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MEASUREMENT OF THE ASYMMETRY OF PHOTOPRODUCTION OF π^- MESONS ON LINEARLY POLARIZED DEUTERONS BY LINEARLY POLARIZED PHOTONS

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The first results of a double polarization experiment to extract the asymmetry of the reaction of photoproduction of a π^- meson by a linearly polarized photon on a tensor-polarized deuteron in the energy range of the virtual photon (300–700 MeV) are presented. The measurements were performed on an internal tensor-polarized deuterium target in the VEPP-3 electron-positron storage ring for the electron beam energy equal to 2 GeV. The experiment employed the method of recording two protons and the scattered electron in coincidence. The obtained measurement results are compared with the theoretical predictions obtained in the momentum approximation with allowance for πN and NN rescattering in the final state.

Keywords: tensor-polarized deuteron, linearly polarized photon, photoproduction of a π meson.

INTRODUCTION

Already in the early stages of investigation of the deuteron, it was concluded that tensor components are present in the potential of the nucleon-nucleon interaction. The tensor components of the nucleon-nucleon interaction have a substantial influence on the static properties of the deuteron, and also on the differential cross sections and polarization observables of electronuclear and photonuclear reactions on a deuteron [1–10]. Studies of the tensor polarization observables of pion photoproduction reactions on a tensor-polarized deuteron make it possible to obtain important information about the structure of the deuteron, the dynamics of NN and πNN systems at small distances, and the influence of the nuclear medium on the properties of nucleons and nucleon resonances. Until recently, there have hardly been any experimental studies on tensor polarization observables since neither tensor-polarization deuterium targets with sufficiently high density and degree of polarization nor electron storage rings with high duty factor and beam intensity have been available. Advances in recent years in perfecting the method of internal gas polarized targets in storage rings have created conditions for performing electronuclear and photonuclear correlation experiments on tensor-polarized deuterons [11, 12]. One distinguishing feature of the setup of the experiment [12] is the high energies (50–200 MeV) of both protons, which corresponds to the range of momenta 300–700 MeV/c. Larger momenta of the protons practically exclude the contribution of the mechanism of quasifree photoproduction of a pion on a nucleon and make it impossible to search for other, more complex mechanisms of the given reaction.

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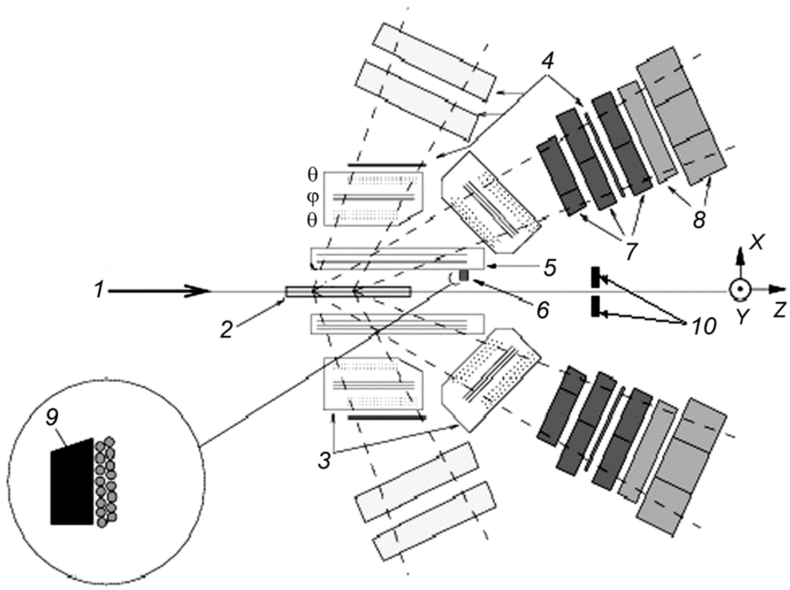

Fig. 1. Diagram of the experiment: *1* is the electron beam, *2* is the storage-ring target-cell, *3* are the drift chambers of the proton hodoscopes, *4* are the trigger scintillation counters, *5* are the vertex drift chambers, *6* is the LQ-polarimeter of the target, *7* are the CsI crystal based scintillation detectors, *8* are the NaI crystal based scintillation detectors, *9* is the tungsten converter, and *10* are the electron shower detectors.

