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GENERAL ANALYSIS OF POLARIZATION EFFECTS IN THE REACTION $\gamma + \mathrm{d} \to \mathrm{d} + \pi + \pi$. I. SINGLE-SPIN ASYMMETRIES

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A general analysis of expressions for polarization observables in the reaction of coherent photoproduction of pair pseudoscalar mesons on deuteron target, $\gamma + \mathrm{d} \to \mathrm{d} + \pi + \pi$, has been performed. This analysis does not depend on the details of the reaction mechanism since it is based on general symmetry properties of the electromagnetic interaction with hadrons. Expressions for the following polarization observables have been obtained: the asymmetries due to the linear or circular polarization of photon beam, the asymmetries caused by the vector or tensor polarized deuteron target. The experimental situation when scattered deuteron and one of the produced pions are detected in coincidence has been considered. The expressions for the single-spin asymmetries in the reaction $\gamma + \mathrm{d} \to \mathrm{d} + \pi$ have been also derived.

KEY WORDS: polarization, cross section, photoproduction, asymmetry, electron, deuteron.

ОБЩИЙ АНАЛИЗ ПОЛЯРИЗАЦИОННЫХ ЭФФЕКТОВ В РЕАКЦИИ $\gamma + d \to d + \pi + \pi$. I. ОДНОСПИНОВЫЕ АСИММЕТРИИ

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Выполнен общий анализ выражений для поляризационных наблюдаемых в реакции когерентного фотообразования пары псевдоскалярных мезонов на дейтронной мишени, $\gamma + \mathrm{d} \to \mathrm{d} + \pi + \pi$. Этот анализ не зависит от деталей механизма реакции, так как он основан на общих свойствах симметрии электромагнитного взаимодействия адронов. Вычислены выражения для следующих поляризационных наблюдаемых: асимметрии, обусловленные линейной или циркулярной поляризацией фотонного пучка, асимметрии, обусловленные векторной или тензорной поляризацией дейтронной мишени. Рассмотрена экспериментальная постановка опыта, когда рассеянный дейтрон и один из образующихся пионов детектируются на совпадения. Получены также выражения для односпиновых асимметрий в реакции $\gamma + \mathrm{d} \to \mathrm{d} + \pi$.

КЛЮЧЕВЫЕ СЛОВА: поляризация, сечение, фоторождение, асимметрия, электрон, дейтрон.

ЗАГАЛЬНИЙ АНАЛІЗ ПОЛЯРИЗАЦІЙНИХ ЕФЕКТІВ У РЕАКЦІЇ $\gamma + d \to d + \pi + \pi$. I. ОДНОСПІНОВІ АСИМЕТРІЇ

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Виконано загальний аналіз виразів для поляризаційних спостережуваних у реакції когерентного фото утворення пари псевдоскалярних мезонів на дейтронній мішені, $\gamma + \mathrm{d} \to \mathrm{d} + \pi + \pi$. Цей аналіз не залежить від деталей механізму реакції тому, що він засновано на загальних властивостях симетрії електромагнітної взаємодії адронів. Вирахувані вирази для наступних поляризаційних спостережуваних: асиметрії, яка обумовлена лінійною або циркулярною поляризацією фотонного пучка, асиметрії, які обумовлені векторною або тензорною поляризацією дейтрона мішені. Розглянута експериментальна постановка досліду, коли розсіюваний дейтрон і один із мезонів що утворюється детектуються на збіг. Вирахувані також вирази для одно спінових асиметрій у реакції $\gamma + \mathrm{d} \to \mathrm{d} + \pi$.

КЛЮЧОВІ СЛОВА: поляризація, переріз, фотоутворення, асиметрія, електрон, дейтрон.

Understanding the structure of hadrons (and, in particular, nucleon) and basic properties of nucleon resonances (the spectrum, decay widths, spin and so on) is an important problem in the physics of the strong interaction. Unfortunately, the existing at present theory of the strong interaction, Quantum Chromodynamics (QCD), is not able to predict these properties since in the low energy regime (scale typical for the nucleon mass and its excited states) it is necessary to use the non-perturbative approach which is absent now.

The complex structure of the nucleon is reflected in a rich excitation energy spectrum. The electromagnetic excitation of the nucleon with real photons and the subsequent decay via mesons allows insight into its structure and couplings. Although studied for a long time with hadron beams, the properties of many baryon resonances are not sufficiently well known to provide a crucial test for quark models and other descriptions of nucleon resonances. So, at present, much of our limited understanding of these baryon resonances comes from various versions of quark models. They predict a number of the resonances with masses above 1.8 GeV that have not been observed in the pion-nucleon channel, the so-called "missing" resonances. Thus, the photoproduction of final states with more than one meson (the so-called multi-meson final states) avoids the pion-nucleon state both in the initial and final states. Such experiments can give the possibility to study the nucleon resonances which are weakly coupled to this channel. The recent progress in the investigation of nucleon resonances with meson photoproduction on nucleons and light nuclei was given in the review [1].

With the advent of new experimental facilities providing continuous tagged photon beams like JLab (USA), MAMI at Mainz, and ELSA at Bonn and availability of the detectors with large solid angle allows one to investigate the decays of the nucleon resonances into multi-meson states. Here, the availability of linearly and circularly polarized photon beam and polarized targets has provided access to observables, which are sensitive to specific resonances.

The experiments on the meson photoproduction showed that double pion photoproduction is an important reaction channel in the second resonance region. The cross sections for single meson photoproduction (pion or η-meson) and double pion photoproduction are almost equal at the photon beam energies in the range $600-800$ MeV [2, 3]. Moreover, most of the rise of the total photoabsorption cross section from dip above the Δ-resonance to the peak of the second resonance bump is due to the double pion photoproduction. This is not only important for resonances on free nucleon, but also for understanding of suppression of second resonance bump in total photoabsorption from nuclei.

