

# Cosmological limits on the masses of neutral leptons

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Cosmological arguments are presented which forbid the existence of stable weakly interacting particles in the mass interval  $30 \text{ eV} < m < 2.5 \text{ GeV}$ . Limits are also imposed on the masses of new neutral leptons if the latter are unstable.

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Recently experimenters at SLAC<sup>[1]</sup> announced the discovery of a new charged lepton  $\tau^\pm$  with mass  $\sim 1.8 \text{ GeV}$  and with a suggested decay channel  $\tau \rightarrow \mu(e) + \nu_{\mu(e)} + \nu_\tau$ . A study of the decay spectrum imposes a rather weak limitation on the mass of the new neutrino  $m(\nu_\tau) < 600 \text{ MeV}$  (90% confidence level).<sup>[2]</sup> We shall show that cosmological arguments lead to a much stronger limitation:  $m_{\nu_\tau} < 30 \text{ eV}$ . For a small mass [ $m(\nu_\tau) < 3 \text{ MeV}$ ] we can reason in the same manner as in the case of the muon neutrino. For the latter, Gershteĭn and Zel'dovich<sup>[3]</sup> using cosmological arguments, obtained  $m(\nu_\mu) < 400 \text{ eV}$ . It is stated in<sup>[4]</sup> that if it is assumed that  $m(\nu_e) = m(\nu_\mu)$  then the limit is  $m < 8 \text{ eV}$ . Finally, arguments are advanced in<sup>[5]</sup> favor  $m(\nu_\mu) = 15 \text{ eV}$ . The idea in the cited paper is the following. When the temperature of the expanding universe is high, i. e.,  $T \gtrsim m_\nu$ , the density of the massive neutrinos is the same as that of the photons. With further expansion and cooling ( $T < m_\nu$ ) the annihilation  $\nu + \bar{\nu} \rightarrow \text{anything}$  does not have time to take place (if  $m_\nu \lesssim 3 \text{ MeV}$ ). At the present time the temperature and the density of the electromagnetic relict radiation are respectively  $2.7 \text{ K}$  and  $400 \text{ cm}^{-3}$ . Taking into account the arguments advanced in<sup>[6]</sup>, we obtain  $n_\nu + n_{\bar{\nu}} \approx 200 \text{ cm}^{-3}$ , and the corresponding mass density is  $\rho_\nu = 200 m_\nu \text{ g/cm}^3$ .

At the contemporary value of the Hubble constant, the critical density is  $\rho_c = 5 \times 10^{-30} \text{ g/cm}^3$ . The large density leads to a closed model of the universe, to a large slowing-down parameter  $q_0 = \Omega/2 = \rho/2\rho_c > 0.5$ , and to a small age of the universe,  $T < 12 \times 10^9$  years. Astrophysical observations contradict this picture. With reasonable caution we can conclude that  $\rho_\nu < 2\rho_c$ . This corresponds to  $m_\nu < 30 \text{ eV}$ .

For  $\nu_\tau$  it is necessary to consider also the case  $m_{\nu_\tau} > 3 \text{ MeV}$ . With increasing mass, the annihilation cross section increases, so that the assumption  $n(\nu_\tau) \approx n(\gamma)$  now turns out to be incorrect. We estimate the residual (quenched) concentration of  $\nu_\tau$ , following,<sup>[7]</sup> where the concentration of the residual quarks was considered.

For the rate of the  $\nu_\tau \bar{\nu}_\tau$  annihilation at rest in the Weinberg-Salam model,

with allowance for the four types of light leptons, we obtain  $\sigma v = G^2 m^2 / \pi$ , where  $G = 10^{-5} / m_p^2$ ,  $m \equiv m_{\nu_\tau}$ .

The time dependence of the relative concentration  $r = n(\nu_\tau) / n(\gamma)$  is determined by the equation

$$\frac{dr}{dt} = -\sigma v n(\gamma) (r^2 - r_{eq}^2), \quad (1)$$

where  $r_{eq}$  is the thermodynamic equilibrium concentration. For small values of  $\Theta = T / m r_{eq} \approx \Theta^{-3/2} \exp(-1/\Theta)$ .  $\Theta = t^{-1/2} (\text{sec}) m^{-1} (\text{MeV})$  so that  $r_{eq}$  decreases rapidly with increasing  $t$ . The instant of quenching is determined by the condition  $4\sigma v n_{eq}(\nu_\tau) t \Theta = 1$ . After this instant,  $r_{eq}$  becomes small in comparison with the real concentration. The residual (as  $t \rightarrow \infty$ ) relative concentration is determined by integrating Eq. (1) with  $r_{eq} = 0$ . The result is

