Two 17-keV Majorana Neutrinos?

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A recent observation of a 17-keV neutrino in tritium beta decay can be incorporated into the standard model with just three light neutrinos. Constraints on neutrino masses suggest that the lepton mass matrices have an approximate global symmetry which results in two of the three neutrinos having masses near 17 keV. A prediction for the mixing angle in $\nu_e \to \nu_\tau$ oscillations is made. Cosmological constraints on the 17-keV neutrino are discussed. Models with majorons or familons are found to be attractive possibilities.

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The recent observation of an anomaly in the electron spectrum in tritium beta decay suggests that the electron neutrino has an amplitude of $\sqrt{(3\%)}$ to be a 17-keV mass eigenstate.[1] This is puzzling because there are many constraints on the neutrino mass matrix from particle physics and cosmology, and it is not trivial to satisfy them all simultaneously. For example, the strong bounds on neutrinoless double beta decay[2] suggest that this 17-keV state is not a single Majorana neutrino. This bound does not apply for a Dirac mass, since lepton number need not be broken. However, we resist the temptation to add right-handed neutrinos in the low-energy theory because it is difficult to understand why Dirac neutrino masses should be so much smaller than the Dirac mass of the charged fermions. If the 17-keV component of the electron neutrino is not a single Majorana state and is not Dirac, then what is it? The only remaining possiblity is that it is a combination of two degenerate Majorana states. In this case, the neutrino mass matrix can have a flavor structure which forbids neutrinoless double beta decay.[3] In this note we will argue that this interpretation of the 17-keV state can occur in a model with just the usual three left-handed neutrinos in the low-energy theory, if the lepton mass matrices have a good approximate global symmetry: $L_e + L_\tau - L_\mu$, where $L_{e,\mu,\tau}$ are the individual lepton numbers. We also consider decays of the 17-keV state which obey cosmological constraints, and find decay via familon emission to be an attractive possibility. We show that our interpretation is subject to a variety of experimental tests in the near future.

For a 2×2 neutrino mass matrix the rate for neutrinoless double beta decay in tellurium would be a factor of about 500 greater than the experimental bounds.[2] Thus a very large suppression of neutrinoless double beta decay is required. We will therefore consider limiting models in which the neutrinoless process is strictly forbidden. To strictly forbid neutrinoless double beta decay, we need a conservation law such as lepton number (L), baryon number minus lepton number ($B-L$), or electron-family number (L_e carried by the electron and its neutrino). But all of these are unacceptable because they either forbid any mass for the neutrinos in the absence of other neutral states (L and $B-L$) or they forbid the 3% mixing of the 17-keV neutrino with the electron (L_e). In fact, there are only two possible symmetries which forbid neutrinoless double beta decay and allow the appropriate mass and mixing, $L_e + L_\mu - L_\tau$ and $L_e + L_\tau - L_\mu$. As we will see below, the possibility of $L_e + L_\mu - L_\tau$ is ruled out by data on neutrino oscillations.[4] Thus, $L_e + L_\tau - L_\mu$ is the unique possibility and we will explore its consequence in the remainder of this note. This simple result is worth stressing. If the 17-keV state is simply a combination of the three left-handed neutrinos, then the only symmetry which can guarantee the absence of neutrinoless double beta decay is $L_e + L_\tau - L_\mu$. However, we are not suggesting that $L_e + L_\tau - L_\mu$ is an *exact* global conservation law. We do not believe in any exact global symmetry, let alone such a peculiar one. It may be that this symmetry is violated by a small amount, giving a small neutrinoless double-beta–decay rate. Since $L_e + L_\tau - L_\mu$ is the only possible symmetry which can do what we want, we will begin by pretending that it is exact. This greatly simplifies our discussion.

To see that $L_e + L_\mu - L_\tau$ is ruled out while $L_e + L_\tau - L_\mu$ is allowed, we look at the Majorana mass matrix for the neutrinos. In the basis in which the first (second, third) row and column refers to the e (μ, τ) weak eigenstate and in which the charged lepton mass matrix is diagonal, the most general mass matrix consistent with $L_e + L_\tau - L_\mu$ is

$$M\begin{pmatrix} 0 & \sin\theta & 0 \\ \sin\theta & 0 & \cos\theta \\ 0 & \cos\theta & 0 \end{pmatrix}, \tag{1}$$

while the most general mass matrix consistent with $L_e + L_\mu - L_\tau$ is

$$M\begin{pmatrix} 0 & 0 & \sin\theta \\ 0 & 0 & \cos\theta \\ \sin\theta & \cos\theta & 0 \end{pmatrix}. \tag{2}$$

