Cosmological and Astrophysical Bounds on Neutrino Masses and Lifetimes

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Abstract

The best upper bounds on the masses of stable and unstable light neutrinos derive from the upper bound on the total mass density, as inferred from the lower limit $t_0 > 13$ Gyr on the dynamical age of the Universe: If the Universe is matter-dominated, $m_\nu < 35(23) \times \max[1, (t_0/\tau_\nu)^{1/2}]$ eV, according as a cosmological constant is (is not) allowed. The best constraints on the radiative decay of light neutrinos derive from the failure to observe prompt gamma rays accompanying the neutrinos from Supernova 1987A: For any $m_\nu > 630$ eV, this provides a stronger bound on the neutrino transition moment than that obtained from red giants or white dwarfs. For $m_\nu > 250$ eV or $\tau_\nu < t_{rec} \sim 7 \times 10^{12}$ sec, the upper limit on the radiative branching ratio is even smaller than that obtained from the limits on $\mu$-distortion of the cosmic background radiation. Our results improve on earlier cosmological and radiative decay constraints by an overall factor twenty, and allow neutrinos more massive than 35 eV, only if they decay overwhelmingly into singlet majorons or other new particles.

1 Mass Limits on Stable and Unstable Neutrinos from the Age of the Universe

The masses of stable neutrinos, $\Sigma m_{\nu_i} = 92\Omega_0 h^2$ eV, are bounded by $\Omega_{0\nu} h^2 < \Omega_0 h^2$, the total cosmological mass density in units of $\rho_{CR}h^{-2} = 10.54$ keV cm$^{-3}$. The best constraint on $\Omega_0 h^2$ does not come from poorly-known limits on $\Omega_0$ and the Hubble constant $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ separately, but from the present dynamical age of the universe, believed to be $t_0 = (13 - 17)$ Gyr. Allowing the generous limits $H_0 = (50 - 100)$ km s$^{-1}$ Mpc$^{-1}$, $0.66 < H_0 t_0 < 1.7$.

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If the Universe is now matter-dominated and there is no cosmological constant, then the age limits allow $\Omega_0 \leq 1$, $\Omega_0 h^2 \leq 0.25$, $m_\nu \leq 23$ eV$^1$. If the dimensionless cosmological constant $\lambda_0 \equiv \rho_{vac}/\rho_{CR} \leq 0.8^2$, the age limits allow $\Omega_0 < 1.5$, $\Omega_0 h^2 < 0.38$, $m_\nu \leq 35$ eV. If we imposed the flat space condition $\Omega_0 + \lambda_0 = 1$ or allowed a presently radiation-dominated Universe, much lower bounds would be obtained. Nevertheless, we conservatively adopt the upper bounds $m_\nu \leq 35(23)$ eV for any stable neutrino with (without) a cosmological constant. Massive neutrinos can evade this cosmological bound only if they either decay into relativistic products (a light neutrino and either a photon or Goldstone boson) at red-shift $1 + z_D > m_\nu/(92\Omega_0 h^2)$. (Annihilation into a pair of majorons is fast enough, only if the $B-L$ symmetry breaking takes place at a very low (< 50 MeV) scale.$^3$)

This redshift is achieved at time $t = (1.7)^{1/2}(\Omega_0 h^2)^{-1/2}(1 + z_D)^{-2} < (7.1 \times 10^4$ Gyr)$(\Omega_0 h^2)^{3/2}(m_\nu/eV)^{-2}$.$^4$. Thus the proper lifetime of the decaying neutrino,

$$\tau_\nu = 2.1 \times 10^{21}(\Omega_0 h^2)^{3/2}(m_\nu/eV)^{-2} < 5.0 \times 10^{20}(m_\nu/eV)^{-2},$$

where hereafter all times are in seconds, all masses in eV. This constraint on $\tau_\nu$ is shown by the horizontally shaded region at the top of Fig. 1, along with the minimum dynamical age $\tau_0 = 13$ Gyr. This argument conservatively assumes nothing more than that radiation is red-shifted in an expanding universe.

