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Investigation of neutrino properties in the process $e^+e^- \to \nu\bar{\nu}\gamma$

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Assuming a nonvanishing neutrino magnetic moment μ we study τ-neutrino properties in the process $e^+e^- \to \nu\bar{\nu}\gamma$ from the single photon searches at colliders. We find that for a sufficiently large value of neutrino mass, i.e., $m > 2.1\times(10^{10}\mu/\mu_B)$ MeV (where $\mu_B = e/2m_e$ is the Bohr magneton), the interference between the diagrams with Z^0 and γ exchange becomes important and should be taken into account in future e^+e^- experiments. Some cosmological and astrophysical implications of this new heavy-neutrino scenario are briefly discussed.

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The search for the neutrino mass and magnetic moment is of great significance for the choice of the theory of elementary particles and for the understanding of phenomena such as supernova dynamics, stellar evolution, and the production of neutrinos by the Sun.

Well-known arguments on allowable cosmological energy density bound the total neutrino mass (for each stable flavor i) as follows:

$$\sum_i m(\nu_i) \leq 92 \text{ eV} \left[\frac{h}{100 \text{ km sec}^{-1}\text{ Mpc}^{-1}}\right]^2 ,$$

where h is the Hubble constant. Nevertheless, from the laboratory point of view the experimental limits [1] on neutrino masses are much wider:

$$m(\nu_e) < 17 \text{ eV}, \quad m(\nu_\mu) < 0.27 \text{ MeV}, \quad m(\nu_\tau) < 35 \text{ MeV} .$$

Moreover recent speculation on the existence of a heavier stable (17 keV) "Simpson" neutrino mass may be in disagreement with the above cosmological arguments.

Therefore it may be worth considering independent bounds on the neutrino mass and magnetic moment, disregarding the cosmological ones.

The recent interest about the question of the neutrino magnetic moment has been motivated by the possible explanation of the solar neutrino deficit [2] as well as the apparent correlation of solar activity with the solar neutrino flux [3]. In the standard theory of electroweak interactions, minimally extended to include massive Dirac neutrinos, the neutrino magnetic moment is extremely small:

$$\mu = \frac{3eG_F}{8\sqrt{2}\pi^2} m \simeq 3\times 10^{-19}\mu_B \left[\frac{m}{1 \text{ eV}}\right] . \tag{1}$$

Even for τ neutrinos this value is less than $10^{-11}\mu_B$. However, in extended models, for example, in the $SU(2)_L \otimes SU(2)_R \otimes U(1)$ theory, in which a small mixing of left and right W bosons occurs, the neutrino magnetic moment may reach the value $10^{-10}\mu_B$.

Modern laboratory bounds [1] on the neutrino magnetic moment are close to $10^{-10}\mu_B$; precisely, we have

$$\mu(\nu_e) < 4\times 10^{-10}\mu_B ,$$
$$\mu(\nu_\mu) < 1\times 10^{-9}\mu_B ,$$
$$\mu(\nu_\tau) < 4\times 10^{-6}\mu_B .$$

From cosmological and astrophysical considerations [4] the upper bound for light neutrinos of

$$\mu \lesssim 10^{-12}\mu_B \tag{2}$$

was derived. However, cosmological limits on the magnetic moment of heavy neutrinos ($m > 1$ MeV) are not

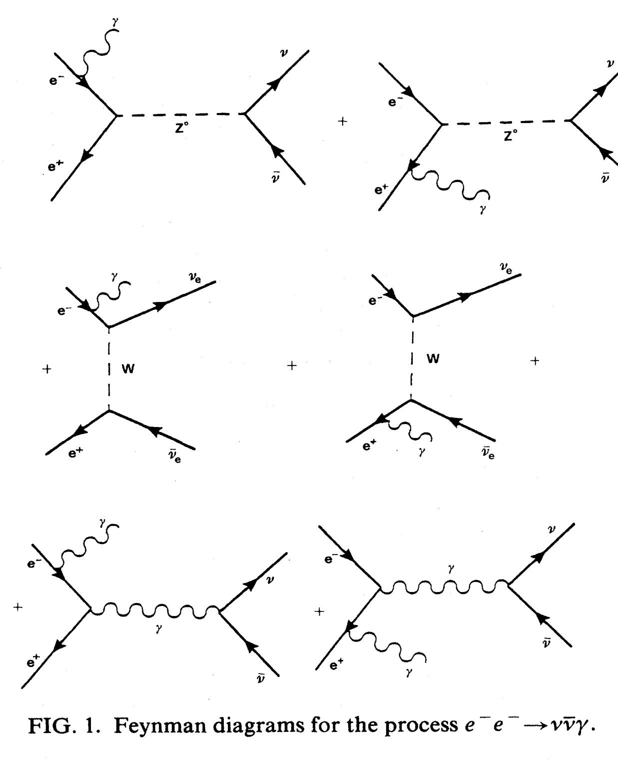

FIG. 1. Feynman diagrams for the process $e^-e^- \to \nu\bar{\nu}\gamma$.

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available. The cosmological bound (2) on the magnetic moment of light neutrinos can be evaded [5] by *ad hoc* values of different models.

