INTRODUCTION TO THE NEUTRINO PROPERTIES LISTINGS

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The following Listings concern measurements of various properties of neutrinos. 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

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

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* had assumed that the dominant eigenstate paradigm applied to neutrinos as well. However, the present results of neutrino oscillation searches show that the mixing matrix contains two large mixing angles. We cannot, therefore, 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 for the neutrino mass that follow are separated into the three associated charged-lepton categories. Other properties (mean lifetime, magnetic moment, charge, and charge radius) are no longer separated this way. If needed, the associated lepton flavor is reported in the footnotes.

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 (*e.g.*, on 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 $\langle m_\beta^2 \rangle = \sum_i |U_{ei}|^2 m_{\nu_i}^2$ 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 $\langle m_\beta^2 \rangle$ implies an *upper* limit on the *minimum* value m_{min}^2 of $m_{\nu_i}^2$, independent of the mixing parameters U_{ei}: $m_{min}^2 \leq \langle m_\beta^2 \rangle$. However, if and when the value of $< m_\beta^2 >$ is determined and 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 $m_{\nu_j}^2 = \langle m_\beta^2 \rangle - \sum_i |U_{ei}|^2 \Delta m_{ij}^2$ can be determined.

All confirmed neutrino oscillation experiments using solar, reactor, atmospheric and accelerator neutrinos can be described using three active neutrino flavors, *i.e.*, two mass splittings and three mixing angles. Combined three neutrino analyses determine the squared mass differences and two of the mixing angles to within reasonable accuracy. For given $|\Delta m_{ij}^2|$, a limit on $\langle m_\beta^2 \rangle$ from beta decay defines an *upper* limit on the *maximum* value m_{max} of m_{ν_i}: $m_{max}^2 \leq \langle m_\beta^2 \rangle + \sum_{i<j} |\Delta m_{ij}^2|$. The analysis of the low energy beta decay of tritium, combined with the oscillation results, thus limits *all* active neutrino masses. Traditionally experimental neutrino mass limits obtained from pion decay $\pi^+ \to \mu^+ + \nu_\mu$, or the shape of the spectrum of decay products of the τ lepton, did not distinguish between flavor and mass eigenstates. These results are reported as limits of the μ and τ based neutrino mass. After the determination of the $|\Delta m_{ij}^2|$'s, the corresponding neutrino mass limits are no longer competitive with those derived from low energy beta decays, with the proviso, however, that the oscillation searches, reported below, can be regarded as a reliable source of *all* $|\Delta m_{ij}^2|$ values.

The spread of arrival times of the neutrinos from SN1987A, coupled with the measured neutrino energies, provided a time-of-flight limit on a quantity similar to $\langle m_\beta \rangle \equiv \sqrt{\langle m_\beta^2 \rangle}$. 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 comparable with the limits from tritium beta decay.

Constraint on the sum of the neutrino masses can be obtained from the analysis of the cosmic microwave background anisotropy, combined with the galaxy redshift surveys and other data. These limits are reported in a separate table (Sum of Neutrino Masses, m_{tot}). Discussion concerning the model dependence of this limit is continuing.