron target has already come into use in deuteron electrodynamics. It suffices to refer to the experiments [1, 2] on elastic scattering of electrons by a tensor-polarized deuteron target. The aim of those experiments has been to find the quadrupole deuteron form factor. Such information can also be obtained by measuring the tensor polarization of elastically scattered deuterons [3]. The results [4] available from tensor-polarized deuteron electrodisintegration, $\vec{d}(e, np)e'$, where k^2 is very small, can be explained [5, 6] in terms of the relativistic impulse approximation (IA).

The asymmetry measurements [7, 8] in vector-polarized deuteron photodisintegration, $\gamma d \to np$, are of importance to specify the mechanism of this reaction, in particular, to clarify the role of dibaryon resonances (DR).

The importance of the polarized deuteron target in the investigation of electromagnetic processes will increase. Indeed, the vector-polarized deuteron target interacting with longitudinally polarized electrons is important for finding the charge form factor of the neutron in the $\vec{d}(\vec{e}, e'p)n$ reaction [9–12]. The measurement of the asymmetries, which are due to

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the tensor polarization of the target, in the $\vec{d}$(e, e'p')n reaction [5, 6], may give the spin structure of the deuteron wave function at short distances. If the target is vector-polarized, then the asymmetry measurements in the $\vec{d}$(e, ep)n reaction are important for the study of DR manifestations [13].

The asymmetry measurement in the $\gamma d \to np$ reaction, when the deuteron target is vector- or tensor-polarized, will be important for the determination of a complicated spin structure of this process, involving 12 independent amplitudes. In principle, such a complete experiment may be important for the $\gamma d \to d\pi^0$ reaction as well. The spin structure of its amplitude contains 9 independent complex amplitudes [14].

So far, in the $\gamma d \to d\pi^0$ reaction only one polarization characteristic has been measured, namely, the asymmetry Σ, which describes the absorption of linearly polarized photons by a nonpolarized target [15–17]. The measurement of other polarization effects in $\gamma d \to d\pi^0$ is the next task to be solved.

It is necessary to stress the difference between the polarization effects in the $\gamma d \to d\pi^0$ process and those in ed → enp, ed → ed or $\gamma d \to np$. The amplitudes of the $\gamma d \to d\pi^0$ reaction, being defined by the amplitudes of the $\gamma N \to N\pi$ process, are complex, while the electromagnetic form factors of the ed → ed process are real, provided that the transfer momenta are spacelike. The amplitudes of the $\gamma d \to np$ and ed → enp reactions are real in the IA too.

Therefore, the *T*-odd polarization effects, e.g., the asymmetry due to vector polarization of the deuteron, do not arise in these processes. This is a strict result of the one-photon mechanism for the ed → ed process. For $\gamma d \to np$ and ed → enp this result is valid in the IA. Yet, such an asymmetry in the $\gamma d \to d\pi^0$ reaction arises in the IA owing to the complexity of the $\gamma N \to N\pi$-amplitudes.

The asymmetries in the $\gamma\vec{d} \to d\pi^0$ reaction, which are due to the vector and tensor polarizations of the deuteron, are important for the solution of a number of problems, such as: a) verification of the IA validity; b) determination of different deuteron form factors. This is essential for the study of the spin structure of the deuteron wave function (DWF) at short distances; c) elucidation of the $\gamma n \to n\pi^0$ amplitude (the amplitude of the $\gamma p \to p\pi^0$ reaction is known); d) clarification of the DR role in the $\gamma d \to d\pi^0$ reaction.

The knowledge of the asymmetries in the $\gamma\vec{d} \to d\pi^0$ reaction will probably be useful for the determination of vector and tensor polarizations of deuterons with very high energies on the basis of the Primakoff effect [18] for the $dZ \to Zd\pi^0$ process (Z is the Coulomb field of heavy nuclei).

This method has already been realized in measurements of the polarization of protons with energies of about a few hundred GeV in the $pZ \to Zp\pi^0$ reaction [19].

In this paper we calculate the asymmetry of π^0-meson angular distribution in the $\gamma d \to d\pi^0$ reaction, which is due to the vector polarization of the target. The only asymmetry T arises if the deuteron polarization is orthogonal to the reaction plane. This asymmetry is non-zero in the IA and is defined by the complexity of the isovector amplitude of $\gamma N \to N\pi^0$. We investigate how the asymmetry T is influenced by the way of taking into account the Fermi motion of nucleons in the deuteron. We also consider the $J^P = 2^+$ and $J^P = 3^-$ DR manifestations in the asymmetries (J is the spin, P is the DR parity).

