Improved cosmological and radiative decay constraints on neutrino masses and lifetimes

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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, accordingly as a cosmological constant is (is not) allowed. The best bounds on the radiative decay of light neutrinos derive from the failure to observe prompt γ 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. Our results improve on earlier cosmological and radiative decay constraints by an overall factor 20 and allow neutrinos more massive than 35 eV only if they decay overwhelmingly into singlet Majorons or other new particles with a lifetime less than one month. We review the 17-keV neutrino situation in order to stress that (1) its existence may be resolved by modest improvements in neutrino oscillation probabilities, and (2) double β decay and nucleosynthesis constraints require that its massive partner be an active neutrino, but allow solar neutrinos to oscillate into low-mass sterile neutrinos.

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I. MASS LIMITS ON STABLE NEUTRINOS FROM THE AGE OF THE UNIVERSE

The masses of stable neutrinos, $\sum m_{\nu_i} = 92\Omega_{0\nu}h^2$ eV, are bounded by $\Omega_{0\nu}h^2 < \Omega_0 h^2$, the total cosmological mass density in units of $\rho_{\rm cr}h^{-2} = 10.54$ keV cm^{-3}. The best constraint on $\Omega_0 h^2$ does not come from poorly known limits on Ω_0 and the Hubble constant $H_0 = 100h$ km s^{-1}Mpc^{-1} separately, but from the present age of the Universe, believed to be $t_0 = 13-17$ Gyr [1]. Allowing the generous limits $H_0 = 50-100$ km s^{-1} Mpc^{-1}, $0.66 < H_0 t_0 < 1.7$. At the lower limit $t_0 = 13$ Gyr, this just allows (but does not demand) the flat-space solution $\Omega_0 = 1$, provided $H_0 = 50$ km s^{-1}Mpc^{-1}.

If the Universe is now matter dominated and there is no cosmological constant, then the age limits allow $\Omega_0 \le 1$, $\Omega_0 h^2 \le 0.25$ [2]. [A good approximation is $H_0 t_0 \approx (1+\frac{1}{2}\Omega_0^{1/2})^{-1}$.] The frequency of multiple imaging of quasi-stellar objects (QSO's) allows a dimensionless cosmological constant $\lambda_0 \equiv \rho_{\rm vac}/\rho_{\rm cr} \le 0.8$ [3]. For a matter-dominated Universe with such a cosmological constant, the age limits allow $\Omega_0 < 1.5$, $\Omega_0 h^2 < 0.38$. [For $H_0 t_0 \sim 2/3$, a fair approximation is $H_0 t_0 \approx (1+\frac{1}{2}\Omega_0'^{1/2})^{-1}$, where $\Omega_0' \equiv \Omega_0 - \lambda_0/\sqrt{2}$.] A lower upper bound $0.26 < \Omega_0 < 0.1$, $0.006 < \Omega_0 h^2 < 0.1$ would be obtained from our age limits $0.66 < H_0 t_0 < 1.7$, if we imposed the flat-space condition $\Omega_0 + \lambda_0 = 1$, for which $H_0 t_0 = \frac{1}{3}\lambda_0^{-1/2}\ln(1+\lambda_0^{1/2})/(1-\lambda_0^{1/2})$. An even lower upper bound $\Omega_0 h^2 < 0.0062$ and $h < 0.75$ would obtain if the Universe is now radiation dominated and there is no cosmological constant, so that $H_0 t_0 = (1+\Omega_0^{1/2})^{-1}$ exactly. Since the observed photon density $\Omega_{\gamma 0}h^2 = 2.6 \times 10^{-5}$ and the baryon density $\Omega_{B0}h^2 = 0.015 \pm 0.005$, the Universe can now be radiation dominated, only if there were a great deal of hot dark matter and the present large-scale structure evolved in an earlier matter-dominated epoch.

We conservatively adopt the upper bound $\Omega_0 h^2 < 0.38$, consistent with a matter-dominated Universe with or without a cosmological constant. With this bound, any stable neutrino mass $m_{\nu_i} < 35$ or 23 eV respectively. Even allowing a cosmological constant, a 17-keV neutrino surviving to the present epoch would overfill the Universe by a factor > 480. 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 ϕ) at a redshift $1+z_D > m_\nu/(92\Omega_0 h^2)$ or pair annihilate into a pair of Majorons. This pair annihilation is fast enough, only if the $(B-L)$-symmetry breaking takes place at a very low (< 50 MeV) scale [4].

