together imply that the Majorana mass matrices are symmetric: $M_L = {M_L}^T, M_R = {M_R}^T$. The diagonalization of the full $(3+n_s) \times (3+n_s)$ mass matrix in Eq. (2) yields $3+n_s$ mass eigenstates, which are, in general, of Majorana type. Since Majorana mass terms violate total lepton number, one sees from a general viewpoint that one does not expect conservation of total lepton number. In particular, the dimension-5 operators discussed above give rise to left-handed Majorana neutrino mass terms and violate total lepton number. Dirac-neutrinos can be constructed from two Majorana-neutrino mass eigenstates whose masses are equal in magnitude [8]. For this reason, Dirac neutrino masses may be considered to be a special (degenerate) case of Majorana neutrino masses, and the latter may be regarded as the generic case. From the similarity transformation which diagonalizes the neutrino mass matrix, together with the similarity transformation which diagonalizes the charged lepton mass matrix (where, of course, only Dirac masses are allowed by electric-charge conservation), one constructs the lepton-mixing matrix U. In general, since U is not the identity, neutrino masses naturally give rise to lepton family number violation.

In supersymmetric extensions of the Standard Model, the neutrinos could, *a priori*, mix with the neutralinos (higgsinos and neutral gauginos). However, the usual R parity which is invoked to forbid unacceptably rapid proton decay also prevents such mixing between neutrinos and neutralinos.

In addition to mass and lifetime limits, this *Review* includes limits on various other possible properties, including electric charge, the CPT-violating difference $m_{\nu_1} - m_{\overline{\nu}_1}$, and a magnetic dipole moment. These are of interest because a massless purely chiral Dirac neutrino cannot have a magnetic (or electric) dipole moment. In the standard electroweak theory, extended to allow for Dirac neutrino masses, the neutrino magnetic dipole moment is nonzero and given [5,9], as

$$\mu_{\nu_j} = \frac{3eG_F m_{\nu_j}}{8\pi^2\sqrt{2}} = 3.2 \times 10^{-19} (m_{\nu_j}/1\ \text{eV})\mu_B \tag{3}$$

where G_F is the Fermi constant and $\mu_B = e/2m_e$ is the Bohr magneton. The neutrino electric dipole moment violates both time-reversal invariance and parity; although it is nonzero in general, it is quite small (see, *e.g.* Ref. 10). Again, however, we note that Dirac neutrinos should be regarded as a special case; the generic case is Majorana neutrinos. The operator products which define the magnetic and electric-dipole moments, *viz.*, $\overline{\nu}\, \sigma_{\alpha\beta}\, \nu\, F^{\alpha\beta}$ and $\overline{\nu}\, \sigma_{\alpha\beta}\, \gamma_5\, \nu\, F^{\alpha\beta}$, respectively (where $F^{\alpha\beta}$ is the electromagnetic field strength tensor) vanish identically if ν is a Majorana neutrino because of the Majorana property that $\nu^c = \pm\nu$. Thus, a Majorana neutrino has identically zero magnetic and electric dipole moments.

Only the diagonal magnetic- and electric-dipole moments are static properties of a given neutrino-mass eigenstate. Transition magnetic and electric dipole moments exist in general for both Dirac and Majorana neutrinos but are not static properties and hence are not considered here. Occasionally, one also finds references to the "neutrino charge radius" in the literature. This is defined via the Taylor series expansion of the generalized vector Dirac form factor multiplying γ_μ in the electromagnetic current matrix element: $F_1^V(q^2) = F_1^V(0) + q^2\, dF_1^V/dq^2|_{q^2=0} + \mathcal{O}[(q^2)^2]$, where q denotes the 4-momentum of the photon [see, *e.g.* Ref. 5 Eq. (2.20)]. The electric charge is $Q = F^V(0) = 0$ for a neutrino, and the charge radius is given by $\langle r^2 \rangle = (1/6)(F_1^V)'(0)$. However, since this is multiplied by q^2 in the Taylor series expansion, it never occurs for a real photon, where $q^2 = 0$, and hence is not an S-matrix element, *i.e.*, not a physical quantity. In a gauge theory, this is manifested in the fact that the charge radius is gauge-dependent.

If one considers the possibility of nonzero masses for neutrinos, for consistency one must then also consider the leptonic mixing which would in general occur concomitantly. Accordingly, this *Review* devotes a section to correlated bounds on neutrino masses and lepton mixing angles. These can be divided into two types. First, there are those due to decays involving neutrinos in the final state, which must be recognized to have the possible multimode structure pointed out above. In the two most sensitive cases suggested as tests for neutrino masses and mixing, one obtains a limit on m_{ν_j} and $|U_{aj}|^2$ individually for each j. The peak-search test proposed in Ref. 6 was applied to existing data in that paper and a subsequent one [7]; it was applied in new experiments on 2-body leptonic decays of K^+ and π^+ by several groups at SIN (PSI), KEK, and TRIUMF. The results are catalogued in corresponding subsections on limits on $|U_{1j}|^2$ and $|U_{2j}|^2$. The kink-search test was also applied by a number of groups. The experimental situation, which was controversial for many years, has recently been clarified (see below).

Second, there are those due to processes involving the propagation and subsequent interaction of neutrinos. The latter are often called neutrino-oscillation limits, although this term is strictly correct only if the differences in neutrino masses are sufficiently small relative to their momenta that the propagation is effectively coherent in a quantum mechanical sense; otherwise, the individual ν_j from a given decay such as $\pi_{\mu 2}$ or $K_{\mu 2}$ propagate in a measurably incoherent manner, and there is no oscillation. Experimentalists usually present their results in terms of a simplifying model in which mixing is assumed to occur only between two neutrino species. The relevant transformation equation becomes

$$\begin{pmatrix} \nu_{\ell_a} \\ \nu_{\ell_b} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix} \tag{4}$$

where ν_{ℓ_a} are the weak-neutrino eigenstates, with $\nu_{\ell_1} = \nu_e$, *etc.*, and ν_i are neutrino mass eigenstates. Let the distance between the source of the neutrinos and their point of interaction be denoted L, and their energy as E. Assume furthermore that the m_{ν_i} are such that the coherence assumption is valid. Then the probability of an initial ν_{ℓ_a}, having propagated for a distance $t = L$ (with $1 - v/c \ll 1$) being equal to ν_{ℓ_b} is given by

$$P \equiv |\langle \nu_{\ell_b} | \nu_{\ell_a}(t) \rangle|^2 = \sin^2 2\theta \sin^2\Big(\frac{\Delta m^2 L}{4E}\Big) \tag{5}$$