Possible Evidence for a Radiatively Decaying Neutrino

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We consider nonstandard electroweak models which are able to explain the observed steplike structure in the cosmic background radiation at $\lambda = 1667 \pm 10$ Å as due to radiative decays of massive cosmic neutrinos. In the standard electroweak theory the corresponding radiative lifetime is several orders of magnitude longer than observed, because of the purely left-handed structure of the charged weak currents. We point out that in models which include also right-handed currents, the lifetime can naturally be short enough to account for the astrophysical observations.

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The possibility that the cosmic ultraviolet (uv) background radiation contains information on the decay of a big-bang relic massive neutrino has attracted attention for many years.[1-4] For a neutrino ν_2 with mass m_2 in the electronvolt region, the radiative decay into a lighter neutrino ν_1,

$$\nu_2 \to \nu_1 + \gamma, \tag{1}$$

would manifest itself as a monochromatic line at E_0 in the far-uv spectrum. Decays during the distant past would cause a redshift of this line, producing a steplike increase at $E \leqslant E_0$.

A first hint of such a step was reported[5] in 1978 and 1979: The diffuse high-latitude spectrum appeared to be flat between ~ 1300 and ~ 1525 Å with an intensity of 260 ± 40 (we use the units photons/s$\cdot$cm$^2\cdot$sr$\cdot$Å throughout), whereas in the range 1680–1800 Å, the mean flux level increased to ~ 600. However, since different detectors were used in the two wavelength bands, different systematic errors could have caused the apparent step.

Some support seems to come from rocket observations[6] with a telescope containing three uv broad-band photometers covering the pass bands 1450–1780 Å (peak sensitivity at 1590 Å), 1610–1950 Å (peak 1720 Å), and 1700–2420 Å (peak 2135 Å). The extragalactic diffuse radiation was estimated in the pass bands to be 550 ± 150, 900 ± 150, and $\lesssim 1300$, respectively.

Recently, more specific support comes from a compilation[7] of exposures at high galactic latitudes with the International Ultraviolet Explorer. A steplike signal of 5σ significance at $\lambda_0 = 1667 \pm 10$ Å is claimed in the otherwise flat continuum. This corresponds to a photon energy $E_0 = 7.4$ eV or a neutrino mass of $m_2 = 14.9$ eV, on the assumption that $m_1 = 0$ eV. Note that photons of this energy propagate freely through the intergalactic medium as well as through the interstellar medium. Thus the criticism by Kimble, Bowyer, and Jacobsen[3] about the limit of Stecker and Brown[2] does not apply. As these photons will not photoionize matter, they are also consistent with the existence of neutral hydrogen clouds in galactic halos.[8]

Of course the astrophysical signal does not fix the absolute values of m_1 and m_2, but just implies the relation $m_1^2 = m_2(m_2 - 2E_0)$.

The intensity change ΔI_0 at the step is[7] 454 ± 274, or within errors the same as in the previously quoted observations.[5,6] One can then deduce the lifetime of a hypothetical ν_2 using the relation[1,2]

$$\tau_{\text{obs}} = cn(\nu_2)/4\pi \Delta I_0 H_0 \lambda_0, \tag{2}$$

where $n(\nu_2)$ is the number density of ν_2's in the Universe today and the Hubble constant is $H_0 = h \times (100 \ \text{km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1})$, $0.5 \leqslant h \leqslant 1$. Assuming the standard cosmological abundance $n(\nu_2) \simeq 100 \ \text{cm}^{-3}$ for the decaying neutrinos, one finds that

$$2\times 10^{15} \ \text{yr} \lesssim \tau \lesssim 16\times 10^{15} \ \text{yr}. \tag{3}$$

Note that this result does not contradict the lower bound, $\tau \geqslant 3\times 10^{15}$ yr, derived[2,3] from other astrophysical data. What makes the result (3) remarkable is that the upper limit is, as discussed below, several orders of magnitude smaller than the lifetime one would expect[9] within the standard $SU(2)_L \otimes U(1)_Y$ theory of electroweak interactions.