2. General analysis of the polarization effects in $\vec{\gamma}\vec{d} \to d\pi^0$

The general properties of asymmetries in $\vec{\gamma}\vec{d} \to d\pi^0$, when the initial particles are polarized, can be determined proceeding only from the P-invariance of electromagnetic interaction of hadrons and transversality of the polarization vector of real photons. Taking the differential cross section for the $\vec{\gamma}\vec{d} \to d\pi^0$ process as a function of the rector e, we can write

$$\frac{d\sigma}{d\Omega} = e_i e_j^* H_{ij} \frac{q}{k}. \tag{1}$$

The dependence of the tensor H_{ij} (which is a bilinear function of the components of hadronic electromagnetic current of the $\gamma d \to d\pi^0$ process) on the polarization characteristics of the initial deuteron is defined by the formula (summation over the final deuteron polarizations is carried out):

$$\begin{aligned} H_{ij} = {} & \hat{m}_i\hat{m}_j h_1 + \hat{n}_i\hat{n}_j h_2 + s\cdot\hat{n}(\hat{m}_i\hat{m}_j h_3 + \hat{n}_i\hat{n}_j h_4) \\ & + s\cdot\hat{m}(\{\hat{m},\hat{n}\}_{ij} h_5 + i[\hat{m},\hat{n}]_{ij} h_6) \\ & + s\cdot\hat{k}(\{\hat{m},\hat{n}\}_{ij} h_7 + i[\hat{m},\hat{n}]_{ij} h_8) \\ & + (s_{ab}\hat{k}_a\hat{k}_b)(\hat{m}_i\hat{m}_j h_9 + \hat{n}_i\hat{n}_j h_{10}) \\ & + (s_{ab}\hat{m}_a\hat{m}_b)(\hat{m}_i\hat{m}_j h_{11} + \hat{n}_i\hat{n}_j h_{12}) \\ & + (s_{ab}\hat{m}_a\hat{k}_b)(\hat{m}_i\hat{m}_j h_{13} + \hat{n}_i\hat{n}_j h_{14}) \\ & + (s_{ab}\hat{k}_a\hat{n}_b)(\{\hat{m},\hat{n}\}_{ij} h_{15} + i[\hat{m},\hat{n}]_{ij} h_{16}) \\ & + (s_{ab}\hat{m}_a\hat{n}_b)(\{\hat{m},\hat{n}\}_{ij} h_{16} + i[\hat{m},\hat{n}]_{ij} h_{18}); \end{aligned} \tag{2}$$

$$\{\hat{m},\hat{n}\}_{ij} = \hat{m}_i\hat{n}_j + \hat{m}_j\hat{n}_i; \quad [\hat{m},\hat{n}]_{ij} = \hat{m}_i\hat{n}_j - \hat{m}_j\hat{n}_i; \quad \hat{k} = k/|k|;$$

$$\hat{n} = k\times q/|k\times q|; \quad \hat{m} = \hat{n}\times\hat{k}.$$

Here k and q are the momenta of γ and π^0 in the centre-of-mass frame of $\gamma d \to d\pi^0$, the vector s and the tensor s_{ab} denote the vector and quadrupole polarizations of the deuteron target, resrectively ($s_{ab} = s_{ba}$, $\mathrm{Tr}\, s_{ab} = 0$); $h_i = h_i(s, t)$ are the real structure functions, $s = (k+P)^2$, $t = (k-q)^2$; k, P and q are the 4-momenta of the photon, the initial deuteron and the pion.

From (2) it follows that for the differential cross section of nonpolarized photon absorption in $\gamma\vec{d} \to d\pi^0$ we have

$$\begin{aligned} 2d\sigma^{(0)}/d\Omega = {} & h_1 + h_2 + s\cdot\hat{n}(h_3+h_4) + (s_{ab}\hat{k}_a\hat{k}_b)(h_9+h_{10}) \\ & + (s_{ab}\hat{m}_a\hat{m}_b)(h_{11}+h_{12}) + (s_{ab}\hat{m}_a\hat{k}_b)(h_{13}+h_{14}). \end{aligned} \tag{3}$$

Hence, the vector polarization of the target, which is perpendicular to the reaction plane, results in the only asymmetry:

$$T = (h_3+h_4)/(h_1+h_2). \tag{4}$$

In its turn, provided that the initial photons are unpolarized, the tensor polarization of the target results in three independent asymmetries.