In either case, we must take $M = 17$ keV to reproduce the massive neutrino state and $\sin^2\theta \sim 0.03$ to reproduce the 3% mixing. In (1), the e and τ neutrinos are mixed, while the μ neutrino does not mix with the others because it carries the opposite value of the conserved quantum number $L_e + L_{\tau-} - L_\mu$. In (2), it is the e and μ which mix. In both cases, the mixing angle is θ. There are limits on θ from neutrino-mixing experiments. For e-τ mixing the quoted limit comes from studies in which one assumes that the electron neutrino mixes with some unspecified neutrino which does not produce e or μ charged-current events. For this type of mixing, the bound on θ is[5]

$$\sin^2 2\theta < 0.07 \text{ at } 90\% \text{ C.L.}, \tag{3}$$

which is in weak conflict with the value from (1),

$$\sin^2 2\theta \approx 0.12. \tag{4}$$

Given the uncertainties in the calculation of the electron-neutrino–beam flux in this experiment, we prefer to regard (3) as an exciting indication that a neutrino of this kind can soon be seen in neutrino-mixing experiments. This also applies to reactor experiments, where the limit is $\sin^2 2\theta < 0.15$.[4] On the other hand, there is a much stronger bound on the ing of the e and μ neutrinos[6]:

$$\sin^2 2\theta < 0.006 \text{ at } 90\% \text{ C.L.} \tag{5}$$

This bound rules out mass matrix (2) which has $L_e + L_\mu - L_\tau$ conservation.

We now consider $L_e + L_\tau - L_\mu$ breaking additions to (1). The ee, $e\tau$, τe, $\tau\tau$ entries must all be quite small, since they give a mass to the previously massless state. For the lightest neutrino to be less than 40 eV, the bound on the $e\tau$ and τe entries is about 250 eV, and, surprisingly, this will turn out to be the largest allowed $(L_e + L_\tau - L_\mu)$-breaking term. Limits from neutrinoless double beta decay require the ee element to be less than ~ 10 eV, but do not restrict the other elements. At first sight it appears that the $\mu\mu$ element could be as large as 250 keV, as this would give the ν_e, ν_μ, and ν_τ masses of 0, 250, 17 keV with small e-τ mixing, and even smaller e-μ mixing. This is not allowed, however, because the $\nu_\mu \leftrightarrow \nu_\tau$ mixing is now very large. As soon as the two heavy states have even a small nondegeneracy, $\nu_\mu \leftrightarrow \nu_\tau$ oscillations occur very rapidly: The $\mu\mu$ element must certainly be less than 1 eV. The same argument applies to the $\tau\tau$ element. However, it is possible that several of the $(L_e + L_\tau - L_\mu)$-breaking entries in (1) could be large, conspiring to avoid these limits.

In addition to neutrino mixing, the mass matrix (1) produces other processes which violate L_e and L_τ conservation. For example, $\tau^- \to e^- e^+ e^-$, $Z \to e^+ \tau^-$, $e^- \tau^+$, and $\tau \to e\gamma$ arise from the flavor mixing in the leptonic charge current. In the corresponding processes involving the hadronic charged current, such as $K^+ \to \pi^+ e^+ e^-$, the Glashow-Iliopoulos-Maiani (GIM)[7] mechanism yields factors such as $(m_1^2 - m_2^2)/M_W^2$ and $\ln[(p^2 + m_1^2)/(p^2 + m_2^2)]$ where m_1 and m_2 are two quark masses, and p^2 is a typical momentum in the decay. The same terms arise in the leptonic case, except that now m_1 and m_2 are neutrino masses which are very small compared to the charged-particle masses and to p^2. Hence, there is always a larger power suppression of $(m_1^2 - m_2^2)/M_W^2$ or $(m_1^2 - m_2^2)/p^2$ in the amplitude, and, consequently, lepton number nonconservation through loop effects is unobservably small.

Processes such as $\mu \to ee\bar{e}, e\gamma$, $\nu_\mu \to \nu_e, \nu_\tau$ are forbidden exactly by $L_e + L_\tau - L_\mu$ conservation. One might think that a ν_μ beam could yield e^+ charged-current events, as this is allowed by $L_e + L_\tau - L_\mu$. However, this requires a helicity flip: $(\nu_\mu)_L \to (\bar{\nu}_e)_R$, which is suppressed by M/E where E is the neutrino energy, and is consequently negligible. We conclude that the pattern of lepton-number nonconservation induced by (1) should show up in $\nu_e \to \nu_\tau$, but nowhere else.

This is not the end of the story. It is well known that cosmologically stable neutrinos either must have a mass less than 100 eV,[8] so that they do not give too large an energy density to the universe, or they must be heavier than a few gigaelectronvolts[9] so that they can annihilate efficiently through weak interactions in the early universe. As the 17-keV state lies in the forbidden region between these limits, either it must decay with a lifetime considerably less than the age of the universe, or a new annihilation mechanism must be found. As our model stands, the 17-keV state has a GIM-suppressed decay to the massless neutrino via photon emission and is cosmologically stable. We must add new physics to the model.

