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BOUNDS ON NEUTRINO MASSES FROM PARTICLE PHYSICS AND COSMOLOGY*

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ABSTRACT

We study the constraints imposed on the masses of ν_e, ν_μ and ν_τ on the basis of direct experimental bounds, cosmological bounds, theoretical calculations of neutrino decay rates, experimental bounds on related decays of charged leptons and the structure of neutrino mass matrices in the "see-saw" mechanism. We consider standard model amplitudes as well as contributions from all "beyond standard" models. Assuming a simple "reasonable" form of the see-saw mechanism, we derive the bounds:

$m(\nu_\tau) \leq\ 65\ eV,\ m(\nu_\mu) \leq\ 4\ eV,\ m(\nu_e) \leq\ 0.02\ eV,\ M(W_R) \geq\ 50\ PeV.$

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EXPERIMENTAL AND COSMOLOGICAL BOUNDS

The minimal standard model (SM) contains neither right-handed neutrinos nor Higgs triplets. Thus, left-handed neutrinos are exactly massless. However, there is no fundamental symmetry principle which prevents the neutrinos from acquiring masses in the presence of new physics effects beyond the SM. Most theories beyond the SM actually allow a variety of contributions to the neutrino mass. We study[1,2] the question of neutrino masses within such theories.

The present direct limits on the masses of the three known left-handed neutrinos are:

$$\begin{aligned} m(\nu_e) &\leq \ 18 \ eV \\ m(\nu_\mu) &\leq \ 250 \ keV \\ m(\nu_\tau) &\leq \ 70 \ MeV \end{aligned} \tag{1}$$

There must be a good explanation for the fact that left-handed neutrinos are much lighter than all other fermions. If there is some physics beyond the SM that corresponds to a new energy scale $\Lambda \gg M_W$, then its low energy effective Lagrangian may include a dimension-five term of the form $\frac{h}{\Lambda}\phi\phi\nu_L\nu_L$, where ϕ is the usual Higgs doublet of the SM, ν_L is any left-handed neutrino and h is an effective coupling constant. With the usual symmetry breaking of the SM, this term yields a neutrino Majorana mass

$$m(\nu) = \frac{h\langle\phi\rangle^2}{\Lambda} \tag{2}$$

which is much lighter than ordinary fermion masses, $h'\langle\phi\rangle$. The best known realization of this mechanism is the "see-saw" matrix[3] for neutrino masses. In our work we assume that neutrinos have masses, and that they are light due to a see-saw mechanism.

Massive neutrinos contribute to the energy density of the universe. The requirement that this contribution does not exceed the present energy density of the universe, excludes a certain range of masses for stable neutrinos, and defines an allowed range for the mass and the lifetime of unstable neutrinos. For stable neutrinos lighter than a few MeV the bound is[4]

$$\sum m(\nu_i) \leq \; 65 \; eV. \tag{3}$$

The bound on unstable neutrinos lighter than a few MeV is[5]

$$[m(\nu_i)]^2 \tau(\nu_i) \leq \; 2 \times 10^{20} \; eV^2 \cdot sec \tag{4}$$

Our analysis runs along the following lines[1]: The cosmological bound, by itself, cannot exclude any neutrino mass-value. However, for any given neutrino decay-mode in any given model we may derive additional relations between the mass and the lifetime of the decaying neutrino. By combining the cosmological and the particle-physics constraints for the decay modes of the same neutrino, we may then be able to exclude certain mass ranges and to derive strong bounds on the neutrino mass.

NEUTRINO DECAY RATES

In an extended SM, in which right-handed neutrinos are added, left-handed neutrinos will have masses and may decay. The possible final states for the decay of an unstable neutrino ν_i into two or three final particles are:

$$\nu_j + \nu_k + \nu_l \; ; \; \nu_j + e^+ + e^- \; ; \; \nu_j + \gamma \; ; \; \nu_j + \gamma + \gamma \tag{5}$$

The νee mode is allowed only for $i = \tau$.

In the SM all coupling constants and intermediate-boson masses are known. Thus we are able to calculate upper bounds on the decay rates (which depend on the mixing among lepton generations). We combine these relations with the cosmological bounds and conclude: Within an extended SM, ν_μ should be lighter than 65 eV, and ν_τ is either lighter than 65 eV, or with a mass between 10 MeV and 70 MeV.

