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NEAR THRESHOLD PION PHOTOPRODUCTION ON DEUTERONS

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Abstract

The study of photoproduction of mesons is a prime tool in understanding the properties of strong interactions. The only photoproduction reaction on deuteron with two-body final state is coherent pion photoproduction reaction. Several theoretical studies are being carried out on the pion photoproduction on deuterons since several decades. On the experimental side, the accelerator and detector technology has improved the developments. In the recent years, measurements of tensor analyzing powers associated with coherent and incoherent pion photoproduction are also being carried out at the VEPP-3 electron storage ring. In one of the recent measurements, Rachek *et al.* [1] have observed discrepancy between theory and experiment at higher photon energies and have suggested for improvement of the theoretical models. In a more recent analysis [2], the role of D-wave component on spin asymmetries has been identified. In view of these developments, the purpose of the present contribution is to study coherent pion photoproduction on deuterons using model independent irreducible tensor formalism developed earlier to study the photodisintegration of deuterons [3].

INTRODUCTION

The study of nuclear reactions between elementary particles and atomic nuclei plays an important role in understanding the interdisciplinary area of Nuclear Physics and Particle Physics. The study of photoproduction of pions describe the coupling among photon, meson and nucleon fields and also gives information about strong interactions that indirectly hold the nucleus together. Deuteron being the simplest nuclei with one proton, neutron and electron, can be used to study reactions involving proton, neutron and electrons. The processes that can be studied are photodisintegration, photoproduction and electro-production. Photoproduction can take place through coherent and incoherent processes.

Pion photoproduction on deuteron are physically possible only through the following reactions,

$$\gamma + d \rightarrow d + \pi^0, \tag{1}$$

$$\gamma + d \rightarrow n + p + \pi^0, \tag{2}$$

$$\gamma + d \rightarrow p + p + \pi^-, \tag{3}$$

$$\gamma + d \rightarrow n + n + \pi^+. \tag{4}$$

The reaction given in Eq. (1) shows the pion photoproduction coherent process, the other three equations [Eqs. (2), (3) and (4)] show pion photoproduction incoherent process. A large amount of experimental data is available for two-body process for comparison, unfortunately not for reactions that end up with three-body processes. Thus it's only logical to study the pion photoproduction reaction channel $\gamma + d \longrightarrow d + \pi^0$ in systems with more than one nucleon.

Theoretical and Experimental Developments on Pion Photoproduction

In the recent years, the study on pion photoproduction reaction on deuterons has attracted special attention from both theorists [4, 5] and experimentalists [1, 6–9]. On the other hand, it allows us to study various properties which are under the influence of nuclear environment like, elementary production amplitude, pion photo production on off-shell nucleon and $N - \Delta$ interaction in nuclear medium. A thorough investigation of the photoproduction process is firmly believed to give first hand information on two important aspects, one being the threshold of π^0 photoproduction amplitude and the other being propagation of low-energy pions in nuclear medium. Since neutral pion produced coherently is found to be sensitive to the pion wave function in the nuclear interior and to entire nuclear matter distribution.

On the theoretical side, the reaction $\gamma + d \longrightarrow d + \pi^0$ has been studied by several authors using Impulse Approximation as early as in the 1950's [10–13]. Employing the well known CGLN amplitudes [14] for photo pion production on nucleons, good agreement was obtained [15] with the then existing experimental data. The differential cross section leading to the different final spin states with $m = 0, \pm 1$ have also been calculated and it was found that the forward cross section for $m = 0$ state predominates. The pion photoproduction reactions have been studied using different potential and models like, Bonn potential [16–20], Statistical model [4,21], Impulse Approximation implying Chew - Goldbarger - Low - Nambu (CGLN) amplitudes [22], Radioactive Capture Method [23], Final State Interaction Model [24], Effective Lagrangian Approach [25], Maniz Unitary Isobar Model (MAID) partial wave analysis [26], Scattering Analysis Interactive Dial-In partial wave analysis and Bonn-Gotchina (Bn-Ga) Model [27], Argonne National Laboratory - Osaka University (ANL- Osaka) amplitudes [28] in the intervening years.

The reaction $\gamma + d \rightarrow d + \pi^0$ is a source of information on elastic π^0 scattering but unfortunately the life time of neutral pion is very short making it impossible to study reactions like these. The rate of photoproduction of π mesons is in µ seconds. Reactions like these can now be precisely studied with the growing accuracy of the experiments.

