LEPTONS

NOTE ON NEUTRINOS

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In addition to the ν_e, ν_μ, and ν_τ sections, the *Review of Particle Properties* includes sections on "Searches for Massive Neutrinos and Lepton Mixing," "Number of Light Neutrino Types," "Heavy Lepton Searches," and "Constraints from Cosmology and Astrophysics."

The theoretical perspective concerning neutrino masses has changed considerably over the past 20 years. Before that time, a standard view was that there was no theoretical reason for neutrinos to have masses, which was in accord with the striking fact that the upper limits on their masses were much smaller than those of the associated charged leptons. It was also noted that experimental data were consistent with the "laws" of lepton family number and total lepton number conservation. (Some early discussions of neutrino oscillations and lepton mixing are given in Refs. 1 and 2). Indeed, even in the literature of the 1970's, one will often find statements asserting that in the standard SU(2)× U(1) electroweak theory (without electroweak-singlet neutrinos) the known (electroweak-doublet) neutrinos are massless.

In contrast, in the modern theoretical view based on the standard electroweak theory (and its supersymmetric extensions which stabilize the hierarchy), small but nonzero neutrino masses are expected on general grounds. The reason for this is as follows. Given only the known left-handed neutrino fields and the usual Higgs field(s) in the Standard Model (and supersymmetric extensions thereof which stabilize the hierarchy), nonzero neutrino masses result generically from higher-dimension operators which are strongly expected to occur at a scale near to that of quantum gravity. This expectation is based on the general consensus that pointlike theories of quantum gravity are nonrenormalizable, and is borne out by explicit calculations of the low-energy, field-theory limit of string theories. Such higher-dimension operators would be suppressed by associated inverse powers of the (reduced) Planck mass, $\kappa^{-1} \equiv \overline{M}_P \equiv \sqrt{\hbar c/(8\pi G_N)} = 2.4 \times 10^{18}$ GeV. For example, there would be a gauge-invariant dimension-5 operator consisting of the weak $I = 1$, $Y = -2$ Majorana bilinear ${\nu_L}^T C \nu_L$ (where generation indices are suppressed) contracted with a symmetric, $I = 1$ quadratic product of the usual $I = 1/2$, $Y = 1$ Higgs, with a coefficient of the form $a/\overline{M}_P$, where a is a dimensionless constant. From the vacuum expectation values of the Higgs, this would give rise to (Majorana) neutrino masses of order $m_\nu \sim av^2/\overline{M}_P$, where $v = 250$ GeV is the scale of electroweak-symmetry breaking. (Here $\overline{M}_P$ is an approximate upper bound on the mass which suppresses such operators; it is possible that new physics occurs at some intermediate mass scale $v \ll M_I < \overline{M}_P$ in such a way that dimension-5 operators of this type would give rise to neutrino masses of order av^2/M_I.) This not only leads one to expect nonzero neutrino masses but explains why they are so small.

In retrospect, one sees that this change in theoretical perspective is associated with the change in viewpoint concerning quantum field theory. For decades after the success of quantum electrodynamics in the late 1940's, renormalizability was taken as a necessary property for an acceptable fundamental quantum field theory. It was this implicit theoretical assumption which led to the oft-repeated statements in the 1970's that in the standard electroweak theory (without electroweak-singlet neutrinos) the known neutrinos are massless. More recently, it has been appreciated that renormalizability and, in particular, the great success of the Standard Model with its exclusion of any higher-dimension nonrenormalizable operators, may well be due only to the fact that the electroweak scale v is much smaller than $\overline{M}_P$ (or possibly even some lower scale, M_I), *i.e.*, a consequence of the hierarchy. Once one includes such higher-dimension operators in one's considerations, the realization that neutrino masses are generic follows immediately. A summary of this modern view is given, *e.g.*, in Ref. 3.

In contrast to this mechanism for neutrino mass, which only relies upon the known neutrinos, together with the Higgs field(s) of the Standard Model (or its supersymmetric extensions), there is another more speculative mechanism which we mention here for completeness. It is not known whether there exist any electroweak-singlet neutrino fields. If they do exist, then they could lead, via renormalizable, dimension-4 operators, to neutrino masses $m_\nu \sim v^2/M_R$, where the scale M_R of the electroweak-singlet neutrino mass is naturally $\gg v$, again yielding, albeit for a different reason, very small m_ν [4].

In turn, a natural concomitant of (nondegenerate) neutrino masses is lepton mixing, which is thus also a general expectation. The lepton-mixing angles are functions of ratios of elements of neutrino-matrix elements and of charged lepton mass matrix elements, and even though left-handed neutrino masses are small, some of these ratios could, in principle, be $\mathcal{O}(1)$, which raises the issue of why such effects have not been seen. This question was answered as follows: a set of conditions for natural suppression of observable lepton flavor violation were formulated, and it was shown that the Standard Model (generalized to include nonzero m_ν) satisfies these [5]. This explains why the "law" of lepton family number conservation is obeyed to such high accuracy.

After these theoretical points, let us return to a description of the quantities upon which various experiments put limits. As an aid to understanding the limits on neutrino masses and lepton mixing, we recall that, in contrast to other particles in this *Review*, the neutrinos ν_e, ν_μ, and ν_τ are defined as weak eigenstates (the weak $I_3 = 1/2$ components of the $\mathrm{SU}(2)_L$ lepton doublets) which couple with unit strength to e, μ, and τ, respectively. These neutrino weak eigenstates are not, in general, states of definite mass. If one assumes that neutrinos are massless, and hence degenerate, then it is possible to define the