The effective matrix element for the decay (1) compatible with gauge invariance is of the general form[10]

$$\mathcal{M} = \epsilon^\mu q^\nu \bar{\nu}_1(p_1)\sigma_{\mu\nu}(a + b\gamma_5)\nu_2(p_2), \tag{4}$$

where ϵ^μ and $q^\nu = (p_2 - p_1)^\nu$ are the polarization vector and the momentum of the photon, respectively. From (4) one derives the width

$$\tau^{-1} = \Gamma(\nu_2 \to \nu_1\gamma) = \frac{1}{8\pi}\left(\frac{m_2^2 - m_1^2}{m_2}\right)^3 (|a|^2 + |b|^2)$$
$$= \pi^{-1}E_0^3(|a|^2 + |b|^2). \tag{5}$$

The decay (1) in the standard model proceeds (in the unitary gauge) through the two one-loop diagrams shown in Fig. 1. A full standard-model calculation[9] in the case of ν_1 and ν_2 being Dirac particles gives (under the assumption that $m_l << m_l, M_w$)

$$a_D = -\frac{eG_F}{8\sqrt{2}\pi^2}(m_1 + m_2)\sum_l U_{1l}U_{2l}^* F(r_l),$$
$$b_D = -\frac{eG_F}{8\sqrt{2}\pi^2}(m_2 - m_1)\sum_l U_{1l}U_{2l}^* F(r_l), \tag{6}$$

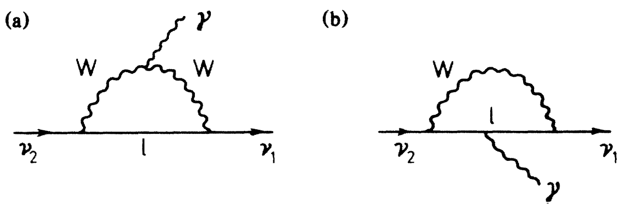

FIG. 1. The two unitary gauge diagrams contributing to the radiative decay $\nu_2 \to \nu_1 \gamma$ in the standard model.

where U is the leptonic mixing matrix and the sum runs over the charged leptons l. The $F(r_l)$ is a smooth function of $r_l = (m_l/M_W)^2$ defined in Ref. 9. For Majorana neutrinos one has $a_{\rm Maj}=0$, $b_{\rm Maj}=2b_D$, or $a_{\rm Maj}=2a_D$, $b_{\rm Maj}=0$, depending on whether the relative CP quantum number of ν_1 and ν_2 is $+1$ or -1. For $m_2 = 15$ eV and $m_1=0$ one obtains from Eqs. (5) and (6)

$$\tau_{\rm stand}^{-1} = \Gamma(\nu_2 \to \nu_1\gamma) = \frac{K\alpha G_{\rm F}^2}{128\pi^4} m_2^5 \left|\sum_l U_{1l} U_{2l}^* F(r_l)\right|^2$$
$$\approx K(3\times 10^{23}\ {\rm yr})^{-1} |\textstyle\sum_l U_{1l} U_{2l}^* F(r_l)|^2, \quad (7)$$

where $K=1$ (or 2) for Dirac (or Majorana) neutrinos. With the presently known three light charged leptons ($r_l << 1$), the leading term in the sum is canceled because of the unitarity of the matrix U, and the rate is thus additionally suppressed by the factor r_l^2. Nevertheless, even if this Glashow-Iliopoulos-Maiani cancellation were avoided by our adding new heavy generations[9] or making the unitarity sum incomplete (e.g., with an extra singlet ν), the natural lower bound the radiative lifetime of a 15-eV neutrino in the $SU(2)_L \otimes U(1)_Y$ gauge theory is $\tau \gtrsim 10^{23}$ yr.

We remark that if the neutrino masses are taken to be $m_2 = 54$ eV and $m_1 = 46$ eV, in strict agreement with the upper limit $\sum m_i \lesssim 100$ eV set by the energy density of the Universe, $\tau_{\rm stand}$ will be decreased by a factor of $\simeq 20$ for Dirac and CP-opposite Majorana neutrinos and increased by a factor of $\simeq 4$ for CP-equal Majorana neutrinos.

The essential feature of Eq. (7) is that the scale is (apart from $G_{\rm F}$) set solely by the mass of the neutrino. This is a direct consequence of the pure left-handed structure of $W^{\pm}$-lepton interactions, a built-in property of the standard model. Indeed, if the two $Wl\nu_i$ vertices in the decay amplitude (see Fig. 1) are both of the same chirality, only the momentum part of the internal charged-lepton propagator $(p_l - m_l)^{-1}$ contributes to the matrix element. All terms of the gauge-invariant form (4) are then proportional to the neutrino mass, and thus yield the result $\Gamma \propto m_2^5$.

If, on the other hand, the $Wl\nu$ vertex should contain a right-handed piece, also the mass part of the lepton propagator would contribute to the amplitude. This has a dramatic effect on the decay rate as we shall show in what follows.

