Theoretical Studies on Pion Photoproduction on Deuterons

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Abstract

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 mesons has a long history going back to $1950's$. It was in the next decade studies on photoproduction of π meson on deuteron started. Since then coherent and incoherent photoproduction of π meson on deuteron have been studied theoretically and experimentally. 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. 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 photoproduction amplitude and the other being propagation of low-energy pions in nuclear medium. The purpose of the present contribution is to theoretically study pion photoproduction on deuterons using model independent irreducible tensor formalism developed earlier to study the photodisintegration of deuterons.[1]

Introduction

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,

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

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

The reaction eqn. (1) is coherent reaction and eqn. (2) are incoherent reactions. 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. 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 [2, 3] and experimentalists [4, 5, 6, 7]. 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 [8]. Employing the well known CGLN amplitudes [9] for photo pion production on nucleons, good agreement was obtained [10] 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. Several model calculations like the MAID [11] and SAID [12] partial wave analysis, effective Lagrangian approach model [13] have also been carried out in the intervening years.

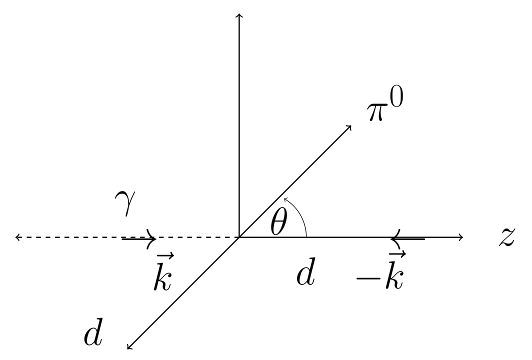
On the Experimental side, a review on the measurement of production of mesons using photon beams is presented[14]. In this review a brief description of various experimental facilities like Jefferson lab, CLAS, ESRF, MAMI and many other are also presented. Rachek *et. al.,* [5] have measured the tensor analyzing power T_{20} in the reaction $\gamma + d \rightarrow d + \pi^0$ at the VEPP-3 storage ring at Budker Institute in the energy range $200 < E_\gamma < 500\, MeV$. They have observed that below $350\, MeV$ there is a good agreement between theory and experiment and noted that 'the quality of agreement between theory and experiment decreases at higher photon energies, hence an improvement in theoretical model seems to be needed'. Recently, theoretical calculations on the tensor target spin asymmetries in coherent π^0-photo production on the deuteron were carried out [3] and when their measurements were compared with the experimental data [15, 16], there was a discrepancy for the T_{21} and T_{22} asymmetries.

In view of these experimental and theoretical developments, we are theoretically studying coherent pion photoproduction on deuterons, $\gamma + d \longrightarrow d + \pi^0$ at near threshold energies using model independent irreducible tensor formalism developed earlier[1, 17, 18, 19]. We discuss the Tensor Deuteron target spin asymmetry A_0^2 for the reaction $\gamma + d \longrightarrow d + \pi^0$.

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 [20]. 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.

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



Using the same notations [1] the reaction matrix for coherent pion photoproduction can be written in the form The reaction matrix for coherent photoproduction is written in the form

$$M(\mu) = \sum_{\lambda=0}^{2} \left(S^\lambda(1,1) \cdot \mathcal{F}^\lambda(\mu) \right) \tag{3}$$

where S_ν^λ of rank λ are defined following [17] and μ denotes photon polarization following [20]. The notations are the same as in [17]. It is important to note that the reaction can be described by only 6 irreducible tensor amplitudes $\mathcal{F}_\nu^\lambda(\mu)$ with $\lambda = 0, 1, 2$ and $\mu = \pm 1$ at all energies. It is also interesting to note that irreducible tensor amplitudes $\mathcal{F}_\nu^\lambda(\mu)$ can be expressed in terms of partial wave 2^L multipole amplitudes F_L^{lj} as

