PHYSICAL REVIEW D VOLUME 46, NUMBER 6 15 SEPTEMBER 1992

Constraints on radiative decay of massive neutrinos

Boqi Wang

Department of Astronomy and Physics, and Center for Particle Astrophysics, University of California, Berkeley, California 94720

(Received 27 January 1992)

Recent β-decay experiments provide evidence for the existence of neutrinos with a mass of 17 keV. If they do exist, they should decay into lighter particles in order to avoid overclosing the Universe. Radiative decay may leave an imprint on the relic radiation from the big bang, and energy injection into the cosmic microwave background radiation should have observational consequences. In particular, the limits recently obtained on the y distortion of the blackbody spectrum of the cosmic microwave background provide stringent constraints on the radiative-decay properties of these neutrinos. We have found that the photon branching ratio has to be $B_\gamma \lesssim 10^{-5}$ for the neutrino lifetime $\tau \simeq 10^{10}-10^{11}$ s. For $\tau \gtrsim 10^{11}$ s, B_γ is constrained by the upper limits on the extragalactic background radiation at optical and UV wavelengths; the upper limit on B_γ decreases to about 10^{-6} at $\tau \simeq 10^{12}$ s.

PACS number(s): 98.80.Cq, 13.35.+s, 14.60.Gh, 98.70.Vc

Recent β-decay experiments have suggested the possible existence of neutrinos with a mass of about 17 keV [1]. If 17-keV neutrinos do exist, they should have significant implications for our understanding of the Universe. Their number density in the Universe is expected to be about the same as those of other known neutrinos such as electron neutrinos, provided that they decouple from the radiation when they are still relativistic. Thus, their total energy density in the present epoch would be about two orders of magnitude larger than the critical density of the Universe if 17-keV neutrinos created in the hot bath of radiation in the early Universe remained completely unchanged until the present epoch. This contradiction between the predicted and the observed densities of the Universe can be avoided only if 17-keV neutrinos decay into relativistic particles at early times, so that their energy density decreases rapidly as the Universe expands. Knowledge of the decay properties of 17-keV neutrinos is of fundamental importance in understanding the nature of these neutrinos. Here we consider the possibility of radiative decay, i.e., some of the decay products are photons. Radiation produced in the decay process may leave some imprint on the relic radiation from the big bang. Observations of this radiation therefore may constrain the photon-decay properties of 17-keV neutrinos. In particular, precise measurements of the blackbody spectrum of the cosmic microwave background radiation (CMBR) have been obtained recently by the Cosmic Background Explorer (COBE) satellite. The stringent limits on the deviation of the CMBR from a perfect blackbody spectrum can be used to constrain the photon branching ratio and the lifetime of 17-keV neutrinos.

The effects of energy injection into the CMBR depend on when this energy injection occurs. The results can be divided roughly into three different regimes [2]: (1) At redshift z larger than about 10^6, photon production due to thermal bremsstrahlung and double Compton scattering is so efficient that any energy injection will be redistributed into a new thermal equilibrium, and the resultant spectrum is still a perfect blackbody. (2) For $10^6 \gtrsim z \gtrsim 10^5$, the creation of photons is negligible, so the photon number is roughly conserved. However, Compton scattering of CMBR photons off electrons is rapid enough that the radiation field may reach an equilibrium in which the resultant spectrum is a Bose-Einstein distribution with a finite chemical potential. This so-called μ distortion results because the radiation spectrum is no longer a perfect blackbody but has a dimensionless chemical potential μ. (3) Finally at $z \lesssim 10^5$, the time scale of Compton scattering becomes longer than the age of the Universe, so the CMBR may not have time to adjust itself to bring about an equilibrium. Instead, Compton scattering results in a shift of the whole spectrum toward higher frequencies, and the so-called y distortion occurs. Here, we will concentrate on the y distortion resulting from the radiative decay of 17-keV neutrinos: As we shall see later, this is the regime in which the most interesting constraints can be extracted from CMBR observations.

The physics of the y distortion due to the radiative decay of 17-keV neutrinos can be easily understood; high-energy photons produced in the decay process heat up electrons via Compton scattering. The hot electrons then inversely Compton scatter the CMBR photons, resulting in an increase in the frequency of individual CMBR photons. A convenient parameter in calculations of the y distortion can be defined as $y=\int n_e \sigma_T (T_e/m_e) dt$, where n_e, T_e, and m_e are the number density, temperature, and mass of electrons, σ_T is the Thomson cross section, and $c=k=\hbar=1$. The spectral signature of the y distortion is uniquely determined by the y parameter; $\Delta T_{\rm CMBR}/T_{\rm CMBR} \simeq 2y$ on the Rayleigh-Jeans side of the spectrum and $\simeq 2\pi y \nu / T_{\rm CMBR}$ on the Wien side [3], where $\Delta T_{\rm CMBR}/T_{\rm CMBR}$ is the temperature perturbation of the CMBR due to Compton scattering, and ν is the frequency. The fractional energy change in the CMBR is simply proportional to y:

$$\Delta u / u = 4y \ , \tag{1}$$

where u is the photon energy density. The current limits for y, determined by recent COBE observations [4], is $y \lesssim 5\times10^{-4}$.

