Limitation on right-handed currents in $SU_L(2) \otimes SU_R(2) \otimes U(1)$-symmetry model

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The cross section for the helicity-changing scattering of neutrinos by electrons is calculated. It is larger by more than five orders of magnitude than the cross section for the elastic scattering in the electromagnetic channel due to the magnetic moment of neutrinos. A model discussed here yields a new astrophysical limitation on the mixing angle (ζ) for the mixing of left-handed and right-handed W bosons: $\sin 2\zeta \lesssim 0.01$.

In the $SU_L(2) \otimes SU_R(2) \otimes U(1)$-symmetry model,[1] the diagram in Fig. 1(b) contributes along with the well-known vacuum magnetic moment,[2] μ_ν^{vac} [which corresponds to the diagram in Fig. 1(a)], to the helicity-changing elastic scattering of neutrinos by electrons, $\nu_{e_L} + e^- \rightarrow \nu_{e_R} + e^-$. The diagram in Fig. 1(b) describes a scattering through charged currents; it has previously been ignored. The corresponding matrix elements are[1)]

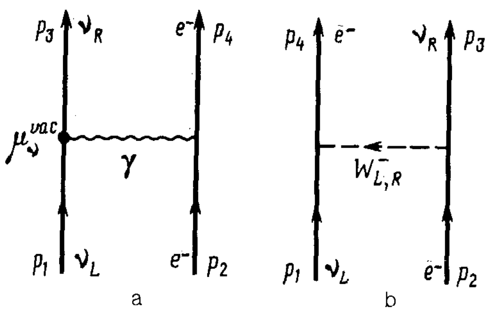

FIG. 1. Feynman diagrams for the helicity-changing elastic scattering $\nu_L + e^- \to \nu_R + e^-$. a—Electromagnetic scattering through the magnetic moment of the neutrino, μ_ν^{vac} and a virtual photon; b—contribution to νe scattering of charged currents with a mixed Green's function, $\langle W_\mu^{(L)} W_\nu^{(R)+} \rangle = \cos\zeta \times \sin\zeta \left[\langle W_{1\mu} W_{1\nu}^+ \rangle - \langle W_{2\mu} W_{2\nu}^+ \rangle \right]$ (ζ is the mixing angle in the model of Ref. 1).

$$M^{(a)}_{\nu_L \to \nu_R} = \frac{i\mu_\nu^{vac} e}{q^2} \bar{u}(p_4) \gamma^\mu u(p_2) \bar{\nu}_R(p_3) \sigma_{\mu\nu} q^\nu \nu_L(p_1), \tag{1}$$

$$M^{(b)}_{\nu_L \to \nu_R} = \frac{G_F(\epsilon^2 - 1)}{\sqrt{2}} (\bar{u}(p_4)(1 + \gamma_5) u(p_2))(\bar{\nu}_R(p_3) \nu_L(p_1)), \tag{2}$$

where the magnetic moment of the neutrino in the model of Ref. 1 is, according to Ref. 2,

$$\mu_\nu^{vac} = \mu_B \frac{G_F m_e^2 (\epsilon^2 - 1)}{2\pi^2 \sqrt{2}}. \tag{3}$$

Here $G_F \approx 10^{-5}/m_p^2$ is the Fermi constant, $m_{e,p}$ are the masses of the electron and the proton, $\mu_B = e/2m_e$ is the Bohr magneton, and e is the electric charge of an electron ($e^2 = \alpha = 137^{-1}$). These matrix elements have been written in the approximation of a point interaction. The derivation of expression (2) made use of a Fierz transformation; the circumstance that the contribution of the right-handed currents is described by the single parameter $\epsilon = (1 + \tan\zeta)/(1 - \tan\zeta)$ in the approximation of an infinitely large mass of the heavy W boson was taken into account (the experimental limitation is $m_{W_2} \gtrsim 470$ GeV; Ref. 3). This parameter is determined by the mixing angle of the left-handed and right-handed W bosons ($W_1 = W_L \cos\zeta + W_R \sin\zeta$).

