Neutron polarization in disintegration of deuterons using 100% linearly polarized lasers

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The primordial abundance of deuterium [1] is of crucial importance and has been referred to as the baryometer in the context of the Big Bang Nucleosynthesis. As such considerable interest has been evinced in recent years [2, 3] in the study of deuteron photodisintegration using 100 % linearly polarized photons from the High Intensity Gamma-ray Source (HIGS) at the Duke free electron laser laboratory at near threshold and threshold energies of interest to astrophysics. Apart from the potential model calculations, the reaction has been studied theoretically using effective field theory and GDH sum rule. A model independent theoretical formalism [4] was advocated to analyze the observations taking into consideration the isoscalar amplitudes in addition to the dominant isovector amplitudes. A highlight of this formalism is that the reaction is described in terms of four irreducible tensor amplitudes $\mathcal{F}^{\lambda}_{\nu}(s)$ of rank $\lambda = |1-s|$ to $(1+s)$ leading to the final $n-p$ system in the singlet and triplet states $s = 0, 1$. At low energies of interest to astrophysics, $\mathcal{F}^{1}_{\nu}(0)$ is proportional to the isovector magnetic dipole amplitude $M1_v$ and $\mathcal{F}^{0}_{0}(1)$ is proportional to the isovector magnetic dipole amplitude $E1_v$, where as $\mathcal{F}^{1}_{\nu}(1)$ is proportional to the isoscalar magnetic dipole amplitude $M1_s$ and $\mathcal{F}^{2}_{\nu}(1)$ is proportional to the isoscalar electric quadrupole amplitude $E2_s$, if one assumes that the $E1_v$ amplitude is the same in all the three channels with conserved total angular momentum $j = 0, 1, 2$ i.e., if one assumes that $E1^{j=0}_v = E1^{j=1}_v = E1^{j=2}_v$. This assumption was not made in [4] and as such it was shown that an additional term proportional to $\cos\theta$ appears in the differential cross section for $d(\vec{\gamma}, n)p$. In a recent experimental study [3], the first experimental observation of the splitting of the three $E1^{j}_{v}$ amplitudes has been reported in the context of a study aimed at the GDH sum rule [5]. In view of this finding, we have recently discussed $\vec{d}(\vec{\gamma}, n)p$ with aligned deuterons [6].

The purpose of the present contribution is to examine neuteron polariztion in $d(\vec{\gamma}, \vec{n})p$, as this experiment can be carried out much more easily than $\vec{d}(\vec{\gamma}, n)p$. Using the same notations as in [4], the neutron polarization is given by

$$\mathbf{P} = Tr(\boldsymbol{\sigma}_n \mathbf{M}\mathbf{M}^{\dagger})/Tr(\mathbf{M}\mathbf{M}^{\dagger}) \quad (1)$$

where $\boldsymbol{\sigma}_n$ refers to neutron spin and the reaction matrix $\mathbf{M} = \mathbf{M}(+1) + \mathbf{M}(-1)$ may be expressed in terms of irreducible tensor amplitudes $\mathcal{F}^{\lambda}_{\nu}(s) = \mathcal{F}^{\lambda}_{\nu}(s, +1) + \mathcal{F}^{\lambda}_{\nu}(s, -1)$. These amplitudes may be reduced to the compact form

$$\mathcal{F}^{\lambda}_{\nu}(s) = \sum_{L=1}^{\infty}\sum_{l=0}^{\infty} G(Lls;\lambda) g^{\lambda}_{\nu}(lL), \quad (2)$$

where

$$G(Lls;\lambda) = \sum_{j=|l-s|}^{l+s} (-1)^j \frac{[L][j]^2}{[s]} W(L1ls;j\lambda) \sum_{I=0,1} \frac{[1-(-1)^{l+s+I}]}{2} F^{Ij}_{ls;L} \quad (3)$$

contains the complex valued partial wave multipole amplitudes $F^{Ij}_{ls;L}$ which depend on c.m. energy E, while

$$g^{\lambda}_{\nu}(lL) = i^{L-l} \sum_{\mu=+1,-1} (f^{\lambda}_{\nu}(l, L, \mu) \quad (4)$$

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governs completely the angular dependance in c.m. frame. Explicitly, $g^{\lambda}_{\nu}(lL)$ takes the form

$$g^{\lambda}_{\nu}(lL) = 4\pi\sqrt{2\pi}\, i\{[(-1)^{L-l} \\ C(l, L, \lambda; \nu+1, -1, \nu) Y_{l\,\nu+1}(\theta, \phi) \\ -C(l, L, \lambda; \nu-l, 1, \nu) \quad Y_{l\,\nu-1}(\theta, \phi)]\}. \quad (5)$$

Using standard Racah techniques and known properties of irreducible tensor operators [7], we reduce $\mathbf{MM}^{\dagger}$ to the form

$$\mathbf{MM}^{\dagger} = 3 \sum_{s's''\lambda'\lambda''L'L''l'l''} (-1)^{1-s''}[\lambda'][\lambda''] \\ G(l'L's';\lambda')\, G(l''L''s'';\lambda'')[s'']^{-1} \\ \sum_{K} W(s''\lambda''s'\lambda';1K) \\ (S^{K}(s's'') \cdot (g^{\lambda'}(l'L')) \otimes (g^{\dagger\lambda''}(l''L''))^{K}) \quad (6)$$

This is a convenient form out of which $Tr(\mathbf{MM}^{\dagger})$ gets contributions [8] only from

$$S^{0}_{0}(00) = \frac{1}{4}(1 - \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_p) \quad (7)$$

$$S^{0}_{0}(11) = \frac{1}{4}(3 + \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_p) \quad (8)$$

which are identical respectively to the well known singlet and triplet projection operators. On the other hand, the numerator in Eq. (1) derives contributions from the terms with $K = 1$ only. That corresponds to s', s'' taking values (0,1), (1,0) and (1,1). viz.,

$$S^{1}_{\nu}(01) = \frac{1}{2\sqrt{2}}(\boldsymbol{\sigma}_n \otimes \boldsymbol{\sigma}_p)^{1}_{\nu} - \frac{1}{4}(\boldsymbol{\sigma}_n - \boldsymbol{\sigma}_p)^{1}_{\nu} \quad (9)$$

$$S^{1}_{\nu}(10) = \frac{\sqrt{3}}{2\sqrt{2}}(\boldsymbol{\sigma}_n \otimes \boldsymbol{\sigma}_p)^{1}_{\nu} + \frac{\sqrt{3}}{4}(\boldsymbol{\sigma}_n - \boldsymbol{\sigma}_p)^{1}_{\nu} \quad (10)$$

$$S^{1}_{\nu}(11) = \frac{\sqrt{3}}{2\sqrt{2}}(\boldsymbol{\sigma}_n + \boldsymbol{\sigma}_p)^{1}_{\nu} \quad (11)$$

In view of the observations made in the first paragraph about the irreducible tensor amplitudes $\mathcal{F}^{\lambda}_{\nu}(s)$ and the recently reported [3] experimental observation of the splitting of the three $E1_v$ amplitudes, analysis of the results at low energies of astrophysical interest will be presented with the focus on the role of the isoscalar amplitudes.

Acknowledgements

One of us (SPS) is thankful to the Principal and Management of K.S.S.E.M. for their encouragement.

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