The events of the reaction were extracted in [12] by detecting the two final protons in coincidence, the scattered electron was not recorded. Such a setup of the experiment corresponds to the situation in which a beam of unpolarized quasireal photons interacts with a tensor-polarized deuterium target. In this case, however, it is possible to measure only single-spin polarization observables – the components of the tensor analyzing power of the reaction. At the same time, double polarization experiments in which the polarized beam interacts with a polarized target have aroused great interest. Such experiments offer the fundamental possibility of measuring the so-called double (two-spin) polarization observables. An analysis of the obtained experimental data on double polarization observables can give new information and add to existing information on the structure of the deuteron and the dynamics of NN, πN, and πNN systems at small distances.

In the given work, we present first results of a double polarization experiment on extracting the asymmetry of the reaction of photoproduction of a π^- meson on a tensor-polarized deuteron by a linearly polarized, quasireal photon.

SETUP OF THE VEPP-3 EXPERIMENT

The experiment was carried out on the VEPP-3 electron-positron storage ring with energy of the electron beam equal to 2 GeV. Figure 1 displays a diagram of the experiment. The two arms of the main detector, recording two hadrons in coincidence, were arranged symmetrically relative to the electron beam axis. In each arm of the detector, identification of protons took place, along with measurement of their emission angles in the range of polar angles $\Delta\theta = 50 - 90^\circ$ and azimuthal angles $\Delta\varphi = \pm 30^\circ$ relative to the median plane of the detecting system, measurement of the energy of the protons in the range 50–200 MeV with accuracy not worse than 10% and determination of the coordinates of the vertex of the pp events with an accuracy of 1 mm. A more detailed description of the proton hodoscopes and the polarized deuterium target is given in [12]. Electrons, scattered out to an angle of (1.6 ± 0.4)°, were recorded by two nonmagnetic shower detectors which were situated symmetrically relative to the beam of incident electrons, and their median plane coincided with the median plane of the main detector. The shower detectors were mounted in the vacuum chamber of the storage ring at a distance of 630 mm from the center of the target and ensured efficient recording of electrons with energy greater than 1.3 GeV in the range of scattering angles $\theta_e = 1.2 - 2^\circ$ and $\Delta\varphi_e = \pm 30^\circ$.

The flux of polarized deuterium atoms with intensity $8.2 \cdot 10^{16}$ at/s was created in a polarized atom source (PAS) and transported into the storage-ring target-cell, located in the accelerator ring. The PAS created a beam of deuterium atoms in two polarized states $P_{zz} = +1$ and –2. To lower the systematic error of the measurements, the polarization state of the beam of deuterium atoms in the experiment was reversed every 30 s. Vector polarization of the beam of deuterium atoms was absent: $P_z = 0$. A beam of polarized deuterons was injected into a storage-ring cell with open faces. The cell had an elliptical cross section with dimensions 13×26 mm and length 400 mm. To increase the density of the target, the cell was cooled to the temperature of liquid nitrogen. The polarization of the atoms stored in the cell was lowered due to the action of various depolarizing processes; therefore, the degree of tensor polarization of the gaseous target was constantly monitored by an LQ polarimeter. Toward this end, the polarimeter measured the tensor asymmetry of angular ed-scattering for a momentum transfer equal to 1.6 fm^{-1}. The measured mean tensor polarization of the target during the time of the experiment with allowance for systematic and statistical errors was equal to $P_{zz}^{+} = 0.397 \pm 0.013 \pm 0.018$, $P_{zz}^{-} = -2P_{zz}^{+}$. The spin orientation of the deuterons of the internal target was controlled by the direction of the magnetization vector $\boldsymbol{H}$ of the guiding magnetic field. The magnetization vector $\boldsymbol{H}$ lay in the median plane of the detector, its polar angle θ_H was 120° relative to the direction of the electron beam.

