Prospects for detecting photons produced by the decay of primordial neutrinos in the universe

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Neutrinos of finite mass surviving from the big bang may undergo observable radiative decay. Recent observations place lower limits on the neutrino lifetime. The effects of galactic opacity on the photons resulting from such decays are discussed.

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CONTENTS

1. INTRODUCTION

Last year experimental evidence was reported indicating that the electron-type neutrino has a nonzero rest mass. The following constraints on the ν_e mass were obtained[1,2] from an analysis of the form of the tritium β-spectrum: 14 eV $< m_{\nu_e} <$ 46 eV. Further evidence for a massive neutrino comes from the claim[3] that oscillations of reactor antineutrinos $\bar{\nu}_e$ have been observed.

Penzias and Wilson's 1965 discovery of cosmic microwave background radiation at a temperature $T \approx 3$ °K represented a direct proof of the big bang model for the universe. One implication of that model is that the universe should today contain primordial neutrinos with a number density $n_\nu \approx 150$ cm^{-3} for each kind of neutrino (the subject is discussed more fully in a recent review by Dolgov and Zel'dovich[4]). Can these surviving neutrinos be detected? That is the question we shall discuss in this brief review.

A neutrino of finite mass may break up into another neutrino and a photon. The estimates given in Sec. 2 show that neutrinos may have a lifetime much longer than the age of the universe,[1] $t_0 \approx H_0^{-1} \approx 1.8 \cdot 10^{10}$ yr. Hence the only way to observe neutrino decays would be to record the photons created in the decay of primordial neutrinos. De Rujula and Glashow[5] have considered the sources of these photons, namely decays of primordial neutrinos distributed isotropically throughout the universe and decays of neutrinos coming from the halo of our Galaxy. For some time satellite-borne telescopes have been recording the photon flux from the universe in the frequency range pertinent to searches for decays of primordial neutrinos. We shall describe the satellite data and the lower bounds they place on the neutrino lifetime—limits several orders of magnitude below conservative theoretical estimates. In the years to come, though, major progress may be expected in the field of space astronomy, which is so vital to searches for decaying primordial neutrinos, and there are prospects that the decay photons may eventually be detected.

Our review is organized as follows. In Sec. 2 we set forth the estimates for the neutrino lifetime[6-9] implied by various versions of the standard Glashow–Weinberg–Salam "electroweak" model and by the experimental constraint on the probability of $\mu \to e\gamma$ decay.[5] Section 3 discusses the flux of photons from decays of primordial neutrinos distributed isotropically in the universe,[5,10,11] as well as the transparency of our Galaxy to these photons and the limits on the neutrino lifetime that can be inferred from satellite data.[12-14] Decays of neutrinos from the galactic halo are considered in Sec. 4, and further restrictions on the neutrino lifetime are given.

Two recent investigations[15,16] examine the ionization of interstellar gas by photons formed through decays of primordial neutrinos. Rephaeli and Scalay[15] point out that the photons produced by decay of neutrinos with

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[1] The reason for this enviable longevity of the neutrino is made plain by the following simple estimate: $\tau_\nu \sim \tau_\mu (1/\alpha)\ (m_\mu/m_\nu)^5$, where $\tau_\mu = 2 \cdot 10^{-6}$ sec is the lifetime of the μ meson and $\alpha \approx 1/137$ is the fine structure constant. If we take $m_\nu = 100$ eV we would have $\tau_\nu \sim 10^{26}$ sec. We are indebted to Ya. B. Zel'dovich for this example.

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lifetimes of 10^{12}–10^{25} sec would strongly ionize neutral hydrogen, thereby shortening the era in the evolution of the universe when neutral hydrogen predominated. Observations of neutral hydrogen clouds in the vicinity of the Andromeda Nebula (the galaxy M31) set a lower limit of 10^{24} sec on the neutrino lifetime.[15] Sciama and Melott[16] suggest that the highly ionized carbon and silicon observed several kiloparsecs away from the plane of the galaxy may have been produced by a stream of photons of about 50-eV energy emitted as primordial neutrinos with a 10^{27} sec lifetime decayed.