The standard method of calculating the y-distortion resulting from high-energy decay photons would be to solve the Fokker-Planck equation for the photon distribution function, or the simplified form first derived by Kompaneets [5]. This can be tedious and difficult because one has to solve the full partial differential equation. However, here we will adopt a simpler approach [6]. We assume that all the energy transferred from decay photons into electrons is deposited in the CMBR. This is a valid assumption because there are many orders of magnitude more CMBR photons than electrons, so the Compton cooling time for electrons is much shorter than the heating time. As a result, the electron temperature is relatively small compared with the photon energy, and all the energy it gained through Compton scattering off the decay photons is lost to the CMBR. This is also shown in the detailed numerical calculations [7]. We can calculate the energy loss of decay photons due to Compton scattering by following the evolution of individual decay photons. The above assumption then allows us to obtain the y parameter because the energy injection from the decay photons is proportional to y [Eq. (1)].

A decay photon suffers energy loss due to the expansion of the Universe and Compton scattering [6]:

$$d\epsilon=\frac{\epsilon}{(1+z)}d(1+z)-\frac{\epsilon^2}{m_e}n_e\sigma_T dt \ , \tag{2}$$

where ϵ is the photon energy. We assume that the initial photon energy is about half that of the neutrino mass, based on energy and momentum conservation in the decay process. In order to calculate the energy loss, a relation between redshift and time is required. In the presence of 17-keV neutrinos, the Universe becomes matter dominated (MD) at $z_\nu \simeq n_\nu m_\nu/\rho_r \simeq 4\times10^6$, where n_ν is the comoving number density of 17-keV neutrinos before they decay which is assumed to be the same as that of the known species of neutrinos (e.g., electron neutrinos), $m_\nu=17$ keV is the mass of these neutrinos, and ρ_r is the energy density of all the relativistic particles. At z_d, when the age of the Universe is equal to the neutrino lifetime, most neutrinos decay into relativistic particles (including photons) and the Universe becomes radiation dominated (RD) again. This RD era may be followed by another MD era depending on z_d and the density of all matter other than 17-keV neutrinos, ρ_m. This MD regime occurs at $z_m \simeq (1+z_d)\rho_m/n_\nu m_\nu - 1$. Obviously, this MD era can exist only if $z_d \gtrsim n_\nu m_\nu/\rho_m \simeq 160h^{-2}/\Omega_m$, where h is the current Hubble constant in units of 100 km/s Mpc and Ω_m is the density parameter for all matter other than 17-keV neutrinos. The above requirement on z_d, with Ω_m replaced with unity, is equivalent to the requirement that the total density of the Universe not exceed the critical density. Here, we will consider the range of z_d within which the present-day density of the Universe is less than the critical density. (For $H=0.5$ and $\Omega_m=1$, $z_d \simeq 700$.)

Solutions can be obtained for the dynamical equations of the universe in the presence of 17-keV neutrinos [8]. In general, as one would expect, in a MD era we have $t \propto (1+z)^{-3/2}+$ const and in a RD era $t\propto(1+z)^{-2}+$ const. Indeed, an approximation in which one adopts an instantaneous transition from one regime to another results in only about 10% inaccuracy [8]. Equation (2) then can be numerically integrated and the energy loss due to Compton scattering can be obtained for individual decay photons which are created at a rate proportional to $B_\gamma \exp(-t/\tau)$. Here B_γ is the branching ratio for the radiative decay, and τ is the lifetime of 17-keV neutrinos. By summing up the energy loss for all the decay photons, one obtains the total energy deposited into the CMBR, and using (1) we obtain the y parameter for given B_γ and τ.

