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Cosmological Upper Bound on Heavy Neutrino Lifetimes

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An upper bound on the lifetime of a massive, neutral, weakly interacting lepton, ν_H, is derived from standard big bang cosmology. Saturation of the bound and reasonable assumptions about the weak interaction of the ν_H then yield a prediction of approximately 10 MeV for its mass.

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Recently Lee and Weinberg[1] have pointed out that stable neutrinos with masses in the GeV range are capable of "hiding" a cosmological energy density on the order of

$$\rho = \rho_c = 10^{-2}\ \text{MeV/cm}^3 \qquad (1)$$

This density is an order of magnitude greater than the proven mass reserves such as galaxies and the cosmic microwave background but is suggested by current best values for the Hubble constant and deceleration parameter.[2] It was shown in 1972 by Cowsik and McClelland[3] that stable neutrinos with masses on the order of 16 eV could also hide such a cosmological energy density. The purpose of the present note is to describe a more general picture in which the massive neutrinos can be unstable.

Our picture is as follows: (a) Massive neutrinos, ν_H, are in thermal equilibrium with electron neutrinos (and other particles) just after the big bang through reactions like

$$\nu_H + \bar{\nu}_H \leftrightarrow \nu_e + \bar{\nu}_e \qquad (2)$$

(b) Assuming (2) proceeds through a V-A interaction with the usual weak coupling constant, one can calculate for a given mass m for ν_H, the temperature T_D at which the ν_H thermally decouple and are not further annihilated, the age t_D when this occurs (typically a fraction of a second), and their number density $n(T_D)$ at this time. (c) Given m, T_D, t_D, and $n(T_D)$ one can find a lifetime τ for ν_H, assuming its principle decay mode is

$$\nu_H \to \nu_e + \gamma \quad , \tag{3}$$

such that the present energy density of the ν_e's, after taking account of their red shift from $t_D + \tau \approx \tau$ to the present age of the universe, t_U, is ρ_c. The essence of our picture is the observation that the energy m/2 of a ν_e from ν_H decay at time τ is only red shifted by a factor of $(\tau/t_U)^{1/2}$ in comparison to the red shift $(t_D/t_U)^{1/2}$ of a massless particle decoupling at t_D.[4] The ν_e's from ν_H decays are therefore $(\tau/t_D)^{1/2}$ more energetic than the usual background ν_e's.

Our calculation of $T_D(m)$, $t_D(m)$, and $n(T_D)$ is standard. We followed the procedure of Szalay and Marx[5] of determining t_D by setting it equal to the time at which the reaction rate for (2)

$$\frac{\langle n(T)\rangle}{\langle n(T)n(T)\sigma(\nu_H+\bar{\nu}_H \to \nu_e+\bar{\nu}_e)|v|\rangle} \tag{4}$$

exceeds the lifetime of the universe[6]

$$\frac{10^{20}}{T^2}\ \text{sec} \tag{5}$$

where T is in °K. For simplicity we have used the equilibrium number density in (4)

$$dn(T) = \frac{8\pi}{h^3}\,\frac{p^2dp}{e^{E/kT}+1} \tag{6}$$

Details and subtleties (such as the assumption of (6)) will be reported elsewhere.[7]

In Table I we give our results for T_D and $n(T_D)$ for a number of values of m. The decoupling time is given by (5) with $T = T_D$. The sum of the present ν_e and $\bar{\nu}_e$ energy densities is then given by

$$\rho = mn(T_D)\left(\frac{1.9°K}{T_D}\right)^3 \int_{t_D}^{t_U} \left(\frac{t}{t_U}\right)^{1/2} \frac{1}{\tau}\, e^{-(t-t_D)/\tau}\, dt \tag{7}$$

We solve (7), for each m, for the lifetime $\tau \equiv \tau_{cos}$ that makes $\rho = \frac{1}{2}\rho_c$. The results are also given in Table I. It may be noted that $\tau \to t_U$ as $m \to 47$ eV (this value differs from the 16 eV of Ref. 3 only because we used 1.9°K as the present neutrino temperature rather than 2.7°K) and as $m \to 7.2$ GeV.[8] The limit is not smooth because, if the ν_H are stable the critical density is given by (1) but, if the ν_H are unstable, the universe is radiation dominated and the critical density is one-half of (1).