Let us note that investigation of the photoproduction reaction on the proton target alone does not permit a total determination of the amplitude of the process, primarily its isospin structure. So, to investigate this structure it is necessary to use the reactions on nuclei, especially on the deuteron and ^{3}He, which are usually used as the neutron targets. Note that not only quasifree, but also coherent reactions like $d(\gamma,\pi^0\eta)d$, can give important information [4].

Up to now the majority of the experiments on the double pion photoproduction have been done on the proton targets. At present there exist a number of experiments which use the deuteron target [5] – [9]. The isospin channels involving neutron targets have been studied in quasifree kinematics on the deuteron.

In the last time, the polarization observables in the double meson photoproduction reactions on the proton target have been measured in a number of the experiments. The beam asymmetry, caused by the linear polarization of the photon beam, was measured for the $\gamma p \to \pi^0 \eta p$ reaction [10]. The asymmetries due to the circularly polarized photon beam were measured in the double-charged-pion photoproduction on the proton target [11, 12]. The polarization observable which is caused by the acoplanar kinematics of multi-meson final state produced via linearly polarized photon beam in the reaction $\gamma p \to \pi^0 \eta p$ has been measured for the first time [13]. The helicity dependence of the total cross section for the reaction $\gamma p \to n\pi^+\pi^0$ has been measured for the first time at photon beam energies $400-800$ MeV [14]. The circularly polarized photon beam and longitudinally polarized proton target are used in this experiment. The first polarization measurement on the neutron target has been done at photon beam energies $0.6-1.5$ GeV [15]. The beam asymmetry due to the linearly polarized photon beam was measured in the reaction of the double π^0-meson photoproduction on the neutron.

From the theoretical point of view, the analysis of the polarization effects in the reaction of the double-meson photoproduction on the nucleon target has been performed in a few papers [16] – [17]. The formalism for the investigation of the polarization observables for the processes $\gamma N \to \pi\pi N$ and $\pi N \to \pi\pi N$, using both helicity and hybrid helicity-transversity basis, has been considered in Ref. [16]. The expressions for the differential cross section and the recoil polarization including beam and target polarization have been derived for the $\pi^0\eta$ photoproduction on the proton [17]. Numerical results for the linear and circular photon beam asymmetries for this reaction have been obtained within an isobar model.

A general analysis of the polarization observables in the reaction of coherent photoproduction of pair pseudoscalar mesons on the deuteron target, $\gamma d \to \pi\pi d,$ has been derived in this paper. To do this we use the approach suggested in Ref. [18], where a general analysis of the polarization phenomena for the processes with three-body final states (in noncoplanar kinematics) has been presented. Our analysis does not depend on the details of the reaction mechanism since it is based on general symmetry properties of the electromagnetic interaction with hadrons. Expressions for the following polarization observables have been obtained: the asymmetries due to the linear or circular polarization of photon beam, the asymmetries caused by the vector or tensor polarized deuteron target. The experimental situation when scattered deuteron and one of the produced pions are detected in coincidence has been considered. The expressions for the same single-spin asymmetries in the reaction $\gamma d \to \pi d,$ have been also derived.

The aim of the paper is the analysis of the polarization observables in the reaction $\gamma d \to \pi\pi d,$ which can help in elucidation of the reaction mechanism and clarify the properties of the "missing" resonances.

MATRIX ELEMENT AND DIFFERENTIAL CROSS SECTION

We consider the process of the photoproduction of the pair of the pseudoscalar mesons ($\pi\pi$, $\pi\eta$ and etc.) on the deuteron target

$$\gamma(k)+d(p_1)\to d(p_2)+\pi(q_1)+\pi(q_2), \tag{1}$$

where the four-momenta of the particles are given in the brackets.

Let us note that considered reaction is of the following type $1+2\to 3+4+5$ and the main feature of the process with three particles in the final state is noncoplanarity of the kinematics. It means that this reaction is characterized by two (instead of one for the case of the binary reactions) reaction planes: one plane is determined by the momenta of the photon beam and scattered deuteron and other plane is defined by the momenta of the one of the pions and photon beam.

In the paper [18] it was suggested the approach which permits to do a general analysis of polarization phenomena for the three-body processes with noncoplanar kinematics. The main feature of this approach is introduction of pseudoscalar acoplanarity parameter. The spin structure of the matrix element and the polarization phenomena for such processes contain new contribution, with respect to binary processes, which can be conveniently expressed as functions of this parameter.

We apply now the formalism of parametrization of the reaction amplitude with the help of the orthonormal basis to the case of the photoproduction of two pseudoscalar mesons (pion or η-meson) on the deuteron. Since this reaction is of the type $2\to 3$ process we use the approach of the paper [18]. In the $2\to 3$ process the momenta of all particles do not lie, in general, in one plane and as a result we have a non-zero relativistic invariant (a pseudoscalar)

$$P_{inv}=\varepsilon_{\mu\nu\rho\sigma}p_{1\mu}p_{2\nu}q_{1\rho}q_{2\sigma}=-\sqrt{s}\varepsilon_{ijk}p_{1i}p_{2j}q_{1k},$$

where $s=(k+p_1)^2$ is the square of the total energy of the reaction. This relation is written in the reaction CMS (we use the convention $\varepsilon_{1234}=1$). It is evident that in the center-of-mass system (CMS) of the reaction $1+2\to 3+4+5$ P_{inv} will be proportional to the following product of the three-momenta $\mathbf{p}_1\cdot\mathbf{p}_2\times\mathbf{q}_1$ which defines noncoplanarity of the particles three-momenta. Namely, the parameter P_{inv} is connected with the angle between two reaction planes.

Let us introduce the set of the orthonormal unit vectors

$$\hat{\mathbf{k}}=\frac{\mathbf{k}}{|\mathbf{k}|},\qquad \mathbf{n}=\frac{\mathbf{k}\times\mathbf{q}}{|\mathbf{k}\times\mathbf{q}|},\qquad \mathbf{m}=\mathbf{n}\times\hat{\mathbf{k}}, \tag{2}$$

where $\mathbf{k}(\mathbf{q})$ is the momentum of the photon (first pion) in CMS of the reaction under consideration. The coordinate system is chosen as: *z* axis is directed along the momentum of the photon $\mathbf{k}$, and the momentum of the first pion lies in the xz plane. In this case the unit vector $\mathbf{m}$ is directed along *x* axis, the unit vector $\mathbf{n}$ is directed along *y* axis and the unit vector $\hat{\mathbf{k}}$ is directed along *z* axis.

