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Closing the windows on MeV tau neutrinos

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We analyze various constraints on the "visible" decay modes of a massive τ neutrino, $\nu_\tau \to \nu' \gamma$ and $\nu_\tau \to \nu' e^+e^-$, where ν' is a light neutrino. We point out that the BEBC experiment implies a new upper limit on the ν_τ transition magnetic moment, $\mu_{\rm tran} \leqslant 1.1 \times 10^{-9}$ $({\rm MeV}/m_{\nu_\tau})^2$ $\mu_{\rm B}$. Combining BEBC constraints with constraints arising from supernova observations and primordial nucleosynthesis calculations, we show that these "visible" modes cannot be the dominant decay modes of the MeV τ neutrino.

The tau neutrino (ν_τ) has eluded direct detection thus far. Yet, its existence has been inferred, along with some salient properties such as its spin, from τ lepton decay and neutrino interaction data. At present, there is an experimental bound on its mass, $m_{\nu_\tau} \leqslant 31$ MeV [1].

A ν_τ with a mass in the MeV range has profound implications for laboratory experiments, as well as for cosmology and astrophysics. For example, it has recently been pointed out that $m_{\nu_\tau} \geqslant 0.3$ MeV (for Dirac neutrino) or $\geqslant 0.5$ MeV (for Majorana neutrino) will contradict primordial nucleosynthesis calculations, if the ν_τ lifetime is longer than $\mathcal{O}(100)$ seconds [2]. This constraint is independent of the decay products, and is a consequence of the fact that the energy density of a non-relativistic species decreases with the cosmic scale factor R as R^{-3}, while that of a massless species decreases as R^{-4}. Thus, we may conclude that an MeV ν_τ should decay into relativistic particles with a lifetime of less than $\mathcal{O}(100)$ seconds (or annihilate sufficiently fast), so as to ameliorate the nucleosynthesis bound [#1]. This might occur if the neutrino has a large diagonal magnetic moment [4], or possibly a non-zero electric charge [5], which would allow rapid annihilation in the early universe into e^+e^- pairs. Alternatively, ν_τ may decay into $\nu'\gamma$ or into $\nu' e^+e^-$, where ν' stands for a lighter neutrino (i.e. ν_e , ν_μ, a sterile neutrino, or their antiparticles). In this note, we use the BEBC (Big European Bubble Chamber) beam dump experiment (WA66 Collaboration) to greatly constrain the possible visible decay modes of ν_τ. Then, combining these constraints with the nucleosynthesis bound and constraints arising from supernova observations, we rule out the "visible" modes as the dominant ones.

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[#1] If ν_τ decays into a light neutrino and a Goldstone boson (Majoron), the decay lifetime is constrained to be < 40 s for ν_τ mass in the MeV range [3].

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In ref. [6], Cooper-Sarkar et al. have shown how the BEBC beam dump experiment restricts the diagonal magnetic moment of a stable ν_τ to be $\mu_{\text{diag}} \leqslant 5.4 \times 10^{-7} \mu_{\text{B}}$, thus severely restricting the cosmological annihilation scenario [4]. This bound is the consequence of a limit on the rate of ν_τ scattering into electrons. It is noted here that the transition magnetic moment of ν_τ is also constrained by the same experiment. We determine a new upper limit, $\mu_{\text{tran}} \leqslant 1.1 \times 10^{-9}\ (\text{MeV}/m_{\nu_\tau})^2\ \mu_{\text{B}}$, from the non-observation of the radiative decay, $\nu_\tau \to \nu' \gamma$. The lifetime for the decay $\nu_\tau \to \nu' e^+ e^-$ is bounded by $\tau_{\nu' e^+ e^-} \gtrsim 0.18\ (m_{\nu_\tau}/\text{MeV})$ s. Both of these limits hold for arbitrary ν_τ masses, but assume that the ν_τ lifetime is $\tau \gtrsim 10^{-12}$ s Furthermore, the electric charge of ν_τ may be bounded by $Q_{\nu_\tau} \leqslant 4 \times 10^{-4} e$, which is comparable to the limit from the SLAC beam dump experiment [7].