There are two types of electroweak models where right-handed interactions occur: left-right-symmetric models[11] and mirror models.[12] In both kinds of models the leptonic charged weak current is of the general form

$$\mathscr{L} = -W_\mu^{\pm} \frac{g}{2\sqrt{2}} \sum_{i=1,2} \sum_l \bar\nu_i \gamma^\mu (V_{li} - A_{li}\gamma_5) l. \quad (8)$$

The parameters a and b appearing in Eq. (4) are then in leading order given by[10,13]

$$a = -\frac{eG_{\rm F}}{8\sqrt{2}\pi^2} \sum_l m_l f(r_l)(V_{l1}V_{l2}^* - A_{l1}A_{l2}^*),$$
$$b = -\frac{eG_{\rm F}}{8\sqrt{2}\pi^2} \sum_l m_l f(r_l)(V_{l1}A_{l2}^* - V_{l2}A_{l1}^*), \quad (9)$$

where $f(r_l)$ is a smooth function of the order of unity.[13] These leading terms obviously vanish in the standard model where $V_{li}/A_{li} = 1$. From Eqs. (5) and (9) we see that without such an accidental cancellation the natural scale of the width is $\Gamma \sim G_{\rm F}^2 m_l^2 m_2^3$.

Let us consider in some detail both types of models with right-handed interactions. In the left-right-symmetric model,[11] based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$, a right-handed (1,2,−1) neutrino ν_R can decay radiatively to a left-handed (2,1,−1) neutrino ν_L (or vice versa), provided that the vector bosons $W_R^{\pm}$ and $W_L^{\pm}$ mix (see Fig. 2). The lighter of the two vector-boson mass eigenstates, $W_1 \equiv \cos\zeta\, W_L + \sin\zeta\, W_R$, couples to leptons according to

$$\mathscr{L} = -W_1^\mu (g/\sqrt{2})(\cos\zeta\, \bar\nu_L \gamma_\mu l_L + \sin\zeta\, \bar\nu_R \gamma_\mu l_R) + {\rm H.c.}, \quad (10)$$

where ζ is the bosonic mixing angle. (We neglect here for clarity the possible intergenerational mixing and the mixing between ν_L and ν_R, which are inessential to our argument.) The contribution of the diagrams mediated by the heavier vector boson W_2 can be neglected since $M_{W_2} \geqslant 20 M_{W_1} \simeq 1.6$ TeV from the K_L-K_S mass difference and other low-energy constraints.[14]

To apply Eq. (9) we note that now

$$V_{l1} = A_{l1} = \cos\zeta, \quad V_{l2} = -A_{l2} = \sin\zeta. \quad (11)$$

The decay width for $\nu_R \to \nu_L\gamma$ (or $\nu_L \to \nu_R\gamma$) is then

$$\tau_{LR}^{-1} = \Gamma(\nu_R \to \nu_L\gamma) \approx (4\times 10^{13}\ {\rm yr})^{-1} [E_0/(7.4\ {\rm eV})]^3 [m_l/(1\ {\rm MeV})]^2 \sin^2 2\zeta, \quad (12)$$

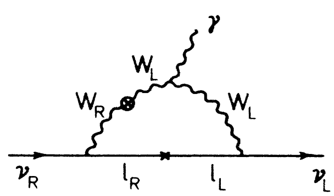

FIG. 2. The typical diagram for the decay $\nu_R \to \nu_L \gamma$ in the left-right-symmetric model.

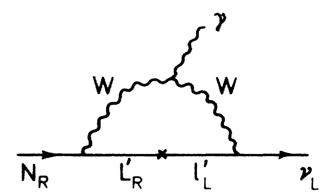

FIG. 3. The typical diagram for the decay $N_R \to \nu_L \gamma$ in the mirror model. The primes indicate weak eigenstates of fermions.

independently of the neutrino masses for fixed E_0.

The lifetime one deduces from astrophysical observations depends on the present cosmological density $n(\nu_R)$ of the ν_R. This may be smaller than the density of the standard left-handed neutrinos, $n(\nu_L) \simeq 100$ cm^{-3}, since the more weakly interacting right-handed neutrinos decouple from the thermal equilibrium earlier.[15] If they decoupled after the muons were annihilated they would today be as abundant as the ν_L. In this case (and always for the decay $\nu_L \to \nu_R \gamma$) we obtain, by comparing Eqs. (3) and (12), the condition

$$0.05 \leq [m_l/(1\ \text{MeV})]\sin 2\zeta \leq 0.14, \tag{13}$$

which gives us a prediction for the value of the left-right mixing angle ζ. If ν_R belongs to the electron family, Eq. (13) requires that $\zeta \gtrsim 0.05$. This possibility is clearly excluded since the experimental upper bound from the K_L-K_S mass difference is $\zeta_{\text{expt}} \lesssim 0.004$.[14] On the other hand, the ν_R could still be a member of the μ or τ family; then Eq. (13) predicts that $\zeta = (2\text{–}7)\times 10^{-4}$ or $\zeta = (1\text{–}4)\times 10^{-5}$, respectively.

