Neutrino oscillations and νe scattering

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The neutrino oscillations in the ν_e scattering processes are examined. It is shown that the neutrino oscillations in the Weinberg-Salam model effectively increase the cross section for $\nu_\mu e$ scattering and decrease the cross section for $\nu_e e$ scattering.

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Experimental evidence for the existence of a neutrino rest mass[1] and neutrino oscillations[2,3] has been reported recently. The general case of a neutrino mass matrix was examined in Refs. 4 and 5, with allowance for various mixing of the neutrino states, including the CP-violating effects. The purpose of this paper is to analyze the neutrino oscillations[6] in the experimental study of νe scattering.

The scattering of ν_e by electrons is determined by the superposition of charged and neutral currents, whereas the $\nu_i e$ scattering $(i \neq e)$ proceeds only via the neutral currents. At $\sin^2\theta_W \approx 1/4$ the cross section for scattering due to neutral currents is much smaller than that for $\nu_e e$ scattering. This difference, in particular, gives rise to the fact that the $\nu_\mu \Leftrightarrow \nu_e$ oscillations effectively increase the cross section for $\nu_\mu e$ scattering and decrease the cross section for $\nu_e e$ scattering. Because of this, a study of the νe scattering may be an effective way to look for neutrino oscillations.

We shall assume that only left-handed neutrinos, which satisfy the equation $\nu_L = \frac{1+\gamma_5}{2}\nu_L$, participate in the weak interactions. Let us denote by A_i the amplitude for scattering of the ith kind of neutrinos by an electron $(i = e, \mu, \tau, \ldots)$. These neutrinos ν_i, which do not have a specific mass, are superpositions of the diagonal states which we denote by ν_A (in general, when the mass Lagrangian contains both the Dirac and the Majorana masses $A = 1, \ldots, 2N$ for N kinds of charged leptons):

$$\nu_{iL} = \sum_A U_{iA}\,\nu_{AL}. \tag{1}$$

The amplitudes for the scattering processes of diagonal neutrinos by an electron $\nu_A e \to \nu_B e$ apparently are

$$A_{AB} = \sum_i U^+_{Bi}\,A_i\,U_{iA}\,. \tag{2}$$

Since the neutrinos cannot be recorded in the final states in the cases of interest to us, we must sum over the different $B = 1, ..., 2N$ in the calculation of the probability of the process. The original state of neutrinos in the scattering processes, however, is a coherent superposition of the diagonal states of ν_A, which is determined by the U matrix, by the masses m_A of the diagonal states, and by the distance from the source L. Let us assume that a neutrino of the ith kind is produced in the source. The original state, therefore, is characterized by a superposition

$$\sum_A U^*_{jA}\,\nu_A\, e^{-i\frac{m_A^2 L}{2E}} \equiv \sum_A C_{jA}\,\nu_A. \tag{3}$$

Henceforth the index j will denote the neutrinos produced in the source ($j = e,\mu,\tau,...$). The cross section for $\nu_j e$ scattering at a distance L from the source is

$$\sigma(\nu_j e) = \sum_{A,C} C_{jA} C^*_{jC}\,\sigma_{AC}\,, \tag{4}$$

where

$$\sigma_{AC} = \int \sum_B A_{AB} A^*_{CB}\, d\tau = \int \sum_i U^*_{iC}\,|A_i|^2 U_{iA}\, d\tau\,,$$

$\int d\tau$ is the integral over the phase volume. Finally, taking Eq. (3) into account, we obtain

$$\sigma(\nu_j e) = \sum_i w(j \to i)\,\sigma_i\,. \tag{5}$$

Here $w(j \to i)$ is the transition probability of a jth type neutrino to an ith type:

$$w(j \to i) = \Big|\sum_A U_{iA} U^*_{jA}\, e^{-i\frac{m_A^2 L}{2E}}\Big|^2, \tag{6}$$

and $\sigma_i = \int |A_i|^2 d\tau$.

For numerical estimates, we shall consider two types of neutrinos (ν_e, ν_μ), disregarding the oscillations $\nu_e \Leftrightarrow \nu_\tau$ and $\nu_\mu \Leftrightarrow \nu_\tau$. The cross section for scattering of ν_μ by an electron in this case is

$$\sigma(\nu_\mu e) = w(\mu \to e)\,\sigma^{(0)}(\nu_e e) + w(\mu \to \mu)\,\sigma^{(0)}(\nu_\mu e)\,, \tag{7}$$

where $\sigma^{(0)}(\nu_{e,\mu}e)$ is the cross section for scattering of neutrinos by an electron without oscillations. In the Weinberg-Salam model, for example, (for $E_\nu \gg m_e$)

$$\sigma(\nu_\mu e) = \left\{ w(\mu \to e)\left[(2\xi+1)^2 + \frac{1}{3}(2\xi)^2\right] + w(\mu \to \mu)\left[(2\xi-1)^2 + \frac{1}{3}(2\xi)^2\right]\right\}\frac{G^2 m_e E_\nu}{2\pi},$$

where $\xi = \sin^2\theta_W$. We note that in general $w(\mu \to e) + w(\mu \to \mu) \neq 1$, because of transitions to the sterile states.[5] In the purely Dirac or Majorona case the sum is equal to unity. Thus,

$$w(\mu \to e) = \sin^2 2\theta \sin^2 \frac{(m_1^2 - m_2^2)L}{4E}, \qquad (9)$$

$$w(\mu \to \mu) = 1 - w(\mu \to e),$$

where θ is the angle of mixing. Clearly, the maximum oscillations occur at $\theta = 45°$; moreover,

$$\frac{\sigma(\nu_\mu e)_{max}}{\sigma(\nu_\mu e)_{min}} = \frac{\sigma^{(o)}(\nu_e e)}{\sigma^{(o)}(\nu_\mu e)} \approx 6.1. \qquad (10)$$

for $\sin^2\theta_W = 0.23$.

If the oscillator multiplier is averaged for any reason (because of a broad neutrino spectrum or because of large dimensions of the source or the detector), then we can expect that

$$\sigma(\nu_\mu e) = \langle \sigma(\nu_\mu e) \rangle \approx 3.5\sigma^{(o)}(\nu_\mu e)$$

for $\theta = 45°$. In general, when there are oscillations between N types of neutrinos ($N > 2$), and also in the case of transitions to the sterile states, the effective enhancement factor of the averaged cross section for $\nu_\mu e$ scattering is smaller than that in the case considered above.

The effects discussed by us should also appear in the $\nu_e e$ cross section. In this case, however, an opposite effect is apparently produced, i.e., the $\sigma(\nu_e e)$ cross section is effectively reduced.

The oscillation amplitude of the cross section is smaller in the scattering of antineutrinos and the ratio $\sigma(\tilde{\nu}e)_{max}/\sigma(\tilde{\nu}e)_{min} \approx 3$ for $\sin^2\theta_W = 0.23$.

Thus, the oscillation effects $\nu_\mu \wedge \nu_e$ should manifest themselves more clearly in the $\nu_\mu e$ scattering processes. Since the known experimental data apparently do not allow us to draw an unambiguous conclusion whether or not there are such oscillations, an investigation of such processes is highly desirable.

We note that at high energy the oscillation effects $\tilde{\nu}_\mu \wedge \tilde{\nu}_e$ may lead to the inelastic scattering processes $\tilde{\nu}e \to$ hadrons (Ref. 7) in the $\tilde{\nu}_\mu$ beams: $\tilde{\nu}_\mu \to \tilde{\nu}_e, \tilde{\nu}_e e \to \pi^- \pi^0, 3\pi, KK, \ldots$.

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