Before explaining our detailed numerical calculations, it is illuminating to estimate the expected magnitude of the energy loss of decay photons due to Compton scattering, and the resulting constraints on B_γ and τ, since such estimates can provide insight into our calculations. Compton scattering is most efficient at high redshifts when the electron density is high [Eq. (2)]. Thus, the fractional energy loss for decay photons may be estimated at the time of the decay (at redshift z_d):

$$\delta\epsilon/\epsilon \simeq n_e\sigma_T\epsilon/m_e H \simeq 5\times10^{-5}(1+z_d)(\Omega_b h/0.05) \ ,$$

where Ω_b is the baryon-density parameter, and H is the Hubble constant at z_d which is assumed to be $H\simeq H_0(1+z_d)^2$ since after the decay the Universe enters a RD era. Clearly, for $z_d \gtrsim 2\times10^4$, a decay photon loses all its energy due to Compton scattering, so $\delta\epsilon/\epsilon\simeq1$ independent of z_d. The energy deposited in the CMBR per unit volume is $\Delta u \simeq \delta\epsilon B_\gamma n_\nu(1+z_d)^3$. Using (1) we obtain $B_\gamma \lesssim 0.02y(\Omega_b h/0.05)^{-1}$ for $z_d\lesssim 2\times10^4$ and $B_\gamma \lesssim 10^{-6}(1+z_d)y(\Omega_b h/0.05)^{-1}$ otherwise. For the current upper limit of $y\lesssim5\times10^{-4}$, we expect that B_γ has to be below about 10^{-5} if z_d is less than about 2×10^4, and the upper limit on B_γ increases as $(1+z_d)$ for larger z_d.

Obviously, if 17-keV neutrinos decay at $z_d\gtrsim2\times10^4$, the efficiency of converting their energy into the CMBR is 100%, and all the available energy in the decay photons is deposited in the CMBR. Because the ratio of the total available energy to that of the CMBR decreases however as $(1+z_d)^{-1}$ and CMBR observations constrain the fractional energy deposited, for fixed y the range of allowed B_γ is larger for larger z_d. In contrast, in the regime $z_d \lesssim 2\times10^4$, the efficiency decreases as $(1+z_d)$ as z_d decreases, and not all the photon energy is deposited in the CMBR. The ratio of the energy deposited into the CMBR to that of the CMBR is roughly constant, and as a result, the obtained upper bound on B_γ is therefore roughly constant.

The results of our numerical calculations are presented in Fig. 1, where we plot the upper limit on B_γ as a function of τ. As expected, the upper limit decreases for decreasing z_d (increasing τ), and levels off at $z_d\simeq2\times10^4$. For $z_d\lesssim2\times10^4$ the limit is roughly constant at a value of about 10^{-5}. In the calculations, we have assumed that $\Omega_m=1$, $h=0.5$, and $\Omega_b=0.1$. Our results are not very sensitive to the assumed value of $\Omega_m=1$. This assump-

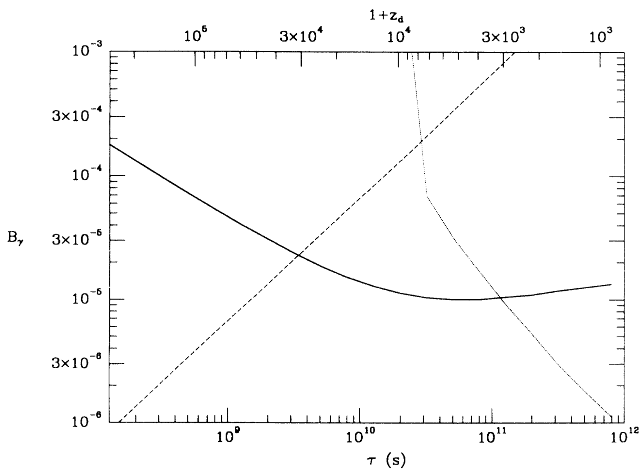

FIG. 1. Upper limits on the photon branching ratio B_γ as a function of the lifetime of 17-keV neutrinos, τ, in seconds (lower abscissa), or as a function of the decay redshift z_d (upper abscissa). The solid curve is from our calculations of the y distortion. The dotted line is obtained by comparing directly the extragalactic background from IR to UV wavelengths with the predicted present-day intensity of the decay photons. The dashed line, based on γ-ray observations of SN 1987A, is taken from Ref. [12].

tion will mostly affect the existence of another MD era, but since the dominant Compton scattering occurs at the time of the decay, the existence of the last MD era has little effect on our final results. The upper limit on B_γ is sensitive to Ω_b and h and scales as $(\Omega_b h)^{-1}$ (see discussions above).