If the ν_R density $n(\nu_R)$ is less than the standard neutrino density $n(\nu_L)$, the value of τ_{obs} in Eq. (3) is reduced by a factor $n(\nu_R)/n(\nu_L)$ and correspondingly larger values of the angle ζ are required.

In the mirror model[12] the situation is favorable in the following two respects. Firstly, the cosmological density of mirror neutrinos N_R is never suppressed since their neutral-current interactions have the same strength as those of the standard left-handed neutrinos. Secondly, charged mirror leptons, L, must be heavy, $20 \lesssim m_L \lesssim 250$ GeV, and therefore the radiative width increases. The relevant part of the weak Lagrangean is given by[16]

$$\mathscr{L} = -W^\mu (g/\sqrt{2})(-\sin\theta_l \bar{\nu}_L \gamma^\mu L_L + \cos\theta_l \bar{N}_R \gamma^\mu L_R) + \text{H.c.}, \tag{14}$$

where θ_l is the lL mixing angle parametrizing the mixing between the weak eigenstates of the charged lepton l and its mirror partner L. One typical diagram contributing to the decay $N_R \to \nu_L \gamma$ is shown in Fig. 3. From Eq. (14) one can read off the couplings

$$V_{l1} = A_{l1} = -\sin\theta_l, \quad V_{l2} = -A_{l2} = \cos\theta_l. \tag{15}$$

The width for $N_R \to \nu_L \gamma$ (or $\nu_L \to N_R \gamma$) is then (independently of the neutrino masses for fixed E_0)

$$\tau_{\text{mirror}}^{-1} = \Gamma(N_R \to \nu_L \gamma) \approx K(2\times 10^5\ \text{yr})^{-1}[E_0/(7.4\ \text{eV})]^3[m_L/(20\ \text{GeV})]^2 \sin^2 2\theta_l. \tag{16}$$

Comparing this to the lifetime, τ_{obs} [Eq. (3)], suggested by the astrophysical observations, we find for $20 \leq m_L \leq 250$ GeV

$$2\times 10^{-7} \lesssim \theta_l \lesssim 1\times 10^{-5}, \tag{17}$$

which is far below the present experimental upper limit,[16] $\theta_l \lesssim 0.1$. Let us note that values of the mixing angle in this range are suggested by some specific mirror models.[17]

The standard electroweak model cannot account for the short radiative lifetime, $\tau_{\text{obs}} \lesssim 10^{16}$ yr, of a massive neutrino, as suggested by astrophysical observations.[5-7] This is because of the purely left-handed structure of the weak interactions which makes the radiative width $\Gamma_{\text{rad}}(\nu_2 \to \nu_1 \gamma)$ proportional to $E_0^3 m_2^2$, where $E_0 = 7.4$ eV is the observed photon energy and m_2 is the mass of ν_2. Accordingly, in the standard model the radiative lifetime for neutrinos in the allowed range ($m_i \lesssim 50$ eV) is always larger than 10^{22} yr.

In nonstandard electroweak models which encompass also right-handed currents, Γ_{rad} is proportional to $E_0^3 m_l^2$, where l is a charged lepton. Consequently, the lifetime is shortened by the enormous factor $(m_l/m_2)^2$ compared to the standard model. This enables right-handed models to explain the astrophysical observation. In the left-right-symmetric models,[11] if the intergenerational mixing is neglected, the radiatively decaying neutrino ($\nu_2 = \nu_R$ or ν_L) could belong to the muon or tau family, but not to the electron family. In the mirror model,[12] the neutrino ($\nu_2 = N_R$ or ν_L) could belong to any lepton family. The predictions for the model parameters are given in Eqs. (13) and (17), respectively. The implied small mixing angles would make it very hard to see the effects of right-handed interactions of known particles in laboratory experiments. However, N_R would contribute to the total width of Z^0 by an equal amount as the standard neutrino.

We note that ν_R or N_R will, together with ν_{eL}, $\nu_{\mu L}$, and $\nu_{\tau L}$, saturate the famous cosmological bound of at most four light neutrinos, derived from the present helium abundance in the Universe. If this limit is taken seriously, the right-handed or mirror neutrinos of the other families should be much heavier or much more unstable than the one discussed here.

Although the astrophysical information used is controversial,[5] scanty,[6] or preliminary,[7] there is hope for very precise data in the near future, when the Berkeley Extreme Ultraviolet/Far Ultraviolet Shuttle Telescope will be launched on the Space Shuttle.[18]

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