

NEGATIVE PION PHOTOPRODUCTION OFF POLARIZED DEUTERON TARGET

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It is discussed whether the target asymmetry (TA) for $\gamma n \rightarrow \pi^- p$ can be extracted from data on $\gamma d \rightarrow \pi^- pp$. An exclusive experiment that enhances production of pions on neutron at rest and suppresses contributions of the recoil mechanism is shown to correspond to this purpose. The relation between the TAs for the reactions on deuteron and neutron is established taking into account pion and active nucleon rescattering in the final state and neglecting effects due to interaction with the spectator nucleon.

PACS: 13.60.LE, 25.20.LJ

The attention paid to the process $\gamma d \rightarrow \pi^- pp$ springs to some extent from the hope to obtain observables for $\gamma n \rightarrow \pi^- p$ in the absence of a neutron target and to acquire information on the elementary neutron amplitude. Thus, for example, it was shown [1] that the differential cross sections of the quasifree exclusive reaction and the process off nucleon are proportional in the framework of the spectator model up to the plane-wave approximation. So, the reaction on deuteron under certain kinematic conditions can be useful for exploring the properties of the elementary operator for pion photoproduction.

As known, studies of the polarization phenomena can bring detailed information about different aspects of the reaction mechanisms. Influence of small amplitudes on spin observables is enhanced providing possibility to investigate subtle dynamical effects. The TA in photoproduction of negative pions off polarized deuteron was measured in experiments [2-4] covering the energy range from 0.280 GeV to 2 GeV. Data analysis in articles [2-4] has been carried out with the help of a procedure that introduces polarization of active nucleon. In its turn, this quantity is determined by the deuteron D-state probability and is model dependent.

In the present article we attempt to establish a relation between TAs in the reaction on deuteron and one for the process on free neutron, elucidate necessary assumptions and to determine kinematic conditions favorable for reduction of the various corrections violating the relation.

To describe the polarized deuteron target the formalism of density matrix is commonly used. The density matrix for deuteron in magnetic field collinear to the y-axis can be written as [5,6]

$$\hat{\rho}^d = \frac{1}{3} \left(1 + \frac{3}{2} p_y^d \hat{\Pi}_y + \frac{1}{2} p_{yy}^d \hat{\Pi}_{yy} \right), \quad (1)$$

where the Goldfarb operators $\hat{\Pi}_y = \hat{S}_y$ and $\hat{\Pi}_{yy} = 3\hat{S}_y^2 - 2\hat{I}$, the spin operator is \hat{S} , and \hat{I} is a unit 3×3 -

matrix. Formally, the polarization parameters p_y^d and p_{yy}^d are constrained [5,6] by the inequalities $-1 \leq p_y \leq 1$ and $-2 \leq p_{yy} \leq 1$.

We use the right-handed coordinate system specified as follows. The z-axis is taken along the photon momentum k , the y-axis is directed along the vector $k \times q$, where q is the momentum of the ejected pion. The reaction plane is defined by the vectors k and q .

The polarization and the alignment are $p_y^d = w(1) - w(-1)$ and $p_{yy}^d = 1 - 3w(0)$, where the spin level populations are denoted by $w(M_d)$ ($\sum_{M_d} w(M_d) = 1$) with M_d being the projection of the deuteron total momentum on the z-axis. On the supposition that the deuteron spin system can be described by a single temperature T_d , the populations $w(M_d)$ at low temperature and for a large magnetic field H take the form [7-10] of a Boltzmann distribution $w(1)/w(0) = w(0)/w(-1) = \exp(\alpha)$, where $\alpha = \mu_d H / kT_d$, μ_d is the deuteron magnetic moment, k is the Boltzmann constant. One has

$$w(0) = (1 + 2 \operatorname{ch} \alpha)^{-1}, \quad (0 < w(0) \leq \frac{1}{3})$$

$$w(\pm 1) = \frac{1}{2} (1 - w(0) \pm u), \quad (0 < w(\pm 1) < 1)$$

where $u = \pm (1 - 2w(0) - 3w^2(0))^{1/2}$. Sign \pm in the expression for u corresponds to the direction of the magnetic field parallel (antiparallel) to the y-axis.

In the framework of the model discussed, the polarization parameters satisfy $-1 < p_y^d < 1$, $0 \leq p_{yy}^d < 1$ and $3p_y^2 + p_{yy}^2 - 4p_{yy} = 0$. For instance, in Kharkov experiment [3] $p_y^d = 0.35 \dots 0.42$ and according to the model $p_{yy}^d = 0.09 \dots 0.14$.

For the deuteron spin state described by the density matrix (1) the cross section of $\gamma d \rightarrow \pi^- pp$ casts into the form $\sigma^d = \sigma_0^d (1 + \frac{3}{2} p_y^d T_y^d + \frac{1}{2} p_{yy}^d T_{yy}^d)$, where is the cross section for the reaction with the unpolarized particles $\sigma_0^d = \frac{1}{3} R^d \text{Tr} A A^\dagger$, the vector and tensor TAs $\sigma_0^d T_y^d = \frac{1}{3} R^d \text{Tr} A \hat{\Pi}_y A^\dagger$ and $\sigma_0^d T_{yy}^d = \frac{1}{3} R^d \text{Tr} A \hat{\Pi}_{yy} A^\dagger$, the amplitude of the process is denoted by A . The explicit form of the kinematic factor R^d is determined by a choice of the independent kinematic variables (see, e.g., [1,11,12]).

