would provide a plausible mechanism for closing the universe.

One of us (S.W.) would like to thank Robert Wagoner for helpful conversations, and the other (B.W.L.) wishes to thank Robert Pearson for his assistance in computer calculations.

[a]Deceased.

[b]Operated by Universities Research Association Inc. under contract with the U. S. Energy Research and Development Administration.

[c]On leave 1976–1977 from Harvard University.

[1]See e.g., G. Marx and A. S. Szalay, in *Proceedings of the Neutrino-1972 Conference*, edited by A. Frankel and G. Marx (OMDK-TECHNIOFORM, Budapest, 1972), Vol. I, p. 191; R. Cowsik and J. McClelland, Phys. Rev. Lett. 29, 669 (1972), and also Astrophys. J. 180, 7 (1973).

[2]For a review with references to the original literature, see S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (Wiley, New York, 1972), Chap. 15.

[3]This includes a factor $\frac{3}{4}$ for the effects of Fermi statistics; a factor $\frac{4}{11}$ because electron-positron annihilation has increased the photon temperature by an extra factor of $(\frac{11}{4})^{1/3}$; and a factor of 2 because both neutrinos and antineutrinos are included. The massive neutrinos are, like the photons, supposed to exist in two helicity states. (The 40-eV upper limit given here differs from the 8-eV bound given by Cowsik and McClelland in Ref. 1, because we take account of the heating of photons by electron-positron annihilation, and because we do not assume that the muon and electron-type neutrinos have equal mass.)

[4]To take account of the uncertainty in galactic evolution, we assume that $q_0 < 2$. A value $H_0 = 50.3 \pm 4.3$ km/sec/Mpc is given by A. Sandage and G. A. Tammann, Astrophys. J. 210, 7 (1976). The desntiy 2×10^{-29} g/cm^3 corresponds (for zero cosmological constant) to $q_0 = 2$ and $H_0 = 50$ km/sec/Mpc. [These quantities are defined in terms of the cosmic scale factor $R(t)$ as $(dR/dt)_0 \equiv R_0 H_0$ and $(d^2R/dt^2)_0 \equiv -R_0 H_0^2 q_0$, a subscript 0 denoting the present instant.]

[5]See, e.g., B. W. Lee and S. Weinberg, Phys. Rev. Lett. 38, 1237 (1977). It is possible that the heavy neutral leptons in this model actually have lifetimes which are shorter than the age of the universe, in which case the lower bound on m_L derived here need not be satisfied. [For calculations of neutral-lepton decay rates, see J. N. Bahcall, N. Cabibbo, and A. Yahil, Phys. Rev. Lett. 28, 318 (1972); W. J. Marciano and A. I. Sanda, Phys. Lett. 67B, 303 (1977); T. Goldman and G. J. Stephenson, Jr., Los Alamos Laboratory Report No. LA-UR-77-941 (to be published); and H. Fritsch and P. Minkowski, Phys. Lett. 62B, 72 (1976).]

[6]We suppose here that the chemical potentials associated with any conserved quantum numbers carried by L^0 are vanishingly small. If there were any appreciable degeneracy, the mass density of the heavy neutrinos would greatly exceed reasonable cosmological limits.

[7]This includes contributions of $\gamma, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, e^-, e^+, \mu^-, \mu^+$; plus three color triplets u, d, s, of quarks and the corresponding antiquarks; plus eight massless spin-one gluons.

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.

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

$$\rho = \rho_c = 10^{-2}\ \mathrm{MeV/cm^3}. \quad (1)$$

This density is an order of magnitude greater than 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 has been shown 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 this Letter 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

$$\nu_H+\overline{\nu}_H \leftrightarrow \nu_e+\overline{\nu}_e. \tag{2}$$

(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 principal decay mode is

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

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 $\frac{1}{2}m$ 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 more energetic than the usual background ν_e's by a factor $(m/2kT_D)(\tau/t_D)^{1/2}$.

