What Do We Know About the Tau Neutrino?

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Abstract

In this talk I review the present bounds on the tau neutrino, concentrating on the possibility of bringing the mass bound below an MeV.

1 Introduction

Given the recent evidence for the detection of the top quark, all the particles in the standard model have been directly detected, save for the tau neutrino and the Higgs particle. Of course, while it would not be difficult to believe in a world with no Higgs, one would be rather hard pressed to find a theory consistent with the data that did not contain a tau neutrino. Thus, I mention the direct detection issue only to point out that, compared to the other leptons, we know very little about the tau neutrino.

Neutrinos are notoriously slippery objects as a consequence of their small masses and cross sections. One need only look at the checkered history of neutrino mass searches to appreciate this fact. The tau neutrino is even more troublesome to detect, compared to the other neutrino species, due the short lifetime of the tau lepton. Below I will review the experimental status of tau neutrino mass searches as well as bounds on the tau neutrino magnetic moment. I will deal here only with direct searches. As will be seen, the bounds are rather weak compared to the other neutrino species.

More stringent limits can be obtained from the fact the the primordial helium abundance is sensitive to massive neutrinos. This fact is really a fortunate numerical accident. The present lab bounds on the tau neutrino mass\(^2\) (24 MeV) is just in the range where primordial nucleosynthesis feels the effects of the mass. The nucleosynthesis bounds will rule out neutrino masses from the lab bound down to a few hundred keV. The great success of the primordial nucleosynthesis predictions give us confidence in these bounds. However, as Gary Steigman discussed in his talk, there have been some difficult issues raised lately regarding a dearth of Helium. I will not discuss this issue
here and refer the interested reader to Steigmans’ talk in these proceedings.

The bounds derived from primordial nucleosynthesis will only apply for lifetimes greater than $O(100) \text{ sec}$. Thus, if we really want to rule out MeV neutrinos, then a detailed study of possible decay modes is necessary. In this talk I will address the issue of excluding possible decay windows. Some decay modes may be ruled out without recourse to model considerations. But for other modes I will be forced to resort to theoretical arguments to rule out regions of parameter space.

It will be shown that an MeV neutrinos will most probably have to decay rapidly ($\tau < O(100) \text{ sec.}$) to a massless scalar or three light neutrinos. Cosmologically, a tau neutrino mass may fit quite nicely. Given the family hierarchy structure it is expected that the tau neutrino should be the heaviest of the three neutrinos. Thus, it is tempting to use a heavy tau neutrino to address several cosmological issues. For instance, an MeV Majorana neutrino mass could play a role in generating a lepton number in the early universe, which in turn could be transformed into a net baryon asymmetry through non-perturbative effects [1]. Thus, ruling out MeV neutrinos would exclude a body of theoretical proposals.

2 Lab Bounds

Recently the lab bound on the tau neutrino mass has decreased from 30 MeV to 24 MeV at 95% CL. This bound comes from looking for missing energy in the decay $\tau \rightarrow 5\pi^\pm(\pi^0)$. The improvement in the bound was rather fortuitous as it essentially comes from one event. Prospects for improving the bound are limited by the transverse momentum resolution.

The bounds on the magnetic moment are:

\[
\mu_{\tau\tau} < 5.4 \times 10^{-7} \mu_B \quad ^3
\]
\[
\mu_{\tau\tau} < 10^{-9} \left(\frac{m_\nu}{\text{MeV}}\right)^2 \mu_B \quad ^4
\]
\[
\mu_{\tau\tau} < 4.0 \times 10^{-6} \mu_B \quad ^5
\]

If there is no mass dependence stated above, then the bound is mass independent. I’ve copied these bounds here, because, as we will see later, ruling out MeV neutrinos will entail the use of these bounds [1]. The bounds for the mass and the magnetic moments, are much less stringent than the bounds for the lighter neutrinos. However, we may do much better using constraints from cosmology and astrophysics.

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[1] There are more stringent constraints on the magnetic moment coming from stellar cooling. But they will not apply for MeV neutrinos.
3 Cosmological and Astrophysical Bounds

It has been known for quite some time that a neutrino species with mass in the range

\[
90 \text{ eV} \lesssim m_\nu \lesssim 2 \text{ GeV}
\] (2)

would lead to our universe being much younger than it is. The reason for this is that as we increase the energy density in neutrinos, the expansion rate of the universe increases, thus the universe would have evolved to its present state is a much shorter period. This is a statement of flatness. Given the smallness of the spatial curvature, we see that the potential energy is commensurate with the kinetic, thus any increase in the potential energy must result in a faster expansion rate.

