$N-N$ Spin Entanglement in Photodisintegration of Deuteron with 100% Linearly Polarized Photons

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Introduction

The study of polarization effects in reactions $d + \gamma \rightleftharpoons n + p$ play an important role both in Nuclear physics as well as Astrophysics. As the Big Bang Nucleosynthesis (BBN) entered the precision era [1] the need for precise knowledge of $d + \gamma \rightleftharpoons n + p$ was highlighted [2] and this led to a series of experiments [3] on the photodisintegration of deuterons using 100% linearly polarized photons at the Duke free electron laser laboratory. Several photonuclear reactions on polarized deuterons [4] are being studied at higher energies with linearly polarized photon beams at VEPP-3 electron storage ring. A major international program to carry out laboratory studies on astrophysical $r-$process [5] is also underway. The induced neutron spin polarization in $\gamma + d \to \vec{n} + p$ was discussed using effective field theory by [6–8] in view of the mismatch between theory [9] and experiment [10]. We may quote Young et. al. " Because the measured induced neutron polarization P_y' in $\gamma + d \to \vec{n} + p$ and theoretical calculation using the phenomenological potential model show a discrepancy [6, 9, 10], it is desirable to have a model independent calculation".

We present here a model independent approach for the spin polarization observables in photodisintegration of deuterons and study the N-N entanglement in final state.

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Theoretical formalism

Following [11, 12], the reaction matrix for $d + \gamma \to n + p$ 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

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

The spin density matrix in the final state is then given by

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

whose elements are given by

$$\rho^f = \sum_{s,s',\Lambda} (S^{\Lambda}(s,s') \cdot P^{\Lambda}(s,s')) \quad (4)$$

The irreducible spin operator $S^{\Lambda}_q(s,s')$ are expressible in terms of $\boldsymbol{\sigma}_n$ and $\boldsymbol{\sigma}_p$ as

$$S^0_0(0,0) = \frac{1}{4}(1 - \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_p) \quad (5)$$

$$S^0_0(1,1) = \frac{1}{4}(3 + \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_p) \quad (6)$$

$$S^1_{\nu}(0,1) = \frac{1}{2\sqrt{2}}(\boldsymbol{\sigma}_n \otimes \boldsymbol{\sigma}_p)^1_{\nu} - \frac{1}{4}(\boldsymbol{\sigma}_n - \boldsymbol{\sigma}_p)^1_{\nu} \quad (7)$$

$$S^1_{\nu}(1,0) = \frac{\sqrt{3}}{2\sqrt{2}}(\boldsymbol{\sigma}_n \otimes \boldsymbol{\sigma}_p)^1_{\nu} + \frac{\sqrt{3}}{4}(\boldsymbol{\sigma}_n - \boldsymbol{\sigma}_p)^1_{\nu} \quad (8)$$

$$S^1_\nu(1,1) = \frac{\sqrt{3}}{2\sqrt{2}}(\boldsymbol{\sigma}_n + \boldsymbol{\sigma}_p)^1_\nu \quad (9)$$

so that $P^0_0(0,0)$ measures the entanglement of the nucleons in the singlet state and $P^0_0(1,1)$ in the triplet state.

Explicitly, we have

$$P^\Lambda_q(s,s') = \frac{1}{6}\sum_{s,s',\lambda,\lambda',\Lambda} C(\frac{1}{2}\frac{1}{2}s; m_n m_p m_s) C(\frac{1}{2}\frac{1}{2}s'; m'_n m'_p m'_s)(-1)^{s'-1}[s'][\lambda][\lambda'] W(s'\lambda' s\lambda; 1\Lambda)(\mathcal{F}^\lambda(s) \otimes \mathcal{F}^{\dagger\lambda'}(s'))^\Lambda). \quad (10)$$

It is interesting to note that on solving eq.(4),(5) and eq.(8) we get

$$(\boldsymbol{\sigma}_n)^1_\nu = \frac{1}{\sqrt{3}}S^1_\nu(10) - \frac{1}{\sqrt{3}}S^1_\nu(01) + \frac{\sqrt{2}}{\sqrt{3}}S^1_\nu(11) \quad (11)$$

so that

$$(P_n)^1_\nu = \frac{1}{\sqrt{3}}P^1_\nu(10) - \frac{1}{\sqrt{3}}P^1_\nu(01) + \frac{\sqrt{2}}{\sqrt{3}}P^1_\nu(11) \quad (12)$$

gives the model independent result for neutron polarization in the final state. More details will be presented.

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