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

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

exceeds the lifetime of the universe,[6]

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

where T is in degrees kelvin. For simplicity we have used the equilibrium number density in (4) so that

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

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 $\overline{\nu}_e$ energy densities is then given by

$$\rho=mn(T_D)\left(\frac{1.9^\circ\text{K}}{T_D}\right)^3\int_{t_D}^{t_U}\left(\frac{t}{t_U}\right)^{1/2}\times\frac{1}{\tau}\exp\left[\frac{-(t-t_D)}{\tau}\right]dt. \tag{7}$$

TABLE I. 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 upper bound on the ratio τ/t_U between the lifetime, τ, for the decay $\nu_H\to\nu_e+\gamma$, and t_U, the lifetime of the universe.

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}	3.14×10^{-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

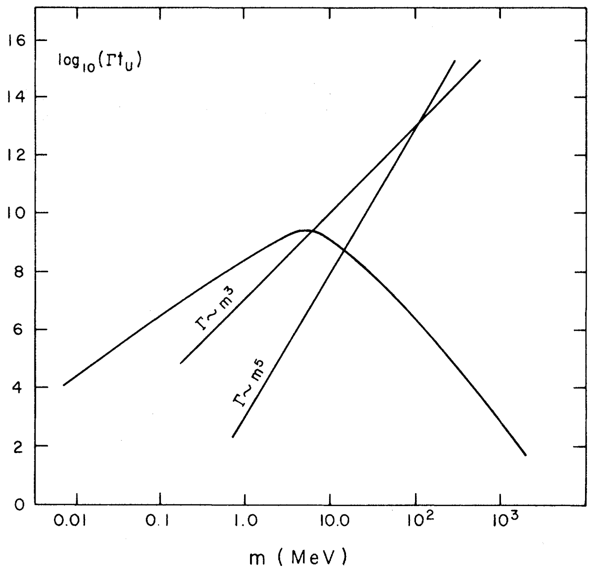

FIG. 1. The decay width for $\nu_H \to \nu_e + \gamma$ vs the mass of ν_H. The curve is the minimum width allowed by the cosmological missing mass. The straight lines are the widths if it scales as m^3 or m^5 and the branching ratio for H-number nonconservation is 10^{-10}. A branching ratio of 10^{-8} raises the curve by two units and makes $\nu_H = \nu_\mu$ more likely if heavy, charged leptons mix with light ($m\beta$ scaling).

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 that given in (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

$$\tau_{\rm Th}(m) = 10^{10}(m_\mu/m)^\alpha \tau_\mu \,, \qquad (8)$$

with $\alpha = 3$ or 5.[9] In Fig. 1 we plot $\tau_{\rm Th}(m)$ 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[10]) 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.[11]

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.[12] (2) The photons from $\nu_H \to \nu_e + \gamma$ are thermalized by Thomson scattering unless they come from ν_H decay occurring after

$$t \approx t(z=7) = t_U/64. \qquad (9)$$

We have checked that, except for m near the uppermost values of its range, the intensity of unthermalized photons in the 1 keV to 1 MeV range is below the measured cosmic x-ray background.[13] (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 $\tau_{\cos}(m)$.

It is a pleasure to acknowledge helpful conversations with K. Brecher, J. Broderick, J. Condon, B. Dennison, A. Gleeson, P. Morrison, L. Sartori, and S. Weinberg. One of us (V.L.T.) was fortunate to have had the opportunity to discuss this work with B. W. Lee shortly before his untimely death in mid-June; we would like to express our sense both of personal loss and of loss to our discipline.

[a]Work supported in part by the U. S. Energy Research and Development Administration, Contract No. E(40-1)3992.

[b]Work supported in part by the National Science Foundation.

[1]B. W. Lee and S. Weinberg, preceding Letter [Phys. Rev. Lett. 39, 165 (1977)]. We are grateful to Professor Luke Mo for obtaining for us an advance copy of their preprint and to B. W. Lee for an interesting discussion.