DIFFERENTIAL CROSS SECTION AND ASYMMETRY OF THE REACTION

The general expression for the differential cross section of the reaction of coplanar (the momenta of the three final particles lie in the same plane) photoproduction of a π meson on a tensor-polarized deuteron by a polarized photon has the form [13]

$$\begin{aligned} d\sigma = d\sigma_0 \{ & 1 + P_l^\gamma \Sigma^l \cos(2\varphi) + 2^{-1/2} P_{zz} \big(T_{20} d_{00}^2(\theta_H) + T_{21} d_{10}^2(\theta_H)\cos(\varphi - \varphi_H) \\ & + T_{22} d_{20}^2(\theta_H) \cos[2(\varphi - \varphi_H)] \big) + 2^{-1/2} P_{zz} P_c^\gamma \big(T_{21}^c d_{10}^2(\theta_H) \sin(\varphi - \varphi_H) \\ & + T_{22}^c d_{20}^2(\theta_H) \sin[2(\varphi - \varphi_H)] \big) + 2^{-1/2} P_{zz} P_l^\gamma \big(T_{20}^l d_{00}^2(\theta_H) \cos(2\varphi) \\ & + T_{21}^l d_{10}^2(\theta_H) \cos(3\varphi - \varphi_H) + T_{22}^l d_{20}^2(\theta_H) \cos(4\varphi - 2\varphi_H) \big) \}, \end{aligned} \tag{1}$$

where

$$d_{00}^2(\theta_H) = \frac{3}{2}\cos^2(\theta_H) - \frac{1}{2}, \quad d_{10}^2(\theta_H) = -\sqrt{\frac{3}{8}}\sin(2\theta_H), \quad d_{20}^2(\theta_H) = \sqrt{\frac{3}{8}}\sin^2(\theta_H). \tag{2}$$

In expression (1) $d\sigma_0$ is the differential cross section of the reaction of photoproduction of a pion by an unpolarized photon on an unpolarized deuteron, φ is the azimuthal angle of the coplanar plane of the reaction (in our case $\varphi = 0$), Σ is the photon asymmetry of the reaction, T_{20}, T_{21}, and T_{22} are the components of the tensor analyzing power of the reaction with respect to the polarization of the deuteron, T_{21}^c and T_{22}^c are the components of the correlation coefficient of the circular polarization of the photon and the tensor polarization of the deuteron, and T^l_{20}, T^l_{21}, and T^l_{22} are the components of the correlation coefficient of the linear polarization of the photon and the tensor polarization of the deuteron. Note that the components T^c_{21}, T^c_{22}, T^l_{20}, T^l_{21}, and T^l_{22} are double polarization observables. The spin state of the deuteron in expression (1) is determined by the degree of its tensor polarization P_{zz} and the direction θ_H, φ_H of the guiding magnetic field $\boldsymbol{H}$ in the coordinate system whose z axis is aligned with the momentum of one of the protons, while the xz plane is determined by the momentum of one of the protons. The polarization state of a photon is defined by two parameters: its circular polarization P^γ_c and its linear polarization P^γ_l. In our case, the unpolarized scattered electrons were recorded by the two shower detectors in the range of polar angles $\theta_e = 1.2 - 2^\circ$ and in the range of azimuthal angles $\varphi_e = (-30^\circ, 30^\circ) \cup (150^\circ, 210^\circ)$. Here, the square of the 4-momentum transfer did not exceed 0.0025 (GeV/c)^2. Therefore, the virtual photons emitted during scattering of the electron are quasireal and their longitudinal polarization can be neglected. In this case, the density matrix of the photon can be represented in the form [14]

$$\rho_\gamma = \frac{1}{2}\begin{pmatrix} 1 & \varepsilon\exp(2i\psi) \\ \varepsilon\exp(-2i\psi) & 1 \end{pmatrix}, \tag{3}$$

where

$$\varepsilon = \left[1 - 2\frac{|\boldsymbol{q}|^2}{q^2}\tan^2\frac{\theta_e}{2}\right]^{-1}, \tag{4}$$

$q^2 = q_0^2 - \boldsymbol{q}^2 = (k - k')^2$ is the square of the 4-momentum transfer, and ψ is the angle between the coplanar plane of the reaction and the scattering plane of the electron.

