Massive Neutrinos and Lepton Mixing
THIS IS PART 1 OF 5

To reduce the size of this section's PostScript file, we have divided it into five PostScript files. We present the following index:

PART 1

PART 2

PART 3

PART 4

PART 5

Massive Neutrinos and Lepton Mixing, Searches for

Searches for massive neutral leptons and the effects of nonzero neutrino masses are listed here. These results are divided into the following main sections:

A. Heavy neutral lepton mass limits;
B. Sum of neutrino masses;
C. Searches for neutrinoless double-β decay (see the note by P. Vogel on "Searches for neutrinoless double-β decay" preceding this section);
D. Other bounds from nuclear and particle decays;
E. Bounds from particle decays;
F. Solar ν experiments (see the note on "Solar Neutrinos" by K. Nakamura preceding this section);
G. Astrophysical neutrino observations;
H. Reactor $\overline{\nu}_e$ disappearance experiments;
I. Accelerator neutrino appearance experiments;
J. Disappearance experiments with accelerator and radioactive source neutrinos.

Direct searches for masses of dominantly coupled neutrinos are listed in the appropriate section on ν_e, ν_μ, or ν_τ. Searches for massive charged leptons are given elsewhere, and searches for the mixing of $(\mu^- e^+)$ and $(\mu^+ e^-)$ are given in the muon listings.

Discussion of the ν_e and ν_μ mass limits and the theory of mixing are given in the note on "Neutrinos" by R.E. Shrock in the ν_e section near the beginning of these Particle Listings. Several reviews are also listed there.

Most of the results of the present section are correlated upper bounds on mixing matrix coefficients U_{aj} versus neutrino mass. In some of these cases (*e.g.* accelerator neutrino oscillation experiments), results are presented assuming that mixing occurs only between two neutrino species. In this case limits or results can be shown as allowed regions on a plot of $|\Delta m^2|$ as a function of $\sin^2 2\theta$, where $\Delta m^2 = m^2_{\nu_i} - m^2_{\nu_j}$. Although there are three flavors, data are usually analyzed assuming an oscillation between just two of them, *e.g.*, $\nu_\tau \leftrightarrow \nu_e$. The same remark applies to lepton-number violating mixing between two states, *e.g.*, $\nu_e \leftrightarrow \overline{\nu}_\mu$ or $\nu_\mu \leftrightarrow \overline{\nu}_\mu$. However, in a comprehensive analysis of all current data on limits on (or positive reports of) neutrino oscillations, one should use a three-generation mixing framework.

The simplest situation occurs in an "appearance" experiment, where one searches for interactions by neutrinos of a variety not expected in the beam. An example is the search for $\overline{\nu}_e$ interactions in a beam of neutrinos from the π^+ decay chain, which (among other possibilities) might be taken as evidence for $\overline{\nu}_\mu \to \overline{\nu}_e$. For oscillation between two states, the probability that the "wrong" state will appear is given by Eq. 5 in Shrock's "Note on Neutrinos" at the beginning of the Quark and Lepton Particle Listings. For our present purposes, this may be rewritten as

$$P = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E) \; , \qquad (1)$$

where L is the distance from the neutrino's production point to its interaction point, and E is its energy. In the above, $|\Delta m^2|$ is in eV^2 and L/E is in km/GeV or m/MeV. Since in a real experiment L and E have some spread, one must average P over the appropriate distributions. As an example, let us make the somewhat unrealistic assumption that $b \equiv 1.27 L/E$ has a Gaussian distribution with standard deviation σ_b about a central value b_0. Then:

$$\langle P \rangle = \tfrac{1}{2} \sin^2 2\theta [1 - \cos(2b_0 \Delta m^2) \exp(-2\sigma_b^2 (\Delta m^2)^2)] \qquad (2)$$

The value of $\langle P \rangle$ is set by the experiment. For example, if 230 interactions of the expected flavor are detected and none of the wrong flavor are seen, then $P = 0.010$ at the 90% CL. We can then solve the above expression for $\sin^2 2\theta$ as a function of $|\Delta m^2|$. This function is shown in Fig. 1 for the parameter assumptions given in the caption. Note that:

(a) since the fast oscillations are completely washed out by the resolution for large $|\Delta m^2|$, $\sin^2 2\theta = 2 \langle P \rangle$ in this region;
(b) the maximum excursion to the left is to approximately $\langle P \rangle$, and it occurs at $|\Delta m^2| = \pi/2b_0$ eV^2;
(c) for large $\sin^2 2\theta$, $\Delta m^2 \propto (\sin^2 2\theta)^{-1/2}$; and
(d) the intercept at $\sin^2 2\theta = 1$ is at $\sqrt{\langle P \rangle}/b_0$.