2. ESTIMATES OF NEUTRINO LIFETIME

Three different estimates will be given in this section for the survival time of a neutrino. The first and most conservative estimate rests on the standard Glashow–Weinberg–Salam electroweak model. In the second estimate, the GIM mechanism (see below) is assumed not to operate in the lepton sector of the electroweak model. And the third estimate derives from the experimental limit on the $\mu \to e\gamma$ decay probability.

The starting point here will be the assumption that three finite-mass neutrinos ν_1, ν_2, ν_3 exist, from which the particles ν_e, ν_μ, ν_τ participating in weak interactions can be obtained by a unitary transformation. It will henceforth be convenient to regard ν_μ as sterile—a justifiable approximation, because in accelerator experiments ν_μ does not transform into other types of neutrinos with any appreciable probability. Then the heavier of the remaining neutrinos, ν_H, may decay into the lighter one, ν_L, and a photon. This decay may be described by diagrams such as those of Fig. 1, or by diagrams with an electron in an intermediate state.

Correct expressions for these diagrams have been published,[6-8] but the literature also contains erroneous calculations. In particular, De Rújula and Glashow[5] have used improper equations to estimate the lifetime of ν_H. We have performed detailed calculations[9] which confirm the earlier results.[6-8] The expression obtained in calculating the diagrams depicted in Fig. 1 has the form

$$M_{\nu_H \to \nu_L \gamma} = \frac{eg^2}{8} \frac{i}{16\pi^2 M_W^2} \cos\theta \cdot \sin\theta \times \bar{\nu}_H \left[(m_H + m_L)\,\sigma_{\alpha\beta} + (m_H - m_L)\,\sigma_{\alpha\beta}\gamma_5\right] \nu_L k_\beta \left(3 - \frac{3}{2}\frac{m_\tau^2}{M_W^2}\right) \varepsilon_\alpha. \tag{1}$$

Here θ is the mixing angle of ν_L, ν_H; m_H, m_L denote the mass of ν_H, ν_L; k_β, ε_α represents the photon momentum and polarization vector; and $\sigma_{\alpha\beta} = (\gamma_\alpha\gamma_\beta - \gamma_\beta\gamma_\alpha)/2$. The Lorentz structure of the expression (1) is fixed by two requirements: because of *CP* invariance the diagonal grams give a nonzero magnetic moment for the neutrino,

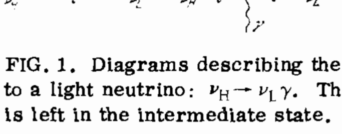

FIG. 1. Diagrams describing the decay of a heavy neutrino into a light neutrino: $\nu_H \to \nu_L\gamma$. The heaviest charged lepton τ is left in the intermediate state.

$$\mu_\nu = \frac{3eG_F}{16\sqrt{2}\,\pi^2} \cdot 2m_\nu. \tag{2}$$

According to the expression (2) the magnetic moment is independent of the neutrino mixing angles, and the values for the three neutrinos ν_1, ν_2, ν_3 differ only because of the difference in mass. Some idea of the value of amplitude should lack the $\sigma_{\alpha\beta}\gamma_5$ term (the electric dipole moment), and since the weak interaction is effected by left-hand currents, the vanishing of m_H or m_L will entail only the left component for the corresponding neutrino.

One small digression: the analogous Feynman dia- μ_ν is given by the following estimate: Spin reversal of an ultrarelativistic particle whose magnetic moment is equal to the nuclear magneton requires a field strength of 100 kilogauss over a distance of 1 meter. On the other hand, Eq. (2) implies that $\mu_\nu = 5 \cdot 10^{-7}\,(m_\nu/m_e)m_N$. So tiny a magnetic moment at first might seem incapable of having any physical consequences, but it has lately been found[17] that left neutrinos formed in nuclear reactions within supernovae should become depolarized by the magnetic fields of these stars, leaving the supernovae unpolarized.