The vector asymmetry can be found from measurement of the cross section $\sigma^d(p_y^d)$ with $p_y^d = \pm p^d$. Really, one has $T_y^d = (\sigma^d(p^d) - \sigma^d(-p^d)) / (3\sigma_0^d p^d)$. To get the cross section σ_0^d from the values of $\sigma^d(\pm p^d)$ one needs to know the tensor asymmetry T_{yy}^d since

$$\sigma_0^d = (\sigma^d(p^d) + \sigma^d(-p^d)) / (2 + p_{yy}^d(p^d) T_{yy}^d).$$

On the other hand, the TA for the process on neutron can be determined from the values of the cross section $\sigma^n(p_y^n) = \sigma_0^n (1 + p_y^n T_y^n)$ with the neutron polarization $p_y^n = \pm p^n$. The observables are given by

$$T_y^n = (\sigma^n(p^n) - \sigma^n(-p^n)) / (2\sigma_0^n p^n),$$

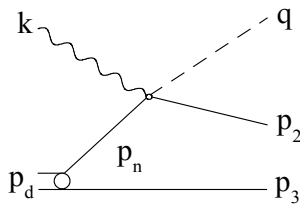
$$\sigma_0^n = (\sigma^n(p^n) + \sigma^n(-p^n)) / 2.$$

The TA can be calculated from $T_y^n = (\text{Tr} f f^\dagger)^{-1} \times \text{Tr} f \hat{\sigma}_y f^\dagger$, where $\hat{\sigma}$ is the Pauli vector in the spin space of the nucleon. Note, that the photoproduction operator f includes contributions arising from the pion-proton rescattering.

The amplitude for $\gamma d \rightarrow \pi^- pp$

$$A_{SM_s M_d}^\lambda = B(p_2, p_3; SM_s, M_d, \lambda) + (-1)^S B(p_3, p_2; SM_s, M_d, \lambda), \quad (2)$$

can be expressed in terms of the same operator f . In Eq. (2) the photon polarization is denoted by λ , the total spin (its projection) of the pair of protons is $S(M_S)$, the momenta of the outgoing active and spectator protons are p_2 and p_3 . The first (second) term in r.h.s of the above equation corresponds to the direct (recoil) mechanism of the reaction. The contribution of the direct mechanism is visualized in the figure below.



Direct mechanism of $\gamma d \rightarrow \pi^- pp$ process. Effects of rescattering on proton-spectator are not included. The deuteron (neutron) momentum is p_d (p_n)

Neglecting interaction between the outgoing protons, we take the antisymmetrized product of two plane waves $|p_2, p_3; SM_s, T = M_T = 1\rangle = \frac{1}{\sqrt{2}} (1 - (2,3)) |p_2\rangle_2 |p_3\rangle_3 |SM_s\rangle |T = M_T = 1\rangle$

for the final NN-system, where $(2,3)$ is the transposition of the space, spin and isospin coordinates of the protons with numbers 2 and 3, $T(M_T)$ is the total isospin (its projections) of the pair of protons.

We use the deuteron WF in the form

$$\varphi_M^d(p) = \sum_{LM_L} C_{LM_L 1M}^{1M_d} Y_{LM_L}(n_p) \varphi_L(p),$$

where $p = \frac{1}{2}(k_2 - k_3)$, $n_p = p/|p|$, k_2 and k_3 are the nucleon momenta, M is the projection of the deuteron spin, $\varphi_L(p)$ are the WF components with the orbital angular momentum $L = 0, 2$, and C_{ab}^{ck} is the Clebsch-Gordan coefficient.

For the amplitudes in the r.h.s. of Eq. (2) we have

$$B(p_2, p_3; SM_s, M_d \lambda) = \langle SM_s | f^\lambda | \varphi(p_d/2 - p_3), M_d \rangle.$$

To find a relation between the TAs T_y^n and T_y^d we consider the spherical components of the observables. The expansion of the neutron and deuteron density matrices $\hat{\rho}^n = \rho(S = 1/2)$ and $\hat{\rho}^d = \rho(S = 1)$ over the spherical tensors (ST) can be written as

$$\hat{\rho}(S) = \sum_{kk} t_{kk}^*(S) \hat{T}_{kk}(S),$$

where [14] $\hat{T}_{1k}(S = 1/2) = \frac{1}{\sqrt{2}} \hat{\sigma}_k$, $\hat{T}_{1k}(S = 1) = \frac{1}{\sqrt{2}} \hat{S}_k$ and $\hat{T}_{2k}(S = 1) = \sum_{M'M''} C_{1M' 1M}^{2k} \hat{S}_{M'} \hat{S}_{M''}$. The cyclic components of the spin operators are $\hat{\sigma}_\pm$ and \hat{S}_M .