Can these bounds be evaded in models beyond the SM ? Theories with a new energy scale Λ at the GUT scale or at the Planck scale are unlikely to lead to fast neutrino decays, and - through the see-saw mechanism - will produce neutrino masses well below 1 eV.

Our best hope for heavier left-handed neutrinos and for faster neutrino decays which could be consistent with the cosmological bounds is from new physics at relatively "nearby" scales, around 1 TeV to 1 PeV. Such scales are consistent with Left-Right symmetric (LRS) models, horizontal symmetries, and substructure. Therefore, we pay special attention to these cases[2].

In LRS models, the electroweak group is extended to an $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge group. Leptons transform as $\left(\frac{1}{2}, 0\right)_{-1} + \left(0, \frac{1}{2}\right)_{-1}$ representations. In the minimal LRS model[6] the Higgs fields Φ, Δ_L and Δ_R transform like $\left(\frac{1}{2}, \frac{1}{2}\right)_0$, $(1,0)_2$ and $(0,1)_2$ representations, respectively. The model is "minimal" in the sense that it has the minimal Higgs content that gives hierarchical symmetry breaking and predicts heavy right-handed neutrinos and very light left-handed ones.

The Δ_L^0 member of the Higgs triplet mediates the decay $\nu_i \to \bar{\nu}_j \nu_k \nu_l$ with an amplitude proportional to

$$\frac{h_{ij} h_{kl}}{\left[M(\Delta_L^0)\right]^2}. \tag{6}$$

In the ν_μ case, the only possible mode is $\nu_\mu \to \bar{\nu}_e \nu_e \nu_e$. The width of this decay is proportional to

$$\frac{(h_{e\mu} h_{ee})^2}{\left[M(\Delta_L^0)\right]^4} \left[m(\nu_\mu)\right]^5 . \tag{7}$$

We do not know the values of $M(\Delta_L^0)$, h_{ee} and $h_{e\mu}$. Consequently, we cannot derive a relation between $m(\nu_\mu)$ and $\tau(\nu_\mu)$. However, the Δ_L^{++} member of the Δ_L Higgs triplet can mediate the decay $\mu^- \to e^+ e^- e^-$. The amplitude for this decay is related to the ν_μ-decay amplitude through the gauge symmetry. The Yukawa couplings are exactly the same for both decays. The decay width is thus proportional to

$$\frac{(h_{e\mu} h_{ee})^2}{\left[M(\Delta_L^{++})\right]^4} \left[m(\mu)\right]^5 . \tag{8}$$

All other factors are equal for both widths. The ratio between the widths is

$$\frac{\Gamma(\nu_\mu \to \bar{\nu}_e \nu_e \nu_e)}{\Gamma(\mu^- \to e^+ e^- e^-)} = \left[\frac{M(\Delta_L^{++})}{M(\Delta_L^0)}\right]^4 \left[\frac{m(\nu_\mu)}{m(\mu)}\right]^5 . \tag{9}$$

The three components of the Δ_L-triplet are approximately degenerate, with mass-squared $O(v_R^2)$:

$$\frac{\left|[M(\Delta_L^{++})]^2 - [M(\Delta_L^0)]^2\right|}{[M(\Delta_L^{++})]^2} \sim O\left[\frac{k^2}{v_R^2}\right] \sim O\left[\frac{M(W_L)}{M(W_R)}\right]^2 < 2.5 \times 10^{-3} \tag{10}$$

As $\left[\frac{M(\Delta_L^{++})}{M(\Delta_L^0)}\right]^4 = 1 + O(10^{-3})$, eq. (9) reduces to[7]:

$$\frac{\Gamma(\nu_\mu \to \bar{\nu}_e \nu_e \nu_e)}{\Gamma(\mu^- \to e^+ e^- e^-)} = \left[\frac{m(\nu_\mu)}{m(\mu)}\right]^5 . \tag{11}$$

The experimental upper bound on the branching ratio is[8]

$$BR(\mu \to 3e) \leq 2.4 \times 10^{-12}. \tag{12}$$

Then eq. (11) gives

$$\tau(\nu_\mu)\,[m(\nu_\mu)]^5 \geq 1.2 \times 10^{46}\ eV^5 \cdot sec. \tag{13}$$

Combining this with the cosmological bound one obtains

$$m(\nu_\mu) \geq 35\ MeV \tag{14}$$

in clear conflict with the experimental bound $m(\nu_\mu) \leq 250\ keV$. Within LRS models ν_μ cannot be heavier than 65 eV.

