Constraints on radiative decay of the 17-keV neutrino from COBE measurements

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It is shown that, for a nontrivial radiative decay channel of the 17-keV neutrino, the photons would distort the microwave background radiation through ionization of the Universe. The constraint on the branching ratio of such decays from Cosmic Background Explorer measurements is found to be more stringent than that from SN 1987A. The limit on the branching ratio in terms of the Compton y parameter is $B_\gamma \leq 1.5 \times 10^{-7} [\tau_\nu/(10^{11} \text{ sec})]^{0.45} (y/10^{-3})^{1.11} h^{-1}$ for an $\Omega = 1$, $\Omega_B = 0.1$ universe.

INTRODUCTION

The existence of a neutrino with a mass of 17 keV and a mixing angle with ν_e of about 10% has been recently suggested from the studies of β-decay spectra of different substances [1]. Various constraints have been put on its properties from accelerator data, and cosmological and astrophysical considerations [2]. A number of theoretical models have also been put forward to accommodate the 17-keV neutrino and the constraints [3].

In brief, constraints from neutrinoless $\beta\beta$ decay and upper limits on the neutrino mass seem to suggest that it is predominantly a 17-keV τ neutrino (see, e.g., Ref. [2]). To avoid making the age of the Universe too small, the heavy neutrino must decay into relativistic particles, with a $\tau_{\nu_H} \leq 4 \times 10^{12} (\Omega h^2)^{3/2}$ sec, if the comoving number density is not decreased enormously by some exotic process (entropy production or enhanced annihilation) after the "freeze out." This implies that, in a radiation-dominated universe, the redshift of decay $z_d \geq 190$. The possible decay channels that have been discussed are (a) $\nu_H \to \nu_L + \gamma$, (b) $\nu_H \to \nu_L + \chi$, and (c) $\nu_H \to 3\nu_L$, where $\nu_{H,L}$ denote heavy and light neutrinos and χ denotes a pseudoscalar.

Cosmological and astrophysical implications of the radiative decay are interesting. Observations from the supernova 1987A have been used to put an upper bound on the branching ratio of the radiative decay B_γ [4]. The failure of the Solar Maximum Mission satellite to detect any γ-ray signal from 1987A indicates that $B_\gamma \leq \tau_\nu/4.9 \times 10^{13}$ sec. Dicus, Kolb, and Teplitz [5] discussed a limit on the lifetime for radiative decays of massive neutrinos in a hot and *ionized* universe. They argued that if $B_\gamma \sim 1$, then the energetic photons would need enough time to thermalize to the energy density of the background radiation, which limits the lifetime to less than ~ 1 yr. This has been interpreted as a hint that radiative decay is not the dominant decay mechanism for the massive neutrino.

In the standard cosmology, the Universe recombined at around $z \sim 1100$ [6]. If the heavy neutrinos decayed after this epoch, the energetic photons would first interact with neutral atoms. The processes of photoionization and recombination would then be important. Collisional ionization by the hot electrons could aid the decay photon in ionizing the Universe and the cosmic background radiation (CBR) spectrum would become vulnerable to distortion by the hot electrons by inverse Compton scattering [7]. This process, therefore, offers us another independent limit on the branching ratio for radiative decay.

In this paper we show that the distortion of the CBR spectrum through ionization of the Universe and the inverse Compton effect is significant. The recent measurement of the CBR spectrum from the Cosmic Background Explorer (COBE) is then shown to put severe bounds on B_γ as a function of τ_ν.

IONIZATION OF THE UNIVERSE

Consider the following scenario. The heavy neutrino decays into relativistic particles at a redshift z_d along with a fraction B_γ of it decaying into photons. The relativistic particles make the Universe radiation dominated at z_d [2]. For such a universe, the corresponding lifetime of the heavy neutrino,

$$\tau_{\nu_H} = \frac{1}{2H_0(1+z)^2} \sim \frac{1.5 \times 10^{17} \sec h^{-1}}{(1+z)^2} .$$

We shall be concerned with decays after the recombination epoch in the standard big bang model, i.e., $z_d \leq 1100 (\tau_{\nu_H} \geq 1.24 \times 10^{11} \sec h^{-1})$. For simplicity, we shall assume a universe with $\Omega = 1$, $\Omega_b = 0.1$. We shall also assume that the decays are instantaneous.

