Angular distribution in $d(\vec{\gamma}, n)p$ close to astrophysical energies

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Recent experimental studies [1–6] at the Duke Free Electron Laser Laboratory use 100% linearly polarized laser beams from HIGS to study deuteron photodisintegration close to astrophysically relevant range of energies, to sharpen [7] the predictions of the Big Bang Nucleosynthesis (BBN) and also of stellar evolution.

We may recall that model calculations have led to traditional forms referred to as Rustgi parametrization [8] and Partovi parametrization [9] for the differential cross section with unpolarized photons. Our model independent approach[10] for $d(\vec{\gamma}, n)p$ (with 100% linearly polarized photons) led to the following expression

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

where as the form used by Schreiber et al [1] following Weller et al [11] is

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

which does not take into consideration the interference between the isovector $E1$ and isoscalar $M1$ amplitudes that lead to the $\cos\theta$ term in (1). Sawatzky [4] and Blackston [5] have presented their data as empirical expansions in terms of associate Legendre polynomials going up to order l =4, in which a $\cos\theta$ term can occur both in $l = 1$ and $l = 3$.

It is therefore of interest to generalize and present the theoretical cross section formula based on our model independent approach in a form similar to the empirical expansion used in [4] and [5] and identify the expansion coefficients in terms of all the allowed multipole amplitudes which are shown in Table 1.

TABLE I: All the allowed multipole amplitudes

Continuum eigen state	Notation used for the Multipoles
$^1S_0, I = 1$	$M1_v$
$^3S_1, I = 0$	$M1_s, E2_s$
$^1P_1, I = 0$	$E1_s^{j=0}, M2_s$
$^3P_0, I = 1$	$E1_v^{j=0}$
$^3P_1, I = 1$	$E1_v^{j=1}, M2_v$
$^3P_2, I = 1$	$E1_v^{j=2}, M2_v, E3_v$

Using the same notations as in [10], the relevant irreducible tensor amplitudes

$$\mathcal{F}^\lambda_\nu(s) = \frac{1}{\sqrt{2}}(\mathcal{F}^\lambda_\nu(s, +1) + \mathcal{F}^\lambda_\nu(s, -1)) \quad (3)$$

for $d(\vec{\gamma}, n)p$ may be expressed in a form convenient for our present purpose as

$$\mathcal{F}^\lambda_\nu(s) = \sum_{L,I,l,j}[G_\alpha H_\alpha Y_{lm_l}(\theta, \phi)] \quad (4)$$

where $(-1)^{l+s+I}$ must be -1 and

$$G_\alpha = (-1)^j[L][j]^2[s]^{-1}W(L1ls; j\lambda) \quad (5)$$

denote geometric factors,

$$H_\alpha = iE_\alpha\pi_eC_- + M_\alpha\pi_oC_+ \quad (6)$$

where E_α and M_α denote respectively the electric and magnetic multipole amplitudes $F^{Ij}_{ls;L}$ with α denoting collectively I, j, l, s, L

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and π_e, π_o are projection operators

$$\pi_{e/o} = (-i)^{L-l} \begin{cases} 1 & \text{if } (L-l) \text{ is even/odd} \\ 0 & \text{if } (L-l) \text{ is odd/even} \end{cases}$$

while $C_{\mp} = C(lL\lambda; m_l - 1\nu) \mp C(lL\lambda; m_l 1\nu)$. Thus we may express

$$\frac{d\sigma}{d\Omega} = \frac{1}{6} \sum_s (2s+1) \sum_{\lambda,\nu} |\mathcal{F}_\nu^\lambda(s)|^2$$

$$= \frac{1}{6} \sum_{\lambda,\nu,\alpha',\alpha''} \delta_{ss'}(2s+1) \sum_{\lambda,\nu,\alpha',\alpha''} G_{\alpha'} G_{\alpha''} H_{\alpha'} H^*_{\alpha''} Y_{l'm'_l}(\theta,\phi) Y^*_{l''m''_l}(\theta,\phi) \quad (7)$$

where the product of the two spherical harmonics may be expressed as a linear combination. This leads to

$$\frac{d\sigma}{d\Omega} = \sum_{l,m_l}^{l} A_{l,m_l} Y_{lm_l}(\theta,\phi). \quad (8)$$

where the coefficient A_{l,m_l} are bilinear in multipole amplitudes. Noting that $Y_{lm_l}(\theta,\phi) = \sqrt{\frac{4\pi}{2l+1}} P_l^{m_l}(\cos\theta) e^{im_l\phi}$, we can readily compare (8) with the empirical form used in [4, 5] where the experimental estimates are as shown in Table II for $\sqrt{3}A_{10}$.

TABLE II: Estimates of $\sqrt{3}A_{10}$ from experiment

E_γ MeV	$\sqrt{3}A_{10}$
3.5	0.2325 ± 0.0722
4	0.1084 ± 0.0391
6	0.0160 ± 0.0141
10	-0.1413 ± 0.0074
14	-0.056 ± 0.006
16	-0.077 ± 0.006

In terms of the multipole amplitudes listed in Table I, with $L = 1$, we have

$$\sqrt{3}A_{10} = 8\sqrt{6} Re\big[E1_v M1_s^*\big]. \quad (9)$$

where the experimental values in Table II shows at once that
1) $E1_v = 2E1_v^{j=0} + 3E1_v^{j=1} - 5E1_v^{j=2} \neq 0$
2) $M1_s \neq 0$ and that
3) the relative phase between these two can not be $\pi/2$. This is a significant result and it is of crucial interest to astrophysics that the interference between $M1_s$ and $E1_v$ amplitudes shows an increasing trend as E_γ decreases i.e., as we approach astrophysically relevant energies. Since it is known [12] that $E1_v$ increases with energy, the recent experimental results [4, 5] shown in Table II suggest that $M1_s$ must be increasing as we move towards astrophysical energies. Further details of these calculations and the results for A_{l,m_l} for $l > 1$ and including multipoles $L > 1$ will be presented.

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