Change in the helicity of neutrinos in a dense plasma

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A change in the helicity of a Dirac neutrino in the course of an electromagnetic scattering by nuclei becomes possible in a dispersive medium in the symmetric electroweak model $SU_L(2) \otimes SU_R(2) \otimes U(1)$ (to which right-handed currents are added). This change in helicity is unrelated to the existence of a vacuum anomalous magnetic moment, but it is a more effective mechanism for the sterilization of soft neutrinos with energies $E \ll p_{F_e}$, where p_{F_e} is the Fermi momentum of the electrons of the medium. A new limitation on the mixing parameter of the left-handed and right-handed bosons $W_{L,R}$ is found on the basis of this model.

Nötzold[1] studied the elastic scattering of Dirac neutrinos by nuclei in a collapsing star and found an astrophysical limitation on the anomalous magnetic moment of neutrinos: $\mu_\nu \lesssim 10^{-12}\mu_B$, where $\mu_B = e/2m_e$ is the Bohr magneton.[1)] An intensification of this change in helicity at $\mu_\nu > 10^{-12}\mu_B$ would have led to the observation of some additional high-energy neutrinos (more than 100 of them, according to the estimates of Ref. 1) from supernova SN1987A, which would have been sterile as they left the neutrinosphere of the collapsar. In the magnetic field of the star and galaxy, right-handed neutrinos could have become left-handed again and could have been detected in experiments with the Kamiokande II detector. The absence of these signals leads to a limitation on the magnetic moment, as mentioned above.

In the present letter we suggest another sterilization mechanism, which is unrelated to a magnetic moment of neutrinos and which leads to further limitations on the parameters of the theory when the arguments of Ref. 1 are used.

As in Ref. 1 we consider the elastic νA scattering of a Dirac neutrino by a Coulomb center (an ion of charge Z) which is at rest in a plasma. In the model of the minimal symmetry $SU_L(2) \otimes SU_R(2) \otimes U(1)$, a Feynman diagram with a change in helicity (Fig. 1) is added (along with the interaction of the anomalous magnetic

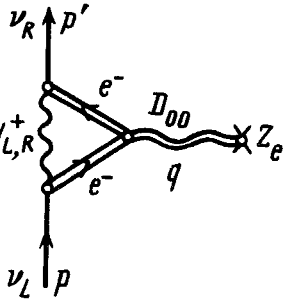

FIG. 1. Feynman diagram of the elastic scattering of a neutrino by a Coulomb center in a medium with a change in chirality (left $\rightleftharpoons$right). In the ultrarelativistic approximation ($m_\nu \approx 0$), the notation is the same for a change in helicity ($r = -1 \rightleftharpoons r = +1$). The double lines represent the electron and photon propagators in the medium.

moment with the electromagnetic field of the charged particles, which was studied in Refs. 1 and 3) to the known terms which are due to neutral currents and the polarization of the plasma which screens the cross section for νA scattering.[2] The contribution of this helicity-change diagram is determined by the matrix element (in the rest frame of the medium as a whole)

$$M_{fi} = \frac{\sin 2\zeta G_F \sqrt{2} Z r_D^2}{1 + (k r_D)^2} \left[\frac{k^2 B(\omega, k)}{\omega} \right]_{\omega = 0} \bar{\nu}_f(\mathbf{p}') \nu_i(\mathbf{p}) \frac{2\pi\delta(E - E')}{2\sqrt{EE'}} . \tag{1}$$

Here $G_F = \pi\alpha/\sqrt{2} M_W^2 \sin^2\theta_W \cong 10^{-5}/m_p^2$ is the Fermi constant; $\alpha = 137^{-1}$; θ_W is the Weinberg angle; M_p and M_W are the mass of the proton and that of the W boson; $q_\mu = p_\mu - p'_\mu$ is the momentum transfer ($\omega = E - E' = 0$, $k = 2E \sin\theta/2$). In the limit which we are using here, $m_{W_2} \to \infty$, the dominant contribution from the W_1 boson with a mixing $W_1 = \cos\zeta W_L + \sin\zeta W_R$, determined by the angle ζ (in this limit we have $m_{W_1} \approx M_W$), is taken into account. The Green's function of a plasmon, $D_{00} = 4\pi/(k^2 + r_D^{-2})$, is determined by the Debye length ($r_D \approx r_{D_i}$) in a plasma with degenerate electrons, $p_{F_e} \gg T$, where p_{F_e} is the Fermi momentum of the electrons, and T is the temperature of the medium. Finally, the new form factor $B(\omega, k)$ in (1), which arises at the electromagnetic vertex of the Dirac neutrino, $\Gamma_\mu^{(D)}(\omega, k)$, in the model under consideration here, is determined by a vector contribution which is not present in the case of Majorana neutrinos and which is equal to the conserved ($\Gamma_\mu q^\mu = 0$) quantity

$$\frac{G_F\sqrt{2}}{4\pi\alpha} \sin 2\zeta B(\omega, k) \left[q_\mu - \frac{q^2 \Omega_\mu}{(q\Omega)} \right] \tag{2}$$