The BEBC beam dump experiment produces so-called "prompt" neutrinos, from the decays of heavy charmed mesons D and D_s, produced upstream where a proton beam impacts on a fixed target [8]. The target is sufficiently thick to re-absorb the lighter mesons, K and π, before their decay, thus suppressing the production of non-prompt relative to prompt neutrinos. The experiment thereby offers a wide kinematic window on neutrino masses, roughly $M_\nu \lesssim \mathcal{O}(M_D)$. The results in this paper will only require that the ν_τ's be produced in the decay of the D_s mesons, $D_s \to \tau \nu_\tau$. This allows us to constrain tau neutrino masses in the range, $m_{\nu_\tau} \lesssim m_{D_s} - m_\tau \simeq 180\,\text{MeV}$, which greatly exceeds the present experimental bound of 31 MeV [1]. The beam dump experiment has been used in the past to obtain stringent bounds on production and decays of ν_τ. The results were presented as limits on the mixing angles in the leptonic sector [9].

If the ν_τ's are sufficiently long-lived, they will bypass the bubble chamber before decaying. Conversely, if they are sufficiently short-lived, they will all decay before reaching the bubble chamber and again no decays will be observed. Thus, a null result in the search for ν_τ decays implies both an upper and lower bound on the lifetime. The number of decays expected to be seen in a detector of length d ($\sim$ 1 m) at a distance L ($\sim$ 400 m) from the source is given by

$$N = \Phi(\nu_\tau) \exp\{-L/\gamma\tau\} [1 - \exp\{-d/\gamma\tau\}] \times (\tau/\tau_p) A\epsilon\,, \tag{1}$$

for a given flux $\Phi(\nu_\tau)$ of tau neutrinos. The Lorentz factor is denoted by γ, and the partial width to the observed channel is $1/\tau_p$. The acceptance A is determined by the detector geometry with a Monte Carlo simulation. The efficiency ϵ of the detector is determined from the efficiencies of the various detector elements for detecting the products in a given decay channel. Eq. (1) reduces in the limit of a large total lifetime, $d/\gamma\tau \ll L/\gamma\tau \ll 1$, to

$$N \simeq \Phi(\nu_\tau) d A \epsilon / \gamma \tau_p\,. \tag{2}$$

Since the ν_τ flux in the WA66 experiment was $\mathcal{O}(10^7)$ cm^{-2}, the detector volume was $\simeq$ 16.6 m^3, and the average neutrino energy was $\mathcal{O}(10)$ GeV, it is clear from eq. (2) that the experiment was sensitive to a partial lifetime $\tau_p \sim \mathcal{O}(1)$ s for $m_{\nu_\tau} \sim \mathcal{O}(1)$ MeV. The bounds on the partial lifetime τ_p to be explained below will not apply if

$$\tau \lesssim 2.5 \times 10^{-12} \left\{ \frac{m_{\nu_\tau}}{\text{MeV}} \right\} \text{s}\,, \tag{3}$$

in which case the number of events recorded in the bubble chamber will be $\lesssim 1$.

No events were observed in the experiment consistent with radiative $\nu_\tau \to \nu' \gamma$ decay [10]. This implies a model-independent lower bound on the partial lifetime [10]

$$\tau_{\nu'\gamma} \gtrsim 0.15 \left\{ \frac{m_{\nu_\tau}}{\text{MeV}} \right\} \text{s}\,. \tag{4}$$

This constraint leads immediately to an upper bound on the transition magnetic moment of the tau neutrino, μ_{tran}. The partial lifetime for the radiative decay, due to a transition magnetic moment μ_{tran}, is

$$\tau^{-1}_{\nu'\gamma} = \frac{\alpha}{8} \left(\frac{\mu_{\text{tran}}}{\mu_{\text{B}}} \right)^2 \left(\frac{m_{\nu_\tau}}{m_e} \right)^2 m_{\nu_\tau}\,, \tag{5}$$

resulting in the bound

$$\mu_{\text{tran}} \lesssim 1.1 \times 10^{-9} \left\{ \frac{\text{MeV}}{m_{\nu_\tau}} \right\}^2 \mu_{\text{B}}\,. \tag{6}$$

This bound is much more stringent for MeV ν_τ than the corresponding bound for the diagonal magnetic moment [6], and is valid for arbitrarily small ν_τ mass.

