

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 $\gamma + d \rightarrow \vec{n} + p$ 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 $\gamma + d \rightarrow \vec{n} + p$ 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.

Theoretical formalism

Following [11, 12], 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

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

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 $S_q^\Lambda(s, s')$ are expressible in terms of σ_n and σ_p as

$$S_0^0(0, 0) = \frac{1}{4} (1 - \sigma_n \cdot \sigma_p) \quad (5)$$

$$S_0^0(1, 1) = \frac{1}{4} (3 + \sigma_n \cdot \sigma_p) \quad (6)$$

$$S_\nu^1(0, 1) = \frac{1}{2\sqrt{2}} (\sigma_n \otimes \sigma_p)_\nu^1 - \frac{1}{4} (\sigma_n - \sigma_p)_\nu^1 \quad (7)$$

$$S_\nu^1(1, 0) = \frac{\sqrt{3}}{2\sqrt{2}} (\sigma_n \otimes \sigma_p)_\nu^1 + \frac{\sqrt{3}}{4} (\sigma_n - \sigma_p)_\nu^1 \quad (8)$$

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$$S_\nu^1(1, 1) = \frac{\sqrt{3}}{2\sqrt{2}}(\sigma_n + \sigma_p)_\nu^1 \quad (9)$$

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

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

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

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

so that

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

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

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