II. MASS LIMIT ON DECAYING NEUTRINOS

If a neutrino decays at the large redshift $1+z_D > m_\nu/(92\Omega_0 h^2)$, the curvature of the Universe is negligible and the energy density is dominated by any massive neutrinos decaying into relativistic products. The redshift $1+z_D$ is achieved at time

$$t_D \approx \tfrac{1}{2}(\Omega_0 h_0^2)^{-1/2}(1+z_D)^{-2} < (4.2\times 10^4 \text{Gyr}) \times (\Omega_{0\nu}h^2)^{3/2}(m_\nu/\text{eV})^{-2} .$$

Thus if τ_ν is the proper lifetime of the decaying neutrino,

$$\Omega_{0\nu}h^2 \approx (0.383)(m_\nu/100 \text{ eV})^{4/3}(\tau_\nu/\text{Gyr})^{2/3} .$$

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Kolb and Turner [5] integrate from the matter-dominated epoch into the new radiative-dominated epoch and obtain an exact expression with 0.383 replaced by 0.265. With their equality and our conservative bound $\Omega_{0\nu}h^2 < \Omega_0 h^2 \le 0.38$,

$$\tau_\nu = 2.1\times10^{21}(\Omega_{0\nu}h^2)^{3/2}m_\nu^{-2} < 5.0\times10^{20}m_\nu^{-2} , \quad (1)$$

where hereafter all times are in seconds, all masses in eV. Our constraint on τ_ν is shown by the horizontally shaded region at the top of Fig. 1, along with the minimum dynamical age $t_0 = 13$ Gyr. A neutrino lifetime $\tau_\nu < 6\times10^4$ years is required, if a 17-keV neutrino is not to overclose the Universe. Even allowing for a possible cosmological constant, our constraint is still five times stronger than that obtained by imposing $\Omega_0 = 1$ and $h < 1$ separately [5].

This decay would, however, leave the Universe radiation dominated. In order to allow a matter-dominated epoch long enough for the evolution of a large-scale structure, a massive neutrino must decay even earlier, with $\tau_\nu < 1$ yr [6].

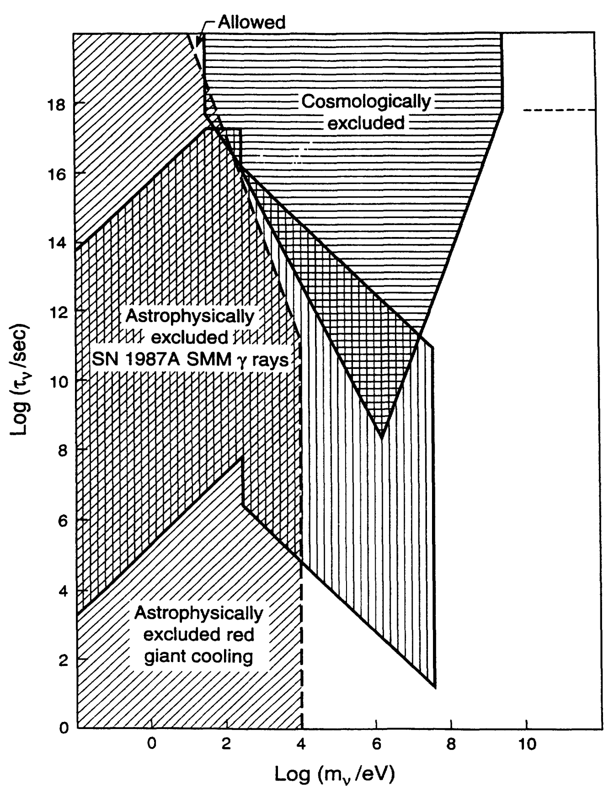

FIG. 1. Neutrino masses and lifetimes that are excluded cosmologically by the age of the Universe ($\Omega_0 h^2 \le 0.38$) and astrophysically by the absence of gamma rays accompanying the supernova 1987A neutrinos. The latter constraint plotted is on τ_ν/B_γ, the radiative decay lifetime, and shows that a neutrino of mass between 35 eV and 40 MeV can exist only if it decays superfast by exotic (nonradiative) modes.