The differential cross section of linearly polarized photon absorption is as follows:

$$\frac{d\sigma}{d\Omega}(\vec{\gamma}\vec{d} \to d\pi^0) = \frac{d\sigma^{(0)}}{d\Omega} + \cos 2\varphi \frac{d\sigma^{(1)}}{d\Omega} + \sin 2\varphi \frac{d\sigma^{(2)}}{d\Omega};$$

$$2d\sigma^{(1)}/d\Omega = h_1 - h_2 + s \cdot \hat{n}(h_3 - h_4) + (s_{ab}\hat{k}_a\hat{k}_b)(h_9 - h_{10})$$

$$+ (s_{ab}\hat{m}_a\hat{m}_b)(h_{11} - h_{12}) + (s_{ab}\hat{m}_a\hat{k}_b)(h_{13} + h_{14});$$

$$d\sigma^{(2)}/d\Omega = s \cdot \hat{m}h_5 + s \cdot \hat{k}h_7 + (s_{ab}\hat{k}_a\hat{n}_b)h_{15} + (s_{ab}\hat{m}_a\hat{n}_b)h_{17}. \tag{5}$$

Here the azimuthal angle φ defines the mutual orientation of the reaction plane (which is formed by the k and q vectors) and the polarization plane (which is formed by the e and k vectors). It is clear from (4) that if the linearly polarized photons are absorbed by the nonpolarized target, only one asymmetry continues to exist:

$$\Sigma = \left[\frac{d\sigma}{d\Omega}\bigg|_{\varphi=0} - \frac{d\sigma}{d\Omega}\bigg|_{\varphi=\frac{\pi}{2}}\right] \Bigg/ \left[\frac{d\sigma}{d\Omega}\bigg|_{\varphi=0} + \frac{d\sigma}{d\Omega}\bigg|_{\varphi=\frac{\pi}{2}}\right] = \frac{h_1 - h_2}{h_1 + h_2}. \tag{6}$$

If the linearly polarized photons strike the vector-polarized target, there arise 3 asymmetries; in the tensor polarization case, there are 5 asymmetries. Finally, the circular polarization of photons in the $\gamma d \to d\pi^0$ reaction can show up only if the deuteron target is polarized: vector-polarized, if s is in the reaction plane (here the structure functions h_6 and h_8 manifest themselves) or tensor-polarized, if the s_{xy} and s_{zy} components are non--zero (here the structure functions h_{16} and h_{18} manifest themselves).

If all 18 structure functions are known, then the problem of finding 9 complex amplitudes, which characterize the process $\gamma d \to d\pi^0$, could be solved. This is the minimal complete experiment. Because of obvious ambiguities other polarization experiments would be useful, where the polarization of scattered deuterons could be measured.

3. *Impulse approximation for $\gamma d \to d\pi^0$*

The amplitude of the $\gamma d \to d\pi^0$ process, which corresponds to the triangle diagram in Fig. 1a (IA), can be written down as follows (the dependence of the amplitude on the initial and final deuteron polarization vectors U_1 and U_2 is separated)

$$m^{(0)} = LF_1 U_1 \cdot U_2^* + 2LF_2(3U_1 \cdot \hat{Q}U_2^* \cdot \hat{Q} - U_1 \cdot U_2^*)$$

$$+ i(F_3+F_4)K \cdot U_1 \times U_2^* - 3iF_4 K \cdot QQ \cdot U_1 \times U_2^*; \quad \hat{Q} = Q/|Q|. \tag{7}$$

Here $Q = k-q$, $F_i = F_i(Q^2)$ are the deuteron form factors which generally occur in the IA of the $\gamma d \to d\pi^0$ reaction; L and K define the spin structure of the $\gamma N \to N\pi$ amplitude:

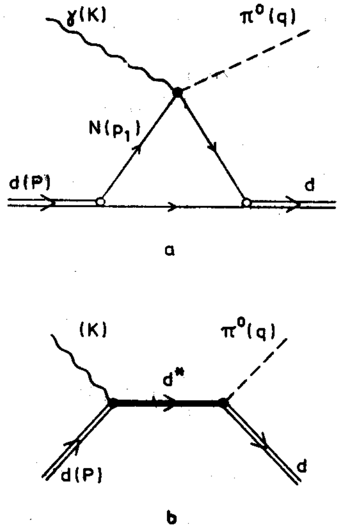

Fig. 1. Mechanisms of the $\gamma d \to d\pi^0$ reaction: a — impulse approximation; b — DR contribution

$F_{\gamma N} = \varphi_z^+ \times (\sigma \cdot K + L)\varphi_1$, where φ_1 and φ_2 are the two-component spinors of the initial and final nucleons.