Can such a model accommodate a ν_τ, with $m(\nu_\tau)$ anywhere between 65 eV and 70 MeV ? We now analyze the Δ_L-mediated ν_τ decay.

In general, the Δ_L^0 exchange provides ν_τ with six different decay modes:

$$\nu_\tau \to \bar{\nu}_\mu \nu_\mu \nu_\mu,\ \bar{\nu}_\mu \nu_\mu \nu_e,\ \bar{\nu}_\mu \nu_e \nu_e,\ \bar{\nu}_e \nu_\mu \nu_\mu,\ \bar{\nu}_e \nu_\mu \nu_e,\ \bar{\nu}_e \nu_e \nu_e. \tag{15}$$

The decay width, summed over all six modes, is proportional to

$$\Gamma(\nu_\tau \to \bar{\nu}_i \nu_j \nu_k) \propto \frac{\sum_{ijk} (h_{\tau i} h_{jk})^2}{\left[M(\Delta_L^0)\right]^4} [m(\nu_\tau)]^5 . \tag{16}$$

However, there are also six possible decay modes for the τ lepton, mediated by the Δ_L^{++} Higgs particle:

$$\tau \to \mu^+\mu^-\mu^-,\ \mu^+\mu^-e^-,\ \mu^+e^-e^-,\ e^+\mu^-\mu^-,\ e^+\mu^-e^-,\ e^+e^-e^-. \qquad (17)$$

The total decay width for these modes is proportional to

$$\Gamma(\tau^- \to \ell_i^+\ell_j^-\ell_k^-) \propto \frac{\sum_{ijk}(h_{\tau i}h_{jk})^2}{\left[M(\Delta_L^{++})\right]^4}\left[m(\tau)\right]^5. \qquad (18)$$

The combinations of Yukawa couplings which appear in eqs. (16) and (18) are identical. The same argument as in the case of ν_μ decay now yields:

$$\frac{\Gamma(\nu_\tau \to \bar{\nu}_i\nu_j\nu_k)}{\Gamma(\tau^- \to \ell_i^+\ell_j^-\ell_k^-)} = \left[\frac{m(\nu_\tau)}{m(\tau)}\right]^5 \qquad (19)$$

The ARGUS collaboration has recently reported a new experimental upper bound for all channels of $\tau \to 3\ell$. They obtain[9]:

$$BR(\tau \to 3\ell) \leq 3.8 \times 10^{-5}. \qquad (20)$$

Then eq. (19) gives

$$\tau(\nu_\tau)\left[m(\nu_\tau)\right]^5 \geq 1.4 \times 10^{38}\ eV^5 \cdot sec. \qquad (21)$$

Combining this with the cosmological bound (4) we obtain:

$$m(\nu_\tau) \geq 900\ keV. \qquad (22)$$

We conclude: Within LRS models, in order to obey the cosmological bound on the neutrino mass and lifetime, $m(\nu_\tau)$ must be either below 65 eV or between 0.9 MeV and 70 MeV.

We calculated other decay rates within the LRS model. We studied, in similar ways, neutrino decays within models of horizontal symmetries and theories of substructure[2]. Our results remain the same:

$$\begin{aligned} &m(\nu_\mu) \leq 65\ eV \\ &m(\nu_\tau) \leq 65\ eV \quad or \quad 0.9\ MeV \leq m(\nu_\tau) \leq 70\ MeV. \end{aligned} \tag{23}$$

These results are valid in a very broad class of models, with the possible exception of some ad-hoc schemes of global symmetries.

THE SEE-SAW MECHANISM

The bounds in eq. (23) are independent of the specific form of the neutrino mass matrix. We considered additional possible constraints which may be imposed on neutrino masses by the see-saw mechanism.

