Interaction of massive neutrinos with electrons

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We have investigated the process $\nu_H e \rightarrow \nu_L e$ in which heavy neutrinos interact with electrons and convert to massless neutrinos. In principle the process could be used to investigate primordial nonzero-mass neutrinos. However, the cross section is too low for the process to be useful with the currently available experimental techniques.

There is considerable evidence from a variety of analyses that the mass of the Universe is greater than the mass of the objects which are observable with current astronomical techniques. An understanding of the problem of the missing mass is fundamental to our appreciation of the evolution of the Universe. A recent comprehensive review of the problem has been given by Sciama.[1]

One of several possibilities is that the missing mass is due to unobserved nonzero-mass neutrinos. Lubimov and co-workers[2,3] have found evidence that neutrinos have a mass ~ 30 eV which is in the mass range which could resolve the missing-mass problem. Even though some recent investigations of the tritium β decay,[4,5] and analyses of the neutrinos associated with SN 1987A (Ref. 6), have obtained limits for the neutrino mass below the value obtained by Lubimov and co-workers, the possibility of a nonzero neutrino mass is still an open question.

The standard big-bang theory predicts the existence of a primordial cosmic neutrino background. If the neutrino is massless the general consensus seems to be that they no is massless the general consensus seems to be that they will be unobservable. Langacker, Leveille, and Sheiman[7] have shown that several proposals to investigate the primordial neutrinos are either incorrect, or the effect is immeasurably small. While they are still in their infancy many techniques are being studied and developed.[8] Although nonzero-mass primordial neutrinos are still enormously difficult to detect there are some physical effects which, at least in principle, may allow their detection. Clearly the observation of primordial neutrinos would be of great significance.

For a neutrino mass of ~ 30 eV it is possible in some theories of galaxy formation[9,10] that primordial neutrinos in our Galaxy will have densities of $\sim 10^7-10^8/\mathrm{cm}^3$; if the neutrino is massless the density will be $\sim 10^2/\mathrm{cm}^3$. In 1983 Irvine and Humphreys[11] suggested that 34-eV mass neutrinos could be detected by inverse β decay on tritium. A narrow peak is expected above the tritium end point but the background problems will be formidable. It should be noted that Weinberg[10] made a verbal suggestion of this possibility in 1980.

Since a direct observation of the primordial neutrinos is of great significance, it is important to analyze all physical processes which, even in principle, could allow the neutrinos to be detected. We have studied the process $\nu_H e \rightarrow \nu_L e$ in which heavy neutrinos interact with electrons and convert to massless neutrinos. This process gives energy transfers which are of the order of the heavy-neutrino mass and may allow detection in some recently proposed superconducting detectors.[12]

The Feynman diagram for the $\nu_H e \rightarrow \nu_L e$ process is given in Fig. 1. Within the framework of the standard model the process proceeds by the virtual exchange of $W^{\pm}$ bosons. We employ a simple model in which the electron neutrino is a linear combination of a heavy and light neutrino. Then

$$\nu = U_H \nu_H + U_L \nu_L \ . \tag{1}$$

In standard notation the amplitude S_{fi} for the process in the low-energy approximation is

$$S_{fi} = \frac{i2G}{\sqrt{2\pi}} U_L^* U_H \bar{\nu}_L(q')\gamma_\mu(1-\gamma_5)\nu_H(q,s) \times \int d^4x \, \exp[-i(q-q')x]\bar{\psi}_f(x)\gamma^\mu(1-\gamma_5)\psi_i(x) \ , \tag{2}$$

where ν and ψ represent neutrino and electron wave functions, respectively, and q and q' are the four-momenta of the heavy and light neutrino, respectively. The spin index s enters only in the heavy-neutrino wave function because the spin of the massless neutrino is not specified.