The following argument may be used as a basis for a plausible choice of m from this range: We know the lifetime

τ_μ of the muon and we also know that weak interaction lifetimes scale as m^{-5} (or perhaps as $m^{-3}(\delta M^2)^{-1}$ in some models with mass mixing). We may assume that the branching ratio for H-number nonconservation is of the order of the 10^{-10} that appears to characterize muon number nonconservation if it occurs. Thus we expect $\tau(m)$ to behave as

$$\tau_{Th}(m) = 10^{10}\left(\frac{m_\mu}{m}\right)^\alpha \tau_\mu \qquad (8)$$

with $\alpha = 3$ or 5. In Fig. 1 we plot $\tau_{Th}(m)$ and $\tau_{cos}(m)$. One sees that they intersect in the few MeV region--too heavy for ν_H to be ν_μ (m_{ν_μ} is less than ~0.6 MeV[9]) but a very reasonable value for a neutrino associated with charged leptons involved in the rise in the electron positron total cross section and the Perl events.[10]

Deferring details to Ref. 7, we note here briefly the following points: (1) We have checked that the present ν_e density from ν_H decays is too low for the energetic ν_e's to be observed in the Davis solar neutrino experiment.[11] (2) The photons from $\nu_H \to \nu_e + \gamma$ are thermalized by Thomson scattering unless they come from ν_H decay occurring after

$$t \approx t(z=7) = \frac{t_U}{64} \qquad (9)$$

We have checked that, except for m near the uppermost values

its range, the intensity of unthermalized photons in the 1 keV to 1 MeV range is below the measured cosmic X-ray background.[12] (3) We have checked that the densities in our model of energetic ν_e's and $\bar{\nu}_e$'s at the time of nucleosynthesis ($t \approx 200$ sec) is not large enough to effect the ratio of neutrons to protons thereby changing the calculation[6] of the presently observed Helium abundance. (4) We have checked that the present density of energetic ν_e's is not large enough to make a noticeable effect in the proton cosmic ray spectrum in analogy to the 10^{20} eV cutoff produced by thermal photons through $\gamma + p \to \pi + n$.[6] (5) Other decay schemes for ν_H, such as $\nu_H \to \nu_e + \pi$, $\nu_H \to \nu_e + e^+ + e^-$, and so forth, must all end in one or more massless neutrinos. Our value for $\tau_{cos}(m)$ is therefore model independent although approximate. Any neutral lepton must have a lifetime less than $\tau_{cos}(m)$.

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Table Caption

The second and third columns give the decoupling temperature and the equilibrium number density at decoupling for different values of the mass of the heavy neutrino. The fourth column gives the bound on the lifetime, τ, for the decay $\nu_H \to \nu_e + \gamma$ where t_U is the lifetime of the universe.

Figure Caption

The decay width for $\nu_H \to \nu_e + \gamma$ vs. the mass of ν_H. The curve is the minimum width allowed by the cosmological missing mass. The straight lines are the width if it scales like m^3 or m^5 and the branching ratio is 10^{-10}.