While this bound is quite stringent, it is only valid for neutrinos which are effectively stable, and, as such not as powerful as we would have hoped. There are several ways in which one can do better. Let us first consider the effects of an MeV neutrino on the primordial element abundances. The relevant scale for nucleosynthesis is \(O(\text{MeV})\), thus we would expect that a neutrino species with a mass in the range we’re interested in could indeed have an effect (this is the fortuitous numerics mentioned in the introduction). A neutrino species with an MeV mass will enhance the energy density relative to the contribution from a massless neutrino at 1 MeV\([13,15,14]\). This is because the energy density in the massless species will be redshifted and hence diluted relative to the energy density of a massive species. The resulting increased expansion rate will have the effect of increasing the neutron to proton ratio at the time of the freeze out of the weak interactions, which is at about \(T \approx 1\text{MeV}\). Once the weak interaction freezes out the neutron to proton ratio will decrease only as a result of free neutron decay. This decrease will continue until the onset of deuterium formation, which begins at \(T = .065 \text{ MeV}\). Essentially all the free neutrons left at this temperature will end up in Helium.

One calculates the final Helium abundance by solving the Boltzmann kinetic equation, as has become routine for practitioners in the field\[8\]. Here I only mention an effect that differs from the standard calculations. Since our result will be sensitive to the time between weak freeze out and deuterium formation we must be mindful to calculate the time temperature relation with care. In the case where the energy density is dominated by either relativistic or non-relativistic species the time temperature relationship is given by

\[
\frac{d}{dt}T = -HT.
\] (3)

However, if there are relativistic and non-relativistic species contributing nearly commensurate
amounts to the energy density, and furthermore they are exchanging energy, then covariant energy conservation demands that the time temperature relation be [3]

\[
\frac{d}{dt} T = -H \left( 1 + \frac{0.2r}{g_{*}^{rel} + 0.42r \frac{m}{T}} \right) - \frac{14r(\frac{3}{2} + \frac{m}{T})}{g_{*}^{rel} + 0.42r \frac{m}{T}}.
\] (4)

Where \( g_{*}^{rel} \) counts the number of degrees of freedom in relativistic species and \( r \) is the ratio of the number density of massive neutrinos to massless.

After solving the kinetic equations necessary to calculate the Helium abundance it is found that for majorana masses the forbidden mass range is [13]

\[
0.5 < m_m < 35 \text{ MeV},
\] (5)

and for Dirac neutrinos the forbidden range is

\[
3 < m_D < 35 \text{ MeV}.
\] (6)

This range is found by imposing the constraint that the net Helium abundance be less than the amount of Helium that would have been produced had there been 3.3 massless Weyl neutrino species. I refer the reader to Gary Steigmans’ talk in these proceedings for considerations regarding the confidence of this bound.

In arriving at the bounds on the Dirac mass we have assumed that the right handed species does not reach thermal equilibrium below the temperature of the QCD phase transition, if the neutrino mass is less than 300 keV [23]. However, we can do better than this [24]. Even if the right handed neutrino does not reach thermal equilibrium, its out of equilibrium production rate can yield a contribution to the energy density which can still enhance the Helium abundance. Right handed neutrinos can be produced through the following processes

\[
\pi^0 \rightarrow \nu_\tau + \bar{\nu}_\tau^+,
\]

\[
l_1 l_2 \rightarrow l_3 \nu_\mu(\tau)^+,
\]

\[
l\bar{l} \rightarrow \nu_\mu(\tau)^+ + \bar{\nu}_\mu(\tau)^+.
\] (7)

In this list the + subscript refers to the “wrong” helicity state, that is, right handed neutrinos and left handed anti-neutrinos. Once we take into account these out of equilibrium processes it is found that the upper bound on the Dirac neutrino mass is 190 keV if the temperature of the QCD phase transition is assumed to be 200 MeV. We again use the constraint \( N_{eff} < 3.3 \). The bound depends upon the temperature of the QCD phase transition because all right handed neutrinos produced
prior to the transition will be have their energy diluted due to the net entropy dumped into the bath from the transition. Thus as the temperature of the transition is raised the bound becomes more stringent.

The bounds discussed above all assumed that the neutrino is stable on the time scale of nucleosynthesis, which is about 100 seconds. What if the neutrino decays with a lifetime shorter than this scale? Is this a viable scenario? Consider the possible decay modes:

\[ (i) \quad \nu_\tau \rightarrow 3\nu \]
\[ (ii) \quad \nu_\tau \rightarrow \nu + \gamma \text{ or } \nu e^+ e^- \]
\[ (iii) \quad \nu_\tau \rightarrow \nu + H. \]  

We would like to be able to eliminate possibilities in a model independent fashion. However, for the decay into three neutrinos the observational consequences for laboratory experiments are nil. There is one interesting effect for such decays. It has been pointed out in ref. [11], that an MeV neutrino decaying into electron neutrinos can affect nucleosynthesis yields by distorting the electron neutrino phase space distribution. Such distortions can lead to either increasing or decreasing the Helium abundance depending on the mass. For masses less than 10 MeV, the Helium abundance can be drastically reduced [12].