On the Experimental side, due to several advances in the accelerator technology, it is possible to produce pho-

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ton beams of the order of GeV energy. This facility initially focused attention on photonuclear reactions. Since the threshold for pion photoproduction was reached, the usage of photon beams for hadron physics became a reality. A review on the measurement of production of mesons using photon beams is presented [29]. In this review a brief description of various experimental facilities like Jefferson lab, CLAS, ESRF, MAMI and many other are also presented. Recently several experimental measurements have been reported on tensor analyzing powers in coherent [6] and incoherent [7] neutral pion photoproduction on deuteron also. Incoherent pion photoproduction on the deuteron was studied theoretically for photon energies from threshold up to 1 GeV [4], where polarization observables were given special emphasis. The purpose of the present study is to focus attention on coherent neutral pion photoproduction, that is $\gamma + d \longrightarrow d + \pi^0$ using model independent irreducible tensor formalism devolped earlier for photodintegration of deuteron.

THEORETICAL FORMALISM

Let $\mathbf{k} = k\hat{\mathbf{k}}$ denotes the photon momentum which is chosen along the $z-$axis. The polarization of photon is denoted by $\mu = \pm 1$ following Rose [30]. Let $\hat{\mathbf{q}}$ denote the the $c.m.$ momentum of π^0 in the case of $d + \gamma \longrightarrow d + \pi^0$. We may conveniently choose a right-handed Cartesian coordinate system with $\mathbf{q}$ coming out with an angle θ in the $zx-$plane as shown in Fig. 1.

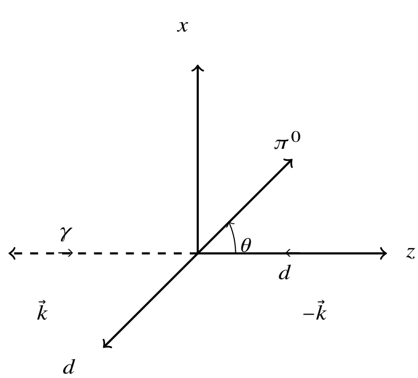

Figure 1: The reaction $\gamma + d \longrightarrow d + \pi^0$ in c.m frame in the $z - x$ plane.

Using the same notations [3] the reaction matrix for coherent pion photoproduction can be written in the form

$$M(\mu) = \sum_{\lambda=0}^{2} \left(S^{\lambda}(1,1) \cdot \mathscr{F}^{\lambda}(1,\mu) \right), \tag{5}$$

where $S^{\lambda}_{\nu}(1,1)$ of rank λ are defined following [31] which represent the spin transition tensors. $\mathscr{F}^{\lambda}_{\nu}(1,\mu)$ represents the irreducible tensor amplitudes of rank λ which are expressed in terms of multipole amplitudes. These irreducible tensor amplitudes are given by

$$\mathscr{F}^{\lambda}_{\nu}(1,\mu) = \sum_{L=1}^{\infty} \sum_{l=0}^{\infty} \sum_{j=L-1}^{j=L+1} (-1)^{j+L} (i)^{L-l} \\ W(1L1l;j\lambda)\ [j]^2 [L]\ g^{\lambda}_{\nu}(l,L,\mu), \tag{6}$$

where the orbital angular momentum is represented by l and total angular momentum of the photon represented by L. We have used the short hand notation $[L]$ to represent $\sqrt{2L+1}$ and the conserved total angular momentum of the reaction is represented by j. $W(1L1l;j\lambda)$ represents the racah coefficients. The angular dependence and also the dependence on photon polarization is taken care by $g^{\lambda}_{\nu}(l,L,\mu)$ which is given as

$$g^{\lambda}_{\nu}(l,L,\mu) = 4\pi\sqrt{2\pi} F^{lj}_{L} C(lL\lambda; m_l - \mu\nu)\ Y_{lm_l}(\hat{\mathbf{q}}), \tag{7}$$

where

$$F^{lj}_{L} = \frac{1}{2}\left[P_+\ \mathscr{M}^{lj}_{L} + i\mu P_-\ \mathscr{E}^{lj}_{L}\right] \tag{8}$$

are the partial multipole amplitudes which depend only on the C.M energy E. The operator

$$P_{\pm} = \frac{1}{2}[1 \pm (-1)^{L-l}] \tag{9}$$

assume either of the values 0, 1 such that, if $p^+ = 1$ implies $p^- = 0$ and vice versa. The $F^{j}_{ls;L}$ denotes electric 2^L-pole amplitudes, if $p^+ = 1$ and magnetic 2^L-pole amplitudes, if $p^- = 1$. $\mathscr{M}^{lj}_{L}$ and $\mathscr{E}^{lj}_{L}$ represent the magnetic and electric multipole amplitudes respectively.

