Tensor analyzing powers in forward angle exclusive $\pi$-meson photoproduction on deuteron.

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Abstract

The target tensor analyzing powers of the process $\gamma d \rightarrow \pi^- pp$ had been studied in the plane wave impulse approximation, if both ejected protons are detected in coincidence and in the directions, symmetrical respect to the incoming photon momentum, being in the proton plane. The matrix elements of the studied reaction become essentially simple, if the magnitudes of the proton momenta $p_1 = p_2 = p$ are equal. That proton kinematics keeps the ejected pion angle near zero, therefore the one body pion production operator does not include the spin-non-flip term. Moreover, the transition to the triplet, spatially antisymmetric final $pp-$ state is strongly suppressed from the symmetrical deuteron $S-$ state as well as matrix elements have a large dependence from the orientation of the deuteron spin. The values of the $T_{22}(\vec{p})$ component, calculated with three realistic deuteron wave functions in the proton momentum region $p \geq 350 MeV/c$ and proton polar angle $\theta \geq 40^\circ$, differ one from another noticeably.

Meson photoproduction from nuclei on a level with elastic and inelastic electron scattering for a long time is an important reaction used for the investigation of the nuclear structure and dynamics. To examine the pion photoproduction on the neutrons, that is great particular interest, as a rule, the investigation of the reaction $\gamma d \rightarrow \pi NN$ is being used. However the extraction of the information even on the simplest nucleus structure as well as on pion production on a neutron is very complicated by uncertainties aroused from initial and final state interaction, Fermi motion, off-mass-shell effects. Moreover for the charge pion production exclusion principle effect on the final $nn$ or $pp$ system should be taken into consideration. The experimental and theoretical studies of the pion photoproduction reactions involving polarized deuteron target have received considerable attention at present. It is apparent that the polarization observables may provide a means of obtaining additional nuclear dynamics information.

We have studied experimentally the differential cross section and tensor target asymmetries of the process

$$\gamma d \rightarrow \pi^- pp$$

(1)

by recording two protons in coincidence in the reaction

$$ed \rightarrow pp\pi^- e'$$

(2)

at the photon point, using the internal polarized deuterium target of the VEPP-3 storage ring [1]. The experimental data have been obtained at large ejected proton momenta $300 MeV/c < p < 700 MeV/c$. The detector angular
acceptance was $63^\circ < \theta < 83^\circ$, $\Delta \varphi = 40^\circ$. As the experimental yield proved to be not very prosperous, we have to divide the whole data into bins, corresponding to a range division of one in a six independent parameters only. So the presented differential cross section and asymmetry components had been effectively integrated over five remaining parameters in their allowed boundaries. The resulting differential cross section and asymmetry components differed significantly from the results obtained in a plane wave impulse approximation (PWIA).

The recent example of the theoretical investigation of the single spin asymmetries for the inclusive reactions $d(\gamma, \pi)NN$ is [2]. One can arrive at a conclusion that measurements of $T_{22M}$ would not allow us discriminate between physically reasonable deuteron wave function (DWF) with different percentage D - state. Actually, the tensor analyzing powers, obtained with DWF of the Bonn potential[6] instead of the one of the Paris potential[7] had a minor differences.

The matrix element of the process (1) in PWIA is given by [2]:

$$M_{sm,m_d}(\vec{k}, \vec{q}, \vec{p}_1, \vec{p}_2) = \sqrt{2} \sum_{m'} s m l < s m l | t(\vec{p}_{1}, \vec{k}, \vec{q}) - \vec{p}_2 > \psi_{m'm_d}(\vec{p}_2) + (-1)^s \vec{p}_2 [t(\vec{p}_{1}, \vec{k}, \vec{q}) - \vec{p}_1 > \psi_{m'm_d}(\vec{p}_1)] |1m' > ,$$

(3)

where $s$, $m$– total spin and projection of the two outgoing protons,

$$\psi_{m'm_d}(\vec{p}) = (2\pi)^{3/2} \sqrt{2E_d} \sum_{L=0,2} \sum_{m_L} \delta^L < Lm_L 1m'_d > u_L(\vec{p})Y_{Lm_L}(\hat{\vec{p}})1_{m_d}$$

(4)

is the deuteron wave function in the momentum space, $\hat{\vec{p}} = \vec{p}/|\vec{p}|$. $Z$– axis of our right - handed coordinate system is directed along the momentum $\vec{k}$ of the incoming photon, and $y$– axis along $\vec{p}_2 \times \vec{p}_1$.

Matrix element (2) possesses the symmetry under interchange of the proton momenta, so the elementary operator $t(\vec{p}_{1}, \vec{k}, \vec{q})$ acts on the nucleon with number 1 only. This operator has a general form [3]:

$$t(\vec{p}_{1}, \vec{k}, \vec{q}) = i\hat{\vec{k}} \vec{p}_{1} F_1 + (\hat{\vec{k}} \times \vec{m}_{1} ) F_2 + i(\hat{\vec{k}} \vec{p}_{1} \vec{q}) F_3 + i(\hat{\vec{q}} \vec{m}_1 \vec{q}) F_4.$$  

(5)

Here $\hat{\vec{k}} = \vec{k}/|\vec{k}|$, $\hat{\vec{q}} = \vec{q}/|\vec{q}|$ and $\vec{m}_1$ is photon polarization vector of helicity $m_1$.

