Spin entanglement in photodisintegration of deuteron

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Introduction

As the Big Bang Nucleosynthesis entered the precision era [1], attention has been focussed [2] on an accurate estimation of the primordial abundance of deuterium which has been referred to as the Cosmic Baryometer. In view of this, a series of experiments [3] are carried out at the Duke Free Electron Laser Laboratory using 100 % linearly polarized photons from the High Intensity Gamma-ray source (HIGS). These measurements have been analyzed using a theoretical formalism [4] where, the $M1_v$ multipole contribution which is dominant at thermal neutron energies and the $E1_v$ multipole contribution which is dominant at threshold photodisintegration, are calculated separately. Breit and Rustgi [5] were the first to propose a polarized target-beam fusion experiment to look for an isoscalar magnetic dipole amplitude denoted as $M1_s$. The model independent theoretical formalism [7] showed that the differential cross section in $d(\vec{\gamma}, n)p$ contains a term representing the interference between $E1_v$ and $M1_s$ amplitudes which is non-zero if the three $E1_v$ amplitudes are unequal. Blackston et al., [6] have recently reported the first experimental observation of the splitting of the three $E1_v$ amplitudes at 14 and 16 MeV. In view of these developments, it is important to continue the experimental studies more incively. For eg., it has been suggested recently [8] that aligned deuterons could be employed as targets.

The purpose of the present contribution is to
(i) examine the spin state of the final neutron-proton system using the model independent approach, taking into consideration the $M1_v$, $E1_v$ and $M1_s$ amplitudes and
(ii) discuss the nature of spin entanglement in the final state.

Model Independent Approach

Following [7] 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

$$\mathcal{F}^{\lambda}_{\nu}(s) = \sum_{\mu=\pm 1} \mathcal{F}^{\lambda}_{\nu}(s,\mu), \quad (2)$$

in terms of the irreducible tensor amplitudes $\mathcal{F}^{\lambda}_{\nu}(s,\mu)$ given by eq.(3) of [7] and $S^{\lambda}_{\nu}(s,1)$ are irreducible tensor operators of rank λ in hadron spin space [9] 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 spin state of the final n-p system is then given by the density matrix

$$\rho^f = \frac{1}{3}\mathbf{M}\mathbf{M}^{\dagger} \quad (3)$$

whose elements are given by

$$\rho^f_{m_n m_p; m_n' m_p'} = \sum_{q,t_n,t_p,\Lambda} (-1)^{-(m_p+m_n)} C(\frac{1}{2}\frac{1}{2}t_n; m_n' m_n - q_n) C(\frac{1}{2}\frac{1}{2}t_p; -m_p' m_p - q_p) C(t_n t_p \Lambda; -q_n - q_p q) \quad P^{\Lambda}_{q} \quad (4)$$

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where

$$P_q^\Lambda = \sum_{s,s',\lambda,\lambda'} (-1)^{\Lambda-s'}[s']^3[s][t_n][t_p] \left\{ \begin{array}{ccc} \frac{1}{2} & \frac{1}{2} & s' \\ \frac{1}{2} & \frac{1}{2} & s \\ t_n & t_p & \Lambda \end{array} \right\} W(s'\lambda's\lambda;1\Lambda) (\mathcal{F}^\lambda(s)\otimes\mathcal{F}^{\dagger\lambda'}(s'))_q^\Lambda[\lambda][\lambda'] \tag{5}$$

The final $n-p$ spin state is entangled.

Study of entanglement using covariance matrix formalism

The nature of spin entanglement may be examined using the covariance matrix formalism [10], as the covariance matrix elements are related to quantum correlations. The necessary and sufficient condition for entanglement in symmetric two qubit states has been investigated by Usha Devi et al., [10] which gives powerful entanglement criteria. Using the covariance matrices of locally measurable observables, a framework was designed [11] which decides whether a quantum state is separable or entangled. Quantification of entanglement in bipartite systems[12] has also been studied. In contrast to a recent analysis on a polarized spin $\frac{1}{2}$ beam and a polarized spin $\frac{1}{2}$ target [13], where the spin system is primafacie not entangled but a correlation of the II kind appears when a spin 1 projection of the system is taken, we have here an entangled system of two spin-$\frac{1}{2}$particles even when a spin-1 projection is not taken. A spin-1 projection of the entangled system is readily obtained here by considering only $s = s' = 1$ in eq.(5). A detailed discussion using the above considerations will be presented.

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