Table I

Neutrino Mass (MeV)	Decoupling Temperature (°K)	Number Density at Decoupling (cm^{-3})	Bound from Energy Density
7.2×10^3	3.62×10^{12}	4.76×10^{30}	stable
5.0×10^3	2.62×10^{12}	5.28×10^{30}	$\frac{\tau}{t_U} \leq 3.14 \times 10^{-1}$
1.0×10^3	6.74×10^{11}	8.64×10^{30}	8.50×10^{-4}
5.0×10^2	3.85×10^{11}	1.12×10^{31}	7.03×10^{-5}
1.0×10^2	1.14×10^{11}	2.38×10^{31}	2.62×10^{-7}
50	7.23×10^{10}	3.68×10^{31}	2.85×10^{-8}
10	3.50×10^{10}	1.62×10^{32}	4.74×10^{-10}
5	3.30×10^{10}	3.35×10^{32}	3.11×10^{-10}
1	3.40×10^{10}	5.85×10^{32}	3.05×10^{-9}
10^{-1}	3.40×10^{10}	6.04×10^{32}	2.92×10^{-7}
10^{-2}	3.40×10^{10}	6.04×10^{32}	2.92×10^{-5}
10^{-3}	3.40×10^{10}	6.04×10^{32}	2.92×10^{-3}
10^{-4}	3.40×10^{10}	6.04×10^{32}	2.92×10^{-1}
4.7×10^{-5}	3.40×10^{10}	6.04×10^{32}	stable

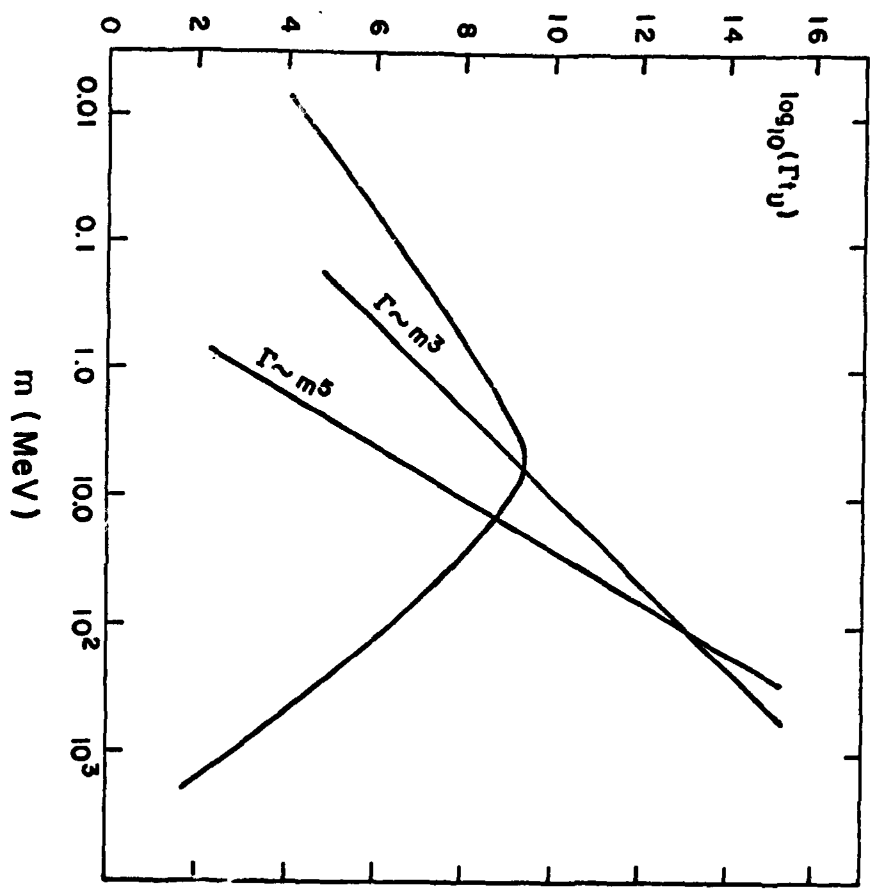

FIGURE 1

References

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8. Lee and Weinberg, in Ref. 1, get 1 to 4 GeV for this lower bound for the heavy neutrino to be stable. In view of the independent estimates for unknown parameters the results are surprisingly close. Whenever we were forced to make approximations we have endeavored to be

cautious, thereby getting a worse bound or limit. Ways of reducing our bounds will be discussed in Ref. 7.

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