In order to determine the lifetime of ν_H one must add to the expression (1) an analogous amplitude with an electron in an intermediate state. The main term in brackets in Eq. (1) will then cancel out, leaving only a term of order $(m^2 - m_e^2)/M_W^2$. [In the case of quarks the corresponding effect is called Glashow–Iliopoulos–Maiani (GIM) compensation; it is caused by the unitary property of the mixing matrix for quarks and leptons. See a recent review[18] for further details.]

The amplitude (1) yields the following expression for the decay probability[9]:

$$W_{\nu_H \to \nu_L \gamma} = \frac{9\alpha G_F^2}{2^{11}\pi^4} \frac{\sin^2 2\theta}{4} \frac{m_\tau^4}{M_W^4} m_H^5 \left(1 + \frac{m_L^2}{m_H^2}\right)\left(1 - \frac{m_L^2}{m_H^2}\right)^3. \tag{3}$$

If we suppose that $m_H \gg m_L$ and $\sin 2\theta = 1$, we will have for the neutrino lifetime

$$\tau_{\nu_H} = 2 \cdot 10^{34} \left(\frac{100\ \text{eV}}{m_H}\right)^5 \text{sec}. \tag{4}$$

For $m_H = 10$-100 eV the lifetime (4) far exceeds the age of the universe, so in principle it would be possible to record photons from the decay of primordial neutrinos. But the photon flux will be inversely proportional to $\tau_{\nu H}$. We have to see whether the lifetime τ_{ν_H} can be made shorter than the estimate (4), so as to increase the prospective photon flux.

In our second estimate the aim is to remove the suppression by the GIM mechanism in the lepton sector. The neutrino lifetime will then shorten by a factor $(M_W/m_\tau)^4 \approx 4 \cdot 10^6$. For this purpose it suffices to assume that a fourth generation of fermions exists and that the fourth charged lepton has a mass close to M_W, or that the three neutrinos are augmented by a fourth, isosinglet neutrino.[5] The lepton mixing matrix will then become rectangular, and in off-diagonal transitions between neutral leptons the constant term will not cancel out. Accordingly, if $m_H \gg m_L$ this estimate will give

$$\tau_{\nu_H} = 5 \cdot 10^{27} \left(\frac{100\ \mathrm{eV}}{m_H}\right)^5 \mathrm{sec}. \tag{5}$$

The third estimate for the lifetime of ν_H utilizes the experimental limit on the $\mu \to e\gamma$ decay probability. Writing the amplitude of the $\mu \to e\gamma$ transition in the form

$$M = \frac{e}{m} k_\alpha \bar{\mu} \sigma_{\alpha\beta} e a_\beta,$$

where m is the unknown mass, and adopting an analogous expression for $M_{\nu_H \to \nu_L \gamma}$, De Rújula and Glashow[5] obtained $\tau_{\nu_H} = (m_\mu/m_H)^3 \cdot \tau_\mu / B_{\mu \to e\gamma}$, where τ_μ is the lifetime of the μ meson and B is the relative $\mu \to e\gamma$ decay probability. Appealing to the experimental constraint $B_{\mu \to e\gamma} < 10^{-10}$, they concluded[5] that

$$\tau_{\nu_H} > 10^{22} \left(\frac{100\ \mathrm{eV}}{m_H}\right)^3 \mathrm{sec}. \tag{6}$$

The question of the neutrino mass is important for the discussion to follow. As mentioned in Sec. 2, experiment[1,2] provides the limits 14 eV $< m_{\nu_e} <$ 46 eV. But there is also a cosmological upper bound on the combined mass of the various kinds of neutrinos whose lifetime exceeds the age of the universe[4]:

$$\sum_i m_{\nu_i} < 40\ \mathrm{eV}. \tag{7}$$

This condition may be inferred from the limit $t_0 > 8 \times 10^9$ yr on the age of the universe, which in turn follows from nuclear chronology and the currently accepted value for the Hubble constant, $H_0 = 55$ km sec^{-1} $\times$ Mpc^{-1}. These two numbers enable a limit to be placed on $\Omega \equiv \rho/\rho_{cr}$, where ρ is the mean density of matter in the universe and $\rho_{cr} = 5 \cdot 10^{-30}$ g/cm^3. The explicit estimate (7) is obtained for the value $\Omega = 2$, which gives $t_0 = 10^{10}$ yr. If however $\Omega = 5$ and $t_0 = 8 \cdot 10^9$ yr the limit (7) will be replaced by

$$\sum_i m_{\nu_i} < 100\ \mathrm{eV}, \tag{8}$$

which is the constraint we shall henceforth adopt on the combined neutrino mass.

