CONSTRAINTS ON RADIATIVE DECAY OF THE 17-keV NEUTRINO FROM COBE MEASUREMENTS

Biman B. Nath

Department of Astronomy
University of Maryland
College Park, MD 20742

Abstract

It is shown that, for a non-trivial 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 COBE 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 $B_{\gamma} \leq 1.5 \times 10^{-7} \left( \frac{\tau_{\nu}}{10^{11} \text{s}} \right)^{0.45} \left( \frac{y}{10^{-3}} \right)^{1.11} h^{-1}$ for an $\Omega = 1$, $\Omega_B = 0.1$ universe.

PACS no. 98.70.Vc, 13.35.+s, 14.60.Gh, 98.80.Cq
Introduction

The existence of a neutrino with a mass of 17 keV and a mixing angle with $\nu_e$ of about 10% has been recently suggested from the studies of $\beta-$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 neutrino mass seem to suggest that it is predominantly a 17-keV $\tau$ neutrino (see, e.g., ref. 2). To avoid making 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) $\nu_H \rightarrow \nu_L + \gamma$, (b) $\nu_H \rightarrow \nu_L + \chi$, and (c) $\nu_H \rightarrow 3\nu_L$, where $\nu_{H,L}$ denote heavy and light neutrinos and $\chi$ denotes a pseudo-scalar.

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_{\gamma}$$^4$. The failure of the Solar Maximum Mission satellite to detect any $\gamma$-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 $\sim 1$ year. 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 photo-ionization and recombination would then be important. Collisions of 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 inverse Compton effect is significant. The recent measurement of the CBR spectrum from COBE is then shown to put severe bounds on $B_{\gamma}$ as a function of $\tau_{\nu}$.

Ionization of the universe
Consider the following scenario. The heavy neutrino decays into relativistic particles at a redshift $z_d$ along with a fraction $B_\gamma$ of it decaying into photons. The relativistic particles make the universe radiation dominated at $z_d$ \textsuperscript{2}. For such a universe, the corresponding lifetime of the heavy neutrino, $\tau_{\nu H} = \frac{1}{2H_0(1+z)^2} \sim \frac{1.5 \times 10^{17} \text{sec} h^{-1}}{(1+z)^2}$. We shall be concerned with decays after the recombination epoch in the standard big bang model, i.e., $z_d \leq 1100 \ (\tau_{\nu H} \geq 1.24 \times 10^{11} \text{sec} h^{-1})$. For simplicity, we shall assume a universe with $\Omega = 1$, $\Omega_b = 0.1$. We shall also assume that the decays are instantaneous.

Initially, photo-ionization 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 $\alpha_{rec}$, the recombination coefficient. The evolution of the fraction of ionization, $f(=n_{ion}/n_{neutral})$, is governed by the equation

$$
\frac{dn_{total}}{dt} = n_{neutral} (\sigma_{photo} n_\gamma c + \sigma_{coll}(T_e) n_e(T_e) v_e) - \alpha_{rec}(T_e) n_e^2,
$$

where $\sigma_{photo}$ and $\sigma_{coll}$ are the ionization cross-sections for photons and electrons, $T_e$ is the electron temperature, $v_e$ is the thermal velocity, $n_{total} = n_{neutral} + n_{ion}$ (number per unit volume), and we assume that $n_e = n_{ion}$. 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\textsuperscript{8}, then recombinations to all but the ground level need to be considered. We shall use $\alpha_{rec} = 2 \times 10^{-11} T_e^{-1/2} \text{cm}^3/\text{sec} \ (T_e \text{ in the units of degree kelvin})$ and $\sigma_{coll} = 4 \times 10^{-14} cm^2 \ln(U)$, where $\chi$ is the ionization threshold in eV (13.6 for hydrogen) and $U$ is energy of the electron in the units of $\chi$ \textsuperscript{10}. In an $\Omega = 1$, $\Omega_B = 0.1$ universe, $n_{total} \ (z = 0) \sim 10^{-6} h^2$, assuming primordial abundance and $n_{total} \propto (1+z)^3$ due to the expansion of the universe. The number density of neutrinos is given by the big bang nucleosynthesis model: $n_{\nu} = \frac{3}{14} n_{\gamma CBR} \sim 120$ per cc at $z = 0$. The number density of decay photons $n_\gamma$ 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 $n_{\gamma eff} = f_{\gamma eff} n_\gamma$ instead of $n_\gamma$, where

\begin{align*}
\sigma_{photo} &= 5.1 \times 10^{-20} cm^2 \left( \frac{E_\gamma}{250 eV} \right)^{-p}, \quad p = 2.65, \ 25 eV \leq E_\gamma \leq 250 eV \\
&= 3.30. E_\gamma \geq 250 eV
\end{align*}
\[ n_\gamma \frac{d\gamma_{\text{eff}}}{dt} = -n_{\text{neutral}} \sigma_{\text{photo}} n_{\gamma_{\text{eff}} c}. \] 

(3)

The first equation is thus rewritten as

\[ n_{\text{total}} \frac{df}{dt} = n_{\text{neutral}} (\sigma_{\text{photo}} n_{\gamma_{\text{eff}} c} + \sigma_{\text{coll}}(T_e) n_e(T_e) v_e) - \alpha_{\text{rec}}(T_e)n_e^2. \] 

(1a)

The energy density in electrons \( \epsilon_e = \frac{3}{2} n_e kT_e \) is to be determined by considering various energy sources and sinks. Recombinations and inverse Compton scattering of CBR photons reduce the electron energy density \( \epsilon_e \), whereas photo-ionization 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 the following:

\[ \frac{d\epsilon_e}{dt} = -(\epsilon_e/t_{\text{i.C.}}) - \left( \frac{5\epsilon_e}{2t_U} \right) + (E_{\text{photo}} n_{\text{neutral}} \sigma_{\text{photo}} + \frac{E_{\gamma} - 4kT_e}{m_e c^2} E_{\gamma} n_e \sigma_T) n_{\gamma_{\text{eff}} c}. \] 