To use the approach of the paper [18], it is necessary to introduce the acoplanarity parameter which takes into account the features of the three-body processes. We introduce the following pseudoscalar $P=\mathbf{n}\cdot\mathbf{p}/|\mathbf{p}|$ which is proportional to $\sin\phi$, where $\mathbf{p}$ is the scattered deuteron momentum and ϕ is the azimuthal angle of its momentum.

The number n of independent helicity amplitudes for $1+2\to 3+4+5$ is given, in general, by $n=(2s_1+1)$ $(2s_2+1)(2s_3+1)(2s_4+1)(2s_5+1)$, where s_i is the spin of the i-th particle. So, for our case this number is $n=18$.

The presence of the noncoplanarity $(P\neq 0)$ has to be taken into account in establishing the spin structure of the matrix element for the reaction (1). If the $P-$invariance of the strong and electromagnetic interactions holds, the matrix element is described by the following general parametrization (in CMS of the considered reaction)

$$M=\bar{A}+P\bar{B}, \tag{3}$$

$$\bar{A} = \mathbf{e}\cdot\mathbf{m}[f_1\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{m} + f_2\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{n} + f_3\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + f_4\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + f_5\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{m}] +$$
$$+\mathbf{e}\cdot\mathbf{n}[f_6\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{n} + f_7\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{n} + f_8\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{m} + f_9\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\hat{\mathbf{k}}],$$

$$\bar{B} = \mathbf{e}\cdot\mathbf{m}[f_{10}\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{n} + f_{11}\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{n} + f_{12}\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{m} + f_{13}\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\hat{\mathbf{k}}] +$$
$$+\mathbf{e}\cdot\mathbf{n}[f_{14}\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{m} + f_{15}\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{n} + f_{16}\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + f_{17}\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + f_{18}\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{m}],$$

where $\mathbf{U}_1(\mathbf{U}_2)$ and $\mathbf{e}$ are the polarization three-vectors of the initial (scattered) deuteron and photon, respectively. Quantities f_i, $i = 1-18$, are the scalar independent amplitudes for the reaction (1) which are functions of the five kinematical variables.

Let us single out the photon polarization three-vector and write down the matrix element in the following form

$$M = ee_iJ_i, \tag{4}$$

where e is the electron charge.

Since the photon polarization three-vector is orthogonal to the photon momentum (vector $\mathbf{k}$), then the general form of the hadronic current can be written as

$$J_i = m_iA + n_iB, \tag{5}$$

where

$$A = f_1\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{m} + f_2\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{n} + f_3\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + f_4\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + f_5\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{m} +$$
$$+g_{10}\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{n} + g_{11}\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{n} + g_{12}\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{m} + g_{13}\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\hat{\mathbf{k}},$$

$$B = f_6\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{n} + f_7\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{n} + f_8\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{m} + f_9\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} +$$
$$+g_{14}\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{m} + g_{15}\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{n} + g_{16}\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + g_{17}\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + g_{18}\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{m},$$

where we introduce the designation $g_i = Pf_i, (i = 10-18)$. The square of the matrix element can be written as

$$|M|^2 = 4\pi\alpha\rho_{ij}^{(\gamma)}H_{ij}, \tag{6}$$

where the tensor $\rho_{ij}^{(\gamma)} = e_ie_j^*$ describes the polarization state of the photon beam and hadronic tensor is defined as $H_{ij} = J_iJ_j^*$. The general structure of the hadronic tensor can be represented by the formula

$$H_{ij} = m_im_jAA^* + n_in_jBB^* + \mathrm{Re}(AB^*)(m_in_j + m_jn_i) + i\,\mathrm{Im}(AB^*)(m_in_j - m_jn_i).$$

The differential cross section of this reaction can be written as, in the reaction CMS, in terms of the reaction matrix element for the case when the scattered deuteron and one of the pseudoscalar mesons are detected in coincidence

$$\frac{d\sigma}{d\omega_1 d\Omega_\pi d\Omega_d} = \frac{(2\pi)^{-5}}{32ME_\gamma}\frac{p^2|\vec{q}_1||M|^2}{p(W-\omega_1) + E_2|\vec{q}_1|\cos\chi}, \tag{7}$$

where $E_\gamma = (s - M^2)/2M$ is the energy of the photon beam in the laboratory system, $s = W^2 = (k + p_1)^2$ is the square of the total energy, M is the deuteron mass, $\omega_1(|\vec{q}_1|)$ and $E_2(p)$ are the energy (magnitude of the momentum) of the first meson and scattered deuteron in the reaction CMS, χ is the angle between momenta of the scattered deuteron and the first meson.

POLARIZATION STATE OF PHOTON BEAM AND DEUTERON TARGET

To describe the polarization state of the photon beam we use the general expression for the photon polarization three-vector which is determined by two real parameters β and δ and it can be written as [19]

$$\mathbf{e} = \cos\beta\mathbf{m} + \sin\beta\exp(i\delta)\mathbf{n}. \tag{8}$$

If the parameter $\delta = 0$ then this photon polarization vector determines the linear polarization state of the photon at an angle β to the x axis. The parameters values $\beta = \pi/4$ and $\delta = \pm\pi/2$ denote circular polarization of the photon. Arbitrary β and δ correspond to the elliptic polarization of photons. In the formalism of the photon spin-density matrix such description corresponds to the particular choice of the Stokes parameters

$$\xi_1 = \sin 2\beta\cos\delta, \qquad \xi_2 = \sin 2\beta\sin\delta, \qquad \xi_3 = \cos 2\beta.$$

These parameters satisfy the following condition: $\xi_1^2 + \xi_2^2 + \xi_3^2 = 1$. The value $\delta = 0$ (the linear polarization) corresponds to $\xi_1 = \sin 2\beta, \xi_2 = 0, \xi_3 = \cos 2\beta$ and the value $\delta = \pm 90^\circ, \beta = 45^\circ$ corresponds to $\xi_1 = \xi_3 = 0, \xi_2 = \pm 1$. Let us stress that such choice of ξ_i is not the most general expression for the photon spin-density matrix.