An MeV ν_τ may also decay into $\nu' e^+ e^-$, where ν' is ν_e, ν_μ, a sterile neutrino, or their antiparticles. The CHARM experiment rules out this possibility for ν_τ masses greater than 10 MeV if the decay is rapid [11]. For the decay into $\nu' e^+ e^-$, the BEBC experiment provides a model-independent bound similar to eq. (4) [10]:

$$\tau_{\nu' e^+ e^-} \gtrsim 0.18 \left\{ \frac{m_{\nu_\tau}}{\mathrm{MeV}} \right\} \mathrm{s} \quad \text{if} \quad \mathrm{m}_{\nu_\tau} \gtrsim 2\mathrm{m}_e . \tag{7}$$

The slight (20%) improvement relative to eq. (4) is due to the difference in conversion efficiencies. Note that this limit is model-independent, and does not assume the decay to occur via neutrino mixing in the charged current. As such, it applies to scenarios where the decay is mediated by exotic particles.

The BEBC beam dump experiment also implies an upper limit on the electric charge of ν_τ, $Q_{\nu_\tau} = q\, e$, from a consideration of the elastic scattering, $\nu_\tau e^- \to \nu_\tau e^-$. (The weak contributions are too small and can be ignored [12].) The cross section for scattering into a forward cone defined by the BEBC cut on the electromagnetic shower energy, $T_e \gtrsim T_{\min} = 0.5$ GeV, is

$$\sigma \simeq 4\pi\, r_e^2 \, \frac{q^2}{32\pi^2} \, \frac{m_e}{T_{\min}} , \tag{8}$$

in the limit $m_e \lesssim m_{\nu_\tau} \ll T_{\min} \ll E \sim 20$ GeV. Comparing this to the upper bound on the cross-section implied by the upper bound on the diagonal magnetic moment [6], we obtain $q \leqslant 4 \times 10^{-4}$. This bound is comparable to the SLAC beam dump limit [7]. It may be possible to strengthen this bound by a detailed Monte Carlo simulation.

The BEBC beam dump limits are complementary to the various constraints on MeV ν_τ from cosmology and astrophysics. For the most part, these indirect limits from cosmology and astrophysics are not applicable when the lifetimes become very short. Eqs. (4), (7) and (3) constrain the lifetime of an MeV ν_τ to be either greater than a second or less than about 10^{-12} seconds. We summarize the relevant cosmological and astrophysical limits and show how both these allowed windows are excluded for dominant decays into visible modes.

The radiative lifetime can be bounded from gamma ray observations by the Solar Maximum Mission Satellite which was in operation at the time when the supernova SN1987A explosion was reported. In ref. [13], it was found that for neutrinos with masses less than about 50 MeV, the radiative lifetime must satisfy

$$\tau_{\nu' \gamma} > 8.4 \times 10^8 \left\{ \frac{\mathrm{MeV}}{m_{\nu_\tau}} \right\} \mathrm{s} . \tag{9}$$

A similar bound applies to the lifetime for $\nu_\tau \to \nu' e^+ e^-$ decay [14,15]. However, these bounds do not apply if the decay of ν_τ is so rapid that the photon gets trapped inside the progenitor, which has a radius of $R_{\mathrm{pro}} \lesssim 3 \times 10^{12}$ cm. Using the temperature of the neutrino sphere to be $T_\nu \sim 6$ MeV, we see that the constraint on decay does not apply if

$$\tau \lesssim \begin{cases} 10\,(m_{\nu_\tau}/\mathrm{MeV})\ \mathrm{s}, & \text{if } m_{\nu_\tau} \lesssim 10\ \mathrm{MeV}, \\ 50\,(m_{\nu_\tau}/\mathrm{MeV})^{1/2}\ \mathrm{s}, & \text{if } m_{\nu_\tau} \gtrsim 10\ \mathrm{MeV}. \end{cases} \tag{10}$$

For shorter lifetimes, there are other bounds which must be considered. It has been shown that, if the neutrino decays within the progenitor into visible channels, then the energy which it deposits (10^{53} ergs) will greatly enhance the supernova luminosity, thus conflicting with the measured light curves. However, if the neutrino decays within the neutrino-sphere, then its visible decay products will thermalize, thus avoiding the constraint from the supernova luminosity [14,15]. Assuming the neutrino-sphere radius is be $\mathcal{O}(10)$ km $\sim \mathcal{O}(10^{-6}) R_{\mathrm{pro}}$, we find that the supernova luminosity (SNL) bound does not apply if the lifetime is less than $\mathcal{O}(10^{-6})$ times the bound in eq. (10). This bound is complementary to the regions ruled out by BEBC, as seen in fig. 1.

