INELASTIC SCATTERING OF NEUTRINOS BY DEUTERONS

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The cross section for the reaction $\nu + d \to \nu + p + n$ for S and P states of the np pair is calculated. The weak interaction Hamiltonian with a neutral neutrino current was used.

THE problem of the possible existence of a neutral neutrino current in the Hamiltonian of the universal weak interaction and of the interaction of the neutrino with nucleons has been considered in a number of papers.[1-5] Experimentally, this process can be studied with a copious neutrino (or anti-neutrino) beam in the high energy region, using the accelerator method,[6] or in the low energy region, using nuclear reactions with low thresholds. In the latter case one may apply the experimental method of Reines and Cowan[7] or the method proposed recently by Mikaélyan and Spivak.[8] The high energy studies are mainly concerned with the muonic neutrino, whereas the electronic neutrino is used at low energies. Therefore, the investigation of the interaction of neutrinos with nuclei at low energies is of an interest independent of the accelerator experiments.

From this point of view, it is useful to have a theoretical estimate of the cross section for the disintegration of the deuteron in the inelastic scattering of a neutrino at low energies. The Hamiltonian for this process has the form

$$H = 2^{-1/2} G \left[\overline{\Psi}_N \gamma_\mu (1 + \lambda\gamma_5)(A\hat{I} + \beta\hat{\tau}_z)\Psi_N\right] \times \left[\overline{\Phi}_\nu \gamma_\mu (1+\gamma_5)\Phi_\nu\right];$$

$$A = {}^1/_2(\lambda_1 + \lambda_2), \qquad B = {}^1/_2(\lambda_1 - \lambda_2),$$

where $G\lambda_1$ and $G\lambda_2$ are the weak interaction constants for the coupling of the neutrino to the proton and neutron, respectively.

In the region of low energies (up to 15 Mev) of the incident neutrinos one can neglect the recoil energy and make use of the usual approximations of allowed and forbidden transitions as in β decay, which follow from a series expansion of the exponential in the matrix element. Then the total energy set free in the reaction is given by the relation

$$E_0 = E_{\nu'} - E_d = E_\nu + \mathbf{q}^2/M = E_\nu + E_k,$$

where $E_{\nu'}$ is the energy of the incoming, E_ν the energy of the outgoing neutrino, E_d is the deuteron binding energy, E_k and $\mathbf{q}$ are the energy and momentum of the relative motion of the np pair, and M is the nucleon mass. In the approximation of an allowed transition the final state of the np system will be $^1S_0$, and the differential cross section for the process $\nu' + d \to n + p + \nu$ is, in the effective range approximation, given by the formula

$$d\sigma = (\lambda_1 - \lambda_2)^2 d\sigma_1,$$

$$d\sigma_1 = G_V^2\lambda^2 \frac{2}{\pi^2} \lambda\!\!\!{}^-{}_e^2 \frac{\sqrt{E_d}}{1 - \sqrt{E_d M} r_T} \frac{(E_0 - E_k)^2 E_k^{1/2}}{(E_d + E_k)^2}$$

$$\times \frac{[a_s\sqrt{ME_d} - (1 - {}^1/_2 a_s r_s M E_k) - {}^1/_4 a_s (r_s + r_T) M (E_d + E_k)]^2}{a_s^2 M E_k + (1 - {}^1/_2 a_s r_s M E_k)^2} dE_k$$

$$= 10.3\cdot 10^{-22} G_V^2 \lambda^2 \frac{(E_0 - E_k)^2 E_k^{1/2}}{(4.36 + E_k)^2} \frac{(5.25 + 0.059E_k)^2}{7E_k + (1 + 0.368E_k)^2} dE_k,$$

$$G_V = G_V{}^\beta \left(\frac{m_e^2 c}{\hbar^3}\right),$$

where the masses and the energies are given in units of the electron mass m_e, and the lengths and effective ranges in units of the Compton wavelength of the electron $\lambda\!\!\!{}^-{}_e$; G_V is the dimensionless weak interaction constant ($G_V = 0.3 \times 10^{-11}$).

It is natural to assume that $\lambda = G_A/G_V$ has the same value as in β decay. The curves for the

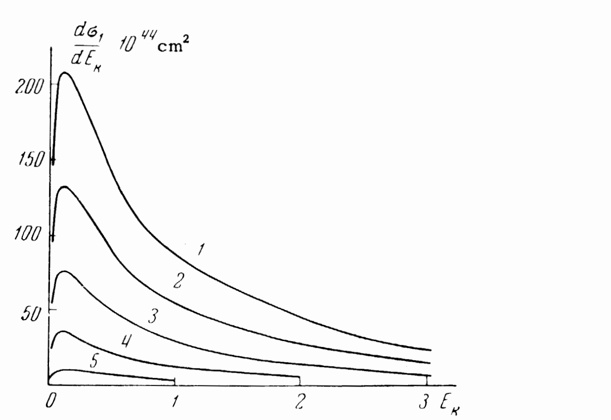

FIG. 1. Differential cross section $d\sigma_1/dE_k$ as a function of E_k for different values of E_0 (E_k and E_0 in units of m_e): curve 1: $E_0 = 25$, 2: 20, 3: 15, 4: 10, 5: 5.