If we assume the initial electron is at rest, then in the plane-wave approximation the differential cross section $d\sigma/dT_e$ is given by

$$d\sigma/dT_e = 4|U_L^* U_H|^2 \frac{G^2 m_e}{2\pi|\mathbf{q}|^2}\epsilon_H \left[\epsilon_H + \frac{m_H^2}{2m_e}\right] , \tag{3}$$

where ϵ_H is the total energy of the massive neutrino and m_H is its mass. T_e is the kinetic energy of the final-state electron and m_e is the electron mass. If we use the re-

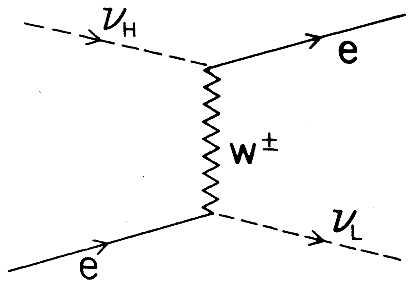

FIG. 1. A Feynman diagram for the process.

sults of Irvine and Humphreys the kinetic energy of the massive neutrinos is only $\sim 2\times 10^{-4}$ eV and we can replace ϵ_H with m_H and use $m_H \ll m_e$ to obtain

$$d\sigma/dT_e = 4|U_L^* U_H|^2 \frac{G^2 m_e m_H^2}{2\pi|\mathbf{q}|^2} . \tag{4}$$

In order to obtain an estimate for the process we set $|U_L^* U_H|^2 \sim 1$ and, integrating over the appropriate range of electron kinetic energy, the total cross section σ for the process is

$$\sigma = \frac{4G^2}{\pi}\frac{m_H^3}{|\mathbf{q}|} . \tag{5}$$

If we take the same values as Irvine and Humphreys then $m_H = 34$ eV and $v_H = 3.4\times 10^{-3}c$. This gives a value for σ of about 2×10^{-50} cm^2.

However, the effect of electron binding could give dramatic differences in the cross sections. We therefore calculated the cross section for the $\nu_H e \rightarrow \nu_L e$ process on bound electrons with free electrons in the final states. We employ the electron wave functions in the nonrelativistic approximation

$$\psi_j = e^{-i\epsilon_j t}\begin{bmatrix} \phi_j w_j \\ \frac{1}{2im_e}(\sigma\cdot\nabla)(\phi_j w_j) \end{bmatrix} , \tag{6}$$

where w_j are two-component spinors and ϕ_j are solutions of the Schrödinger equation for the electron in the Coulomb field. Index j indicates initial or final electron states i or f, respectively.

After summation over spins we obtain

$$\begin{aligned}\sum_{\text{spins}} |S_{fi}|^2 = 2G^2|U_L^* U_H|^2[2\pi\delta(\epsilon_i-\epsilon_f+\epsilon_H-\epsilon_L)]^2\frac{4}{m_e^2}\\ \times[2\epsilon_H\epsilon_L|\mathbf{A}|^2+(\mathbf{q}\cdot\mathbf{A})(\mathbf{q}'\cdot\mathbf{A}^*)\\ +(\mathbf{q}\cdot\mathbf{A}^*)(\mathbf{q}'\cdot\mathbf{A})\\ +i(\epsilon_L\mathbf{q}-\epsilon_H\mathbf{q}')\cdot(\mathbf{A}\times\mathbf{A}^*)] ,\end{aligned} \tag{7}$$

where

$$\mathbf{A} = 2m_e(\epsilon_i-\epsilon_f)\int \psi_f^* \mathbf{x}\psi_i d^3x . \tag{8}$$

By solving Eq. (8) one obtains[13]

$$\frac{d\sigma}{dT_e} = \frac{64G^2}{|\mathbf{q}|m_e}|U_L^* U_H|^2\left[(m_H-B-T_e)^2 m_H\left[\frac{B}{B+T_e}\right]^3 \times\frac{\exp(-4\xi\,\mathrm{arccot}\xi)}{1-\exp(-2\pi\xi)}\right] , \tag{9}$$

where $\xi^2 = B/T_e$ is the ratio of the electron binding energy B to the kinetic energy T_e of the final-state electron.

If we again take the same values for m_H and ϵ_H as Irvine and Humphreys and integrate Eq. (9) over the allowed T_e values, assuming a B of 13.6 eV, we obtain $\sigma = 6.9\times 10^{-56}$ cm^2.

Unfortunately this cross section is too small to allow the process to be used in the detection of primordial neutrinos with the currently available experimental techniques.

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