We study see-saw matrices of the form[3]

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \tag{24}$$

The Dirac submatrix m_D is expected to be of the same order of magnitude as the Dirac mass matrix for charged leptons, $m_D(\ell)$. We do not know the form of the M_R-matrices. Two "reasonable" possibilities are:

(*i*) The new physics that leads to the Majorana mass matrix M_R is "blind" to whatever mechanism which is responsible for the mass hierarchy among generations. In the basis where M_R is diagonal this means

$$M_{Re} \sim M_{R\mu} \sim M_{R\tau} \tag{25}$$

If m_D and M_R can be diagonalized simultaneously we get $m(\nu_i) \sim \frac{[m(\ell_i)]^2}{M_R}$, and in particular:

$$\frac{m(\nu_\tau)}{m(\nu_\mu)} \sim \left[\frac{m(\tau)}{m(\mu)}\right]^2 \tag{26}$$

(ii) The mechanism that gives the mass hierarchy among generations in m_D acts in a similar way in M_R. In the basis where M_R is diagonal this gives

$$M_{Re} : M_{R\mu} : M_{R\tau} \propto m(e) : m(\mu) : m(\tau) \tag{27}$$

If m_D were diagonal at the same time, mass ratios between neutrinos would be similar to those between charged leptons, and in particular:

$$\frac{m(\nu_\tau)}{m(\nu_\mu)} \sim \frac{m(\tau)}{m(\mu)}. \tag{28}$$

In the general case, m_D and M_R cannot be simultaneously diagonalized. However, it turns out that in most cases, a "reasonable see-saw" matrix, namely one that follows either of the assumptions *(i)* and *(ii)* gives:

$$\frac{m(\nu_i)}{m(\nu_j)} \sim \left[\frac{m(\ell_i)}{m(\ell_j)}\right]^p \quad with \;\; 1 \leq p \leq 2. \tag{29}$$

In order to have $p > 2$ we need, in general, a matrix M_R with an inverted hierarchy, *e.g.* $\frac{M_{R\tau}}{M_{R\mu}} \sim \frac{m(\mu)}{m(\tau)}$. We do not know any sensible model with such a prediction, but we cannot completely exclude it and we found[2] some peculiar forms of M_R that lead to $p \sim 3$.

We have shown that the cosmological bound on the energy density of the universe can be fulfilled only if

$$m(\nu_\mu) \le 65\ eV \quad ; \quad m(\nu_\tau) \le 65\ eV \ \textit{or}\ m(\nu_\tau) \ge 0.9\ MeV \tag{30}$$

On the other hand, the "reasonable see-saw" assumption puts an upper limit on the mass ratio (the $p \le 2$ limit of eq. (29)):

$$\frac{m(\nu_\tau)}{m(\nu_\mu)} \le \left[\frac{m(\tau)}{m(\mu)}\right]^2 \sim 300 \tag{31}$$

However, if ν_τ is heavier than 0.9 MeV, the same mass ratio must obey $\frac{m(\nu_\tau)}{m(\nu_\mu)} \ge 14000$, demanding $p \ge 3.4$, in clear conflict with the "reasonable see-saw". This leads to the conclusion

$$m(\nu_\mu) \le 65\ eV \quad ; \quad m(\nu_\tau) \le 65\ eV \tag{32}$$

If neutrinos are light as a consequence of a "reasonable see-saw" mechanism, then it is impossible to accommodate the cosmological constraints on their masses, unless they are all lighter than 65 eV.

The strong limits obtained in eq. (32) have further implications. The lower bound on the mass ratio among neutrinos (the $p \ge 1$ limit of eq. (29)) can be combined with $m(\nu_\tau) \le 65\ eV$ to give:

$$m(\nu_\mu) \le 4\ eV \quad ; \quad m(\nu_e) \le 0.02\ eV. \tag{33}$$

Thus, the "reasonable see-saw" hypothesis, together with our previous conclusions, leads us to an extremely strong new upper bound on the masses of ν_τ, ν_μ and ν_e.

As the mass of ν_τ is assumed to be approximately given by $m(\nu_\tau) = \frac{[m(\tau)]^2}{M_R}$, the above upper bound on $m(\nu_\tau)$ gives a lower bound on the scale M_R:

$$M_R \geq \frac{[m(\tau)]^2}{65\ eV} \sim 50\ PeV. \tag{34}$$

This is a very significant bound if M_R is the scale of LRS-breaking or of a horizontal gauge-symmetry breaking.

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