This decay of a massive neutrino would leave the Universe radiation-dominated. In order to allow a later matter-dominated epoch long enough for the evolution of large-scale structure, a massive neutrino must decay even earlier, with $\tau_\nu < 1$ yr.$^5$ This stronger lifetime limit depends on theories for the evolution of large-scale structure, which we need not assume.

## 2 Cosmological Bounds on Radiative Decays

Massive neutrino decay into photons must be slow enough that the decay photons not unacceptably distort the cosmic background radiation spectrum accurately observed by COBE. From the observed limit on $\mu$-distortion, following Altherr et al$^6$, we obtain the radiative branching ratio limits

$$B_\gamma \leq \begin{cases} 
1.4 \times 10^7 \tau_\nu^{-2/3}/m_\nu \leq 0.012/m_\nu, & \tau_\nu < t_{rec} \\
9.1 \times 10^{-15} \tau_\nu, & \tau_\nu > t_{rec}.
\end{cases}$$

Here $B_\gamma$ is the branching ratio into photons, and we have taken $T_\gamma(t_{rec}) = 0.308$ eV, $t_{rec} = 4.39 \times 10^{12}(\Omega_0 h^2)^{-1/2}$ for the epoch of radiation-matter recombination.

Direct searches of the ultra-violet background for photons entering our Galaxy with red-shifted energies below the hydrogen ionization threshold$^7$, already show that, provided absorption by dust may be neglected, the radiative branching ratio must be $B_\gamma < 10^{-6} - 10^{-5}$. 

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3 Bounds on Radiative Decay from Supernova 1987A

The strongest constraint on radiative decays derives generally from the failure of the Solar Maximum Mission Gamma Ray Spectrometer (GRS)\(^8\) to detect any prompt gammas from Supernova 1987A in the Large Magellanic Cloud at distance \(\tau_{\text{LMC}} = 5.7 \times 10^{12}\) light seconds from Earth.\(^9\) Underground neutrino detectors observed an electron antineutrino fluence on Earth \(\phi_{\bar{\nu}_e} = (8 \pm 3) \times 10^9 \bar{\nu}_e \, \text{cm}^{-2}\), emitted from a \(\nu_e\)-neutrinosphere at temperature \(T = 4.2\) MeV and mean energy \(< E_{\bar{\nu}_e} > = 12.5\) MeV. Because \(\nu_{\mu,\nu}\) and \(\bar{\nu}_{\mu,\tau}\) were emitted from deeper in the star, at \(T = 8 \) MeV with average energy \(< E_{\nu}\bar{\nu}_e > = 25\) MeV and half the fluence of \(\bar{\nu}_e\), the combined fluence of \(\nu_\tau + \bar{\nu}_\tau\) must have been \(\approx \phi_{\bar{\nu}_e}\).

For a \(T = 8\) MeV Fermi-Dirac spectrum of decaying \(\nu_{\mu,\tau}\), a fraction \(\gamma = 0.6\) of the decay photons would fall in the detector’s 10-25 MeV window. If \(F\) is the fraction of \(\nu_\tau\) that decay before reaching us and \(B_\gamma\) the branching ratio into photons, then the expected gamma fluence \(\phi_\gamma \approx 2\) photons cm\(^{-2}\) sec\(^{-1}\). From those gammas that might have arrived within 10 sec after the \(\bar{\nu}_e\) pulse, because the decaying neutrino was light or decayed fast enough. In this way we obtain the bounds

\[
B_\gamma F \leq \begin{cases} 
2 \times 10^{-12} m_\nu & 50 < m_\nu < 250 \text{ eV} \\
8 \times 10^{-11} & m_\nu > 250, < 50 \text{ eV},
\end{cases}
\]

where \(F\) is the fraction of \(\nu\) decaying before reaching Earth. Here \(\tau_{\text{LAB}} = \tau_\nu(E/m)\) is the massive neutrino’s lifetime in the laboratory, \(\tau_\nu\) is its proper lifetime, and \(t^* = 20(E/m_\nu)^2\) is the time within which a massive neutrino must decay in order that its light decay products arrive no later than 10 sec after the \(\bar{\nu}_e\) burst. Thus, \(t_{\text{LMC}}/\tau_{\text{LAB}} = 2.4 \times 10^3 m_\nu/\tau_\nu, \ t^*/\tau_{\text{LAB}} = 5.0 \times 10^6/\tau_\nu m_\nu\) for 25 MeV \(\nu_\tau\).

