

Neutron polarization observables in $d(\vec{\gamma}, \vec{n})p$ at low energies of interest to astrophysics

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Deuteron being the simplest nuclei with a proton neutron pair, is an example for a bound two-body system that has been studied for many decades now. Precise knowledge of the reactions $d + \gamma \longleftrightarrow n + p$ play very important role in Nuclear Physics, to understand Nucleon–Nucleon interactions, in Solar Physics, pp-chain reactions [1, 2] and in Astrophysics in sharpening the predictions on Big Bang Nucleosynthesis [3] along with the inputs from other reactions involving ^{3}He, ^{4}He, ^{7}Li and ^{7}Be [4]. Experimental measurements have been carried out by radiative capture on neutrons by protons [5, 6]. On the other hand several experimental measurements [7–12] have been carried out on $d + \gamma \longrightarrow n + p$ at the Duke Free Electron Laser Laboratory using High Intensity γ-ray Source (HIGS).

Although it was known quite early that the thermal neutron capture by protons is dominated by the isovector magnetic dipole amplitude $M1_v$, Breit and Rustgi [13] were the first to propose a polarized target-beam experiment to look for an isoscalar $M1_s$ amplitude in view of the then existing 10 % discrepancy between theory and experiment. The suggestion was more or less ignored in view of the surprising accuracy with which the 10 % discrepancy was explained [14] as due to Meson exchange currents (MEC). However, the measured values for analyzing powers in $p(\vec{n}, \gamma)d$ as well as for neutron polarization in photodisintegration of the deuteron were both found to differ [15, 16] from theoretical calculations which included MEC effects. Rustgi, Vyas and Chopra [17] drew attention to the unambiguous disagreement between experiment and theory on $d(\gamma, n)p$ at photon energy 2.75 MeV which widens when two body effects are taken into account.

Attention was focused on photon polarization in $n{-}p$ fusion reaction [18]. In this paper it was shown that the photon polarization which arises due to the interference of isovector $M1$ amplitude with isoscalar $M1$ and $E2$ amplitudes can be studied using polarized beam and target experiment. On the other hand the role of isoscalar amplitudes was highlighted in the theoretical study on analyzing powers in $d + \gamma \to n + p$ [19] with unpolarized photons. Theoretical analysis of the photodisintegration of deuterons with aligned deuteron targets and linearly polarized photon beams was carried out [20] in which an analysis of the experimental data of [21] was also presented.

It is pertinent to mention that several photo-nuclear reactions on polarized deuterons are being studied at higher energies using linearly polarized photons at the VEPP-3 storage rings [22–24]. Since the advent of polarization measurements, there are new mysteries and polarization of emerging neutron (P'_y) in reaction $d(\gamma, \vec{n})p$ is a good example. There is also a mention about the unsolved puzzle of P'_y in the work of Gilman and Gross [25]. Working in the framework of pion less effective field theory with dibaryons [26] for neutron polarization showed a significant discrepancy with experiment [27], which points to "The necessity of further studies both experimental and theoretical of the spin observables in the $\gamma d \to np$ reaction" [26]. This discrepancy is observed at low energies, energies close to those of interest to Big Bang nucleosynthesis, which hinders our understanding of processes in the early universe. We propose to study the polarization of emerging neutron of the reaction $\vec{\gamma} + d \longrightarrow \vec{n} + p$ using a model independent irreducible tensor formalism with initially circularly polarized photons. Following [19, 28, 29], we express the reaction matrix as,

$$M(\mu) = \sum_{s=0}^{1} \sum_{\lambda=|l-s|}^{l+s} \left(\mathcal{S}^{\lambda}(s,1) \cdot \mathcal{F}^{\lambda}(s,\mu) \right)$$

in terms of irreducible tensor operators, $\mathcal{S}^{\lambda}_{\nu}(s,1)$ of rank λ in hadron spin space connecting the initial spin 1 state of the deuteron with the final singlet and triplet states, $s = 0, 1$ of the $n{-}p$ system in the continuum. The irreducible tensor amplitudes, $\mathcal{F}^{\lambda}_{\nu}(s,\mu)$ of rank λ are defined following [28]. The density matrix, ρ characterizing the neutron polarization in the final state is then defined in terms of its elements,

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$$\rho_{m_n m'_n} = \sum_{K,q} \frac{1}{2}(-1)^q [K] C(\frac{1}{2}\, K\, \frac{1}{2}; m'_n\, -q\, m_n) \mathcal{P}^K_q, \quad (1)$$

where

$$\mathcal{P}^K_q = \frac{1}{3\sqrt{2}} \sum_{s,s',\lambda,\lambda'} (-1)^{s+s'+1} [s]^2 [s']^2 [\lambda][\lambda'] \\ W(s'\lambda' s\lambda; 1K) W(s\, \frac{1}{2}\, s'\, \frac{1}{2}; \frac{1}{2}\, K) \\ \left(\mathcal{F}^{\lambda}(s,\mu) \otimes \mathcal{F}^{\dagger\lambda'}(s',\mu)\right)^K_q . \quad (2)$$

The neutron polarization $\mathcal{P}$ is thus obtained on comparing ρ with the standard form $\rho = \frac{1}{2}\,[1 + \sigma \cdot \mathcal{P}]$.

In this contribution, we have studied the neutron polarization using model independent formalism for $d(\vec{\gamma}, \vec{n})p$ reaction with unpolarized photons and with two circular polarization states of the photon. The experimental observation [21] at 14 and 16 MeV, that all the 3 $E1_v^{j=0,1,2}$ amplitudes are not equal is quiet encouraging enough. Since the possible role of $M1_s$ and $E2_s$ amplitudes has been discussed by several authors using different formalism in the past, we feel it is necessary to carry out measurements on neutron polarization in addition to differential cross section. We hope that the experimental measurements on neutron polarization with circularly polarized photons will clarify the role of the isoscalar multipole amplitudes at near threshold energies.

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