[2]A. Sandage, Astrophys. J. 178, 1 (1972). In the absence of better calculations of evolutionary effects on galactic brightness, many consider the determination of the deceleration parameter $q_0 = -\ddot{R}(t_0)R(t_0)/\dot{R}^2(t_0) \approx 1$ to be at best suggestive so that the density of the universe need not in fact be near ρ_c. The Hubble constant $H_0 = \dot{R}(t_0)/R(t_0) \approx 55$ km/sec/Mps is, however, fairly well determined so that a density near ρ_c is necessary if the universe is to be bound and densities more than a few times ρ_c are impossible. Thorough reviews are given by S. Weinberg, *Gravitation and Cosmology* (Wiley, New York, 1972), and C. Misner, K. Thorne, and J. Wheeler, *Gravitation* (Freeman, San Francisco, 1973).

[3]R. Cowsik and J. McClelland, Phys. Rev. Lett. 29, 669 (1972).

[4]If the neutrinos are unstable the universe is radiation dominated with—if the current value of the deceleration parameters is correct—a small "arc parameter." This means the radius is still proportional to the square root of the time. See Misner, Thorne, and Wheeler, Ref. 2.

[5]A. Szalay and G. Marx, Acta Phys. Acad. Sci. Hung. 35, 113 (1974).

[6]Weinberg, Ref. 2.

[7]D. A. Dicus, E. W. Kolb, and V. L. Teplitz, to be published.

[8]Lee and Weinberg, 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.

[9]Less crude calculations than that of Eq. (8) may be made on the basis of specific models. We are aware of two recent ones: S. T. Petcov, Dubna Report No. E2-10176, 1976 (to be published) [$SU(2) \otimes U(1)$ with $\nu_\mu - \nu_e$ mixing, $\alpha \simeq 5$], and T. Goldman and G. J. Stephenson, Jr., to be published (model-independent order of magnitudes, for $\alpha = 3$ and $\alpha = 5$). This second paper discusses some astrophysical implication of ν decay. It should be emphasized that $\nu_H = \nu_\mu$ is not ruled out if the estimate of Eq. (8) is too high by 100.

[10]A. Clark *et al.*, Phys. Rev. D 9, 533 (1974).

[11]M. Perl *et al.*, Phys. Rev. Lett. 35, 1489 (1975).

[12]R. Davis, D. Harmer, and K. Hoffman, Phys. Rev. Lett. 20, 1205 (1968).

[13]D. Schwartz and H. Gursky, in *X-Ray Astronomy*, edited by R. Giacconi and H. Gursky (Dordretch-Holland, Boston, 1974).

Mass-Yield Distributions in the Reaction of ^{56}Fe Ions with ^{238}U

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Radiochemical measurements of cross sections for 173 nuclides produced in the reaction of 538-MeV ^{56}Fe ions with thick ^{238}U targets were performed and the mass-yield curve determined. Seven components were resolved, corresponding to three reaction mechanisms: (1) quasielastic transfer (810 ± 160 mb); (2) quasifission (350 ± 55 mb); (3) fusion-fission (190 ± 30 mb). Comparison with data from other systems indicates that the fusion-fission cross section for heavy targets depends strongly on projectile mass and target- to projectile-mass ratio.

It is by now a well-known[1] fact that in heavy-ion reactions where very heavy targets such as U or Bi are involved, the fusion process becomes increasingly less probable as the projectile Z and A get very large, and that a new process often called quasifission overshadows or even replaces it. This is clearly seen when one compares the radiochemical studies of the systems ^{40}Ar + ^{238}U [2] and ^{84}Kr + ^{238}U.[3] In terms of percentage of total-reaction cross section, 9% quasifission and 55% fusion-fission are observed in the former system, while 38% quasifission and only 4% fusion-fission are seen in the latter.

We report here the first measurements on a thick uranium target irradiated with a projectile with Z and A values intermediate between those of ^{40}Ar and ^{84}Kr, with the objective of obtaining information regarding the rate at which quasifission begins to dominate over fusion-fission as the projectile Z and A increase. In addition, the system studied here leads to a fusion nucleus which is essentially the same as that expected for the