Therefore, in general, it is worth investigating in a deeper way τ-neutrino properties [6] because their bounds are less restrictive. These neutrinos correspond to the more massive third generation of leptons and possibly possess the largest mass and the largest magnetic moment.

In this paper, assuming a nonvanishing neutrino magnetic moment, we study the τ-neutrino properties in the reaction $e^+e^-\to\nu\bar{\nu}\gamma$, which was suggested long ago [7,8] as a neutrino counting experiment. At energies $\sqrt{s}\le M_Z$ there are six Feynman diagrams (Fig. 1) corresponding to the process $e^+e^-\to\nu\bar{\nu}\gamma$ for a nonvanishing magnetic moment of the neutrino. Since the neutrino electromagnetic vertex is $i\mu\sigma^{\alpha\beta}q_\beta$, the differential cross section of this reaction in the limit $\sqrt{s}\gg m_e$ is given by

$$\frac{d\sigma}{dx\,dy}=\frac{\alpha}{6\pi^2}\frac{x^2y^2/4+(1-x/2)^2}{x(1-y^2)}\left\{G_F^2 s(1-x)\left[\frac{N(g_V^2+g_A^2)+2(g_V+g_A)[1-s(1-x)/M_Z^2-\Gamma^2/4M_Z^2]}{[1-s(1-x)/M_Z^2-\Gamma^2/4M_Z^2]^2+\Gamma^2/M_Z^2}+2\right]\right.$$
$$-6\sqrt{2\pi\alpha}G_F\left[m(\nu_e)\mu(\nu_e)+g_V\frac{[1-s(1-x)/M_Z^2-\Gamma/4M_Z^2]}{[1-s(1-x)/M_Z^2-\Gamma/4M_Z^2]^2+\Gamma^2/M_Z^2}\sum_{i=e,\mu,\tau}m(\nu_i)\mu(\nu_i)\right]$$
$$\left.+2\pi\alpha\sum_{i=e,\mu,\tau}\mu^2(\nu_i)\right\}, \tag{3}$$

where $x=2\omega_\gamma/\sqrt{s}$ (ω_γ being the photon energy), $y=\cos\theta_\gamma$, $g_V=2\sin^2\theta_W-\frac{1}{2}$, $g_A=-\frac{1}{2}$, Γ is the width of Z^0, G_F is the Fermi constant, and $\alpha=\frac{1}{137}$ is the fine structure constant.

Under the natural assumptions that both the magnetic moment and the mass of the τ neutrino are larger than the corresponding quantities of the other flavors (ν_e,ν_μ) and $m(\nu_\tau)>m_e$, expression (3) may be reduced in the limit of small energies $m_e\ll\sqrt{s}\ll M_Z$ to the form

$$\frac{d\sigma}{dx\,dy}=\frac{\alpha}{6\pi^2}\frac{x^2y^2/4+(1-x/2)^2}{x(1-y^2)}$$
$$\times\{G_F^2 s(1-x)[N(g_V^2+g_A^2)+2(g_V+g_A)+2]-6\sqrt{2\pi}\sqrt{\alpha}G_F g_V m(\nu_\tau)\mu(\nu_\tau)+2\pi\alpha\mu^2(\nu_\tau)\}\ . \tag{4}$$

We can see that in this limit the electromagnetic part (the last two terms) of the total cross section is energy independent. The diagonal terms of (3) which are proportional to G_F^2 and μ^2 reproduce the well-known expressions for the cross section [9]. But in expression (3) we got explicitly for the first time the additional term (proportional to $m\mu G_F$) corresponding to the interference between diagrams with Z^0 and γ exchange. Usually this interference term is neglected due to the smallness of the neutrino mass. However, as we can see from (4), the interference term becomes greater than the term $\sim\mu^2$ when

$$m(\nu_\tau)>2.1\times(10^{10}\mu/\mu_B)\ \mathrm{MeV}\ . \tag{5}$$

Comparing expressions (1) and (5) we find that, in the framework of the standard model and in the wide range of nonstandard values for μ, the interference term always dominates over the term $\sim\mu^2$. For τ neutrinos with a mass $m(\nu_\tau)=35$ MeV the corresponding value of the magnetic moment $\mu(\nu_\tau)$ is