III. BOUNDS ON RADIATIVE DECAY FROM SUPERNOVA 1987A

The radiative decay $\nu_H \to \nu_L + \gamma$ cannot, however, be so fast, lest the decay photons unacceptably distort the background radiation. Direct searches of the ultraviolet background for photons entering our Galaxy with redshifted energies below the hydrogen ionization threshold [7] already show that, provided absorption by dust is negligible, the radiative branching ratio must be $B_\gamma < 10^{-6} - 10^{-5}$. The strongest constraint comes, however, from the failure of the Solar Maximum Mission (SMM) Gamma Ray Spectrometer (GRS) [8] to detect any prompt γ rays from supernova 1987A in the Large Magellanic Cloud at a distance $t_{\rm LMC} = 5.7\times10^{12}$ light seconds from Earth [9]. Underground neutrino detectors observed an electron-antineutrino fluence $\phi_{\bar\nu_e} = (8\pm3)\times10^9\ \bar\nu_e\ {\rm cm}^{-2}$, emitted from a $\bar\nu_e$ neutrinosphere at temperature $T = 4.2$ MeV and mean energy $\langle E_{\bar\nu_e}\rangle = 1.25$ MeV. Because $\nu_{\mu,\tau}$ and $\bar\nu_{\mu,\tau}$ were emitted from deeper in the star, at $T = 8$ MeV with an average energy of $\langle E_{\nu_\tau}\rangle = 25$ 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 ν_τ, a fraction $W_\gamma = 0.6$ of the decay photons would fall in the detector's 10–25 MeV window. If F is the fraction of ν_τ that decay before reaching us and B_γ the branching ratio into photons, then the expected γ-ray fluence is $\phi_\nu F W_\gamma B_\gamma$. Despite a γ-ray sensitivity 10^{10} times the neutrino sensitivity of the underground detectors, GRS detected no γ rays arriving within 270 sec after the 10-sec-long $\bar\nu_e$ pulse.

The GRS sensitivity depends on the time delay $\Delta t = \frac{1}{2}t(m/E)^2$ by which the γ rays from ν decay at time t lag the $\bar\nu_e$ that were detected. This sensitivity was a maximum for γ rays arriving within 10 sec of the $\bar\nu_e$ burst, but thereafter decreased with integration time as $(\Delta t/10)^{-1/2} = 45 m_\nu^{-1}$ for $\tau = \tau_{\rm LMC}$. For $m_\nu < 250$ eV, the decay products would have arrived within $\Delta t = 270$ sec, so that the γ-ray fluence is bounded by

$$\phi_{\gamma\max} = \begin{cases} 0.4, & m_\nu < 50 \text{ eV}, \\ 0.008 m_\nu, & 50 < m_\nu < 250 \text{ eV} . \end{cases} \quad (2)$$

(All masses are hereafter in eV, fluences in particles ${\rm cm}^{-2}$.) If τ_ν is the ν proper lifetime, then its laboratory lifetime is $\tau_{\rm lab} = \tau_\nu(E/m)$. For $m_\nu < 250$ eV, a fraction F decay early enough, at $t^* = 20(E/m_\nu)^2$, so that their daughter photons still arrive within $\Delta t = 10$ sec, when the detector sensitivity is maximal, $\phi_{\gamma\max} = 0.4$. The fraction of ν decaying before reaching Earth is

$$F = \begin{cases} 1 - \exp(-t_{\rm LMC}/\tau_{\rm lab}) \approx \min[1, t_{\rm LMC}/\tau_{\rm lab}], & m_\nu < 250 \text{ eV} , \\ 1 - \exp(-t^*/\tau_{\rm lab}) \approx \min[1, t^*/\tau_{\rm lab}], & m_\nu > 250 \text{ eV} , \end{cases} \quad (3)$$

where $t_{\rm LMC}/\tau_{\rm lab}=2.4\times10^5 m_\nu/\tau_\nu$, $t^*/\tau_{\rm lab}=5.0\times10^8/\tau_\nu m_\nu$ for 25 MeVν_τ.

