ELECTRON, MUON, AND TAU NEUTRINO LISTINGS

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The following Listings concern measurements of the properties of neutrinos produced in association with $e^{\pm}$, $\mu^{\pm}$, and $\tau^{\pm}$. Nearly all of the measurements, all of which so far are upper limits, actually concern superpositions of the mass eigenstates ν_i, which are in turn related to the weak eigenstates ν_ℓ, via the neutrino mixing matrix

$$|\nu_\ell\rangle = \sum_i U_{\ell i}\,|\nu_i\rangle \quad . \tag{1}$$

In the analogous case of quark mixing via the CKM matrix, the smallness of the off-diagonal terms (small mixing angles) permits a “dominant eigenstate” approximation. Previous editions of this Review have assumed that the dominant eigenstate paradigm applies to neutrinos as well. However, the present results of neutrino oscillation searches suggest that the mixing matrix contains one, or perhaps more, large mixing angles. We can therefore no longer associate any particular state $|\nu_i\rangle$ with any particular lepton label e, μ or τ. Nevertheless, neutrinos are produced in weak decays with a definite lepton flavor, and are typically detected by the charged current weak interaction again associated with a specific lepton flavor. The listings that follow are separated into the three associated charged lepton categories.

Measured quantities (mass-squared, magnetic moments, mean lifetimes, *etc.*) all depend upon the mixing parameters $|U_{\ell i}|^2$, but to some extent also on experimental conditions (energy resolution). Most of these observables, in particular mass-squared, cannot distinguish between Dirac and Majorana neutrinos and are unaffected by CP phases.

Direct neutrino mass measurements are usually based on the analysis of the kinematics of charged particles (leptons, pions) emitted together with neutrinos (flavor states) in various weak decays. The most sensitive neutrino mass measurement to date, involving electron type neutrinos, is based on fitting the shape of the beta spectrum. The quantity $m_{\nu_e}^{2\,\mathrm{(eff)}} = \sum_i |U_{ei}|^2 m_{\nu_i}^2$ is determined or constrained, where the sum is over all mass eigenvalues m_{ν_i} that are too close together to be resolved experimentally. If the energy resolution is better than $\Delta m_{ij}^2 \equiv m_{\nu_i}^2 - m_{\nu_j}^2$, the corresponding heavier m_{ν_i} and mixing parameter could be determined by fitting the resulting spectral anomaly (step or kink).

A limit on $m_{\nu_e}^{2\,\mathrm{(eff)}}$ implies an *upper* limit on the *minimum* value $m_{\nu_{\mathrm{min}}}^2$ of $m_{\nu_i}^2$, independent of the mixing parameters U_{ei}: $m_{\nu_{\mathrm{min}}}^2 \leq m_{\nu_e}^{2\,\mathrm{(eff)}}$. However, if and when the study of neutrino oscillations provides us with the values of *all* neutrino mass-squared differences Δm_{ij}^2 and the mixing parameters $|U_{ei}|^2$, then the individual neutrino mass squares $m_{\nu_j}^2 = m_{\nu_e}^{2\,\mathrm{(eff)}} - \sum_i |U_{ei}|^2 \Delta m_{ij}^2$ can be determined. If only the $|\Delta m_{ij}^2|$ are known, a limit on $m_{\nu_e}^{\mathrm{(eff)}}$ from beta decay may be used to define an *upper* limit on the *maximum* value $m_{\nu_{\mathrm{max}}}$ of m_{ν_i}: $m_{\nu_{\mathrm{max}}}^2 \leq m_{\nu_e}^{2\,\mathrm{(eff)}} + \sum_{i<j} |\Delta m_{ij}^2|$.

The analysis of the low energy beta decay of tritium yields the most stringent limit on $m_{\nu_e}^{\mathrm{(eff)}}$ to date (where $m_{\nu_\ell}^{\mathrm{(eff)}} \equiv \sqrt{m_{\nu_\ell}^{2\,\mathrm{(eff)}}}$). Unphysical negative $m_{\nu_e}^{2\,\mathrm{(eff)}}$ fits, caused by an as yet not understood event excess near the spectrum endpoint, are sometimes encountered. In WEINHEIMER 99 two analyses which either exclude the spectral anomaly by choice of the analysis energy window or by using one of four data sets yield an acceptable $m_{\nu_e}^{2\,\mathrm{(eff)}}$ fit and a $m_{\nu_e}^{\mathrm{(eff)}}$ limit of 2.8 eV. LOBASHEV 99 reports a $m_{\nu_e}^{\mathrm{(eff)}}$ limit of 2.5 eV by introducing an a priori chosen parameterization of the anomalous near-endpoint events into the spectral analysis.

In analogous way, by measuring the muon momentum in the pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$ one constrains the quantity $m_{\nu_\mu}^{2\,\mathrm{(eff)}} = \sum_i |U_{\mu i}|^2 m_{\nu_i}^2$, where the sum is again over all m_{ν_i} that cannot be resolved experimentally. Obviously, the true $m_{\nu_\mu}^{2\,\mathrm{(eff)}}$ cannot be larger than the *maximum* value of $m_{\nu_i}^2$. As pointed out above, this maximum could be restricted by the tritium beta decay, provided *all* neutrino mass-squared differences $|\Delta m_{ij}^2|$ are known. The most sensitive measurement by ASSAMAGAN 96 is $m_{\nu_\mu}^{(\mathrm{eff})} < 170$ keV, more than four orders of magnitude less stringent than the tritium experiments.

Similar remarks can be made about $m_{\nu_\tau}^{2\,(\mathrm{eff})}$ constrained by the shape of the spectrum of decay products of the τ lepton. Again, the true $m_{\nu_\tau}^{2\,(\mathrm{eff})}$ cannot exceed the *maximum* $m_{\nu_i}^2$ value, which could be constrained by *both* $m_{\nu_e}^{2\,(\mathrm{eff})}$ and $m_{\nu_\mu}^{2\,(\mathrm{eff})}$ values or limits, provided the corresponding $|\Delta m_{ij}^2|$ are known. The most stringent limit on $m_{\nu_\tau}^{(\mathrm{eff})}$ by BARATE 98F, 18.2 MeV, is yet another two orders of magnitude less sensitive than the $m_{\nu_\mu}^{(\mathrm{eff})}$ limit. The different sensitivities of the current experiments regarding $m_{\nu_\tau}^{(\mathrm{eff})}$, $m_{\nu_\mu}^{(\mathrm{eff})}$, and $m_{\nu_e}^{(\mathrm{eff})}$ are relevant, however, only if the oscillation searches, reported below, can be regarded as an reliable source of the $|\Delta m_{ij}^2|$ values.

The spread of arrival times of the neutrinos from SN1987A, coupled with the measured neutrino energies, provides a time-of-flight limit on a quantity similar to $m_{\nu_e}^{(\mathrm{eff})}$. This statement, clothed in various degrees of sophistication, has been the basis for a very large number of papers. The resulting limits, however, are no longer competitive with the limits from the tritium beta decay.