It follows from expression (3) that upon scattering of an unpolarized electron the quasireal photon will be linearly polarized perpendicular to the scattering plane. In this case, its linear polarization $P^\gamma_l = \varepsilon$ and its circular polarization $P^\gamma_c = 0$. Statistical modeling by the Monte Carlo method shows that under the kinematic conditions of the experiment, the mean value of the linear polarization of the quasireal photons ε is equal to 0.81. Note that if the scattered electrons are not recorded, then the density matrix given by Eq. (3) must be averaged over ψ in the interval $(0, 2\pi)$. In this case, its nondiagonal components vanish, and as a result we obtain the density matrix of the unpolarized photon. Under the kinematic conditions of the given experiment, the density matrix (Eq. (3)) must be averaged over ψ in the range $\psi = (-60^\circ, 60^\circ) \cup (120^\circ, 240^\circ)$. As a result, we obtain the averaged density matrix of the quasireal photon:

$$\langle\rho_\gamma\rangle = \frac{1}{2}\begin{pmatrix} 1 & \langle\varepsilon\rangle \\ \langle\varepsilon\rangle & 1 \end{pmatrix}, \tag{5}$$

where $\langle\varepsilon\rangle = \left(6\sqrt{3}/8\pi\right)\varepsilon \approx 0.41\varepsilon$. Density matrix (5) corresponds to the values of the averaged polarizations of the photon $\langle P^\gamma_l\rangle = \langle\varepsilon\rangle$ and $\langle P^\gamma_c\rangle = 0$. Thus, we are investigating the asymmetry of a reaction in which the photon beam and the deuteron target are polarized.

Depending on the sign of the tensor polarization of the deuteron and the azimuthal angle of the magnetic field vector $\boldsymbol{H}$, all of the recorded coplanar events of the reaction $\gamma d \to pp\pi^-$ can be assigned to one of four polarization types: $\left\{P_{zz}^+, \varphi_H = 0\right\}$, $\left\{P_{zz}^+, \varphi_H = \pi\right\}$, $\left\{P_{zz}^-, \varphi_H = 0\right\}$, and $\left\{P_{zz}^-, \varphi_H = \pi\right\}$. The experimentally measured asymmetry of the reaction is given by the expression

$$A = \frac{8}{3} \frac{N_{\varphi_H=0}^+ - N_{\varphi_H=0}^- - N_{\varphi_H=\pi}^+ + N_{\varphi_H=\pi}^-}{P_{zz}^+\left(N_{\varphi_H=0}^- + N_{\varphi_H=\pi}^-\right) - P_{zz}^-\left(N_{\varphi_H=0}^+ + N_{\varphi_H=\pi}^+\right)}, \tag{6}$$

where $N_{\varphi_H=0}^+$, $N_{\varphi_H=0}^-$, $N_{\varphi_H=\pi}^+$, and $N_{\varphi_H=\pi}^-$ are the numbers of recorded events of the corresponding polarization types. Employing expression (1), it is possible to show that the asymmetry given by expression (6) can be expressed in terms of three polarization observables: the component T_{21} of the tensor analyzing power of the reaction with respect to the polarization of the deuteron, the component T_{21}^l of the correlation coefficient of the linear polarization of the photon and the tensor polarization of the deuteron, and the photon asymmetry Σ:

$$A = \frac{T_{21} + \left\langle P_l^\gamma \right\rangle T_{21}^l}{1 + \left\langle P_l^\gamma \right\rangle \Sigma}. \tag{7}$$

Note that the double polarization observable T_{21}^l enters into expression (7).

RESULTS OF ASYMMETRY MEASUREMENTS AND THEIR DISCUSSION

Results of the experiment are shown in Fig. 2. Figure 2*a* displays the dependence of the asymmetry A of the reaction $\gamma d \to pp\pi^-$ on the photon energy E_γ and Fig. 2*b* displays the dependence of the asymmetry A on the invariant mass of the pion-nucleon subsystem $M_{p\pi}$. The statistical error and averaging interval (over E_γ or over $M_{p\pi}$) are shown for each point. In each interval, all of the available experimental events were taken into account with allowance for the non-coplanarity restriction on the azimuthal emission angles of the protons: $|\phi_2 - \phi_2 - \pi| < 20^\circ$.

