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 eV $< m <$ 2.5 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[1] announced the discovery of a new charged lepton $\tau^{\pm}$ with mass ~1.8 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 $m(\nu_{\tau}) < 600$ MeV (90% confidence level).[2] We shall show that cosmological arguments lead to a much stronger limitation: $m_{\nu_\tau} < 30$ eV. For a small mass [$m(\nu_{\tau}) < 3$ meV] we can reason in the same manner as in the case of the muon neutrino. For the latter, Gershteĭn and Zel'dovich[3] using cosmological arguments, obtained $m(\nu_{\mu}) < 400$ eV. It is stated in[4] that if it is assumed that $m(\nu_e) = m(\nu_{\mu})$ then the limit is $m < 8$ eV. Finally, arguments are advanced in[5] favor $m(\nu_{\mu}) = 15$ 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 $\nu + \tilde{\nu} \rightarrow$ anything does not have time to take place (if $m_{\nu} \lesssim 3$ MeV). At the present time the temperature and the density of the electromagnetic relict radiation are respectively 2.7 K and 400 cm^{-3}. Taking into account the arguments advanced in[6], we obtain $n_{\nu} + n_{\tilde{\nu}} \approx 200$ cm^{-3}, and the corresponding mass density is $\rho_{\nu} = 200\ m_{\nu}$ g/cm^3.

At the contemporary value of the Hubble constant, the critical density is $\rho_c = 5 \times 10^{-30}$ 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 $m_{\nu} < 30$ eV.

For ν_{τ} it is necessary to consider also the case $m_{\nu_\tau} > 3$ 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 ν_{τ}, following,[7] where the concentration of the residual quarks was considered.

For the rate of the $\nu_{\tau}\tilde{\nu}_{\tau}$ 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

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

where r_{eq} is the thermodynamic equilibrium concentration. For small values of $\Theta = T/m$ $r_{eq} \approx \Theta^{-3/2}\exp(-1/\Theta)$. $\Theta = t^{-1/2}$ (sec)m^{-1} (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 $t \to \infty$) relative concentration is determined by integrating Eq. (1) with $r_{eq} = 0$. The result is

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

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[7] is due to the smallness of the annihilation cross section. The present-day energy density of new neutrinos is

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

where the factor $\frac{4}{11}$ is connected with the increase of the photon density as a result of e^+e^- annihilation.[6] From the upper bound of ρ 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 ν_τ and to the appearance of secondary annihilation. If a fraction β 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

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

where ρ_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 ν_τ much worse. Actually, about half of entire energy release in annihilation goes over ultimately into electromagnetic radiation. The density of the relict radiation is 4×10^{-34}, that of the optical radiation is 4×10^{-36}, and that of the x rays is 10^{-37} g/cm^3. 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 thus 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[1)] 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 ($t_c = 6\times10^{17}$ sec) if $m < 2\times10^{-5}\, m_\mu = 2$ 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 ρ_c if $m > 10^{-4} m_\mu = 10$ keV.

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

It is most probable that the masses of all the neutrinos (ν_e, ν_μ, ν_τ) are equal to zero. It is puzzling why the electric charge in the (l, ν_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.[9] Using the ideas of[10], a limitation on the number of types of neutrinos was obtained in[11].

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[1)] It should be remembered that if τ is of the electronic type, then the existence of the new neutrino is not obligatory.

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