3. PHOTONS FROM DECAY OF PRIMORDIAL NEUTRINOS IN UNIVERSE

The flux density and spectrum of the photons that might arise from decays of primordial neutrinos in the universe and reach the earth are discussed by Stecker.[10] In the mass range here of interest, 10 eV $< m_H <$ 100 eV, primordial neutrinos would be nonrelativistic, and they would decay to produce monochromatic photons. Because of the general expansion, however, an observer on the earth will perceive photons with energies in the range $0 < \omega < \omega_0$, where ω_0 is the energy of the photon emitted in the $\nu_H \to \nu_L \gamma$ decay.

A straightforward estimate of the photon flux density yields the relation

$$n_\gamma\ [\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}\ \mathrm{sr}^{-1}] = \frac{n_{\nu_H}}{\tau_{\nu_H}} \int_0^{r_0} \frac{1}{4\pi r^2} r^2\, dr = \frac{n_{\nu_H} c}{4\pi H_0 \tau_{\nu_H}}; \tag{9}$$

here $n_{\nu_H} = 150$ cm^{-3} is the number density of primordial neutrinos and τ_{ν_H} is the ν_H lifetime. The integral in Eq. (9) diverges at its upper limit (in astronomy this effect is termed the Olbers paradox) and it should be cut off at the "horizon" radius $r_0 = c/H_0$, where H_0 is the Hubble constant and c is the velocity of the light.

A more accurate formula taking the expansion of the universe into account can be obtained as follows. Neutrinos which decayed in unit comoving volume during the time interval between t and $t + dt$ will today furnish the observer with the energy density

$$d\varepsilon = \omega_0 \frac{R(t)}{R(t_0)} n_{\nu_H} \frac{dt}{\tau_{\nu_H}}; \tag{10}$$

the factor $R(t)/R(t_0)$ here describes the redshift of the photons:

$$\frac{R(t)}{R(t_0)} = \frac{\omega}{\omega_0},$$

where ω denotes the energy of a photon detected at the present epoch. Transforming from the dt-photon distribution to the $d\omega$ energy spectrum and using the Einstein equation for the era when matter predominated, we obtain for the photon spectrum the expression

$$\frac{dn_\gamma}{d\omega} = \frac{n_{\nu_H} c}{4\pi H_0 \tau_{\nu_H}} \frac{\omega^{1/2}}{\omega_0^{3/2}} \left[\Omega + (1 - \Omega) \frac{\omega}{\omega_0}\right]^{-1/2}. \tag{11}$$

Introducing the appropriate numbers and setting $\Omega = 1$, we arrive at the following expression for the photon spectrum:

$$\frac{dn_\gamma}{d\omega} = \frac{2 \cdot 10^{29}}{\tau[\mathrm{sec}]} \frac{\omega^{1/2}}{\omega_0^{3/2}}. \tag{12}$$

Integrated over the entire spectrum, the expression (12) will agree with the estimate (9) to within a factor 2/3.

The spectrum (12) was obtained by De Rújula and Glashow,[5] but with a factor 10^{26} rather than 10^{29}. The error has been corrected by Stecker[10] and Kimble *et al.*[11]

We thereby have found an expression for the photons arriving from the universe. The next question is what the transparency of our Galaxy will be to these photons.

