Photodisintegration of aligned deuterons at astrophysical energies using linearly polarized photons

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The Primordial Deuterium Abundance is a key ingredient to sharpen the predictions of Big Bang Nucleosynthesis (BBN) [1, 2] as it varies sharply with baryon density. The formation of primordial deuterium is mainly through n-p fusion [3]. Laboratory measurements play an important role in removing crucial ambiguities to sharpen the predictions in the astrophysical context. As such experimental measurements [4–6] have been reported during the last 10 years on photodisintegration of deuteron using 100 % linearly polarized laser beams at lab photon energies, $E\gamma$ in the range 2.6 MeV $< E_\gamma <$ 6 MeV which corresponds to the center of mass neutron energy E_n in the range 189 keV$< E_n <$ 1948 keV. It is worth mentioning here that while a large number of measurements exist for the n-p fusion cross section at thermal neutron energies which corresponds to $E_n \approx 10^{-6}$ keV, there are only two measurements at astrophysically relevant energies by Suzuki et al., [7] at lab neutron energies $E_n^l = 20$, 40 and 60 keV and by Nagai et al., [8] at $E_n^l = 550$ keV. As compared to the thermal neutron cross section of (334.2 ± 0.5) mb, the measured cross sections at the above four energies are $(318 \pm 2)10^{-3}$ mb , $(203 \pm 19)10^{-3}$ mb, $(151 \pm 7)10^{-3}$ mb and $(35.2 \pm 2.4)10^{-3}$ mb respectively. The reason for this sharp fall with increasing energy is attributed to the fact that the reaction $d + \gamma \rightleftharpoons n + p$ is governed by the dominant isovector $M1_v$ amplitude at thermal neutron energies which decreases sharply with increasing energy while the isovector $E1_v^j, j = 0, 1, 2$ amplitudes are believed to be responsible for photodisintegration cross sections of order of mb at E_γ of a few MeV. Thus all these amplitudes are expected to be comparable at astrophysical energies, where it is possible that the isoscalar amplitude $M1_s$ could also be of the same order of magnitude [9, 10]. Further there could also be another small amplitude like isoscalar $E2_s$ which has been considered by some authors [11]. The purpose of the present paper is to examine the observables associated with the photodisintegration of aligned deuterons using linearly polarized laser beams to detect the presence of these isoscalar amplitudes.

Following [10] and using the same notations, the reaction matrix for $d + \gamma \rightarrow n + p$ with linearly polarized photons is

$$\mathbf{M} = \sum_{s=0}^{1} \sum_{\lambda=|s-1|}^{s+1} (S^\lambda(s, 1) \cdot \mathcal{F}^\lambda(s)), \quad (1)$$

where

$$\mathcal{F}_\nu^\lambda(s) = \sum_{\mu=\pm1} \mathcal{F}_\nu^\lambda(s, \mu). \quad (2)$$

The four irreducible tensor amplitudes, $\mathcal{F}_\nu^\lambda(s, \mu)$ may be written, taking into consideration all these multipole amplitudes, as

$$\mathcal{F}_\nu^1(0, \mu) = -iM1_v f_\nu^1(0, 1, \mu) - \sqrt{3}E1_s f_\nu^1(1, 1, \mu), \quad (3)$$

$$\mathcal{F}_0^0(1, \mu) = \frac{1}{3}E1_v(0) f_0^0(1, 1, \mu), \quad (4)$$

$$\mathcal{F}_\nu^1(1, \mu) = -\frac{1}{6}E1_v(1) f_\nu^1(1, 1, \mu) + iM1_s f_\nu^1(0, 1, \mu) \quad (5)$$

$$\mathcal{F}_\nu^2(1, \mu) = \frac{1}{6}E1_v(2) f_\nu^2(1, 1, \mu) + E2_s f_\nu^2(0, 2, \mu) \quad (6)$$

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where $E1_v(\lambda)$ are linear combinations of the $E1_v^j$ amplitudes. The differential cross section with linearly polarized photons is then given by

$$\frac{d\sigma}{d\Omega} = \frac{2\pi^2}{6}[a + b\sin^2\theta(1+\cos 2\phi) - c\cos\theta], \quad (7)$$

where the presence of c was brought to notice for the first time [10] and c involves the interference between $M1_s$ and $E1_v^j$ amplitudes.

A spin 1 nucleus like the deuteron is said to be aligned, if its vector polarization is zero and tensor polarization is non-zero. It is precisely such a state of polarization that occurs when a nucleus with non-zero electric quadrupole moment is exposed to an external electric quadrupole field, $V_{\alpha,\beta}$[12]. The interaction Hamiltonian is of the form

$$H_{int} = A(3J_z^2 - J^2) + A\eta(J_x^2 - J_y^2), \quad (8)$$

where A is proportional to the nuclear electric quadrupole moment Q through

$$A = \frac{1}{4}QV_{ZZ}, \qquad \eta = \frac{V_{XX} - V_{YY}}{V_{ZZ}}. \quad (9)$$

The energy eigen values are $A(1\pm\eta)$ and $-2A$ with the respective eigen states being

$$|X>= \frac{1}{\sqrt{2}}(|1-1> - |11>), \quad (10)$$

$$|Y>= \frac{i}{\sqrt{2}}(|1-1> + |11>), \quad (11)$$

$$|Z>= |10>, \quad (12)$$

in terms of magnetic substates $|1m>$.
The differential cross section for photodisintegration of aligned deuterons by linearly polarized laser beam is then of the form

$$(\frac{d\sigma}{d\Omega})_{AD} = \frac{d\sigma}{d\Omega}(1 + (\mathcal{A}^2 \cdot t^2)) \quad (13)$$

where t^2_{-q} denote the Fano statistical tensors and $\mathcal{A}^2_q$ denotes the analyzing powers which are given by

$$\mathcal{A}^2_q = \frac{1}{2\sqrt{3}}\sum_{s,\lambda,\lambda'}(-1)^\lambda(2s+1)[\lambda][\lambda']W(12s\lambda;1\lambda')$$
$$(\mathcal{F}^\lambda(s)\otimes\mathcal{F}^{\dagger\lambda'}(s))^2_q \quad (14)$$

A detailed discussion of the above analyzing powers and their sensitivity to the isoscalar amplitudes will be presented. Since linearly polarized photon beams are already available at the Duke Free Electron Laser Laboratory [4–6] and aligned deuterons are expected to be present in molecular environments [12], we believe that it is possible to carry out the above measurements.

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