in the point (Fermi) approximation, where Ω_μ is the 4-velocity of the medium as a whole. In vacuum, there could be no contribution of this type of the vertex Γ_μ, corresponding to the t-channel to a total spin $S = 0$ of the $\nu\tilde{\nu}$ pair ($B_{\rm vac} = 0$), specifically because of the conservation of the 4-current $J_\mu = B_{\rm vac} q_\mu$ (we have $J_\mu q^\mu = 0$ even off the mass shell, $q^2 \neq 0$). In a medium which is at rest as a whole ($\Omega_\mu = \delta_{\mu 0}$) the state limit

$$\lim_{\omega \to 0} \left[\frac{B(\omega, k) k^2}{\omega} \right] = 2 m_e A(0, k) \tag{3}$$

is determined by the magnetic form factor $A(\omega, k)$, which was calculated in Ref. 4. The appearance of a factor m_e—the rest mass of the electron—in (3) corresponds to a spin flip on the internal electron line of the Feynman diagram in the medium (Fig. 1). The quantity $A(0, k)$ given by

$$A(0,k) = -\frac{16\pi^2\alpha}{k}\int_0^\infty p\,dp[f^{(-)}(E_p) - f^{(+)}(E_p)]\ln\left|\frac{2p+k}{2p-k}\right|, \tag{4}$$

is determined by the equilibrium distribution functions of the electrons and positrons,

$$f^{(\mp)}(E_p) = \frac{2}{(2\pi)^3}[\exp[(E_p \mp \mu)/T] + 1]^{-1},$$

and in a degenerate electron gas is given by

$$A(0,k) \simeq -\frac{4\alpha}{\pi k}\left[\frac{kp_{F_e}}{2} + \left(\frac{p_{F_e}^2}{2} - \frac{k^2}{8}\right)\ln\left|\frac{2p_{F_e}+k}{2p_{F_e}-k}\right|\right]. \tag{4'}$$

Substituting (3) and (4′) into (1), we find the cross section in the WKB approximation ($k \ll p_{F_e}$)

$$\sigma = \frac{8}{\pi^3}\left[ZG_F\alpha\sin 2\zeta m_e\frac{p_{F_e}}{E}\right]^2\left[\ln|1+4(Er_D)^2| - \frac{4(Er_D)^2}{1+4(Er_D)^2}\right]. \tag{5}$$

Let us compare this cross section with that in the case of Schwinger scattering (the scattering of an anomalous magnetic moment by a Coulomb center), which was analyzed in[2)] Ref. 1:

$$\sigma = Z^2\mu_\nu^2\alpha\left[\ln|1+4(Er_D)^2| - \frac{4(Er_D)^2}{1+4(Er_D)^2}\right]. \tag{6}$$

In this model the magnetic moment is[5]

$$\mu_\nu = \frac{G_F e m_e \sin 2\zeta}{2\sqrt{2}\pi^2}, \qquad (\mu_\nu \lesssim 10^{-14}\mu_B,\ \sin 2\zeta \lesssim 0.1). \tag{7}$$

It is not difficult to see that the cross section for scattering accompanied by a change in helicity, (5), corresponds to an effective "magnetic moment"

$$\mu_{\text{eff}} = 8\sqrt{\pi}\frac{p_{F_e}}{E}\mu_\nu, \tag{8}$$

which is significantly larger than the small magnetic moment in (7).

Now following the arguments of Ref. 1 (see the discussion above), we should limit the "moment" in (8) to $\mu_{\text{eff}} \lesssim 10^{-12}\mu_B$. This limitation in turn imposes a limitation on the neutrino energy E:

$$E \gtrsim \frac{10\sqrt{2}}{\pi^{3/2}}\sin 2\zeta p_{F_e}.$$

This energy is always smaller than the energy of ultrarelativistic electrons, $E_{F_e} \simeq p_{F_e} (E \ll p_{F_e})$ which form left-handed neutrinos in the urka process. We thus find an astrophysical limitation on the mixing parameter in the model of minimal symmetry $SU_L(2) \otimes SU_R(2) \otimes U(1)$

$$\sin 2\zeta \lesssim \pi^{3/2}/10\sqrt{2} \sim 0.4 \,. \qquad (9)$$

This limitation is less stringent that that found in Ref. 6: $\sin 2\zeta \lesssim 0.1$. If, however, over the time spent by the left-handed neutrinos in diffusing through neutrinosphere sterile neutrinos form even from thermalized neutrinos[3)] (with an energy $E \ll p_{F_e}$), then the astrophysical limitation will be more stringent than (9) (correspondingly, by factor of $p_{F_e}/E \gg 1$). This limitation is a substantial supplement to the laboratory limitation on the mixing parameter.[6]

[1)]We are using a system of units with $\hbar = c = 1$ and the Feynman metric $q^2 = q_\mu q^\mu = \omega^2 - \mathbf{k}^2$; $\mu = 0, 1, 2, 3$.
[2)]The limit $E \gg r_D^{-1}$ with weak screening was used in Ref. 1.
[3)]Left-handed neutrinos lose their energy in νe collisions with degenerate electrons.

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