When we take the interference of processes (1) and (2) into account, we find the total cross section for the scattering $\nu_L e^- \to \nu_R e^-$ to be

$$\sigma_{\nu_L \to \nu_R} = \frac{\sigma_0(\epsilon^2 - 1)^2}{32} \left[\left(\frac{\alpha}{\pi}\right)^2 \ln\left| \frac{q^2_{max}}{q^2_{min}} \right| + \frac{s - m_e^2}{6m_e^2} \left(1 - \left(\frac{m_e^2}{s}\right)^3\right) + \frac{\alpha}{\pi} \left(3 - 2\frac{m_e^2}{s} - \left(\frac{m_e^2}{s}\right)^2\right) \right], \tag{4}$$

where $\sigma_0 = 4G_F^2 m_e^2/\pi = 1.6\times10^{-44}$ cm^2, $s = m_e^2 + 2p_1p_2$, $|q^2_{max}| = (s - m_e^2)^2/s$, $q^2_{min} = -2m_e T_{min}$, and T_{min} is the minimum kinetic energy of the recoil electron.

The first term in square brackets in (4) corresponds to the diagram in Fig. 1(a), with magnetic moment (3). The second term, which may be considerably larger in absolute value, corresponds to the Born diagram in Fig. 1(b). The third term is an interference term. Specifically, if we assume $\ln|q^2_{max}/q^2_{min}| \approx 1$, in order to derive some estimates, we find the following result for neutrino energies $E \gtrsim 1$ MeV:

$$\sigma^{(b)}_{\nu_L\to\nu_R}/\sigma^{(a)}_{\nu_L\to\nu_R} = \frac{1}{6}\left(\frac{\pi}{\alpha}\right)^2 \frac{s - m_e^2}{m_e^2 \ln|q^2_{max}/q^2_{min}|} \gtrsim 1\times10^5, \tag{5}$$

This result is evidence that Born process (2) plays a governing role in the helicity flip. The interference is also important here: $\sigma^{(int)}_{\nu_L\to\nu_R}/\sigma^{(a)}_{\nu_L\to\nu_R} \gtrsim 10^2$. Consequently, following Nötzold's arguments,[4] we can easily find new astrophysical limitations on right-handed currents on the basis of a minimal model.[1]

The limitation

$$\mu_\nu^{vac} \lesssim 10^{-12}\mu_B \tag{6}$$

on the magnetic moment of a neutrino was derived in Ref. 4 on the basis of the maximum permissible value of the cross section for the scattering by nuclei Z in the interior of a collapsing star, in a process accompanied by a change in helicity ($\nu_L \to \nu_R$). That limitation can be reconciled with the neutrino fluxes detected at the earth from supernova SN1987A. The only point of importance for the derivation of limitation (6) is the very fact that a helicity-changing electromagnetic scattering by nuclei occurs, regardless of the model used to explain the magnetic moment of the neutrino. Since a scattering by electrons—a minor process in (1) and the basic process in (2) [see (5)]—should occur along with the scattering of nuclei in the interior of a collapsing star when right-handed currents are taken into account, we can derive a new limitation on the mixing angle in the minimal model by comparing the cross section for Born process (2), averaged over the dense medium, with the cross section for the scattering by nuclei which was used in Ref. 4,

$$\sigma_{\nu_L\to\nu_R}(E_1) \simeq 8\pi Z^2\alpha(\mu_\nu^{vac})^2 \ln(2E_1 r_D), \tag{7}$$

Specifically, we find from (2)

$$\langle \sigma^{(b)}_{\nu_L\to\nu_R}(E_1)\rangle = \frac{G_F^2(\epsilon^2-1)^2}{2n_0^{(e)}} \int \frac{d^3p_2}{(p_1p_2)} f_0^{(e)}(E_2) \int \frac{d^3p_4}{E_4} \frac{1-(2\pi)^3 f_0^{(e)}(E_4)/2}{|\vec{p}_1+\vec{p}_2-\vec{p}_4|}$$

$$\times (p_1p_3)(p_2p_4)\delta^{(1)}(E_1 - |\vec{p}_1+\vec{p}_2-\vec{p}_4| + E_2 - E_4), \tag{8}$$

where $n_0^{(e)} = \int d^3p f_0^{(e)}(E)$ is the electron density in an equilibrium medium with a Fermi distribution $f_0^{(e)}(E)$.