In the derivation of (7) we used the standard factorization condition [20, 21] for $\gamma d \to d\pi^0$, when the amplitudes of the elementary $\gamma N \to N\pi^0$ process are not integrated over the Fermi momentum of nucleons in the deuteron. The elementary process amplitudes are taken at a certain value of the invariant $s^{(1)}$, $s^{(1)} = (k+p_1)^2$. So, the deuteron structure is taken into account by means of the form factors F_i. Of course, the S- and D-components of DWF are included.

To fix the variable $s^{(1)}$, let us choose the component of the p_1 momentum (Fig. 1a) as

$$p_{1z} = (AQ_z - BQ_0)/2(Q_0^2 - Q_z^2); \quad Q_0 = k_0 - q_0; \quad Q_z = k - q\cos\theta;$$
$$A = Q^2 + 2p_{1x}Q_x; \quad B^2 = A^2 + 4(Q_z^2 - Q_0^2)(m^2 + p_{1x}^2). \tag{8}$$

Here m is the nucleon mass, all the momenta are in the xz plane, the z axis is directed along k. The both nucleons in $\gamma N \to N\pi$ are on-shell, the variable t is the same for the $\gamma d \to d\pi^0$ and $\gamma N \to N\pi$ reactions. If p_1 is chosen according to (8), then there is no unphysical kinematic region for $\gamma N \to \pi N$. The p_{1x} component is arbitrary and is conveniently fixed by one of the three conditions:

$$p_{1x} = 0; \tag{9a}$$

$$p_{1x} = \frac{q}{2}\sin\theta; \tag{9b}$$

$$p_{1x} = \frac{q}{4}\sin\theta. \tag{9c}$$

4. *Dibaryon resonances in* $\gamma d \to d\pi^0$

Here we discuss the so-called wide DR [22]. The widths of these DR are about a few hundred MeV. The DR role in the $\gamma d \to d\pi^0$ process was discussed in [23].

We take into account only the s-channel contribution of DR to the $\gamma d \to d\pi^0$ reaction amplitude (Fig. 1b). Then the matrix elements R_2 and R_3, which correspond to the DR with $J^P = 2^+$ or $J^P = 3^-$, can be written as

$$R_2 = g_2 c_i \frac{M_2\Gamma_2}{s - M_2^2 + iM_2\Gamma_2}\left(\frac{kq}{k_2 q_2}\right) U_{1i}(e\times\hat{k})_j\{U_2^*, \hat{q}\}_{ij};$$

$$R_3 = g_3 c_i^2 \frac{M_3\Gamma_3}{s - M_3^2 + iM_3\Gamma_3}\left(\frac{kq}{k_3 q_3}\right)^2 U_{1i}(e\times\hat{k})_j\hat{k}_m\{U_2^*, \hat{q}, \hat{q}\}_{ijm};$$

$$\{U_2^*, \hat{q}\}_{ij} = U_{2i}^*\hat{q}_j + U_{2j}^*\hat{q}_i - \tfrac{2}{3}\delta_{ij}U_2^*\cdot\hat{q};$$

$$\begin{aligned}\{U_2^*, \hat{q}, \hat{q}\}_{ijm} = {}& U_{2i}^*\hat{q}_j\hat{q}_m + U_{2j}^*\hat{q}_i\hat{q}_m + U_{2m}^*\hat{q}_i\hat{q}_j \\ & -\tfrac{1}{5}(\delta_{ij}U_{2m}^* + \delta_{im}U_{2j}^* + \delta_{jm}U_{2i}^*) \\ & -\tfrac{2}{5}U_2^*\cdot\hat{q}(\delta_{ij}\hat{q}_m + \delta_{im}\hat{q}_j + \delta_{jm}\hat{q}_i);\end{aligned} \qquad (10)$$

$$c_i^2 = \frac{(k_i^2 + x^2)(q_i^2 + x^2)}{(k^2 + x^2)(q^2 + x^2)}; \qquad x^2 = 0.12\ \mathrm{GeV}^2.$$

Here M_i, Γ_i ($i = 2, 3$) are the masses and widths of the DR with $J^P = 2^+$ and 3^-; k_i, q_i are the γ and π^0 momenta in the c.m.s. of the $\gamma d \to d\pi^0$ reaction at $s = M_i^2$; g_i are the dimensionless phenomenological constants, which define the DR strength in $\gamma d \to d\pi^0$.