We consider the general case of the polarization state for the deuteron target which is described by the spin–density matrix. We use the following general expression for the deuteron spin–density matrix for the case of spin one in the covariant representation [20]

$$\rho_{\mu\nu} = -\frac{1}{3}\left(g_{\mu\nu} - \frac{p_{1\mu}p_{1\nu}}{M^2}\right) + \frac{i}{2M}\varepsilon_{\mu\nu\alpha\beta}s_\alpha p_{1\beta} + Q_{\mu\nu}, \tag{9}$$

where s_α is the four–vector describing the vector polarization of the deuteron target and satisfying the following conditions, $s^2 = -1$, $s \cdot p_1 = 0$ and $Q_{\mu\nu}$ is the tensor describing the tensor (quadrupole) polarization of the deuteron target and satisfying the following conditions, $Q_{\mu\nu} = Q_{\nu\mu}$, $p_{1\mu}Q_{\mu\nu} = 0$, $Q_{\mu\mu} = 0$ (due to these properties the tensor $Q_{\mu\nu}$ has only five independent components). In laboratory system all time components of the tensor $Q_{\mu\nu}$ are zero and the tensor polarization of the target is described by five independent space components $(Q_{ij} = Q_{ji}, Q_{ii} = 0, i, j = x, y, z)$. The polarization four–vector s_α is related to the unit vector $\vec{\xi}$ of the deuteron vector polarization in its rest system: $s_0 = -\vec{k}\cdot\vec{\xi}/M$, $\vec{s} = \vec{\xi} + \vec{k}(\vec{k}\cdot\vec{\xi})/M(M+E_1)$, E_1 is the deuteron-target energy in the $\gamma + d \to d + \pi + \pi$ reaction CMS.

Below in the paper we assume that the recoil deuteron polarization is not measured. So, its polarization state is described by the following spin–density matrix

$$\rho'_{\mu\nu} = -g_{\mu\nu} + \frac{p_{2\mu}p_{2\nu}}{M^2}. \tag{10}$$

All particles are unpolarized

The differential cross section of the reaction (1) in the experimental set-up when the scattered deuteron and one of the produced pions are detected in coincidence can be written as follows (for the case when all particles participating in the reaction are unpolarized)

$$\frac{d\sigma_{un}}{d\omega_1 d\Omega_\pi d\Omega_d} = KD, \qquad K = \frac{\alpha}{3(4\pi)^4}\frac{p^2|\vec{q}_1|}{s - M^2}\left[p(W-\omega_1) + E_2|\vec{q}_1|\cos\chi\right]^{-1}, \tag{11}$$

where K is the kinematical factor and quantity D is

$$
\begin{aligned}
D = {} & x_1[|f_1|^2+|f_8|^2+|g_{12}|^2+|g_{14}|^2+\gamma^2(|f_5|^2+|g_{18}|^2)]+x_2[|f_2|^2+|f_6|^2+|g_{10}|^2+ \\
& +|g_{15}|^2+\gamma^2(|f_7|^2+|g_{11}|^2)]+x_3[|f_4|^2+|f_9|^2+|g_{13}|^2+|g_{17}|^2+\gamma^2(|f_3|^2+|g_{16}|^2)]+ \\
& +2y_1\mathrm{Re}[f_1g_{10}^*+f_2g_{12}^*+f_6g_{14}^*+f_8g_{15}^*+\gamma^2(f_5g_{11}^*+f_7g_{18}^*)]+ \\
& +2y_2\mathrm{Re}[f_1f_4^*+f_8f_9^*+g_{12}g_{13}^*+g_{14}g_{17}^*+\gamma^2(f_3f_5^*+g_{16}g_{18}^*)]+ \\
& +2y_3\mathrm{Re}[f_2g_{13}^*+f_4g_{10}^*+f_6g_{17}^*+f_9g_{15}^*+\gamma^2(f_3g_{11}^*+f_7g_{16}^*)],
\end{aligned} \tag{12}
$$

where we introduce the following designations

$$
x_1=1+\frac{p^2}{M^2}\sin^2\theta\cos^2\phi,\quad x_2=1+\frac{p^2}{M^2}\sin^2\theta\sin^2\phi,\quad x_3=1+\frac{p^2}{M^2}\cos^2\theta,
$$

$$
y_1=\frac{p^2}{2M^2}\sin^2\theta\sin2\phi,\quad y_2=\frac{p^2}{2M^2}\sin2\theta\cos\phi,\quad y_3=\frac{p^2}{2M^2}\sin2\theta\sin\phi,\quad \gamma=\frac{E_1}{M}.
$$

Here θ and ϕ are the polar and azimuthal angles of the deuteron momentum.

Photon beam is polarized

The differential cross section of the reaction (1) can be written as follows for the case when the photon beam has an elliptical polarization and the particles participating in the reaction are unpolarized

$$
\frac{d\sigma}{d\omega_1 d\Omega_\pi d\Omega_d}=\frac{d\sigma_{un}}{d\omega_1 d\Omega_\pi d\Omega_d}(1+\Sigma_L\cos2\beta+\Sigma_L'\sin2\beta\cos\delta+\Sigma_C\sin2\beta\sin\delta), \tag{13}
$$

where the asymmetries Σ_L, Σ_L' and Σ_C have the following expressions in the terms of the reaction scalar amplitudes

$$
D\Sigma_L=F,\quad D\Sigma_L'=2\mathrm{Re}G,\quad D\Sigma_C=2\mathrm{Im}G, \tag{14}
$$