For an ultrarelativistic, degenerate ($p_{Fe} \gg m_e$) electron gas and for soft neutrinos, $E_1 \ll p_{Fe}$, the cross section found from (8),

$$\langle \sigma^{(b)}_{\nu_L\to\nu_R}(E_1)\rangle \approx \frac{6\pi^2 G_F^2 E_1^4}{5p_{Fe}^2}\sin^2 2\zeta \qquad (8')$$

does not exceed (7) if the following inequality holds:

$$\sin 2\zeta \lesssim 5\cdot 10^5 Z(\ln 2E_1 r_D)^{1/2}\left(\frac{m_p}{E_1}\right)\left(\frac{p_{Fe}}{E_1}\right)\frac{\mu_\nu^{vac}}{\mu_B}. \qquad (9)$$

Assuming an iron nucleus ($Z=26$) and energy $\langle E_1\rangle \approx 10$ MeV and the density $\rho \approx 10^{12}$ g/cm^3, characteristic of a collapsing star ($p_{Fe}\approx 40$ MeV, $r_D^{-1}\approx 3.5$ MeV), and using inequality (6), we find the limitation

$$\sin 2\zeta \lesssim 0{,}01, \qquad (9')$$

This limitation is more severe than the laboratory limitation[5] $\sin 2\zeta \lesssim 0.1$ or the astrophysical limitation[6] $\sin 2\zeta \lesssim 0.4\, E_1/p_{Fe}$.

With regard to laboratory limitations on right-handed currents related to Born process (2), we note that the second term in (4) is invariant under the substitution $\nu_L \to \tilde{\nu}_L$, $\nu_R \to \tilde{\nu}_R$, where the subscript L on the active antineutrino $\tilde{\nu}_L$ means that the clockwise polarized massless antineutrino is participating in an interaction of left-handed currents. Correspondingly, an R on a sterile antineutrino $\tilde{\nu}_R$ corresponds to the case of a counterclockwise polarized antineutrino which is not interacting with the matter in the standard way, except for channel (4), which vanishes in the absence of right-handed currents (i.e., with $\epsilon = 1$). For this reason, the Born term in (4) can also be used to describe the helicity-changing elastic scattering of antineutrinos by electrons ($\tilde{\nu}_L e^- \to \tilde{\nu}_R e^-$). Interestingly, it differs by only a common factor of $(\epsilon^2 - 1)/16$ from the cross section for the elastic scattering of antineutrinos by electrons without a change in helicity in the (V–A) model with charged currents[7] ($\tilde{\nu}_e e^- \to \tilde{\nu}_e e^-$). In other words, we have

$$\sigma(\tilde{\nu}_L e^- \to \tilde{\nu}_R e^-)/\sigma(\tilde{\nu}_L e^- \to \tilde{\nu}_R e^-) = \frac{1}{4}\sin^2 2\zeta, \qquad (6)$$

which states that it would be possible in principle to carry out an independent test of the minimal model in experiments with reactor antineutrinos. The existing laboratory limitations on the mixing angle,[5] $\sin 2\zeta \lesssim 0.1$, were obtained from an analysis of experimental data on muon decay. If it is found possible to measure the cross section within an error no worse than 0.25% in experiments on $\tilde{\nu}e^-$ scattering, then relation (6) will indeed make it possible to test the basic premises of the minimal model.[2)]

A completely similar situation should prevail in the model with a charged $SU_L(2)$ singlet, which is used to derive large magnetic moments.[5]

[1)] We are using a system of units with $\hbar = c = 1$. We are using the Feynman metric, $q^2 = q_\mu q^\mu = \omega^2 - k^2$; $\mu,\nu \neq 0,1,2,3$. We are using the standard representation of the Dirac matrices, with $\gamma_5 = \gamma_5^+ = i\gamma^0\gamma^1\gamma^2\gamma^3$. The left-handed bispinor is thus $\nu_L(p_1) = (1-\gamma_5)\nu(p_1)/2$.

[2)] Switching from the (V–A) model to the standard Weinberg–Salam model results in only insignificant changes in (6). For antineutrinos with energies above 1 MeV, these changes can be dealt with by the approximate replacement $1/4 \to 1/3$.

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