Initially, photoionization of the neutral atoms by the decay photons produces the first hot electrons. Collisional ionization by the energetic electron then takes over. Recombination of ions and electrons competes with these ionizing processes and is characterized by α_{rec}, the recombination coefficient. The evolution of the fraction of ionization $f(=n_{\text{ion}}/n_{\text{neutral}})$ is governed by the equation

$$n_{\text{total}} \frac{df}{dt} = n_{\text{neutral}} [\sigma_{\text{photo}} n_\gamma c + \sigma_{\text{coll}}(T_e) n_e(T_e) v_e]$$

$$- \alpha_{\text{rec}}(T_e) n_e^2 , \qquad (1)$$

where σ_{photo} and σ_{coll} are the ionization cross sections for photons and electrons, T_e is the electron temperature, v_e is the thermal velocity, $n_{\text{total}} = n_{\text{neutral}} + n_{\text{ion}}$ (number per unit volume), and we assume that $n_e = n_{\text{ion}}$. Recombinations also lead to energetic photons and further ionizations. If the recombinations to the ground level are the only ones producing new ionizing photons, and if these are assumed to cause ionizations only locally [8], then recombinations to all but the ground level need to be considered. We shall use $\alpha_{\text{rec}} = 2 \times 10^{-11} T_e^{-1/2} \text{ cm}^3/\text{sec}$ (T_e in the units of degrees kelvin) and

$$\sigma_{\text{photo}} = 5.1 \times 10^{-20} \text{ cm}^2 \left[\frac{E_\gamma}{250 \text{ eV}} \right]^{-p} ,$$

$$p = \begin{cases} 2.65, & 25 \text{ eV} \le E_\gamma \le 250 \text{ eV}, \\ 3.30, & E_\gamma \ge 250 \text{ eV} . \end{cases} \tag{2}$$

The latter is particularly appropriate for a mixture of helium and hydrogen atoms with primordial abundance [9]. For collisional ionization, we shall use

$$\sigma_{\text{coll}} = 4 \times 10^{-14} \text{ cm}^2 \frac{\ln(U)}{\chi^2 U} ,$$

where χ is the ionization threshold in eV (13.6 for hydrogen) and U is energy of the electron in the units of χ [10]. In an $\Omega = 1, \Omega_B = 0.1$ universe, $n_{\text{total}}(z=0) \sim 10^{-6} h^2$, assuming primordial abundance and $n_{\text{total}} \propto (1+z)^3$ due to the expansion of the Universe. The number density of neutrinos is given by the big bang nucleosynthesis model: $n_\nu = (\frac{3}{11}) n_{\gamma \text{CBR}} \sim 120$ per cc at $z=0$. The number density of decay photons n_γ is $B_\gamma n_\nu$.

In solving (1), we should be careful not to use a single photon for more than one ionization event. In other words, as a photon ionizes an atom, it no longer remains available for further ionization. We take this into account by using $n_{\gamma \text{eff}} = f_{\gamma \text{eff}} n_\gamma$ instead of n_γ, where

$$n_\gamma \frac{df_{\gamma \text{eff}}}{dt} = -n_{\text{neutral}} \sigma_{\text{photo}} n_{\gamma \text{eff}} c . \tag{3}$$

The first equation is thus rewritten as

$$n_{\text{total}} \frac{df}{dt} = n_{\text{neutral}} [\sigma_{\text{photo}} n_{\gamma \text{eff}} c + \sigma_{\text{coll}}(T_e) n_e(T_e) v_e]$$

$$- \alpha_{\text{rec}}(T_e) n_e^2 . \tag{1a}$$

The energy density in electrons $\epsilon_e (= \frac{3}{2} n_e k T_e)$ is to be determined by considering various energy sources and sinks. Recombinations and inverse Compton scattering of CBR photons reduce the electron energy density ϵ_e, whereas photoionization of newly recombined and remaining neutral atoms adds to it. Compton scattering by the decay photons transfers energy to the electrons. Adiabatic expansion of the Universe becomes important only later, at smaller redshifts. The energy equation is

$$\frac{d\epsilon_e}{dt} = - \left[\frac{\epsilon_e}{t_{\text{IC}}} \right] - \left[\frac{\epsilon_e}{t_{\text{rec}}} \right] - \left[\frac{5\epsilon_e}{2 t_U} \right]$$

$$+ \left[E_{\text{photo}} n_{\text{neutral}} \sigma_{\text{photo}} + \frac{E_\gamma - 4 k T_e}{m_e c^2} E_\gamma n_e \sigma_T \right] n_{\gamma \text{eff}} c . \tag{4}$$