where the quantities F and G are

$$
\begin{aligned}
F = {} & x_1[|f_1|^2-|f_8|^2+|g_{12}|^2-|g_{14}|^2+\gamma^2(|f_5|^2-|g_{18}|^2)]+x_2[|f_2|^2-|f_6|^2+|g_{10}|^2- \\
& -|g_{15}|^2-\gamma^2(|f_7|^2-|g_{11}|^2)]+x_3[|f_4|^2-|f_9|^2+|g_{13}|^2-|g_{17}|^2+\gamma^2(|f_3|^2-|g_{16}|^2)]+ \\
& +2y_1\mathrm{Re}[f_1g_{10}^*+f_2g_{12}^*-f_6g_{14}^*-f_8g_{15}^*+\gamma^2(f_5g_{11}^*-f_7g_{18}^*)]+ \\
& +2y_2\mathrm{Re}[f_1f_4^*-f_8f_9^*+g_{12}g_{13}^*-g_{14}g_{17}^*+\gamma^2(f_3f_5^*-g_{16}g_{18}^*)]+ \\
& +2y_3\mathrm{Re}[f_2g_{13}^*+f_4g_{10}^*-f_6g_{17}^*-f_9g_{15}^*+\gamma^2(f_3g_{11}^*-f_7g_{16}^*)],
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
G = {} & x_1(f_1g_{14}^*+g_{12}f_8^*+\gamma^2f_5g_{18}^*)+x_2(f_2g_{15}^*+g_{10}f_6^*+\gamma^2g_{11}f_7^*)+ \\
& +y_1[f_1f_6^*+f_2f_8^*+f_4g_{17}^*+g_{13}f_9^*+g_{10}g_{14}^*+g_{12}g_{15}^*+\gamma^2(f_5f_7^*+f_3g_{16}^*+g_{11}g_{18}^*)]+ \\
& +y_2[f_1g_{17}^*+f_4g_{14}^*+g_{13}f_8^*+g_{12}f_9^*+\gamma^2\left(f_3g_{18}^*+f_5g_{16}^*\right)]+ \\
& +y_3[f_2f_9^*+f_4f_6^*+g_{10}g_{17}^*+g_{13}g_{15}^*+\gamma^2\left(f_3f_7^*+g_{11}g_{16}^*\right)].
\end{aligned} \tag{16}
$$

So, the elliptically polarized photon beam leads to three independent asymmetries. The use of linearly polarized photon beam (parameter $\delta = 0$) allows to determine the first two asymmetries. Changing the angle between the polarization vector of the photon beam and x axis we can obtain the asymmetries Σ_L and Σ'_L according to the following relations

$$\Sigma_L = \frac{d\sigma(\beta = 0^\circ) - d\sigma(\beta = 90^\circ)}{d\sigma(\beta = 0^\circ) + d\sigma(\beta = 90^\circ)}, \tag{17}$$

$$\Sigma'_L = \frac{d\sigma(\beta = 45^\circ) - d\sigma(\beta = -45^\circ)}{d\sigma(\beta = 45^\circ) + d\sigma(\beta = -45^\circ)}. \tag{18}$$

The angle $\beta = 0^\circ$ means that the photon polarization vector lies in the plane formed by the momenta of the detected pion and photon beam and the angle $\beta = 90^\circ$ – the photon polarization vector perpendicular to this plane. To determine the third asymmetry it is necessary to use the circularly polarized photon beam (parameter $\delta = \pm 90^\circ$ and $\beta = 45^\circ$). The asymmetry Σ_C is determined as follows

$$\Sigma_C = \frac{d\sigma(\delta = 90^\circ) - d\sigma(\delta = -90^\circ)}{d\sigma(\delta = 90^\circ) + d\sigma(\delta = -90^\circ)}. \tag{19}$$

The momenta of the particles in a single-meson photoproduction on the nucleon target form a single plane (reaction plane). Two-meson photoproduction is not restricted to a single plane. In contrast to a single-meson photoproduction (see, for example, Eq. (36)), here the beam polarization asymmetry can be non-zero if the photon beam is circularly polarized. And the first measurements of this asymmetry in the $\gamma p \to p\pi^+\pi^-$ reaction [11, 12] have demonstrated its significant model sensitivity. The linearly polarized photon beam leads, in the general case, to two independent asymmetries Σ_L and Σ'_L. The first measurement of the Σ'_L asymmetry in the $\gamma p \to p\eta\pi^\circ$ reaction [13] reveals the discrepancies between predictions of some models and the data and this fact underlines the importance of this polarization observable.

The deuteron target is vector polarized

The differential cross section of this reaction for the case of the vector polarized initial deuteron and unpolarized photon beam can be written as

$$\frac{d\sigma}{d\omega_1 d\Omega_\pi d\Omega_d} = \frac{d\sigma_{un}}{d\omega_1 d\Omega_\pi d\Omega_d}(1 + A_x\xi_x + A_y\xi_y + A_z\xi_z), \tag{20}$$

where the quantities A_i, $i = x, y, z$ are the asymmetries caused by the vector polarization of the initial deuteron provided the photon beam is unpolarized (the so–called single target asymmetries). These polarization observables have the following expressions in the terms of the reaction scalar amplitudes

$$\begin{aligned} DA_x = \frac{\gamma}{2}\mathrm{Im}[&x_1(f_8g_{18}^* - f_5g_{12}^*) + x_2(f_2g_{11}^* - f_7g_{15}^*) + x_3(f_9g_{16}^* - f_3g_{13}^*) + \\ +&y_1(g_{15}g_{18}^* - g_{11}g_{12}^* + f_2f_5^* - f_7f_8^*) + y_2(f_8g_{16}^* + f_9g_{18}^* - f_3g_{12}^* - f_5g_{13}^*) + \\ &+ y_3(g_{15}g_{16}^* - g_{11}g_{13}^* + f_2f_3^* - f_7f_9^*)], \end{aligned} \tag{21}$$