While it is true that these supernova bounds hold for Dirac as well as Majorana neutrinos, it has been noted [16] that the supernova data may be used to rule out Dirac neutrinos with masses greater than $\mathcal{O}(20)$ keV. However, it is possible in some models to evade this bound [17]. For MeV neutrinos, the right handed species is already in thermal equilibrium. Therefore, models for trapping are less constrained. The constraint is model dependent and will not be considered further here.

Thus, we see that the only allowed window for visible decay modes is when ν_τ decays so rapidly that its lifetime satisfies eq. (3). However, we are able to show that neither $\nu' \gamma$ nor $\nu' e^+ e^-$ can be the dominant decay mode satisfying eq. (3). Suppose that the radiative decay dominates. From the experimental bound on the ν_τ magnetic moment, viz., $\mu \leqslant 4 \times 10^{-6} \mu_{\mathrm{B}}$ [18], which holds for both diagonal as well as transition moments, we first derive a limit $m_{\nu_\tau} \gtrsim 8$ MeV for

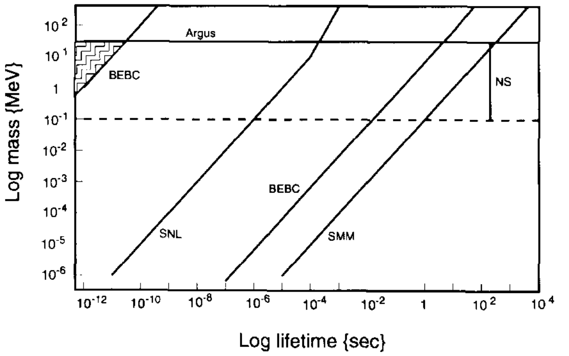

Fig. 1. Bounds on radiative and e^+e^- decays of ν_τ. Curve labels lie on the forbidden side of curves: lab mass bound (Argus), nucleosynthesis (NS), supernova luminosity (SNL), Solar Max Mission (SMM). The bounds apply to the radiative decay for all m_{ν_τ} shown, but apply to the e^+e^- decay only for $m_{\nu_\tau} \gtrsim 2\ m_e$. The hatched region for $\tau \lesssim 10^{-10}$ s is consistent with all bounds plotted, but is ruled out as the dominant decay mode, for non-sterile neutrinos, by the analysis of ν_e and ν_μ magnetic moments in the text.

eq. (3) to be satisfied. For m_{ν_τ} in the range 8–31 MeV, there is an open window for radiative decay, if the transition magnetic moment is near the experimental limit. However, if the decay product involves ν_e, ν_μ or their antiparticles, we can use the better experimental limits on μ_{tran} for ν_e and ν_μ. These limits are $\mu_{\text{tran}} \leqslant 1.08 \times 10^{-9}\ \mu_{\text{B}}$ for ν_e, and $\mu_{\text{tran}} \leqslant 7.4 \times 10^{-10}\ \mu_{\text{B}}$ for ν_μ. So the decay $\nu_\tau \to \nu_{e,\mu}\gamma$ cannot satisfy eq. (3). This leaves decay into a sterile species as the only option. But if a sterile species (ν_s) is involved, the decay may be constrained from nucleosynthesis [19], since ν_s will contribute to the energy density. Helium may be overproduced for lighter ν_τ masses. Thus, the window for the rapid decay into $\nu_s\gamma$ may be closed further with a detailed nucleosynthesis calculation.

Similar arguments can be used to show that $\nu_\tau \to \nu' e^+e^-$ cannot be the dominant decay. There is an upper limit from the search for $e^+e^- \to \nu\bar{\nu}\gamma$ on the effective four-fermion interaction $G_{\text{eff}} \lesssim 6\ G_{\text{F}}$ [20], where G_{F} is the Fermi coupling. As a result, the lifetime will be $\geqslant 10^{-4}$ s, outside the range in eq. (3).

Of course, none of the constraints mentioned above shed any light on neutrino decay into a light neutrino and scalar [3]. Such decays are indeed predicted in many models where the see-saw mechanism is used to generate a neutrino mass. Similarly, invisible decays into three light neutrinos also seem to be a viable scenario [21]. The results of this paper seem to suggest that if the ν_τ mass is in the MeV range, these invisible decays are the only possibilities.

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