The total systematic error does not exceed 10%, so the statistical errors of measurement of A become decisive. The asymmetry A in expression (7) depends (with allowance for the photon energy) on six kinematic variables. The experimental points plotted in Fig. 2 are the result of averaging of the asymmetry A over some six-dimensional regions in kinematic phase space. The statistical weight for averaging of a point in the six-dimensional phase space is proportional to the differential cross section (1). Therefore, for direct comparison of the experimental data with the theoretical predictions, we performed a statistical modeling of the reaction $\gamma d \to pp\pi^-$ using the Monte Carlo method. As the independent kinematic variables, we used the photon energy E_γ, the emission angles of the two protons θ_1, ϕ_1, θ_2, ϕ_2 and the momentum of one of the protons. The energy spectrum of the incident photons used to model the reaction is the Dalitz spectrum [15–18]. After statistical sampling of the six independent kinematic variables, the helicity amplitudes of the reaction $\gamma d \to pp\pi^-$ were calculated; these were then convolved with the density matrix of the tensor-polarized deuteron and the density matrix of the linearly polarized photon. The helicity amplitudes of the reaction $\gamma d \to pp\pi^-$ used in the modeling are described in [19]. The density matrix of the tensor-polarized deuteron could, with identical probability of 1/4, be put in correspondence with one of the four polarization states of the deuterium target. The density matrix of the photon was assigned by expression (5). Next, the differential cross section