$$\begin{aligned} DA_y = \frac{\gamma}{2}\mathrm{Im}[&-x_1(f_1f_5^* + g_{14}g_{18}^*) - x_2(f_6f_7^* + g_{10}g_{11}^*) + x_3(f_3f_4^* + g_{16}g_{17}^*) + \\ +&y_1(f_5g_{10}^* - f_1g_{11}^* + f_7g_{14}^* - f_6g_{18}^*) - y_2(f_1f_3^* + f_4f_5^* + g_{14}g_{16}^* + g_{17}g_{18}^*) + \\ &+ y_3(f_3g_{10}^* + f_7g_{17}^* - f_4g_{11}^* - f_6g_{16}^*)], \end{aligned} \tag{22}$$

$$DA_z = \frac{1}{2\gamma}\mathrm{Im}[x_1(f_1g_{12}^* - f_8g_{14}^*) + x_2(f_6g_{15}^* - f_2g_{10}^*) + x_3(f_4g_{13}^* - f_9g_{17}^*) + \\ + y_1(g_{10}g_{12}^* + g_{14}g_{15}^* + f_1f_2^* + f_6f_8^*) + y_2(f_1g_{13}^* + f_4g_{12}^* - f_8g_{17}^* - f_9g_{14}^*) + \\ + y_3(g_{10}g_{13}^* - g_{15}g_{17}^* + f_6f_9^* - f_2f_4^*)]. \quad (23)$$

From Eq. (20) one can see that for the process of two-meson photoproduction all components of the vector describing the vector polarized deuteron target give, in the general case, non-zero contributions to the differential cross section of the reaction (1). In contrast, for the process of single-meson photoproduction only normal (to the reaction plane) component can give non-zero asymmetry.

The deuteron target is tensor polarized

The tensor polarization of the deuteron is determined, in the general case, by five independent parameters: Q_{zz}, Q_{xz}, Q_{xy}, Q_{yz}, and $Q_{xx}-Q_{yy}$. So, the differential cross section of the reaction (1) for the case of the tensor polarized initial deuteron and unpolarized photon beam can be written as

$$\frac{d\sigma}{d\omega_1 d\Omega_\pi d\Omega_d} = \frac{d\sigma_{un}}{d\omega_1 d\Omega_\pi d\Omega_d}(1 + A_{zz}Q_{zz} + A_{xx}(Q_{xx}-Q_{yy}) + A_{xz}Q_{xz} + A_{xy}Q_{xy} + A_{yz}Q_{yz}), \quad (24)$$

where the quantities A_{ij}, $ij = zz, xx, xz, xy, yz$ are the asymmetries caused by the tensor (quadrupole) polarization of the deuteron target provided the photon beam is unpolarized (the so–called single target asymmetries). These polarization observables have the following expressions in the terms of the reaction scalar amplitudes

$$A_{zz} = \frac{1}{2}[x_1(|f_5|^2 + |g_{18}|^2) + x_2(|g_{11}|^2 + |f_7|^2) + x_3(|f_3|^2 + |g_{16}|^2)] + \\ + \mathrm{Re}[y_1(f_5g_{11}^* + f_7g_{18}^*) + y_2(f_3f_5^* + g_{16}g_{18}^*) + y_3(f_3g_{11}^* + f_7g_{16}^*)] - \\ - \frac{1}{4\gamma^2}[x_1(|f_1|^2 + |f_8|^2 + |g_{14}|^2 + |g_{12}|^2) + x_2(|g_{10}|^2 + |f_2|^2 + |f_6|^2 + |g_{15}|^2) + \\ + x_3(|f_4|^2 + |f_9|^2 + |g_{17}|^2 + |g_{13}|^2)] - \frac{1}{2\gamma^2}\mathrm{Re}[y_1(f_1g_{10}^* + f_2g_{12}^* + f_6g_{14}^* + f_8g_{15}^*) + \\ + y_2(f_1f_4^* + f_8f_9^* + g_{14}g_{17}^* + g_{12}g_{13}^*) + y_3(f_4g_{10}^* + f_2g_{13}^* + f_6g_{17}^* + f_9g_{15}^*)], \quad (25)$$

$$A_{xx} = \frac{1}{4}[x_1(|f_1|^2 - |f_8|^2 + |g_{14}|^2 - |g_{12}|^2) + x_2(|g_{10}|^2 - |f_2|^2 + |f_6|^2 - |g_{15}|^2) + \\ + x_3(|f_4|^2 - |f_9|^2 + |g_{17}|^2 - |g_{13}|^2)] + \frac{1}{2}\mathrm{Re}[y_1(f_1g_{10}^* - f_2g_{12}^* + f_6g_{14}^* - f_8g_{15}^*) + \\ + y_2(f_1f_4^* - f_8f_9^* + g_{14}g_{17}^* - g_{12}g_{13}^*) + y_3(f_4g_{10}^* - f_2g_{13}^* + f_6g_{17}^* - f_9g_{15}^*)], \quad (26)$$

$$A_{xz} = \mathrm{Re}[x_1(f_1f_5^* + g_{14}g_{18}^*) + x_2(f_6f_7^* + g_{10}g_{11}^*) + x_3(f_3f_4^* + g_{16}g_{17}^*) + y_1(f_5g_{10}^* + f_1g_{11}^* + \\ + f_7g_{14}^* + f_6g_{18}^*) + y_2(f_1f_3^* + f_4f_5^* + g_{14}g_{16}^* + g_{17}g_{18}^*) + y_3(f_3g_{10}^* + f_4g_{11}^* + f_6g_{16}^* + f_7g_{17}^*)], \quad (27)$$

$$A_{xy} = \mathrm{Re}[x_1(f_1g_{12}^* + f_8g_{14}^*) + x_2(f_2g_{10}^* + f_6g_{15}^*) + x_3(f_4g_{13}^* + f_9g_{17}^*) + y_1(g_{10}g_{12}^* + g_{14}g_{15}^* + \\ + f_1f_2^* + f_6f_8^*) + y_2(f_1g_{13}^* + f_4g_{12}^* + f_8g_{17}^* + f_9g_{14}^*) + y_3(g_{10}g_{13}^* + g_{15}g_{17}^* + f_6f_9^* + f_2f_4^*)], \quad (28)$$

$$A_{yz} = \mathrm{Re}[x_1(f_5 g_{12}^* + f_8 g_{18}^*) + x_2(f_2 g_{11}^* + f_7 g_{15}^*) + x_3(f_3 g_{13}^* + f_9 g_{16}^*) + y_1(g_{11} g_{12}^* + g_{15} g_{18}^* + \\ + f_2 f_5^* + f_7 f_8^*) + y_2(f_5 g_{13}^* + f_3 g_{12}^* + f_8 g_{16}^* + f_9 g_{18}^*) + y_3(g_{11} g_{13}^* + g_{15} g_{16}^* + f_7 f_9^* + f_2 f_3^*)]. \quad (29)$$