At energies below that of the Lyman-α line (ω_γ = 13.6 eV), the Galaxy is transparent, but above the line the absorption in the interstellar medium is so severe that the best constraint on τ_{ν_H} is given by the flux of photons which the general expansion has shifted below the $L\alpha$ line, even though the cosmic background radiation strengthens toward lower frequencies as well (see below). As for the intergalactic medium, it may be considered transparent throughout the frequency range of interest. (The problem of transparency has been discussed by Kimble *et al.*[11] in connection with the photon flux from primordial neutrinos.) Using satellite measurements of the background radiation[12] (whose source at ultraviolet frequencies is generally thought to be heated gas clouds):

$$\frac{dn_\gamma}{d\lambda} = 300 \pm 60\ \mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}\,Å^{-1}},\quad \lambda = 1350-1550\ \mathrm{Å}, \tag{13}$$

and applying Eq. (12), we find the following lower bounds on the neutrino lifetime:

$$\tau_{\nu_H} > 4\cdot 10^{23}\ \mathrm{sec},\quad \omega_\gamma = 8\ \mathrm{eV}, \tag{14}$$

$$\tau_{\nu_H} > 3\cdot 10^{22}\ \mathrm{sec},\quad \omega_\gamma = 50\ \mathrm{eV}. \tag{15}$$

For comparison, if the GIM suppression mechanism were neglected, Eq. (5) would give much longer lifetimes for ν_H:

$$\tau_{\nu_H} = 4\cdot 10^{30}\ \mathrm{sec},\ m_H = 50\ \mathrm{eV},\quad m_L = 42\ \mathrm{eV}. \tag{16}$$

$$\tau_{\nu_H} = 5\cdot 10^{27}\ \mathrm{sec},\ m_H = 100\ \mathrm{eV},\quad m_L \ll m_H. \tag{17}$$

Thus if the estimate (5) for the neutrino lifetime is not overstated, the level of background radiation in our Galaxy near energy $\omega_\gamma \approx 8$ eV would evidently preclude any chance of observing photons from neutrino decays in the universe.

Let us close this section with a few words on the transparency of interstellar space above the $L\alpha$ line. Dickey *et al.*[13] have inspected the interstellar hydrogen of our Galaxy in the direction toward more than 30 extragalactic sources, as evidenced by 21-cm line absorption. They find that the minimum column density of hydrogen, $(1.3\cdot 1.4)\cdot 10^{20}\ \mathrm{cm^{-2}}$, occurs at high galactic latitudes ($b > 80°$). Near the galactic equator the amount of hydrogen increases, but absorption data are lacking at low latitudes. If we suppose that directions exist in which the column density $N_H \approx 10^{19}\ \mathrm{cm^{-2}}$, then the absorption at energies $\omega_\gamma \approx 50$ eV would drop by up to 90%, and the satellite limits on the background radiation,[14]

$$\frac{dn}{d\omega} < 600\ \mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}\,eV^{-1}},\quad 20\ \mathrm{eV} < \omega_\gamma < 73\ \mathrm{eV}, \tag{18}$$

would allow the limit (15) to be raised by an order of magnitude.

4. PHOTON FLUX FROM GALACTIC NEUTRINO HALO

The observations tell us that gaseous hydrogen is revolving about our Galaxy at a velocity of 200-300 km/sec, and to all appearances the velocity of the gas is independent of its distance from the galactic nucleus. Rotating gas is in fact observed at distances from the nucleus ranging[19,20] from a few kiloparsecs to 500 kpc. The law

$$\rho(r) = \frac{A}{r^2},\quad A = 1.3\cdot 10^{75}\ \mathrm{eV/kpc} \tag{19}$$

may be adopted to fit the density of matter in the Galaxy, and the total mass exceeds the visible mass by about an order of magnitude. Szalay and Marx[21] have suggested that this hidden mass constitutes a neutrino halo around the Galaxy. A qualitative description of the structure of the neutrino halo has been given by Zel'dovich *et al.*[22,23]

Photons produced by the decay of neutrinos in the halo will reach the earth almost monochromatically, with a Doppler broadening $\Delta\lambda/\lambda \approx 10^{-3}$. This circumstance makes the search for ν_H decays in the galactic halo particularly promising.