The matrix elements of the ST are given by [14]

$$\langle SM' | \hat{T}_{kk}(S) | SM \rangle = ((2k+1)/(2S+1))^{1/2} C_{SM' 1k}^{SM}.$$

The ST [14] are related to ones defined in [5] as $\hat{T}_{kk}(S = 1) = \hat{t}_{kk} / \sqrt{3}$. Expression for the TAs [5] in terms of ST [14] reads

$$T_{kk}(S) = (2S+1)^{1/2} \text{Tr} F \hat{T}_{kk}(S) F^\dagger / \text{Tr} F F^\dagger \quad (3)$$

with F being the amplitude f or A for the reaction on neutron or on deuteron. For the cartesian TA T_y^n we have $T_y^n = \frac{i}{\sqrt{2}} (T_{1-1} + T_{1+1})$ with $T_{kk} = T_{kk}(S = 1/2)$. In the case of the process on deuteron the asymmetries are

$$T_y^d = \frac{i}{\sqrt{3}} (T_{1-1} + T_{1+1}),$$

$$T_{yy}^d = -\frac{\sqrt{3}}{2} (T_{2-2} + T_{2+2}) - \frac{1}{\sqrt{2}} T_{20}$$

with $T_{kk} = T_{kk}(S = 1)$.

Retaining only the S-wave component of the deuteron WF and the contribution of the direct mechanism we get the spherical TAs for $\gamma d \rightarrow \pi^- pp$ in the form

$$T_{kk}(S = 1) = 3i \sqrt{3(k+1/2)} (-1)^k \left\{ \begin{matrix} 1 & 1 & k \\ 1/2 & 1/2 & 1/2 \end{matrix} \right\} \tilde{T}_{kk}, \quad (4)$$

where

$$\tilde{T}_{kk} = \sum_{mm'm''\lambda} C_{1/2 m'' k}^{1/2 m' k} f_{mm'}^\lambda f_{m''m}^{\lambda*} / \sum_{m'm''\lambda} |f_{m'm''}^\lambda|^2, \quad (5)$$

$f_{mm'}^\lambda = \left\langle \frac{1}{2} m \left| f^\lambda \right| \frac{1}{2} m' \right\rangle$, and m, m', m'' are the spin projections of the nucleon.

The TA for the process $\gamma n \rightarrow \pi^- p$ reads

$$T_{kk} (S = 1/2) = \sqrt{3} i \tilde{T}_{kk}. \quad (6)$$

Eqs. (4) and (6) yield for the spherical components (3) of the TAs

$$T_{1k} (S = 1) = \sqrt{3/2} T_{1k} (S = 1/2). \quad (7)$$

For the cartesian components of the asymmetries we get

$$T_y^d = \frac{2}{3} T_y^n. \quad (8)$$

Relations (7),(8) between the asymmetries have been obtained without use of any particular form of the operator f for the elementary process $\gamma n \rightarrow \pi^- p$. At the same time, one needs to assume that the relative role of the off-energy-shell effects in photoproduction on bound nucleon are not substantial.

Eqs. (7) and (8) are valid in the frame of reference where both the deuteron and the neutron are at rest. The respective kinematic conditions can be provided, e.g., in an exclusive experiment when the pion and the active proton are detected in coincidence.

Taking into account the angular momentum selection rules in Eqs. (4) or (5) we obtain $T_{2k} (S = 1) = 0$. This property of the tensor asymmetry can be expected in the calculation including only the S-waves. As it was pointed out [14], the tensor asymmetry in the radiative capture of polarized deuteron on protons tends to zero when S-waves are retained in the nuclear WFs.

Thus, we arrive at the conclusion that

$$T_y^n = (\sigma^d (p^d) - \sigma^d (-p^d)) / (p^d (\sigma^d (p^d) + \sigma^d (-p^d))), \quad (9)$$

i.e., the TA of the process $\gamma n \rightarrow \pi^- p$ can be found from the yields for the reaction $\gamma d \rightarrow \pi^- pp$ under the assumptions that the pion production off the active nucleon dominates, neither rescattering on proton-spectator nor the two-body reaction mechanisms are essential, the deuteron D-wave does not affect the observables. Eq. (9) can be used for treatment of the data obtained in the experiment providing kinematic conditions for pion production on neutron at rest for the contributions of direct mechanism. In this kinematics the deuteron D-wave does not affect photoproduction on active nucleon since $\varphi_2(p=0) = 0$.

Simple relation (7) between the observables is derived under the assumption that one can neglect a part of the rescattering effects. Final state interaction can play an important role [15-17] in pion production off deuteron. Certainly, the contributions of the rescattering on proton-spectator as well as ones due to antisymmetrization of final pp-state can make difficult extraction of the TA for elementary process on neutron from the data on $\gamma d \rightarrow \pi^- pp$.

Role of the recoil mechanisms will be studied in forthcoming paper using in calculations the photoproduction operator constructed on basis of SAID and MAID multipole analyses.

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