Table I. Dependence of the cross section σ_1 on the total reaction energy E_0

E_0/m_e	$\sigma_1 \cdot 10^{44}$, cm^2	E_0/m_e	$\sigma_1 \cdot 10^{44}$, cm^2	E_0/m_e	$\sigma_1 \cdot 10^{44}$, cm^2
1	0.089	11	43.3	21	189
2	0.607	12	53.0	22	209
3	1.78	13	63.7	23	230
4	3.71	14	75.5	24	254
5	6.49	15	88.6	25	278
6	10.2	16	102	26	302
7	14.8	17	118	27	329
8	20.5	18	134	28	356
9	27.1	19	151	29	384
10	34.7	20	170	30	414

differential cross section $d\sigma_1/dE_k$ for E_0 = 5, 10, 15, 20, and 25 m_e, as calculated with these assumptions, are shown in Fig. 1. The total cross section $\sigma_1(E_0)$ is given in Table I. For energies $E_0 \gg 1$ the cross section σ_1 can be related to the cross section σ_β for the process $\nu + d \rightarrow 2n + e^+$[9] by the formula

$$\sigma_1 \approx {}^1/_2(\lambda_1 - \lambda_2)^2\sigma_\beta.$$

In the approximation under consideration the cross section has its largest value for $\lambda_1 = -\lambda_2$[2] and vanishes for $\lambda_1 = \lambda_2$. In the latter case one must consider the forbidden transition $^3S_1 \rightarrow {}^1P_1$, the cross section for which contains the factor $\lambda_1 + \lambda_2$. Then, neglecting the interaction in the final state, we obtain

$$d\sigma = (\lambda_1 + \lambda_2)^2 d\sigma_2,$$

$$d\sigma_2 = G_V^2\lambda^2 \frac{2}{\pi^2} \lambda\!\!\!^-{}_e^2 \frac{1}{3M} \frac{\sqrt{E_d}}{1-\sqrt{E_d M} r_T} \frac{(E_0 - E_k)^2 E_k^{3/2}}{(E_d + E_k)^2}$$

$$\times\left[(E_0 + E_d)^2 + (E_0 - E_k)^2 + \frac{2}{9}(E_0 + E_d)(E_0 - E_k)\right] dE_k.$$

The curves for the differential cross section $d\sigma_2/dE_k$ for E_0 = 15, 20, and 25 m_e are shown in Fig. 2. The values of the total cross section $\sigma_2(E_0)$ are given in Table II. For E_0 = 25 the cross section σ_2 amounts to 2% of σ_1. For a given constant G the cross sections σ_1 and σ_2 give the upper and lower limits for the possible cross sections for the inelastic scattering of neutrinos on the deuteron.

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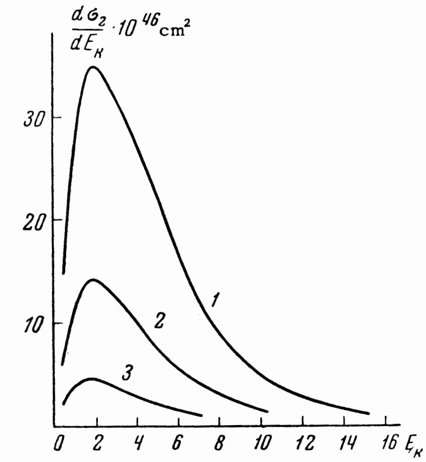

FIG. 2. The same for $d\sigma_2/dE_k$.

Table II. Dependence of the cross section σ_2 on the total reaction energy E_0

E_0/m_e	$\sigma_2 \cdot 10^{46}$, cm^2	E_0/m_e	$\sigma_2 \cdot 10^{46}$, cm^2	E_0/m_e	$\sigma_2 \cdot 10^{46}$, cm^2
1	$7 \cdot 10^{-5}$	11	4.10	21	91.1
2	$1.1 \cdot 10^{-3}$	12	7.02	22	112
3	0.011	13	10.2	23	137
4	0.0421	14	14.3	24	167
5	0.119	15	19.6	25	200
6	0.279	16	26.4	26	238
7	0.574	17	34.8	27	283
8	1.07	18	45.2	28	333
9	1.85	19	57.8	29	389
10	3.02	20	73.0	30	453

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