For numerical estimates, let us begin with the case $\omega_\gamma < 13.6$ eV. In this part of the spectrum, interstellar matter produces no absorption, and the photon flux density at the earth will be

$$N_\gamma = \frac{10^{29}}{\tau_{\nu_H}[\mathrm{sec}]}\,\frac{30\ \mathrm{eV}}{m_H}\ \mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}}. \tag{20}$$

Measurements of the background[24] give

$$\frac{dn_\gamma}{d\lambda} \approx 600\,\mathrm{cm^{-2}\,sec^{-1}\,sr^{-1}\,Å^{-1}},\quad 1680\ \mathrm{Å} < \lambda < 1800\ \mathrm{Å}, \tag{21}$$

imposing on the neutrino lifetime τ_{ν_H} the constraint

$$\tau_{\nu_H} > 10^{24}\ \mathrm{sec},\ \omega_\gamma \approx 8\ \mathrm{eV},\quad m_H = 50\ \mathrm{eV},\quad m_L = 42\ \mathrm{eV}. \tag{22}$$

Stecker[10] remarks that the background of $\lambda \approx 1700$ Å photons [Eq. (21)] is approximately twice the $\lambda \approx 1400$ Å background [Eq. (13)], and suggests that this enhancement of the γ-ray photon flux may result from galactic ν_H decays. It would therefore be a very interesting project to measure the photon flux in this wavelength range with a telescope of better than 120-Å resolution.

We turn now to the flux of more energetic particles. Interstellar matter strongly absorbs photons of energy $\omega_\gamma > 13.6$ eV, due to the large cross section of the photoelectric effect (bound-free absorption). The cross section diminishes toward higher frequencies. Let us estimate the photon flux density at the maximum frequency of interest, $\omega_\gamma = m_H/2 = 50$ eV. Kimble *et al.*[11] assume that the hydrogen number density is $n_H = 0.1\ \mathrm{cm^{-3}}$ out to 100 pc from the earth, but that beyond the interstellar medium may be considered transparent (this assumption reflects the fact that, as indicated in Sec. 3, the hydrogen column density is $N_H \geqslant 1.3\cdot 10^{20}$ cm^{-2} in the Galaxy). For the flux density of photons incident on the earth, Kimble *et al.* obtain

$$n_\gamma = \frac{1}{4\pi m_H}\,\frac{1}{\tau_{\nu_H}}\,\frac{\rho E}{n_H\sigma(\omega)}\left(1 - e^{-n_H\sigma(\omega)\cdot 100\,\mathrm{pc}}\right), \tag{23}$$

where ρ_E denotes the density of the neutrino halo in the neighborhood of the earth, and $\sigma(\omega)$ is the cross section of the photoelectric effect. Cruddace *et al.*[25] have studied the photoelectric effect in the interstellar medium, and they obtain $\sigma(50\ \mathrm{eV}) = 10^{-19}\ \mathrm{cm^2}$ for the effective cross section at 50-eV frequency. Substituting the numbers into Eq. (23) and making use of the limit (18) on the background, we obtain

$$\tau_{\nu_H} > 10^{21}\ \mathrm{sec},\ m_H = 100\ \mathrm{eV},\quad m_L \ll m_H. \tag{24}$$

The limit can be sharpened in three ways: a) by replacing the upper bound (18) by an actual measurement of the background (it is worth noting that in the 80-100 eV energy range the same observers[14] did detect a background $d\eta/d\lambda = 4.0 \pm 1.3$ cm^{-2} sec^{-1} sr^{-1} eV^{-1}); b) by improving the telescope resolution (the line width from halo ν_H decays is ≈ 0.05 eV); c) by seeking directions of enhanced transparency in the Galaxy.

5. CONCLUSION

To analyze the cosmic electromagnetic radiation background in an effort to detect decays of primordial neutrinos represents a task of the highest importance. From an experimental point of view, a search for monochromatic photons produced by the decay of neutrinos in the galactic halo seems an appealing prospect. In the near future substantial progress may be anticipated[11] in the branch of space astronomy of interest to us in this review (particularly in the high-frequency region), and it may prove feasible to increase the limits on the neutrino lifetime by several orders of magnitude. If decays of primordial neutrinos should indeed be recorded, the discovery would be of immense significance both for cosmology—the source of the bulk of the mass in the universe would be revealed—and for elementary particle physics.

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