RESULTS AND DISCUSSION

The spin of deuteron in the initial state is 1 which interacts with a photon to yield neutral pion and deuteron in the final state with channel spin $s = 1$. Since we are looking at only near threshold energies, we may restrict ourselves to only $L = 1, 2$ and to $l = 0, 1, 2$ partial waves. It is pertinent to note that the reaction can be described by only 6 non-zero irreducible tensor amplitudes $\mathscr{F}^{\lambda}_{\nu}(1,\mu)$ with $\lambda = 0, 1, 2$ and $\mu = \pm 1$ at all energies. In terms of these limited number of partial wave multipole amplitudes, the irreducible tensor amplitudes $\mathscr{F}^{\lambda}_{\nu}(1,\mu)$ may explicitly be written in terms of these multipole amplitudes

$$\mathscr{F}^{0}_{0}(1,1) = -3\sqrt{3}g^{0}_{0}(1,1,1) - 5\sqrt{3}g^{0}_{0}(2,2,1), \tag{10}$$

$$\mathscr{F}^{0}_{0}(1,-1) = -3\sqrt{3}g^{0}_{0}(1,1,-1) - 5\sqrt{3}g^{0}_{0}(2,2,-1), \tag{11}$$

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$$\begin{aligned}\mathscr{F}^1_q(1,1) =& i\sqrt{3}g^1_\nu(0,1,1) - \frac{5i}{2}g^1_\nu(1,2,1)\\ &- \frac{i\sqrt{5}}{2}g^1_\nu(1,2,1) + \frac{i\sqrt{3}}{2}g^1_\nu(2,1,1)\\ &+ \frac{i\sqrt{15}}{2}g^1_\nu(2,1,1),\end{aligned} \tag{12}$$

$$\begin{aligned}\mathscr{F}^1_q(1,-1) =& i\sqrt{3}g^1_\nu(0,1,-1) - \frac{5i}{2}g^1_\nu(1,2,-1)\\ &- \frac{i\sqrt{5}}{2}g^1_\nu(1,2,-1) + \frac{i\sqrt{3}}{2}g^1_\nu(2,1,-1)\\ &+ \frac{i\sqrt{15}}{2}g^1_\nu(2,1,-1),\end{aligned} \tag{13}$$

$$\begin{aligned}\mathscr{F}^2_q(1,1) =& \sqrt{3}g^2_\nu(0,2,1) - \frac{i\sqrt{5}}{2}g^2_\nu(1,2,1)\\ &+ \frac{3i}{2}g^2_\nu(1,2,1) - \frac{i\sqrt{3}}{2}g^2_\nu(2,1,1)\\ &+ \frac{3}{2}\sqrt{\frac{3}{5}}g^2_\nu(2,1,1),\end{aligned} \tag{14}$$

$$\begin{aligned}\mathscr{F}^2_q(1,-1) =& \sqrt{3}g^2_\nu(0,2,-1) - \frac{i\sqrt{5}}{2}g^2_\nu(1,2,-1)\\ &+ \frac{3i}{2}g^2_\nu(1,2,-1) - \frac{i\sqrt{3}}{2}g^2_\nu(2,1,-1)\\ &+ \frac{3}{2}\sqrt{\frac{3}{5}}g^2_\nu(2,1,-1).\end{aligned} \tag{15}$$

Using the multipole expansion, partial wave analysis and the known properties of Racah algebra [30], the unpolarized differential cross section for the reaction is given by

$$\frac{d\sigma_0}{d\Omega} = \frac{1}{6}\sum_{\lambda=0}^{2}(-1)^\lambda[\lambda]\sum_\mu\left(\mathscr{F}^\lambda(1,\mu)\cdot\mathscr{F}^{\dagger\lambda}(1,\mu)\right), \tag{16}$$

where $\mathscr{F}^{\dagger\lambda}_\nu(\mu) = (-1)^\nu \mathscr{F}^{\dagger\lambda}_{-\nu}(\mu)^*$.

The irreducible tensor amplitudes $\mathscr{F}^\lambda_\nu(1,\mu)$ can be used to calculate the differential cross section, spin observables with polarizaton, analysing powers, et cetra. It is important to study the spin structure of the amplitudes in photoproduction of pions on deuterons and their expansion in terms of electric and magnetic multipole amplitudes. The irreducible tensors given by Eqs. (10), (11), (12), (13), (14) and (15) will help us in understanding the role of multipole amplitudes for the reaction. In view of the on going experimental studies wide scope exists for theoretical study associated with the reaction $\gamma + d \longrightarrow d + \pi^0$.

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