The parametrization (10) is analogous to that of the nucleon resonances in the $\gamma N \to N\pi^0$ process amplitude.

In (10) we consider only the transitions which correspond both to the minimal multipolarity of the photon absorbed and the minimal orbital momentum of π^0-meson. The amplitude R_2 describes the absorption of the $M1$ photon and π^0-meson production in the P-state (by means of DR with $J^P = 2^+$). The amplitude R_3 describes the production of DR with $J^P = 3^-$ when the $M2$ photon is absorbed and the π^0-meson in the D-state is produced. It is easy to write down the complete spin structure of the resonance contributions, but for our purposes it is enough to limit ourselves to formula (10).

5. *Vector polarization in* $\gamma d \to d\pi^0$

The asymmetries T and Σ are among the simplest polarization characteristics of the $\gamma d \to d\pi^0$ process. Here we discuss the asymmetry T of $\gamma d \to d\pi^0$ in the kinematic region, where $d\sigma/d\Omega$ and Σ have been measured. Namely, we shall discuss the energy dependence of T at fixed $|Q|$ or θ, and the angular dependence of T at a fixed photon energy E_γ (in the laboratory frame).

To study the T behaviour at resonance energies ($E_\gamma \leqslant 0.8$ GeV), we calculate T first in the IA. We vary the choice of the Fermi momentum p_1 and the parametrization of the deuteron wave function. The energy dependence of T at $Q = 354$ MeV (Fig. 2a) is sensitive to the p_1 choice. The positions of the T minimum, when p_1 is defined by (9a) and (9c), differ by about 100 MeV. If $E_\gamma < 500$ MeV, T weakly depends on p_1. However at

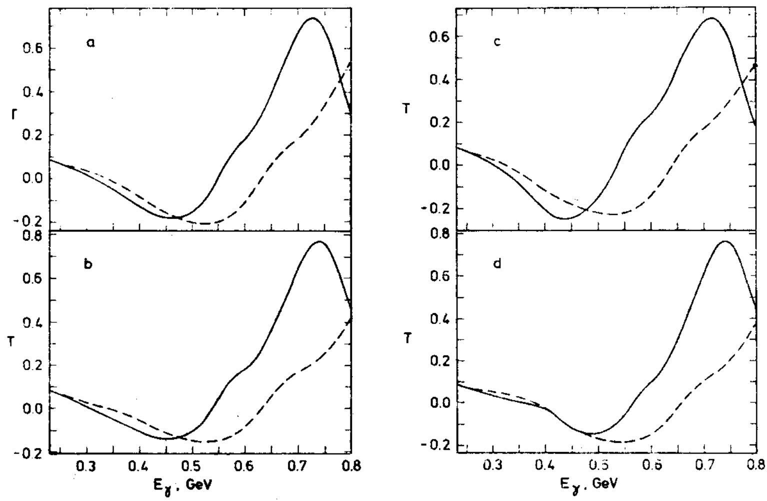

Fig. 2. Energy dependence of the asymmetry T at $Q = 354$ MeV. The momentum of the initial nucleon is calculated according to (9a) (solid curves) or (9c) (dashed curves). All the curves are calculated using the results of the multipole analysis [25] and the Buck-Gross deuteron wave function with $\lambda = 0$ [24]. a — the calculation is made in the IA, $g_2 = g_3 = 0$; b — in the IA + DR with $J^P = 2^+, g_2 = -1.4$; c — IA + DR with $J^P = 3^-$, $g_3 = 1.3$; d — IA + DR with $J^P = 3^-$, $g_3 = -1.9$