As can be seen from equation of the reaction amplitude (3), every measurable variables of the reaction (1) must be a complex function of the two general factors. One of them is determined by meson photoproduction process on a nucleon, while the other by nuclear structure properties.

The simple spectator model is attractive because there is a hope to connect the experimental data analysis of the pion photoproduction on deuteron target with DWF in the momentum representation by the most direct way. However slow nucleon for example $p_1$ can be identified as the spectator, and $\psi_{m'm_d}(\vec{p}_2)$ can be completely neglected, if the other nucleon is much faster $p_2 \gg p_1$.

When $p_1$ and $p_2$ is comparable, correct analysis is essentially more complicate for extracting the free - nucleon data [4].
We have improved the agreement between the calculation results and experimental data [1] taking into consideration effects of the final state interaction, but we were unable to study the nucleon momentum distribution in the deuteron from a relatively direct comparison of the experimental data about the components of tensor target asymmetry with results of the calculations. It is not only because the elementary pion production operator includes the many contributions, but also because the necessity to symmetrize the final pp-state to take into account the Pauli blocking. In [4] it had been estimated that effect of symmetrization is to enhance the spatially symmetric final states, up to a factor 4, and to suppress correspondingly the antisymmetric ones.

As a result of symmetrization, the analyzing power components $T_{2M}$ even in PWIA are expressed in the numerous terms, including varied products of the bilinear combinations of the S- and D-waves of the DWF and the different parts of the elementary amplitude. Effect of the rescattering on polarized observables of the reaction (1) in the Delta-resonance region was studied in [5]. The theoretical analysis of the obtained expressions is complicating infinitely.

The first major objective of this contribute is to determine which measurements are valid for extraction essential information on the free-nucleon data or on nucleon momentum distribution in the deuteron. We have paid attention to the possibility to derive the advantage from the symmetrization of the proton-proton state when both proton momenta are under control. The single pion photoproduction (1) is described by six independent variables, if the incoming photon has energy spectrum. In accordance with the experimental kinematics [1] the proton momenta $p_i$, their angles $\theta_i$ and $\varphi_i$ (i=1,2) has been chosen as independent variables. From the momentum and energy conservation one can obtain the photon energy quantity. First of all, if the both ejected protons are observed in the directions, symmetrical respect to the incoming photon momentum, being in the proton plane, i.e. $\theta_2 \approx \theta_1, \varphi_2 \approx \varphi_1 + \pi$ and the magnitudes of the proton momenta are near to each other, the matrix elements of the reaction (1) become simpler essentially.

The point is that above proton kinematics keeps the ejected pion angle near zero, therefore the one body pion production operator, that is the important ingredient of the studying of the pion production on the deuteron, does not include the spin-non-flip term. The elementary pion production operator $t(\varepsilon_{m'\gamma}, \vec{k}, \vec{q})$ will preserve the first term $i\vec{\sigma}\varepsilon_{m'\gamma}F_1$ only. As a consequence, the transition to the triplet, spatially antisymmetric final pp-state is strongly suppressed for the symmetrical deuteron S-state as well as matrix elements have a large dependence from the orientation of the deuteron spin. Polarization studies are seen to be of the considerable practical importance in these investigations.

As we have analyzed, the square of the matrix element of the reaction (1) after summing over the final spin states and averaging over the photon polarizations for $m_d = 0$ is proportional to the $D-$wave of DWF $w(\vec{p})^2$ only. However the experimental measurements of the cross sections of the process (1), using tensor polarized deuterium target with $m_d = 0$, seemed quite unlikely, because such high value of the target polarization for the present is
unrealizable.

In this paper we shall concentrate on the investigation of the tensor analyzing power components in negative pion photoproduction from deuteron:

\[ T_{2M} = \frac{S\rho M \tau_{2M} M^+}{S\rho M M^+}, \]

(6)

where \( \tau_{2M} \) is the spherical spin - tensor in the deuteron matrix density decomposition.

The elementary pion photoproduction operator does not play any role in the target asymmetry calculations for our symmetrical kinematics because it produces the equal factors in both a numerator and a denominator of (6), so the \( T_{2M} \) is expressed in terms of the \( S \) - and \( D \) - wave of the DWF.

\[ T_{20} = \frac{32\sqrt{2}u^2(p) - 16(3 \cos(2\theta) + 1)u(p)w(p) + \sqrt{2}(-12 \cos(2\theta) + 9 \cos(4\theta) + 19)w^2(p)}{4(16u^2(p) - 4\sqrt{2}(3 \cos(2\theta) + 1)u(p)w(p) + (-6 \cos(2\theta) - 9 \cos(4\theta) + 23)w^2(p))}, \]

(7)

\[ T_{21} = 0, \]

(8)

\[ T_{22} = -\frac{3\sqrt{3} \sin^2(\theta) w(p)(4\sqrt{2}u(p) + 3 \cos(2\theta) + 5)w(p)}{16u^2(p) - 4\sqrt{2}(3 \cos(2\theta) + 1)u(p)w(p) - (6 \cos(2\theta) + 9 \cos(4\theta) - 23)w^2(p)}. \]

