Disintegration of the Deuteron by Reactor Antineutrinos

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Abstract. Cross sections calculated with a new standard reactor antineutrino spectral function are in good agreement with new experimental data.

1 Introduction

The problem of interaction of (anti)neutrinos with the deuteron attracts attention of physicists for several reasons. The (anti)neutrino experiments on the deuteron allow one to study the weak neutral-current effects, which are of principal importance. Besides, these reactions are closely related to astrophysical problems such as the star formation and the thermonuclear processes in the sun [1].

The reactions which can be studied in laboratory conditions are those due to the reactor low-energy electron antineutrinos [2, 3],

\[ \bar{\nu} + d \rightarrow \bar{\nu}' + np, \]  
\[ \bar{\nu} + d \rightarrow e^+ + 2n. \] (1)

We note, however, that such an experiment is a difficult one. For the first time, it was completed by the group of Reines [4]. Now the new experiment is being done at a light-water nuclear power plant [5] with the goal to achieve an accuracy of better than 10% in the measured cross sections. This is a serious challenge for a theorist to revise and improve the accuracy of the calculations.

The calculations dealing with reactions (1 a) and (1 b) depend essentially on the knowledge of the reactor antineutrino spectrum [2]. This spectrum is believed to be known at present with good accuracy [6–8]. The definition of the reactor antineutrino spectrum is discussed in detail by Frampton and Vogel [2] and by Ketov et al. [7]. Since the antineutrinos are essentially soft (\( E_\nu \lesssim 10 \) MeV), the reduced matrix element of the one-nucleon current can be reliably calculated with an accuracy of \( \approx 1\% \), by using the effective-range approximation for both the initial deuteron and the final \(^1S_0\) nucleon-nucleon scattering-state wave functions [9].

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Besides the one-nucleon current, the meson-exchange axial-currents also contribute non-negligibly \[3\], at the level of 3% to 5% of the impulse approximation. In contrast to the latter, the exchange-current effects should be calculated by using realistic nuclear wave functions. The recent calculations \[10\] of the effect for the reaction $\mu^- + d \rightarrow 2n + v_\mu$ show that the velocity-dependent part of the exchange operator, omitted earlier \[3\], tends to damp the size of the effect.

It is clear that only the total cross sections for reactions (1) will be measured in the near future. Here we calculate these cross sections using new spectral functions $n(v)$ from refs. \[6-8\] and we also take into account the recoil of the outgoing nucleon pair. We show that the uncertainty arising from the spectral function $n(v)$ is much larger than the error from neglecting the recoil correction, which we have found to be $\approx 1\%$.

In the second part of the paper, we present the general formalism we need in subsequent calculations. In Sects. 3 and 4, we apply the formalism to reactions (1 a) and (1 b), respectively. Our conclusions are given in Sect. 5 of the paper.

2 General Formalism

We start from the equation for the differential cross section,

$$d\sigma = \frac{1}{(2\pi)^5} \frac{1}{f_1^2} \sum_{l.s.p.} \left| \langle f | \hat{H}_w | i \rangle \right|^2 \delta^{(4)}(P_I - P_f) \, d\mathbf{k} \, dP_1 \, dP_2.$$  \hfill (2)

In Eq. (2), the sum is over nuclear and lepton spin projections (l.s.p.), the momentum $\mathbf{k}$ is that of the outgoing lepton, while the momenta $\mathbf{p}_i (i = 1, 2)$ belong to the outgoing nucleons, and the factor $f_1^2 = 2J_f + 1$ is obtained from averaging over the initial nuclear spin projections. The nuclear matrix element of the weak Hamiltonian is

$$\langle f | \hat{H}_w | i \rangle = -\frac{G_w}{\sqrt{2}} \int e^{i\mathbf{qx}} \, d\mathbf{x} \, \hat{J}_\mu(x) f_{iJ_iJ_i}(0),$$  \hfill (3)

with $\hat{J}_\mu$ the hadron and $j_\mu$ the lepton weak currents and $\mathbf{q} = \mathbf{v} - \mathbf{k}$, where $\mathbf{v}$ is the four-momentum of the incoming lepton. We have for both reactions

$$j_\mu = i\mathbf{v}(\gamma^\mu(1 + \gamma_5))\mathbf{v}(\mathbf{p}).$$  \hfill (4)

In Eq. (4), $\mathbf{v}(\mathbf{p})$ is the solution of the Dirac equation for a physical antiparticle with the momentum $\mathbf{p}$ and the energy $E_p = (\mathbf{p}^2 + m)^{1/2}$.

Applying the technique developed in ref. \[11\], we arrive at a Rosenbluth-type formula,

$$\frac{1}{f_1^2} \sum_{l.s.p.} \left| \langle f | \hat{H}_w | i \rangle \right|^2$$

$$= G_w^2 \frac{4\pi}{f_1^2} \left[ 1 - (\mathbf{v} \cdot \hat{\mathbf{q}})(\mathbf{v} \cdot \hat{\mathbf{q}}) \right] \sum_{J_i \geq 1} \left[ |\langle J_f \parallel \hat{T}_\text{mag} \parallel J_i \rangle|^2 + |\langle J_f \parallel \hat{T}_\text{el} \parallel J_i \rangle|^2 \right]$$

$$- 2\mathbf{q} \cdot (\mathbf{v} - \hat{\mathbf{q}}) \sum_{J_i \geq 1} \text{Im} \langle J_f \parallel \hat{T}_\text{mag} \parallel J_i \rangle \langle J_f \parallel \hat{T}_\text{el} \parallel J_i \rangle^*$$

$$+ \sum_{J_i \geq 1} \left[ (1 - (\mathbf{v} \cdot \hat{\mathbf{q}}) + 2(\mathbf{v} \cdot \hat{\mathbf{q}})(\mathbf{v} \cdot \hat{\mathbf{q}})) \left| \langle J_f \parallel \hat{T}_\text{el} \parallel J_i \rangle \right|^2 \right]$$