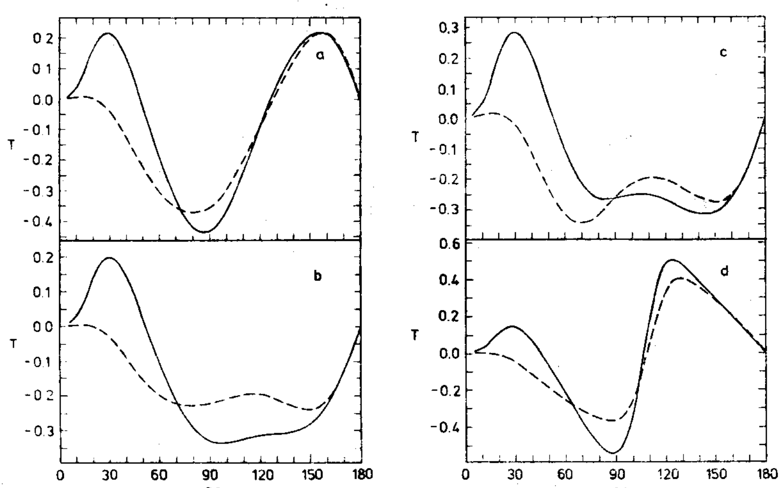

Fig. 3. θ-dependence of the asymmetry T at $E_\gamma = 550$ MeV. The notation of Figs. a–d (and of the curves) is as in Fig. 2

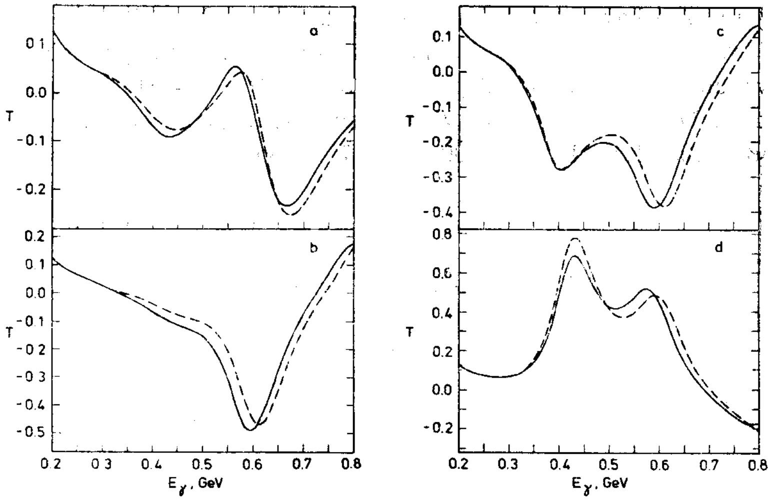

Fig. 4. Energy dependence of the asymmetry T at $\theta = 130°$. The notation of Figs. a to d (and of the curves) is as in Fig. 2

$E_\gamma > 500$ MeV the p_1-dependence of T is strong: at $E_\gamma = 700$ MeV we have $T \mp 0.7$ or $T = 0.1$ for (9a) or (9c) p_1 variants. The form of the energy dependence of T is sensitive to the p_1 choice too. The θ-dependence of T (Fig. 3a) is strong and specific for each p_1 choice.

The energy dependence of T at fixed $\theta = 130°$ (Fig. 4a) is stable with respect to p_1. A rapid change of T with energy is the characteristic feature of this function. Within the range $E_\gamma = 300$–650 MeV, the asymmetry T changes its sign three times and it has two minima: at $E_\gamma = 400$ and 675 MeV. The T value is little affected by the variations of the DWF.

In order to study the DR influence on the asymmetry T, we evaluate the constants g_2 and g_3. We use the data on $d\sigma/d\Omega$ at $\theta = 130°$. $d\sigma/d\Omega$ in this region is especially sensitive to the DR contribution. For simplicity, when fitting to $d\sigma/d\Omega$ we take into account the contribution of only one DR. As a result, we obtained the following four resonance constant values: $g_2 = 1.7$, $g_2 = -1.4$, $g_3 = 1.3$, $g_3 = -1.9$.

It is seen from Fig. 2 that the energy dependence of the asymmetry T at a fixed Q little changes if the DR with $J^P = 2^+$ or 3^- are included.

The θ-dependence of T at fixed E_γ is sensitive to the quantum numbers of DR (Fig. 3).

Of particular interest is the energy dependence of the asymmetry T at $\theta = 130°$ for $E_\gamma > 500$ MeV, where both its shape and the absolute T values are sensitive to the quantum numbers of DR and to the sign of the resonance constants as well.

6. Conclusion

The present evaluation of the asymmetries T, which are due to the vector polarization of the target, is only a qualitative one. It demonstrates the degree of T sensitivity to possible DR contributions. Note that the DR inclusion with the constants, which do not contradict the available data on $d\sigma/d\Omega$ and Σ, leads to qualitative changes (in comparison with IA predictions) in both the θ-dependence and the E_γ-dependence of the asymmetry T. The scale of these changes exceeds the ambiguity brought by the IA. The predicted asymmetry T is, as a rule, large in its magnitude and can be measured in experiments.

Editorial note. This article was proofread by the editors only, not by the authors.

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