$$\mathcal{F}_\nu^\lambda(\mu) = 4\pi\sqrt{2\pi} \sum_{L=1}^{\infty} \sum_{l=0}^{\infty} \sum_{j=L-1}^{j=L+1} (-1)^{j+L} (i)^{L-l}\, W(1L1l; j\lambda)\, [j]^2 [L]\, F_L^{lj} C(lL\lambda; m_l - \mu\nu)\, Y_{lm_l}(\hat{\mathbf{q}}) \tag{4}$$

where, $F_L^{l\,j} = \frac{1}{2}\left[P_+\, \mathcal{M}_L^{lj} + i\mu\, P_-\, \mathcal{E}_L^{lj} \right]$ and $P_\pm = \frac{1}{2}[1 \pm (-1)^{L-l}]$ and $\mathcal{M}_L^{lj}$ and $\mathcal{E}_L^{lj}$ represent the magnetic and electric multipole amplitudes respectively. The unpolarised differential cross section is given by,

$$\frac{d\sigma_0}{d\Omega} = \frac{1}{6} \sum_{\lambda=0}^{2} (-1)^\lambda [\lambda] \sum_\mu \left(\mathcal{F}^\lambda(\mu) \cdot \mathcal{F}^{\dagger\lambda}(\mu) \right) \tag{5}$$

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

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 $s = 1$. The tensor polarized target is described following [21] in terms of Fano Statistical Tensors t_q^k. The spin density matrix of the deuteron can then be written as

$$\rho_d = \frac{1}{3} \sum_{k=0}^{2} \left(S^k(1,1) \cdot t^k \right) \tag{6}$$

with initially unpolarized photons and tensor polarized deuterons the differential cross section is given by,

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left[1 + (t^2 \cdot A^2) \right] \tag{7}$$

where A_q^2 denote the Tensor Analyzing powers which are measurable experimentally.

$$A_q^2 = \frac{\sqrt{3}}{2} \sum_{\lambda,\lambda',\mu} [\lambda][\lambda'] W(121\lambda; 1\lambda') \left(\mathcal{F}^\lambda(\mu) \otimes \mathcal{F}^{\dagger\lambda'}(\mu) \right)_q^2 \tag{8}$$

where $q = 0, \pm 1, \pm 2$. Explicitely A_q^2 can be written as

$$\begin{aligned} A_q^2 = \sum_{\mu=\pm 1} & \frac{1}{\sqrt{2}} \left(\mathcal{F}^0(\mu) \otimes \mathcal{F}^{\dagger 2}(\mu) \right)_q^2 - \frac{\sqrt{3}}{2\sqrt{2}} \left(\mathcal{F}^1(\mu) \otimes \mathcal{F}^{\dagger 1}(\mu) \right)_q^2 - \frac{3}{2\sqrt{2}} \left(\mathcal{F}^1(\mu) \otimes \mathcal{F}^{\dagger 2}(\mu) \right)_q^2 \\ & + \frac{1}{\sqrt{2}} \left(\mathcal{F}^2(\mu) \otimes \mathcal{F}^{\dagger 0}(\mu) \right)_q^2 - \frac{3}{2\sqrt{2}} \left(\mathcal{F}^2(\mu) \otimes \mathcal{F}^{\dagger 1}(\mu) \right)_q^2 + \frac{\sqrt{7}}{2\sqrt{2}} \left(\mathcal{F}^2(\mu) \otimes \mathcal{F}^{\dagger 2}(\mu) \right)_q^2 \end{aligned} \tag{9}$$

These A_q^2 are expressed in terms of the irreducible tensor amplitudes. We have presented a model independent analysis of the Tensor Analyzing Powers in the $\gamma + d \longrightarrow d + \pi^0$ at near threshold energies. This approach is valid at both high as well as low energies. This approach provides an alternative way to analyze the experimental measurements. The measurements of tensor analyzing powers A_q^2 will help us in understanding the coherent pion photoproduction in a better way. In view of the on going experimental studies wide scope exists for theoretical study associated with the reaction $\gamma + d \longrightarrow d + \pi^0$. Further work on the polarization observables is in progress.

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