Comparison with eq. (2) then shows two things:

1. If the neutrino lifetime is short enough \((\tau_\nu < 2.4 \times 10^5 m_\nu < 6 \times 10^4 \text{ sec for } m_\nu < 250 \text{ eV or } \tau_\nu < 5 \times 10^8 m_\nu^{-1} < 2 \times 10^6 \text{ sec for } m_\nu > 250 \text{ eV}), then all neutrinos decay before reaching Earth \((F = 1)\) and the radiative branching ratio must be very small, \(B_\gamma < 10^{-10}\) for \(m_\nu < 50\) eV or \(250\) eV, \(B_\gamma < 2 \times 10^{-12} m_\nu\) for \(50 < m_\nu < 250\) eV;

2. If \(\tau_{\text{LAB}} > t_{\text{LMC}}\) or \(t^*\), the radiative decay lifetime must be long

\[
\tau_\nu/B_\gamma > \begin{cases} 
2.8 \times 10^{15} m_\mu & m_\nu < 50 \text{ eV} \\
1.4 \times 10^{17} & 50 < m_\nu < 250 \text{ eV} \\
6.0 \times 10^{18} m_\mu^{-1} & 50 \text{ eV} < m_\nu.
\end{cases}
\]

The region of radiative decay lifetime excluded (assuming \(B_\gamma > 10^{-10}\)), is shown by the vertical shading in Fig. 1. Our constraint is four times stronger than that in ref. (9) because we have corrected the neutrino average energy and the gamma fraction, energy and fluence limit to be that of \(\nu_\tau\) rather than \(\nu_e\).

Parametrizing the radiative decay rate \(B_\gamma/\tau_\nu = \mu^2 m_\nu^3/8\pi = 5.16(\mu/\mu_B)^2 m_\nu^3\) by a transition magnetic moment \(\mu\), for \(m_\nu > 250\) eV, Eq. (4) requires in Bohr magnetons, \(\mu/\mu_B < 1.8 \times 10^{-10} m_\nu^{-1}\). From the absence of fast cooling of white dwarf or
red giant stars by the transverse plasmon decay into $\nu + \bar{\nu}$, we already know\textsuperscript{10} that $\mu < 3 \times 10^{-12} \mu_B$, but only for $m_\nu < 10$ keV. Because these stars are essentially at temperature 10 keV, the plasmon mass and the mass of any decay products is kinematically constrained to $< 10$ keV. For $m_\nu > 630$ eV, the SMM limits on SN1987A gamma rays therefore provides a stronger bound on the neutrino transition moment than is obtained from red giants or white dwarfs.

Our four-fold improvement in the SMM bound and five-fold improvement in the cosmological bound\textsuperscript{(1)} together require that any unstable neutrino decay with radiative branching ratio $B_\gamma < 4 \times 10^{-4}$ for $m_\nu < 250$ eV and $< 9 \times 10^{-6} m_\nu$ for $m_\nu > 250$ eV. The cosmological bound\textsuperscript{(2)} from the absence of $\mu$-distortion is stronger only when both $m_\nu < 250$ eV and $\tau_\nu < t_{\text{rec}}$, in which case $B_\gamma < 5.6 \times 10^4 \tau_\nu^{-2/3}$. A massive neutrino can exist only if it decays predominantly by non-radiative (invisible) decay modes.

**List of Figures**

FIG. 1. Neutrino masses and lifetimes that are excluded cosmologically, by the age of the Universe ($\Omega_0 h^2 \leq 0.38$) and astrophysically, by the absence of gamma rays accompanying the Supernova 1897A neutrinos. The latter constraint plotted is on $\tau_\nu/B_\gamma$, the radiative decay lifetime, and shows that a neutrino of mass between 35 eV and 40 MeV can exist only if it decays superfast by exotic (nonradiative) modes.

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