The upper bounds $F<\phi_{\gamma\max}/\phi_\nu W_\nu B_\gamma=8\times10^{-11}B_\gamma^{-1}$ for $m_\nu<50$ eV or >250 eV and $F<2\times10^{-12}m_\nu B_\gamma^{-1}$ for $50<m_\nu<250$ eV thus imply two things: (1) If the neutrino lifetime is short enough ($\tau_\nu<2.4\times10^5 m_\nu<6\times10^4$ sec for $m_\nu<250$ eV or $\tau_\nu<5\times10^8 m_\nu^{-1}<2\times10^6$ sec for $m_\nu>250$ 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, $B_\gamma<2\times10^{-12}m_\nu$ for $50<m_\nu<250$ eV; (2) if $\tau_{\rm lab}>t_{\rm LMC}$ or t^*, the radiative decay lifetime must be long:

$$\tau_\nu/B_\gamma>\begin{cases}2.8\times10^{15}m_\nu, & m_\nu<50\text{ eV},\\ 1.4\times10^{17}, & 50<m_\nu<250\text{ eV},\\ 6.0\times10^{18}m_\nu^{-1}, & 250\text{ eV}<m_\nu\,.\end{cases}\quad(4)$$

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 γ-ray fraction, energy and fluence limit to be that of ν_τ rather than ν_e.

Parametrizing the radiative decay rate $B_\gamma/\tau_\nu=\mu^2m_\nu^3/8\pi=5.16(\mu/\mu_B)^2m_\nu^3$ by a transition magnetic moment μ, for $m_\nu>250$ eV, Eq. (4) requires in Bohr magnetons, $\mu/\mu_B<1.8\times10^{-10}m_\nu^{-1}$. 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 [10] that $\mu<2\times10^{-12}\mu_B$, but only for $m_\nu<10$ keV. Because these stars are essentially at density 10^6 g cm^{-3}, the plasmon mass and the mass of any decay products is kinematically constrained by <10 keV. For $m_\nu>630$ eV, the SMM limits on SN 1987A γ rays therefore provide a stronger bound on the neutrino transition moment than is obtained from red giants or white dwarfs. If a $m_\nu=17$ keV neutrino exists, then its transition magnetic moment $\mu<1\times10^{-14}\mu_B$.

Our fourfold improvement in the SMM bound and fivefold improvement in the cosmological bound (1) together require that any unstable neutrino decay with radiative branching ratio $B_\gamma<4\times10^{-4}$ for $m_\nu<250$ eV and $<9\times10^{-6}m_\nu$ for $m_\nu>250$ eV. A 17-keV neutrino can exist only if it decays predominantly ($>85\%$) by nonradiative (invisible) decay modes.

IV. THEORETICAL MODELS FOR SUPERFAST NEUTRINO DECAY

The cosmological constraint on a 17-keV neutrino thus requires that it decay into Majorons ϕ or other exotic particles. The spontaneous breaking of global lepton-number conservation requires $\nu_H\to\nu_L+\phi$ at a rate $\tau_\nu^{-1}=(g^2/16\pi)m_{\nu_H}=5.1\times10^{17}g^2$ sec^{-1}, where g is the flavor-changing Majoron coupling to neutrinos. To make the decay fast enough ($\tau_\nu<6\times10^4$ yr) to not overclose the Universe requires the lower bound $g>1\times10^{-16}$. To make the decay superfast ($\tau_\nu<1$ yr) enough to allow the evolution of large-scale structure requires the lower bound $g>3\times10^{-13}$. (The lowest upper bound $g<10^{-9}$ is provided by the requirement that these Majorons be produced late enough (after $t=2$ seconds) they they will not thermalize and contribute to the expansion rate observed at nucleosynthesis. Weaker upper bounds $g<10^{-5}$ and $g<6\times10^{-7}$ are derived respectively from the requirements that majorons produced by neutrino-antineutrino annihilation not thermalize and that bulk Majoron emission not accelerate the cooling of the hot neutron-star remnant from supernova 1987A [11].)