One can note that for the process of two-meson photoproduction on the deuteron target all components of the tensor, describing the tensor polarized deuteron target, give, in the general case, non-zero contributions to the differential cross section of the reaction (1). So, there are five independent asymmetries. In contrast, for the process of single-meson photoproduction there are only three independent asymmetries since there is one plane (the reaction plane) and, therefore, Q_{xy} and Q_{yz} components of the tensor polarization do not give contributions to the differential cross section.

REACTION $\gamma + d \to d + \pi$

Let us apply the formalism of parametrization of the reaction amplitude with the help of the orthonormal basis to the case of the coherent photoproduction of a pion (or η–meson) on the deuteron

$$\gamma(k) + d(p_1) \to d(p_2) + \pi(q), \quad (30)$$

where the four–momenta of the particles are given in the brackets.

The coordinate frame in the reaction CMS is chosen as: z axis is directed along the momentum of the photon $\mathbf{k}$, and the momentum of the pion $\mathbf{q}$ lies in the xz plane, y axis is directed along the vector $\mathbf{k}\times\mathbf{q}$. Then the four-momenta of the particles have the following components

$$k = (\omega, 0, 0, \omega), \qquad p_1 = (E_1, 0, 0, -\omega),$$

$$p_2 = (E_2, -q\,sin\vartheta, 0, -q\,cos\vartheta), \qquad q = (E_\pi, q\,sin\vartheta, 0, q\,cos\vartheta),$$

where ϑ is the angle between the photon and pion momenta in the reaction CMS, $E_1(E_2)$ and $\omega(E_\pi)$ are the energies of the initial (final) deuteron and photon (pion) in the same frame.

The differential cross section of this process can be written in terms of the reaction matrix element as follows

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 W^2}\frac{q}{\omega}|M|^2, \quad (31)$$

where m_π is the pion mass, and q is the magnitude of the pion three-momentum in the reaction CMS: $q = \sqrt{(W^2 - M^2 + m_\pi^2)^2 - 4m_\pi^2 W^2}\,/\,2W$, $\omega = (W^2 - M^2)/2W$, W is the total energy of the πd or γd system, $W = \omega + E_1 = E_2 + E_\pi$, $d\Omega$ is the solid angle of the pion. For the unpolarized case it is necessary to do summation over the particle spin states and averaging over the spins of the initial particles.

Let us introduce the set of the orthogonal unit vectors for this reaction (the use of this set essentially simplifies the calculation of various polarization characteristics)

$$\hat{\mathbf{k}} = \frac{\mathbf{k}}{|\mathbf{k}|}, \mathbf{n} = \frac{\mathbf{k}\times\mathbf{q}}{|\mathbf{k}\times\mathbf{q}|}, \mathbf{m} = \mathbf{n}\times\hat{\mathbf{k}}. \quad (32)$$

In this case the unit vector $\mathbf{m}$ is directed along the x axis, the unit vector $\mathbf{n}$ is directed along the y axis and the unit vector $\hat{\mathbf{k}}$ is directed along the z axis.

The matrix element of the $\gamma + d \to d + \pi$ reaction can be written as

$$M = e e_i J_i, \quad (33)$$

where e is the deuteron charge and the electromagnetic current is

$$J_i = m_i[g_1\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{n} + g_2\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{n} + g_3\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{m} + g_4\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\hat{\mathbf{k}}] +$$
$$+n_i[g_5\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\mathbf{m} + g_6\mathbf{U}_1\cdot\mathbf{n}\mathbf{U}_2^*\cdot\mathbf{n} + g_7\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + g_8\mathbf{U}_1\cdot\mathbf{m}\mathbf{U}_2^*\cdot\hat{\mathbf{k}} + g_9\mathbf{U}_1\cdot\hat{\mathbf{k}}\mathbf{U}_2^*\cdot\mathbf{m}],$$

where $\mathbf{U}_1(\mathbf{U}_2)$ and $\mathbf{e}$ are the polarization vectors of the initial (scattered) deuteron and the photon, respectively. We use the three–dimensional transverse gauge for the photon: $\mathbf{e}\cdot\mathbf{k}=0$. The quantities g_i, $i=1-9$, are the scalar amplitudes which are the functions of the two kinematical variables: W and $\cos\vartheta$.

All particles are unpolarized

The differential cross section of this reaction for the case of unpolarized particles can be written as

$$\frac{d\sigma_{un}}{d\Omega} = N(F+G), \qquad N = \frac{\alpha}{96\pi W^2}\frac{q}{\omega}, \tag{34}$$

where α is the fine structure constant and for the F and G functions we have the following expressions

$$F = |g_1|^2 + \gamma^2|g_2|^2 + a_1|g_3|^2 + a_2|g_4|^2 + 2a_3\mathrm{Re}(g_3g_4^*),$$
$$G = |g_6|^2 + a_1|g_5|^2 + a_2|g_8|^2 + 2a_3\mathrm{Re}(g_5g_8^*) + \gamma^2[a_1|g_9|^2 + a_2|g_7|^2 + 2a_3\mathrm{Re}(g_7g_9^*)], \tag{35}$$

$$a_1 = 1+\frac{\mathbf{q}^2}{M^2}\sin^2\vartheta, \qquad a_2 = 1+\frac{\mathbf{q}^2}{M^2}\cos^2\vartheta, \qquad a_3 = \frac{\mathbf{q}^2}{2M^2}\sin 2\vartheta, \qquad \gamma = \frac{E_1}{M}.$$

Note that the function F describes the contribution of the photons polarized along the direction of the vector $\mathbf{m}$ and the function G describes the contribution of the photons polarized along the direction of the vector $\mathbf{n}$ which is normal to the reaction plane.

