NEUTRINO MASSES AND MIXING, AND LEPTON NUMBER VIOLATION

Introduction

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The question of possible neutrino masses remains an intriguing one. Since at present there is no understanding of fundamental lepton mass ratios such as $m_\mu/m_e \simeq 207$ or $m_\tau/m_\mu \simeq 16.9$ (or of current quark mass ratios), one should in all humility keep an open mind regarding neutrino masses.

There are two general types of Lorentz invariant mass terms that one can form from spin 1/2 Weyl fields: a Dirac term mass term

$$\mathcal{L}_D = m_D\, \bar{\psi}_L \psi_R + \text{h.c.} \tag{1}$$

and the Majorana mass terms

$$\mathcal{L}_{ML} = m_L\, \psi_L^T C \psi_L \;\; + \text{h.c.} \tag{2a}$$

and

$$\mathcal{L}_{MR} = m_R\, \psi_R^T C \psi_R \;\; + \text{h.c.} \tag{2b}$$

where $C = i\gamma^2\gamma^0$ is the charge conjugation operator and $\psi_{L,R} \equiv P_{L,R}\psi$, with P_{LR} the left-(right-) handed chiral projection operator. $\mathcal{L}_D$ has two important properties: (a) it connects left- and right handed Weyl fields ψ_L, and ψ_R and (b) it is invariant under the transformation $\psi \to e^{i\theta}\psi$, i.e, it conserves total fermion number. In contrast, $\mathcal{L}_{ML}$ connects only left-handed with left-handed Weyl fields, and analogously with $\mathcal{L}_{MR}$. These Majorana mass terms violate total fermion number. Given electric charge conservation, they can only involve neutral particles, among which only neutrinos are fundamental at scales we presently know. Majorana neutrinos are characterized by being self-conjugate, whereas Dirac neutrinos are not. In addition to the question of mass, one of the most outstanding resolved issues concerning neutrinos is the issue of whether they are Dirac or Majorana particles. In the past, it was usually tacitly assumed that the former was the case, since processes which violated lepton number, such as $\bar{\nu}_e n \to e^- p$, or neutrinoless double beta decay, $(Z,A) \to (Z+2,A) + e^- + e^-$, were not observed. More recently, as will be discussed below, this question has been re-opened. One of the reasons for this is that grand unified theories (GUT's) naturally predict the violation of baryon and lepton number. However, it should be stressed that neutrino masses of Dirac or Majorana type have always been a phenomenological possibility and do not logically require grand unification. Furthermore, GUT's do not necessarily predict neutrinos to be massive. For example, in the simplest realistic GUT, based on the gauge group SU(5) with a $\underline{5}_R = \psi_R^\alpha$ and $\underline{10}_L = \psi_L^{\alpha\beta}$ of fermions in each generation and a $\underline{5}$, $\underline{24}$, and perhaps $\underline{45}$ of Higgs, neutrinos are strictly massless. Moreover, although GUT's naturally violate B and L, they can still easily incorporate Dirac masses for neutrinos.

If neutrinos are massive (and non-degenerate), then the weak eigenstates ν_e, ν_μ, ν_τ, etc. will not themselves be mass eigenstates but rather, linear combinations thereof. In a general notation, denote the set of charged leptons in the standard $SU(2)_L \times U(1)$ electroweak theory as $\{\ell_a\} = \{\ell_1 \equiv e, \ell_2 \equiv \mu, \ell_3 \equiv \tau \ldots \ell_n\}$, with $n \geq 3$, and the corresponding set of neutrino weak eigenstates as $\{\nu_{\ell_a}\} = \{\nu_e, \nu_\mu, \nu_\tau \ldots \nu_{\ell_n}\}$. Further, label the neutrino mass eigenstates as $\{\nu_i\} = \{\nu_i \ldots \nu_n\}$. Then the mixing of the mass eigenstates to form weak eigenstates is specified by

$$\nu_{\ell_a} = \sum_{i=1}^{n} U_{ai}\nu_i \tag{3}$$

where $U^\dagger = U^{-1}$. This applies for the left-handed components and, if the theroy is enlarged to contain right handed components for neutrinos, it applies to the full fields $\nu = \nu_L + \nu_R$, since the right-handed components are gauge group singlets. The ordering of the mass eigenbasis is defined such that U is as nearly diagonal as possible, i.e., $|U_{jj}|$ (no sum on j) $\geq |U_{jk}|$, $k \neq j$. This does not imply that $m(\nu_j) > m(\nu_k)$ if $j > k$, although this ordering might be regarded as natural in view of the similar one that obtains in the quark sector. The virtue of this convention is that a mass limit on "$m(\nu_{\ell_a})$" can be used as a definite limit on ν_j, $j = a$, the dominantly coupled mass eigenstate in ν_{ℓ_a}.

These, then, are the three main questions of interest in this section of the workshop:

(1) Are neutrino masses nonzero?

(2) Are neutrinos non-self-conjugate (Dirac), or self-conjugate (Majorana) particles? In the latter case, total lepton number is violated.

(3) What are the bounds on lepton mixing and the concomitant violation of lepton family numbers?

Three reports will address these questions. The first, by R. Shrock, discusses direct neutrino mass experiments and correlated bounds on Dirac and Majorana neutrino masses and mixing from nuclear and particle decays, including peak search experiments. In addition, electromagnetic properties of massive neutrinos are briefly mentioned. The second report, by R. Lanou, deals with the current status of, and future prospects for, neutrino oscillation experiments. The third, by D. Caldwell, is concerned with neutrinoless double β decay, the classic and still most sensitive test for Majorana neutrinos. The reader is referred to the subsection on rare decays in the "Beyond the Standard Model" section for further discussion of lepton family-number-violating μ decays, and to a contributed paper by D. Ayres et al., entitled, "Neutrino Oscillation Search with Cosmic Ray Neutrinos," among other reports, for further discussions relevant to the three questions listed above.