Let us consider rapid three neutrino decay from a model building standpoint. The trouble with this decay mode is that it necessitates flavor changing neutral currents (FCNC). In general it is not a problem to generate FCNC’s. The problems arise when one tries to generate large FCNC’s in the leptonic sector while keeping the FCNC’s small in the quark sector. This problem can be avoided by disentangling the sectors via the imposition of a symmetry, usually in the Higgs sector of the theory. This will, in general, necessitate the introduction of more Higgs multiplets. One possibility is to mediate the decay through a scalar triplet (see figure 1a). As long as triplet doesn’t carry baryon number it will couple only to the leptons. Given that there will be no GIM mechanism in action due to the fact that the neutrinos will get masses from other scalars (the left handed triplet vev is constrained by the rho parameter), we can have large FCNC’s. Such a scenario fits into a left right symmetric model [16]. There is one caveat however, the charged scalar in the triplet will mediate the decay \( \nu_\tau \rightarrow e^+ e^- \nu_e \), as shown in figure 1b. Such a decay would distort the light curves for SN1987A, and as such are ruled out [18]. One could however, avoid this dilemma by having the tau neutrino decay into \( \nu_\mu + \nu_e \bar{\nu}_e \). As was pointed out in [17], this mode will not be constrained by
exotic tau decay bounds, as one might naively expect, unless the bound on the leptonic KM angle $\theta_{\tau\mu}$ is improved by an order of magnitude. Thus, three neutrino decay is viable in this scheme as long as we are willing to suppress certain Yukawa couplings. There may be other viable schemes as well, but it seems clear that any such scheme will demand physics quite a bit beyond the standard model.

We may virtually eliminate the possibility of decay (ii) without recourse to model building considerations. Due to the luminous nature of the decay products there are many observations which disallow this decay mode. I will not reiterate here all the arguments and instead refer the reader to [4] for the details. Figure 1. shows the mass/lifetime exclusion plot. These bounds come from combining the bounds from eq(1) with those from supernova considerations. Notice that there is a small window for extremely rapid decay ($\tau < 10^{-12}\text{sec.}$) into a sterile neutrino and photon. Thus, it is not possible to completely rule out the possibility for this decay, however, such a rapid decay seems very implausible. Furthermore, I believe that a detailed nucleosynthesis calculation would close this tiny window.

Finally let us consider the last decay mode (iii). This mode has been looked at carefully in [14]. The authors found that this is indeed a viable mode, and that this decay is allowed for lifetimes less than 40 seconds. There are some ranges of masses and lifetimes which satisfy this constraint which are disallowed due to the fact that the scalar can contribute significantly to the energy density.
Figure 2: Bounds on radiative and $e^+e^-$ decays of $\nu_\tau$. Curve labels lie on the forbidden side of curves: lab mass bound (LEP), nucleosynthesis (NS), supernova luminosity (SNL)[18], Solar Max Mission (SMM)[19]. The hatched region is allowed for decays into sterile neutrinos. The decay in active neutrinos is disallowed by bounds on off diagonal moments of active neutrinos.

From a model building perspective this decay is perhaps easier to implement than modes (i) and (ii). A simple extension of the standard model including just a singlet Higgs and spontaneous lepton number violation leads to neutrino decay into a massless Goldstone boson (Majoron) [20]. It was originally believed that such a rapid decay is not viable in the simplest version of the Majoron model [21]. However, as has been pointed out, this is not necessarily the case. Rapid decays are feasible as long as there exists a hierarchy in the dirac masses [22].

Before closing let us return to the case of Dirac masses. It is possible to get a more stringent bound than that obtained from nucleosynthesis considerations from supernova luminosity arguments. As was pointed out in [25], if the Dirac mass is greater than 15 keV and its lifetime is greater than
$10^{-6} \text{sec}(m/\text{MeV})$, then the right handed species would have been generated in the core of SN1987A. These right handed neutrinos, if sterile with respect to the composition of the supernova, would have rapidly depleted the core energy. Such an energy depletion would have shortened the length of the observed neutrino pulse. If the neutrino decays into a electron or muon neutrinos, then the more stringent constraint of 1 keV [26] may be obtained by noticing that the neutrinos emitted from the core without thermalizing would be much more energetic than the observed neutrinos.

While these bounds on Dirac masses from supernova arguments are more stringent, I point out that they have the drawback that they assume that the right handed species is sterile [27]. As such, these are model dependent. While it is true that if right handed neutrinos do exist it would seem reasonable that they would be sterile, we must not jump to any conclusions.

4 Conclusions

Given the arguments discussed above what can we say we know about the tau neutrino? Aside from the statement that it must be there, we can only say that its mass should be less than 400 keV if has a Majorana mass, and less than 200 keV if has a Dirac mass. These bounds can be avoided if it decays into a massless scalar and a light neutrino, or three neutrinos with a lifetime less than O(100) seconds. If we are willing to assume that the right handed species is sterile then we may rule out Dirac masses greater than 15 keV for lifetimes greater than $10^{-6} \text{sec}(m/\text{MeV})$. Thus, if the tau neutrino is found to have masses in the disallowed ranges, then it would mean that we would need to invoke physics quite far beyond the standard model. The more likely scenario is that the tau neutrino, if massive, will have masses below the MeV range.

What hope do we have of lowering the bound on the tau neutrino mass? Or for that matter, learning anything more about the tau neutrino? The best prospect for lowering the lab bound on the mass is at the B factory, where a bound of a few MeV can be reached [28]. It seems that to do better than this we must use indirect measurements of the mass through oscillations experiments.
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