If radiative decay occurs at $z_d \lesssim 2\times10^4$, the decay photons will retain part of their energy, and they may show up in the present epoch at various wavelengths as diffuse background radiation. We can calculate the present-day intensity of the background radiation produced by the decay photons for given B_γ and τ. Observations of extragalactic background radiation at different wavelengths then provide upper limits on this diffuse background radiation. In Fig. 1, we also plot the upper limits on B_γ for given τ obtained by requiring that the peak intensity of the decay photons be less than the observed intensities or upper limits of extragalactic background radiation from radio to UV wavelengths. Notice that B_γ thus obtained is directly proportional to the intensity or upper limit of the extragalactic background. The limits obtained from the extragalactic background radiation are in general less stringent than those obtained from the y-distortion calculations. The exception is at optical and UV wavelengths where background radiation is observed to drop precipitously. For $\tau \simeq 2\times10^{10}-10^{12}$ s, most decay photons show up at optical and UV wavelengths. Therefore, the limits obtained from the extragalactic background provide the most stringent constraints on B_γ for this range of τ (Fig. 1). In our calculations, we have taken the upper limits of the extragalactic background at optical and UV wavelengths from Ref. [9], and at infrared wavelengths from Hauser *et al.* [10] from COBE observations. Also shown in Fig. 1 are the upper limits obtained from γ-ray observations of SN 1987A [11,12]. The limits are much stronger than those obtained above for $\tau \lesssim 3\times10^9$ s, or $z_d \gtrsim 3\times10^4$.

The upper limits on B_γ based on CMBR observations for the similar range of τ were previously calculated by Altherr, Chardonnet, and Salati [12]. Their limits are about a factor of 2 less stringent than our values for $\tau \lesssim 2\times10^{10}$ s, and a factor of 2 more stringent than our values at $\tau \simeq 10^{11}$ s. However, in their calculations they have assumed that the perturbation of the blackbody spectrum is a μ distortion. As can be seen in Fig. 1, the most important constraints that can be extracted from the CMBR observations are for $\tau \gtrsim 3\times10^9$ s, or $z_d \lesssim 3\times10^4$. This is the regime in which the rate of Compton scattering is slower than that of the universal expansion, so the microwave radiation does not have time to adjust to a Bose-Einstein distribution with a chemical potential [2]. Thus, the resultant perturbation should instead be the y distortion. Furthermore, the efficiency of transferring energy to the CMBR is not unity for redshifts lower than 2×10^4, so one cannot assume that all the decay-photon energy is deposited into the CMBR as assumed in the previous investigations [12]. Our calculations are, therefore, more appropriate in providing correct upper limits on B_γ and τ based on CMBR observations.

The author thanks Kim Griest, Douglas Scott, Pierre Salati, and Joe Silk for stimulating discussions. He is grateful to Joan Najita for her critical reading of the manuscript and valuable comments. This work was supported in part by NSF Grant No. AST-8819802.

[1] For example, J. J. Simpson, Phys. Rev. Lett. **54**, 1891 (1985); J. J. Simpson and A. Hime, Phys. Rev. D **39**, 1825 (1989); A. Hime and N. A. Jelley, Phys. Lett. B **257**, 441 (1991); B. Sur, E. B. Norman, K. T. Lesko, M. M. Hindi, R. Larimer, P. N. Luke, W. L. Hansen, and E. E. Haller, Phys. Rev. Lett. **66**, 2444 (1991).

[2] J. R. Bond, in *The Early Universe,* Proceedings of the NATO Advanced Study Institute, Victoria, British Columbia, 1986, edited by W. G. Unruh and G. W. Semenoff, NATO ASI Series C, Vol. 219 (Reidel, Dordrecht, 1988), p. 283.

[3] Ya. B. Zeldovich and R. A. Sunyaev, Astrophys. Space Sci. **4**, 301 (1969).

[4] J. C. Mather, E. S. Cheng, R. E. Eplee, and R. B. Isaacman, Astrophys. J. Lett. **354**, L37 (1991); G. Smoot, in *Current Topics in Astro-Fundamental Physics,* edited by N. Sanchez (Reidel, Dordrecht, in press).

[5] A. Kompaneets, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 876 (1957) [Sov. Phys. JETP **4**, 730 (1957)].

[6] B. Wang and G. B. Field, Astrophys. J. Lett. **345**, L9

(1989).
[7] M. Fukugita, M. Kawasaki, and T. Yanagida, Astrophys. J. Lett. **342**, L1 (1989).
[8] M. S. Turner, Phys. Rev. D **31**, 1212 (1985).
[9] Extragalactic background at different wavelengths has been reviewed by M. T. Ressell and M. S. Turner, Comments Astrophys. **6**, 323 (1989); see references therein for detailed information.
[10] M. G. Hauser *et al.*, in *After the First Three Minutes,* Proceedings of the Conference, Baltimore, Maryland, 1990, edited by S. Holt, C. Bennett, and V. Trimble (American Physical Society, New York, 1991), p. 161.
[11] S. Bludman, Phys. Rev. D **45**, 4720 (1992).
[12] T. Altherr, P. Chardonnet, and P. Salati, Phys. Lett. B **265**, 251 (1991).