We start by considering decays of the 17-keV state. The lifetime of one 17-keV neutrino must be less than 2×10^4 yr[10] (in our case, with two neutrinos, this bound should be divided by 4); otherwise the decay products will have insufficient time to undergo a red shift, and will give too large an energy density to the universe today. It is worth noting that conventional weak decay amplitudes $O(G_F)$ are insufficient for this purpose. If extra neutrino states are added to the model so that the neutrino mass matrix is GIM violating, the lifetime is too long even if the GIM violation is maximal. Of course, we do not want to do this anyway, because part of our motivation is to explore the minimal set of neutrino fields. The decay to three light neutrinos could be mediated by some scalar field which has large Yukawa couplings to neutrinos and a mass of perhaps 1–10 GeV. This is very *ad hoc;* it would be much better to try to relate the decay or annihilation of the neutrinos to the scalar sector of the theory which is also responsible for producing their mass. Such a relation occurs if the neutrinos decay or annihilate into Goldstone bosons. Below we mention three schemes involving Goldstone bosons which have widely differing phenomenological consequences.

(1) The Goldstone bosons can couple predominantly only to the left-handed neutrinos. This is the case for the majoron model[11] in which lepton-number conservation is spontaneously broken by a small Higgs triplet vacuum expectation value v, which is also responsible for the neutrino masses. The Goldstone boson, called the majoron, couples directly to the left-handed neutrinos. It also couples weakly to charged fermions, as it contains a small $O(v/\langle\phi\rangle)$ component of the standard model Higgs doublet ϕ. The vacuum expectation value v is subject to a variety of astrophysical constraints, $v < 600$ keV[12] to 900 keV.[13] More stringent constraints, $v < 60$ keV,[12] require model-dependent assumptions about energy loss in red giants. The Yukawa couplings of the majoron to the 17-keV neutrinos are therefore large, giving a mild disagreement with the experimental limits from majoron bremmsstrahlung by neutrinos in K decays[14] (however, see Glashow and Manohar[15]). The introduction of more Higgs triplets helps to avoid these limits. Improved measurements of the μ spectrum in $K \to \mu\nu$ would therefore either discover the majoron or create serious troubles for these models. In these models the neutrinos annihilate to majorons so that their number density drops very quickly as the temperature falls below 17 keV.

In this majoron model new physics is added to the low-energy theory. In the remaining two schemes, the Goldstone bosons are associated with symmetry breaking at a large scale $V >> \langle\phi\rangle$.

(2) The Goldstone bosons may be mainly coupled to $SU(3) \otimes SU(2) \otimes U(1)$-singlet neutrinos which acquire Majorana masses at the scale V. This is the case of the majoron model, where lepton-number conservation is broken at V.[16,17] The coupling of these Goldstone bosons to the light left-handed neutrinos is suppressed by $(\langle\phi\rangle/V)^2$ and couplings to charged fermions are induced only through loops. In these models the 17-keV state can decay to a massless neutrino and Goldstone boson with a lifetime of less than 10^4 yr.[17] However, the lifetime may not be very much less than this if the 17-keV mass is of order $\langle\phi\rangle^2/V$, in which case the neutrinos are cosmologically important. In these models the Goldstone bosons are too well hidden to be important for experiments in particle physics.

(3) The Goldstone bosons could be associated with the breaking of family symmetries,[18,19] in which case these familons would be expected to have similar couplings to all quarks and leptons. Experimental bounds on $K \to \pi f$ and $\mu \to ef$ (f is the familon) require the symmetry-breaking scale $V \gtrsim 10^{10}$ GeV.[19,20] However, the 17-keV neutrino lifetime is of order $(V/10^{10}\ \mathrm{GeV})^2 \times 10^4$ yr, so that V cannot be made much larger than 10^{10} GeV.[20] This is very exciting since a familon interpretation of the 17-keV neutrino decay leads one to expect that future experiments searching for $K \to \pi f$ and $\mu \to ef$ will be successful. The new physics scale is 10^{10} GeV; hence it is quite natural for the neutrino masses to be of order $\langle\phi\rangle^2/10^{10}\ \mathrm{GeV} \sim 10$ keV. Of course, whether $K \to \pi f$ and $\mu \to ef$ actually occur, and what the precise branching ratios are, are model-dependent questions. The bounds on $K \to \pi f$ suggest that the neutrino lifetime is close to its upper bound of 5000 yr. In this case the universe is radiation dominated from the period of neutrino decay (which is just before recombination) until very recent times. Therefore, the growth of perturbations in baryon density is suppressed,[21] giving serious problems for galaxy formation. In this Letter we have not addressed the origin of $L_e + L_\tau - L_\mu$ in the lepton mass matrices.

In this Letter we have pointed out that the recently observed 17-keV neutrino can be simply incorporated in a model with just three conventional neutrinos in the low-energy theory, which has $L_e + L_\tau - L_\mu$ as a good approximate symmetry of the lepton mass matrices. We have discussed three scenarios which allow fast decay or annihilation of the 17-keV neutrino. One favorable possibility is that the 17-keV state decays to the nearly massless neutrino by familon emission. In this case new physics occurs at a scale of 10^{10} GeV, and searches for $K \to \pi f$ and $\mu \to ef$ could soon probe this physics further.

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Note added.—Lincoln Wolfenstein[22] has discussed neutrino mass matrices which have a combination of lepton numbers unbroken.

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