(4)

Here \( E_{\text{photo}} \) is the energy gained by a photo-electron from the decay photon, viz. \( h\nu - 13.6\,\text{eV} \) (for photo-ionization of a hydrogen atom); \( t_{\text{i.C.}} \) and \( t_{\text{rec}} \) are the timescales 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 \( \sim \frac{m_e \nu}{2} (1+z)^2 \). Inverse Compton scattering transfers energy to the CBR in a timescale

\[ t_{\text{i.C.}} = \frac{m_e c^2 \gamma}{3 \sigma_T c^2 \gamma^2 a T_{CBR}^2} \sim \frac{2.6 \times 10^{29} \, \text{sec}}{T_e (1+z)^4}, \] 

for \( T_{CBR}(z = 0) = 2.75^o \, \text{K} \). The recombination timescale is

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

In a radiation dominated universe, the age of the universe

\[ t_U \sim \frac{1.5 \times 10^{17} \, \text{sec}}{(1+z)^2}. \]

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 \( B_\gamma \). Fig. 1 shows the evolution of \( \epsilon_e \) for a few cases. Fig. 2 shows the evolution of electron temperature \( T_e \). Initially, photo-ionization 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, photo-ionization becomes important again and deposits more energy in the electrons. Thus, photo-ionization 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 bigger \( B_\gamma \), the
initial temperature is large and $T_e$ never drops below $10^5$ K for effective recombination and a second phase of photo-ionization to occur.

**Limits from COBE**

Armed with the knowledge of $\epsilon_e$ 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

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

Fig. 3 shows the resulting $y$ for various $B_\gamma$ as a function of $z_d$.

The current upper bound on $y$ comes from COBE and is $\sim 10^{-3}$ \cite{11}. This limit can be translated into a bound on $B_\gamma$ as a function of $\tau_{\nu}$. 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 $B_\gamma \leq 1.5 \times 10^{-7} \left(\frac{\tau_{\nu}}{10^{11} \text{sec}}\right)^{0.45} \left(\frac{y}{10^{-3}}\right)^{1.11} h^{-1}$.

Upper bounds for $B_\gamma$ have also been sought in the past from the diffuse $\gamma$-ray background flux. McKeller and Pakvasa\cite{12} found that, for $m_{\nu H} \sim 75$ keV and $\tau_{\nu H} \sim 10^{11}$ sec, $B_\gamma \leq 1.5 \times 10^{-6}$. The limit from COBE is certainly stronger than this.

A note on the difference between our result and that of Altherr et. al.'s recent paper\cite{13} is in order here. They estimated a bound on $B_\gamma$ from the COBE limit on the chemical potential, $\mu$, of the microwave background. Their result shows that the bound calculated above from Compton $y$ parameter is stronger than that from $\mu$ 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 $B_\gamma$ calculated above will be useful in constructing theoretical models for the massive neutrino.

**Acknowledgements**

I am indebted to Dr. David Eichler for encouraging me and for his valuable comments. I thank Drs. Rabindra Mohapatra, David Spergel and Virginia Trimble for their comments on the manuscript. I am also grateful to Ravi Kuchimanchi and Bikram Phookun, who kept me stimulated with many grueling questions.
References

1. J. Simpson, Phys. Rev. Lett. 54, 1891 (1985); J. Simpson and A. Hime, Phys. Rev. D 39, 1825 (1989); 39, 1837 (1989); A. Hime and N. A. Jelley, Phys. Lett. B 257, 441 (1991).
2. E. Kolb and M. Turner, Phys. Rev. Lett., 67, 5 (1991).
3. S. L. Glashow, Phys. Lett. B 256, 218 (1991); K. S. Babu, R. N. Mohapatra, and I. Z. Rothstein, Phys. Rev. Lett., 67, 545 (1991).
4. E. Kolb and M. Turner, Phys. Rev. Lett., 62, 509 (1987).
5. D. A. Dicus, E. W. Kolb, and V. L. Teplitz, Astrophys. J., 221, 327 (1978).
6. E. Kolb. and M. Turner, The Early Universe, (Addison-Wesley, 1989).
7. Mechanism of a similar kind to distort the CBR spectrum was pursued a few years ago to explain the spurious measurement of a bump in the spectrum which was later proven wrong by COBE (see, e.g., M. Fukugita, Phys. Rev. Lett., 61, 1046 (1988) and the rebuttal, e.g., by G. Field and T. Walker, Phys. Rev. Lett., 63, 117 (1989)).
8. When recombination is appreciable, i.e., at $T_e \sim 10^5$ K, the mean free time of an ionizing photon is $\sim \frac{10^{13} h^{-2}}{(1+z)^2}$ sec, many orders of magnitude smaller than the characteristic expansion time $t_U (\sim \frac{10^{17} h^{-1}}{(1+z)^2}$ sec) of the universe.
9. A. A. Zdziarski and R. Svensson, Astrophys. J., 344, 551 (1989).
10. W. Lotz, Astrophys. J. Suppl., 14, 207 (1967).
11. J. C. Mather et al., Ap. J. Lett., 354, L37-L40 (1990).
12. B. H. J. McKeller and S. Pakvasa, Phys. Lett., 122B, 33 (1983).
13. T. Altherr, P. Chardonnet and P. Salati, Phys. Lett., 265B, 251 (1991).
Figure Captions

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

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

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

Figure 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 $y \leq 10^{-4}$. 