Photon beam is polarized

The differential cross section of this reaction for the case of unpolarized deuterons and polarized photon beam can be written as follows

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{un}}{d\Omega}(1 + A_\perp\cos 2\beta), \tag{36}$$

where $A_\perp$ is the asymmetry caused by the linear polarization of the photon beam and it determines as follows

$$A_\perp = \frac{d\sigma/d\Omega(\beta=0^\circ) - d\sigma/d\Omega(\beta=90^\circ)}{d\sigma/d\Omega(\beta=0^\circ) + d\sigma/d\Omega(\beta=90^\circ)}. \tag{37}$$

This asymmetry has the following expression in the terms of the reaction scalar amplitudes

$$\frac{d\sigma_{un}}{d\Omega}A_\perp = N(F-G). \tag{38}$$

Note that only linear polarization of the photon beam contributes to the differential cross section.

The deuteron target is vector polarized

The differential cross section of this reaction for the case of the vector polarized initial deuteron and unpolarized photon beam can be written as

$$\frac{d\sigma_v}{d\Omega} = \frac{d\sigma_{un}}{d\Omega}(1 + A_y \xi_y), \tag{39}$$

where the quantity A_y is the asymmetry caused by the vector polarization of the initial deuteron provided the photon beam is unpolarized (the so–called single target asymmetry). This polarization observable has the following expression in the terms of the reaction scalar amplitudes

$$\frac{d\sigma_{un}}{d\Omega} A_y = -3\gamma N \,\mathrm{Im}[g_1 g_2^* - a_2 g_7 g_8^* + a_1 g_5 g_9^* + a_3(g_5 g_7^* + g_8 g_9^*)]. \tag{40}$$

Note that real scalar amplitudes (describing the considered reaction, for example, in the impulse approximation) leads to zero single target asymmetry. Only the normal (to the reaction plane) component of the deuteron polarization vector $\vec{\xi}$ gives contribution to the differential cross section. This property can be explained as follows: due to the space parity conservation in this reaction the only scalar that can be constructed using pseudovector $\vec{\xi}$ is $\vec{\xi} \cdot \vec{n}$.

The deuteron target is tensor polarized

The tensor polarization of the deuteron is determined, in the general case, by five independent parameters: Q_{zz}, Q_{xz}, Q_{xy}, Q_{yz}, and $Q_{xx} - Q_{yy}$.

The differential cross section of the reaction under consideration for the case of the tensor polarized initial deuteron and unpolarized photon beam can be written as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{un}}{d\Omega}[1 + A_{zz}Q_{zz} + A_{xx}(Q_{xx} - Q_{yy}) + A_{xz}Q_{xz}], \tag{41}$$

where A_{zz}, A_{xx}, A_{xz} are the asymmetries caused by the tensor polarization of the initial deuteron provided the photon beam is unpolarized. Note that real scalar amplitudes (describing the considered reaction, for example, in the impulse approximation) leads, in the general case, to non-zero single target asymmetry. These polarization observables have the following expressions in the terms of the reaction scalar amplitudes

$$\begin{aligned}\frac{d\sigma_{un}}{d\Omega} A_{zz} &= 3N\{|g_2|^2 + a_2|g_7|^2 + a_1|g_9|^2 + 2a_3\mathrm{Re}(g_7 g_9^*) - \\ &- \frac{1}{2\gamma^2}[|g_1|^2 + |g_6|^2 + a_1(|g_3|^2 + |g_5|^2) + a_2(|g_4|^2 + |g_8|^2) + 2a_3\mathrm{Re}(g_3 g_4^* + g_5 g_8^*)]\},\end{aligned} \tag{42}$$

$$\frac{d\sigma_{un}}{d\Omega} A_{xx} = \frac{3}{2}N[|g_1|^2 - |g_6|^2 + a_1(|g_5|^2 - |g_3|^2) + a_2(|g_8|^2 - |g_4|^2) + 2a_3\mathrm{Re}(g_5 g_8^* - g_3 g_4^*)], \tag{43}$$

$$\frac{d\sigma_{un}}{d\Omega} A_{xz} = 6N \,\mathrm{Re}[g_1 g_2^* + a_1 g_5 g_9^* + a_2 g_7 g_8^* + a_3(g_5 g_7^* + g_8 g_9^*)]. \tag{44}$$

CONCLUSION

The model-independent analysis of the polarization observables in the process of coherent photoproduction of pair pseudoscalar mesons on the deuteron target has been done. This analysis does not depend on the details of the reaction mechanism and does not require the knowledge of the deuteron structure. The formalism used in the analysis is based on the most general symmetry properties of the hadron electromagnetic interaction, such as the gauge invariance and P-invariance.

The polarization observables for the process considered are expressed in terms of the reaction scalar amplitudes. The features of the reaction $\gamma + d \to d + \pi + \pi$, which are due to the three-body final state, are shortly discussed. The following experimental set-ups have been investigated:

- the photon beam is elliptically polarized which includes the particular cases of the linear and circular polarizations of the photon beam;

- the deuteron target is vector polarized;
- the deuteron target is tensor polarized.

The formalism used for the analysis of the polarization observables for the process (1) was applied also to the reaction of coherent photoproduction of pseudoscalar meson on the deuteron target, $\gamma + d \to d + \pi$. We discussed the differences between the polarization observables of this process and the reaction (1).

Let us note that the new results, which are obtained in this paper, are the most general spin structure of the matrix element of the reaction (1), the expressions of the single-spin asymmetries, due to the polarizations of the photon beam and deuteron target, in the terms of the orthogonal reaction scalar amplitudes. They are represented by formulas (3), (12), (15), (16), (21) – (23) and (25) – (29).

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