In the original singlet Majoron model [12], Glashow-Iliopoulos-Maiani (GIM) suppression makes $g=O((m_{\nu_H}/v)^2)\sim3\times10^{-16}$, where $v\sim$TeV is the expected scale of $(B-L)$-symmetry breaking producing neutrino masses and Majorons. Unless symmetry breaking takes place at the unexpectedly low scale $v<30$ GeV, the singlet Majoron model leads to m_{ν_H} decay that is fast but not superfast. In order to make the ν_H decay superfast, the neutrino masses must arise from terms acting differently under the original unbroken $B-L$ symmetry [13–15]. Then $g=O(m_{\nu_H}/v)$ so that, if the $(B-L)$-symmetry-breaking scale lies in the interval 2×10^4 GeV $<v<6\times10^7$ GeV, between the electroweak and intermediate scales, then 2 sec $<t_D<1$ yr and all lifetime constraints can be satisfied. This shows that a contrived enough Higgs sector is theoretically capable of realizing a 17-keV neutrino satisfying all cosmological and astrophysical constraints.

If double β decay and laboratory neutrino oscillation constraints are also to be satisfied, a 17-keV neutrino must be a Majorana ν_τ-ν_e mixture accompanied by a ν_μ Majorana partner that is either degenerate in mass or at least ten times more massive [16,17]. (Neither the 17-keV neutrino nor its partner can be a new, sterile neutrino lest the supernova 1987A remnant neutron star cool too fast.) The existence of a 17-keV neutrino may sooner be resolved by improving limits on large mass-difference neutrino oscillation probabilities than by attempting to reconcile already sensitive β-spectrum measurements: (1) A 30% reduction in the present upper limit on the probability $P(\nu_\mu\leftrightarrow\nu_e)<0.0017$ would exclude the unnatural possibility ν_μ much heavier than ν_τ; (2) a fourfold reduction in the probability $P(\nu_e\leftrightarrow\nu_\tau)<0.07$ would exclude 0.85% mixing of ν_τ with ν_e; (3) a ν_μ degenerate with a $\nu_\tau-\nu_e$ mixture would constitute a 17-keV Dirac neutrino with conserved lepton number $L_e+L_\tau-L_\mu$, so that ν_μ cannot oscillate into ν_e or ν_τ at all [16].

V. A FOURTH, STERILE NEUTRINO?

To obtain MSW oscillations in the Sun requires, on the other hand, that ν_e oscillate into a nearly degenerate partner of millivolt mass. Such a low-mass sterile neutrino will not accelerate supernova cooling nor will it violate the effective number of light neutrinos at nucleosynthesis, $N_\nu<3.4$ if the primordial ^{4}He abundance by mass is less than 0.24. To prevent $\nu_e\to\nu_s$ oscillations in the early Universe from populating ν_s above this bound, the vacuum neutrino mixing angle must be small: this excludes the large-angle branch of the solar Mikheyev-Smirnov-Wolfenstein (MSW) triangle, but allows the theoretically favored nonadiabatic MSW branch [18].

A 17-keV neutrino together with solar neutrino oscillations require both a singlet Majoron into which the 17-keV neutrino can decay and a light ($\sim$ meV) singlet neutrino into which the electron neutrino can oscillate.

Both singlet Majorons and singlet neutrinos do appear in many extended gauge models. Indeed, a *supermassive* singlet Majorana neutrino leads naturally to small masses for the light neutrinos by the seesaw mechanism. Theoretical models for such a hierarchy of a pair of nearly degenerate neutrinos, ν_s and approximately ν_e, separated from another pair, ν_μ and approximately ν_τ, by 17 keV can be contrived [14]. They do not, however, explain naturally why *all* four light neutrinos are so much lighter than charged lepton or quark masses.

If indeed $\nu_e \rightarrow \nu_s$, next-generation neutral-current neutrino detectors such as the Imaging of Cosmic and Rare Underground Signals (ICARUS) detector, SNO, or B solar-neutrino experiment (BOREX) would detect no ν_s but would observe equal suppression of charged and neutral currents. If $\nu_e \rightarrow \nu_{\mu,\tau}$, they would detect the $\nu_{\mu,\tau}$ and would find only charged currents suppressed [19].

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