(9)

We have estimated tensor analyzing power components \( T_{20}, T_{22} \) using DWF of Bonn [6] and Paris [7] potential model and one, obtained in [8], corresponding to a percentage D state \( P_D = 8\% \): Figs. 1.- 4. The \( T_{22} \), as a function of the proton polar angle, calculated using the DWF of Bonn potential differs essentially from it, calculated with DWF of Paris potential, starting from \( p = 350 \text{MeV}/c \). The magnitude of \( T_{22} \) in that region is small, and reaches higher values with increase of the proton momentum: Fig.2., middle and bottom panels. This choice effect for \( T_{20} \) is weaker, but still noticeable particularly for proton polar angles near 30° at proton momenta \( p \geq 400 \text{MeV}/c \).

If ejected proton angles \( \theta \) obey the condition \( 1 + 3 \cos(2\theta) = 0 \), that is equivalently to \( 3 \cos^2(\theta) - 1 = 0 \), i.e. \( Y_{20}(\theta) = 0 \) the expressions, obtained for \( T_{20} \) and \( T_{22} \) in the impulse approximation are as follows:

\[ T_{20} = \frac{2u^2(p) + w^2(p)}{2\sqrt{2}(u^2(p) + 2w^2(p))}, T_{21} = 0, T_{22} = -\frac{\sqrt{3}w(p)(\sqrt{2}u(p) + w(p))}{2(u^2(p) + 2w^2(p))}. \]

Figs. 3,4 show the momentum dependence of the \( T_{20} \) and \( T_{22} \) components of the tensor analyzing power. Whereas the \( T_{20} \) curves, calculated with three DWF, do not differ up to 500\text{MeV}/c, the \( T_{22} \), calculated with Bonn and Paris DWF, differing one from another only a little, exceed in the absolute value result of the calculation with DWF [8] essentially.

As an example we have received in one value of the analyzing power components \( T_{20}, T_{22} \) with obviously poor statistical accuracy, introducing the restrictions on our early experimental data [1] \( |\vec{p}_1 - \vec{p}_2| \leq 50 \text{MeV}/c, |\theta_1 - \theta_2| \leq 3.5° \)
Figure 1: T20 component of the tensor analyzing power as a function of the proton angle $\theta$ at the different proton momenta: top – $p = 200MeV/c$, middle – $p = 300MeV/c$, bottom – $p = 400MeV/c$. Dashed (dash - dotted) curves – calculation using the DWF of Bonn[6] (Paris [7]) potential model. Solid line – calculation using the DWF parametrization of [8] with $P_D = 8\%$.

Figure 2: T22 component of the tensor analyzing power as a function of the proton angle $\theta$ at the different proton momenta: top – $p = 200MeV/c$, middle – $p = 350MeV/c$, bottom – $p = 400MeV/c$. Notation of the curves as in Fig. 1.
Figure 3: T20 component as a function of the proton momentum $p$. Notation of the curves as in Fig. 1.

Figure 4: T22 component as a function of the proton momentum $p$. Notation of the curves as in Fig. 1.

$T_{20}(\langle p \rangle = 400 \text{MeV}/c, \langle \theta \rangle = 71.5^\circ) = 0.68 \pm 0.65, T_{22}(\langle p \rangle = 400 \text{MeV}/c, \langle \theta \rangle = 71.5^\circ) = -0.16 \pm 0.53$. These values do not contradict our predictions.

We shall examine the possibilities of the new experimental data from $\gamma d \rightarrow \pi^- pp$ reaction to study in this frame $w(p)$ and the ratio $u(p)/w(p)$ for the different realistic DWF. The measurements of the $T_{22}$ angular dependence in the region $p \geq 400 \text{MeV}/c$ with high precision, in principle, can allow us to select the most suitable DWF of them, having different $P_D$ values.

The main approximation in this work is the neglect of the final state interaction. So, the differences of the measured $T_{2M}$ from they, predicted by formulae (7), (8) must be expained by the necessity to consider more complicated mechanisms of the reaction (1), and this difference will determine the contributions of the pion - nucleon, nucleon - nucleon rescattering, meson exchange currents to the amplitude.

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References

[1] A.Yu. Loginov et al., JETF Lett. 67, 770 (1998).
[2] E.M. Darwish, nucl-th/0309061 v1 23 Sep 2003.
[3] G.F. Chew, M.L. Goldberger, F.E. Low and Y. Nambu, Phys. Rev. 106, 1345 (1957).
[4] N.W. Dean, Phys. Rev. D5, 1661 (1972).
[5] A.Yu. Loginov et al., Phys. At. Nucl. 63, 391 (2000).
[6] R. Machleidt, K.Holinde, and Ch. Elster, Phys. Rep. 149, 1 (1987).
[7] M. Lacombe et al., Phys. Lett. B101, 139 (1981).
[8] A. Certov, L.Mathelitsch, and M.J. Moravcsik, Phys. Rev. C36, 2040 (1987).