Here E_{photo} is the energy gained by a photoelectron from the decay photon, viz. $h\nu - 13.6$ eV (for photoionization of a hydrogen atom); t_{IC} and t_{rec} are the time scales for inverse Compton scattering and recombination, and t_U is the age of the Universe. The last term in the equation denotes the energy input by Compton scattering. The energy of the decay photon is

$$\sim \frac{m_\nu H}{2} \frac{(1+z)}{(1+z_d)} .$$

Inverse Compton scattering transfers energy to the CBR in a time scale

$$t_{\text{IC}} = \frac{m_e c^2 \gamma}{\frac{4}{3} \sigma T c \gamma^2 \beta^2 a T_{\text{CBR}}^4} \sim \frac{2.6 \times 10^{29} \text{ sec}}{T_e (1+z)^4} ,$$

for $T_{\text{CBR}}(z=0) = 2.75$ K. The recombination time scale

$$t_{\text{rec}} = \frac{1}{n_e \alpha_{\text{rec}}(T_e)} \sim 5 \times 10^{12} \text{ sec} \left[\frac{n_e}{1/cc} \right]^{-1} \left[\frac{T_e}{10^4} \right]^{1/2} .$$

In a radiation-dominated universe, the age of the Universe

$$t_U \sim \frac{1.5 \times 10^{17} \sec h^{-1}}{(1+z)^2} .$$

The three equations (1a), (3), and (4), describing the number densities of ionized matter and decay photons, and the electron energy density, can be numerically solved for specific values of z_d and B_γ. Figure 1 shows the evolution of ϵ_e for a few cases. Figure 2 shows the
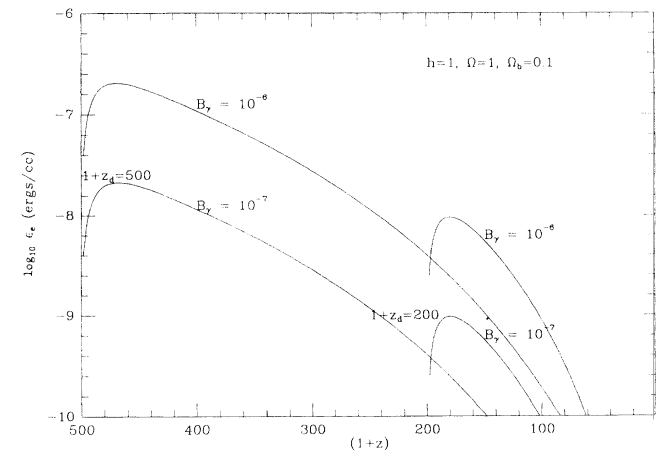

FIG. 1. Evolution of electron energy density with redshift for $1 + z_d = 200,500$ and $B_\gamma = 10^{-6}, 10^{-7}$.
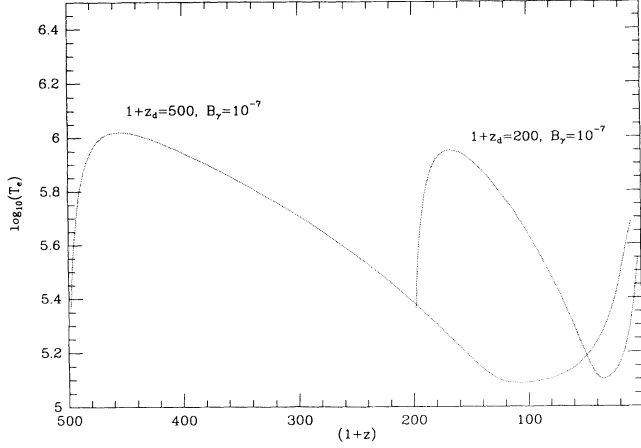
FIG. 2. Evolution of electron temperature with redshift for $1+z_d=200,500$ and $B_\gamma=10^{-7}$.

evolution of electron temperature T_e. Initially, photoionization deposits energy to the electrons till collisional ionization takes over and energy input is then due only to Compton scattering. At high redshift Compton heating competes mainly with cooling due to recombination. Later, as the energy of the decay photons decreases, photoionization becomes important again and deposits more energy in the electrons. Thus, photoionization is important only near the decay redshift, when the first ionizations occur, and at smaller redshifts, when the cross section has increased and an efficient recombination process (due to lowered temperature) produces new neutral atoms to be ionized. For larger B_γ, the initial temperature is large and T_e never drops below 10^5 K for effective recombination and a second phase of photoionization to occur.

