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 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. However, the results of neutrino oscillation searches show that the mixing matrix contains two large mixing angles and a third angle that is not exceedingly small. We cannot, therefore, associate any particular state $|\nu_i\rangle$ with any particular lepton label e, μ or τ. Nevertheless, note that in the standard labeling the $|\nu_1\rangle$ has the largest $|\nu_e\rangle$ component ($\sim 2/3$), $|\nu_2\rangle$ contains $\sim 1/3$ of the $|\nu_e\rangle$ component and $|\nu_3\rangle$ contains only a small $\sim 2.5\%$ $|\nu_e\rangle$ component.

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. Hence, 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 antineutrinos, 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 $\langle m_\beta^2 \rangle$ is determined then its combination with the results derived from neutrino oscillations that give us the values of the neutrino mass-squared differences $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ and the mixing parameters $|U_{ei}|^2$, 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.

So far solar, reactor, atmospheric and accelerator neutrino oscillation experiments can be consistently described using three active neutrino flavors, i.e. two mass splittings and three mixing angles. However, several experiments with radioactive sources, reactors, and accelerators imply the possible existence of one or more non-interacting neutrino species that might be observable since they couple weakly to the flavor neutrinos $|\nu_l\rangle$.

Combined three neutrino analyses determine the squared mass differences and all three 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 $|\Delta m^2_{ij}|$'s and the mixing angles θ_{ij}, the corresponding neutrino mass limits are no longer competitive with those derived from low energy beta decays.

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 $\langle m_\beta \rangle \equiv \sqrt{\langle m^2_\beta \rangle}$. 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.