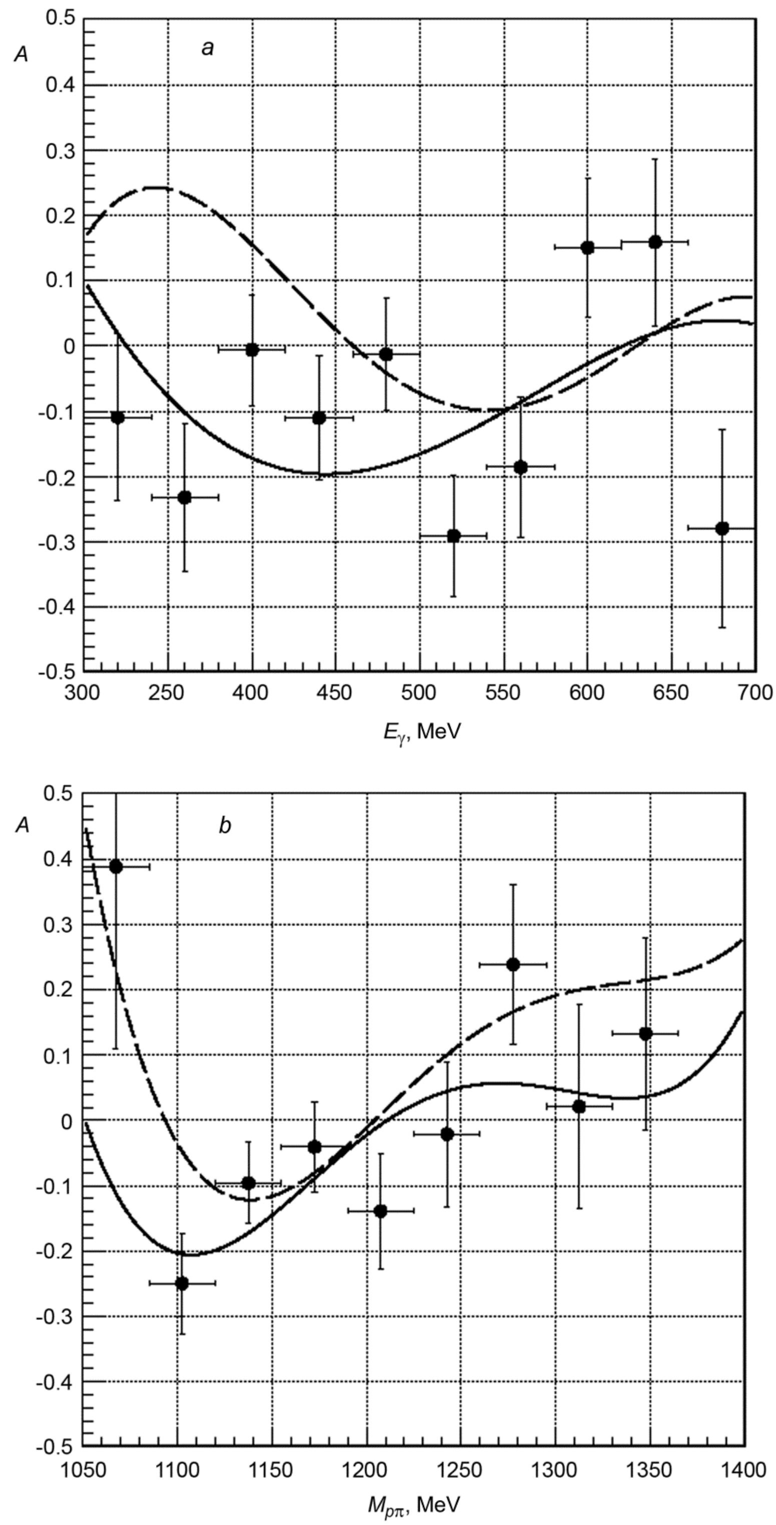

Fig 2. Dependence of the asymmetry A on the photon energy E_γ (a) and on the invariant pion-nucleon mass $M_{p\pi}$ (b): the points plot the experimental data, the dashed curve plots the result of modeling of the reaction in the momentum approximation, and the solid curve plots the result of modeling of the reaction in the momentum approximation with allowance for πN and NN rescattering in the final state.

given by expression (1) was calculated. After that, in accordance with the Neumann method, events were chosen or rejected. In all, $3 \cdot 10^6$ modeled events were rejected, which is three orders of magnitude greater than the number of events rejected in the processing of the experimental data with allowance for the non-coplanarity restriction. Extraction of the asymmetry A from the modeled events was closely similar to its extraction from the experimental events, which made possible a direct comparison of the experimental and the modeled results. The theoretical values of the asymmetry A, obtained in this way and interpolated by cubic splines, are also plotted in Fig. 2.

It follows from Fig. 2 that the greatest divergence between experiment and theory is found in the dependence of the asymmetry A on the photon energy E_γ. At the same time, the behavior of the dependence of the asymmetry A on the invariant pion-nucleon mass $M_{p\pi}$ is found to be in fair agreement with the modeling result. Taking the interaction in the final state (pion-nucleon and nucleon-nucleon rescattering) into account leads on the whole to an improvement in the agreement between theory and experiment.

The difference in the behavior of the measured asymmetry and the modeled asymmetry A suggests that at large momenta of the two protons the employed amplitude [19] does not exhaust all the possible mechanisms of the reaction. Note that the contribution of the mechanism of formation of two pions on a nucleon with subsequent absorption of one pion by the second nucleon [20] turns out to be small in our kinematic region. This is because the effective mass of the two protons, formed in this case as a result of the ΔN interaction, turns out in an overwhelming number of experimental events to be less than the sum of the masses of the Δ-isobars and the nucleon. To improve the agreement between experiment and theory, it may be useful to take account of two-particle mechanisms of the interaction of a photon with a deuteron, the contribution of the isobar component of the deuteron within the framework of the quark model [21], and also the possibility of describing the deuteron on the basis of new mechanisms of interaction of nucleons at small distances.

In the given experiment there were only four polarization states of the photon beam and deuteron target. This number of polarization states allowed us to extract only the asymmetry A, which is a combination of the three polarization observables T_{21}, Σ, and T^l_{21}. To extract one of the double polarization observable in the set T^c_{21}, T^c_{22}, T^l_{20}, T^l_{21}, and T^l_{22} requires not less than eight polarization states of the photon beam and the deuteron target. It is planned to reach this number of polarization states in future double polarization experiments on the VEPP-3 electron-positron storage ring.

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