LIMITS FROM COBE

Armed with the knowledge of ϵ_e as a function of time, we can now calculate the distortion of the CBR. The distortion in terms of the Compton y parameter, characterizing the deviation of the spectrum from Planckian, is given by

$$\frac{dy}{dt} = \frac{\epsilon_e}{m_e c^2} \sigma_T c \ . \tag{5}$$

Figure 3 shows the resulting y for various B_γ as a function of z_d.

The current upper bound on y comes from COBE and is $\sim 10^{-3}$ [11]. This limit can be translated into a bound on B_γ as a function of τ_ν. The limit from SN 1987A is shown along with the COBE limit in Fig. 4. The limit that COBE may give soon ($y < 10^{-4}$), with the collection of new data and continued analysis, is also indicated. The limiting curves in Fig. 4 are well fitted by

$$B_\gamma \le 1.5 \times 10^{-7} \left[\frac{\tau_\nu}{10^{11}\,\text{sec}} \right]^{0.45} \left[\frac{y}{10^{-3}} \right]^{1.11} h^{-1} \ .$$

Upper bounds for B_γ have also been sought in the past from the diffuse γ-ray background flux. McKeller and
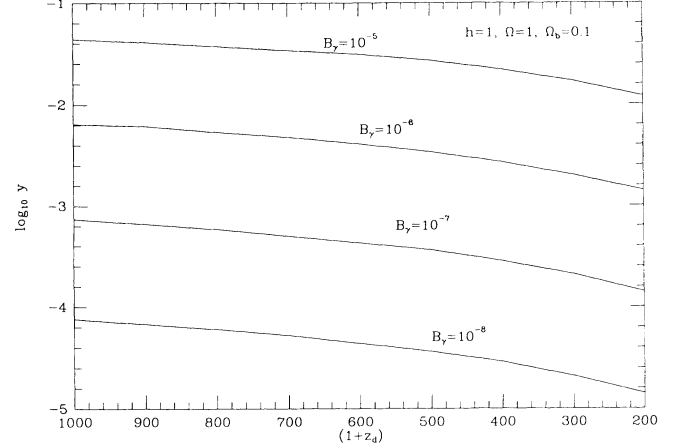

FIG. 3. Distortion of the CBR spectrum for various branching ratios as a function of the decay redshift.

Pakvasa [12] found that, for $m_{\nu_H} \sim 75$ keV and $\tau_{\nu_H} \sim 10^{11}$ sec, $B_\gamma \le 1.5 \times 10^{-6}$. The limit from COBE is certainly stronger than this.

A note on the difference between our result and that of Althere, Chardonnet, and Salati [13] is in order here. They estimated a bound on B_γ from the COBE limit on the chemical potential μ of the microwave background. Their result shows that the bound calculated above from Compton y parameter is stronger than that from μ for decays after recombination. The bound is going to be even stronger if COBE limit on y goes down to 10^{-4}.

Our result pertains only to the process of photoionization of the Universe and subsequent distortion of the microwave background. We, therefore, have not considered the case of decays before recombination; the interaction of photons with baryons in that case would be different from the scenario sketched above. It is hoped that the bound on B_γ calculated above will be useful in constructing theoretical models for the massive neutrino.
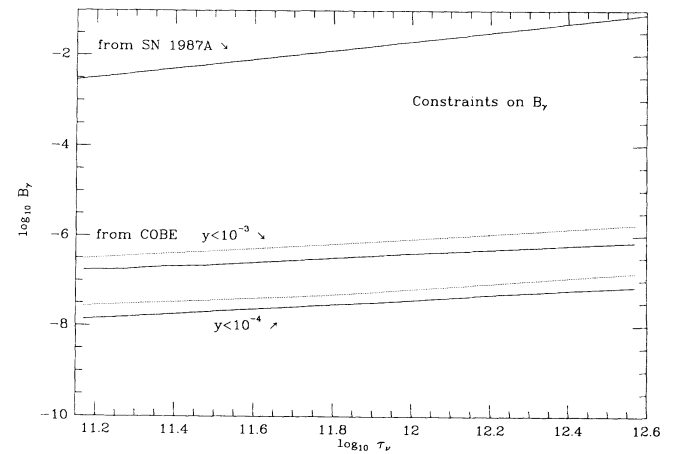

FIG. 4. Limiting curve for the branching ratio from COBE is shown along with the limit from SN 1987A. The dotted and solid curves correspond to the cases $h = 0.5$ and 1.0, respectively. The lowest set of curves denote the limit that COBE may give soon with $y \le 10^{-4}$.

ACKNOWLEDGMENTS

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