$$r_\infty \approx 3 \times 10^{-7} (m_p / m)^3, \quad (2)$$

Numerical integration of Eq. (1) gives the same answer for  $m_\nu \approx 2.5 m_p$ . The increase of the neutrino density in comparison with quarks<sup>[7]</sup> is due to the smallness of the annihilation cross section. The present-day energy density of new neutrinos is

$$\rho(\nu_\tau) = \frac{4}{11} n(\gamma) m^3 \times 10^{-7} (m_p / m)^3 = 7 \times 10^{-29} (m_p / m)^2 \text{ g/cm}^3, \quad (3)$$

where the factor  $\frac{4}{11}$  is connected with the increase of the photon density as a result of  $e^+e^-$  annihilation.<sup>[6]</sup> From the upper bound of  $\rho$  we obtain  $m(\nu_\tau) > 2.5$  GeV. Thus, the only remaining possibility is  $m(\nu_\tau) < 30$  eV.

It should be noted that the condensation of matter into stars can lead to an increase of the density  $\nu_\tau$  and to the appearance of secondary annihilation. If a fraction  $\beta$  of the heavy neutrinos annihilates at a certain red shift  $z$ , the energy density of the decay products will at the present time be smaller by a factor  $(1+z)$ . The resultant energy density, including the remaining heavy neutrinos and products of their decay, is equal to

$$\rho' = \rho_0 (1 - \beta) + \frac{\rho_0 \beta}{1 + z}, \quad (4)$$

where  $\rho_0$  is defined by Eq. (3).

At first glance it appears that at  $(1 - \beta) \ll 1$  and  $z \gg 1$  this makes the limits on the mass of  $\nu_\tau$  much worse. Actually, about half of entire energy release in annihilation goes over ultimately into electromagnetic radiation. The density of the relict radiation is  $4 \times 10^{-34}$ , that of the optical radiation is  $4 \times 10^{-36}$ , and that of the x rays is  $10^{-37}$  g/cm<sup>3</sup>. Even the weakest limit yields

$$\frac{\rho \beta}{1 + z} < 4 \times 10^{-34} \text{ g/cm}^3,$$

and for example, for  $\beta = 0.1$  and  $z = 100$  we obtain  $\rho < 4 \times 10^{-31}$  and  $m > 12$  GeV. We see that the possibility of secondary annihilation improves the lower limit for  $m(\nu_\tau)$ .

The obtained limits are valid for a stable neutral lepton, i. e., for a lepton having a new conserved quantum number. If the new neutral lepton is of the electronic or muonic type<sup>1)</sup> it can decay into  $\nu \bar{\nu} \nu_e$  or  $\nu_e \gamma$ . The lifetime of this particle will be of the order of  $\tau = 2 \times 10^{-6} (m_\mu / m)^5$  sec. This time exceeds the

cosmological ( $t_c = 6 \times 10^{17}$  sec) if  $m < 2 \times 10^{-5} m_\mu = 2$  keV. This condition, however, is not necessary. If the particle has decayed at a certain instant  $t = t_c(1+z)^{-3/2}$ , the energy density at the present time will be smaller by a factor  $(1+z)$ . Even this can be too large. In fact

$$\rho_{\text{today}} = \frac{200m}{1+z} = 200m(\tau/t_c)^{2/3}$$

and this will be less than  $\rho_c$  if  $m > 10^{-4} m_\mu = 10$  keV.

A model for the violation of the muon charge was proposed in<sup>[8]</sup>. In this model  $W(\nu \rightarrow \nu_e + \gamma) = 10^{-2} (m_\nu/m_\mu)^5 \text{ sec}^{-1}$ . In this case the cosmological considerations exclude the mass interval  $30 \text{ eV} < m(\nu_\tau) < 2 \text{ MeV}$ .

It is most probable that the masses of all the neutrinos ( $\nu_e, \nu_\mu, \nu_\tau$ ) are equal to zero. It is puzzling why the electric charge in the  $(l, \nu_l)$  pairs is connected with the mass. Another interesting problem connected with the neutrinos is whether there exists a right-hand neutrino having no weak interaction, but with undisputed gravitational interaction.<sup>[9]</sup> Using the ideas of<sup>[10]</sup>, a limitation on the number of types of neutrinos was obtained in<sup>[11]</sup>.

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<sup>1</sup>It should be remembered that if  $\tau$  is of the electronic type, then the existence of the new neutrino is not obligatory.

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