$$\mu(\nu_\tau)<1.6\times10^{-9}\mu_B \tag{6}$$

below which the interference term in Eqs. (3) and (4) is the dominant one. Of course the contribution of the electromagnetic part to the total cross section which, we recall is energy independent, is rather small: $\sigma_\gamma\le10^{-38}$ cm^2 at $\mu(\nu_\tau)<4\times10^{-6}\mu_B$, where, following the limit in Eq. (5) and the above-mentioned experimental bound on $m(\nu_\tau)$, the interference term is negligible (here we used the experimental cutoff which was discussed in Ref. [10]). At $\mu=1.5\times10^{-9}\mu_B$ we have for the cross section the value $\sigma_\gamma\le10^{-45}$ cm^2, which gives at a luminosity $L=10^{32}$ cm^{-2} sec^{-1} only 3×10^{-6} events/year. However, the construction of accelerators of high luminosity ($L>10^{34}$ cm^{-2} sec^{-1}) [11] gives hope for the extraction of the electromagnetic contribution in the process $e^+e^-\to\nu\bar{\nu}\gamma$. Moreover we should note that if the pure weak diagrams give $\sigma\sim s$, then the electromagnetic part of the cross section is energy independent at $\sqrt{s}\ll M_Z$ and this property of the electromagnetic process allows us to investigate the reaction $e^+e^-\to\nu\bar{\nu}\gamma$ at accelerators of low energies, e.g., $\sqrt{s}\sim100$ MeV, and of large luminosities. If, in this case, the neutrino parameters obey condition (5), then on an experimental basis it would be possible, using formula (4), to restrict the product $m\mu$ of the neutrino parameters which define the main neutrino properties.

However, it must be noticed that the above estimates depend also on the explicit mechanism that is supposed to generate the neutrino magnetic moment [12]. Without entering into details, we only recall that, in general, the expression of μ contains an unknown scale factor Λ, which can be taken into account, in the first approximation, by an "effective" electromagnetic vertex proportional to the small number $1/\sqrt{G_F}\Lambda$. This would clearly imply modifications of the constraints (5), (6) and a decrease in the number of expected events. However, the exact quantification of such effects can only be given in the framework of a specific model of magnetic moment generation for neutrinos. Indeed, recent models lead to a large enhancement of the ratio μ_ν/m_ν and to a more general functional dependence of μ_ν on the effective scale factor. Thus, it is not possible to include in an exact way the role of Λ in our calculations, without resorting to a peculiar model. Our results can be therefore used by looking at μ_ν as a phenomenological neutrino moment (which already incorporates in an unknown way the scale factor Λ), disregarding its actual origin. In this connection, it can be argued that the experimental investigation of the electromagnetic part of cross section (4) may provide information on the size of the scale at which new physics beyond the standard model begins operating.

It is important also to pay attention to the investigation of the reaction $e^+e^-\to\nu\bar{\nu}\gamma$ in the region $\sqrt{s}>M_Z$ that would allow us to study the possibility of the existence of new species of heavy neutrinos with mass $m>M_Z/2$. Of course, evidence for such "ultraheavy" neutrinos cannot be found in standard experiments based on the analysis of the decay width of Z^0. On the contrary, the contribution of the interference term (between Z^0 and γ exchange diagrams) which is proportional to the mass of a heavy neutrino could be in principle detectable in the e^+e^- experiments at $\sqrt{s}>M_Z$.

The search for such heavy neutrinos is very important for cosmology. Any allowable ultraheavy neutrino ν_x, whose mass $m_x>M_Z/2$ overcomes the Zel'dovich-Lee-Weinberg limit [13], should belong to a fourth leptonic generation.[1] Their present number abundance per comoving volume $n(\nu)$ in unity of the entropy density [proportional to the blackbody radiation (BBR) photon number] may be derived by the Boltzmann equation. As long as the neutrino mass is much lighter than the decoupling temperature (for weak interaction $T_d\sim 1$ MeV), its surviving number density is proportional to the BBR photon number. Therefore their mass is bounded (by the critical density $\Omega=1$) within a few tens of eV. If, however, their mass is much larger than the decoupling temperature, their annihilation (due to the Boltzmann factor $e^{-m/kT}$ while in thermal equilibrium) will deplete their surviving number. Therefore x neutrino masses $m_x>2$ GeV are allowable [13]. However at much larger values ($m_x>M_Z/2$) the cross section (at the decoupling temperature) decreases as m_x^{-2}, due to the momentum dependence of the Z^0 propagator. In this region the relic number is proportional to m_x and the energy density increases as m_x^2, reaching the critical value $\Omega_{\nu_x}=1$ for a few TeV. Therefore we would expect that in the cosmological allowable region $(M_Z/2)<m_x<1$ TeV such very heavy neutrinos may exist and play a key role in dark matter and galaxy formation problems. Moreover, their relic presence in the solar core may have important consequences in the solar energy balance (weakly interacting massive particles). Finally, their clustering into degenerate configurations (x neutrino stars) may correspond to a new family of dark neutronlike (or Jupiterlike) stars, with characteristic masses

$$M_{\nu_x}=m_{\mathrm{Pl}}\left[\frac{m_{\mathrm{Pl}}}{m_{\nu_x}}\right]^2\simeq 2\times 10^{29}g\left[\frac{m_{\nu_x}}{100\ \mathrm{GeV}}\right]^{-2}. \quad (7)$$

Of course, these considerations only apply to massive neutrinos with the same couplings to the Z^0 as the conventional ν_e, ν_μ, ν_τ neutrinos. Particles with suppressed couplings could have larger relic densities.

The experiments at colliders in the range of small energies $\sqrt{s}<10$ MeV would be interesting also since in these experiments it could be possible to obtain the limit on the mass of τ-neutrino observing (or nonobserving) the threshold for ν_τ production.

[1]Similar bounds for stable and unstable mirror neutrinos by cosmological and astrophysical arguments have been given in Ref. [14].

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