The intercept for large $|\Delta m^2|$ is just a measure of running time and backgrounds, while the intercept at $\sin^2 2\theta = 1$ also depends on the mean value of L/E. The wiggles depend on the experimental resolution, but aside from such details the two intercepts completely describe the exclusion region: For large $|\Delta m^2|$, $\sin^2 2\theta$ is constant, and for large $\sin^2 2\theta$ the constant slope is known. For these reasons, it is (nearly) sufficient to summarize the results of an experiment by stating the two intercepts, as is done in the following tables. The reader is referred to the original papers for the two-dimensional plots expressing the actual limits.

If a positive effect is claimed, then the excluded region becomes an included region. This is the case for the HIRATA 92 analysis of R(μ/e) for atmospheric neutrinos.

In a "disappearance" experiment, one looks for the attenuation of the beam neutrinos (for example, ν_k) by mixing with at least one other neutrino eigenstate. (We label such experiments as $\nu_k \not\to \nu_k$.) These experiments fall into two general classes:

(a) Those in which the beam neutrino flux is known, from theory or other measurements. In the high-$|\Delta m^2|$ region, where the oscillation length is small compared to the size of the apparatus, the oscillations are in both directions and the beam intensity is reduced by a factor of two (for two-component mixing). In this case, indicated qualitatively by the "Disappearance A" curve in Fig. 1. sensitivity is maintained for large $|\Delta m^2|$, but with no simple rule relating this asymptote to the maximum excursion to the left. An example is provided by the VUILLEUMIER 82 measurements at the Gösgen reactor.

(b) Those in which the intensity must be measured in the apparatus itself (two detectors, or a "long" detector). Then above some minimum $|\Delta m^2|$ the equilibrium is established upstream, and there is no change in intensity over the length of the apparatus. As a result, sensitivity is lost at high $|\Delta m^2|$, as is qualitatively indicated by the curve "Disappearance B" in Fig. 1. See, for example, DYDAK 84.

Finally, there are more complicated cases, such as in the HIRATA 92B analysis of the Kamiokande II solar neutrino data in terms of the MSW parameters. An irregular region on the $|\Delta m^2|$ vs $\sin^2 2\theta$ is excluded for a combination of physical reasons. It is difficult to represent adequately these graphical data within the strictures of our tables.

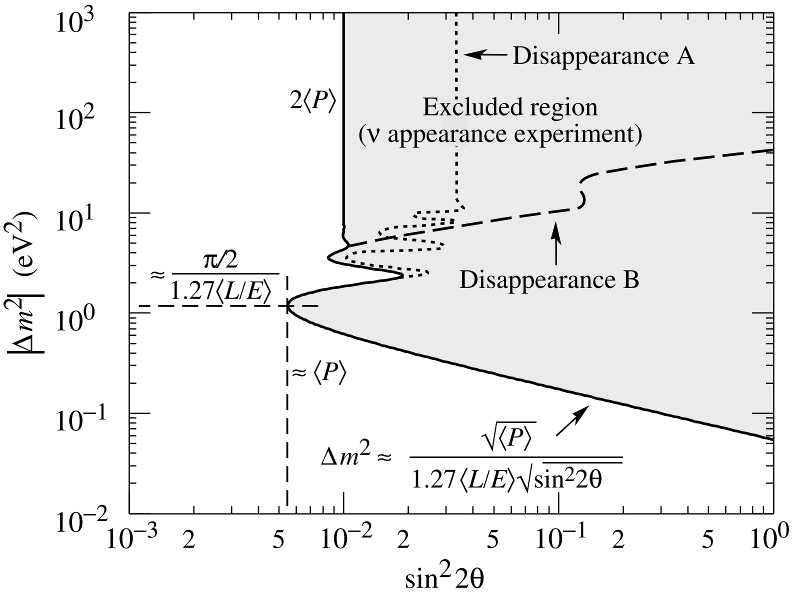

Figure 1: Neutrino oscillation parameter ranges excluded by a toy experiment in which one searches for the appearance of neutrinos not expected in the beam. The probability of appearance, in this case 0.5% at some specified CL, is set by the number of right-flavor events observed and/or information about the flux and cross sections. Here it is assumed that $\langle L/E\rangle = 1$ km GeV^{-1}, and that the distribution of L/E is Gaussian with a 20% standard deviation. The wiggle structure is determined by the resolution function, and the intercepts are determined by the appearance probability and $\langle L/E\rangle$. The leftmost excursion relative to the high-$|\Delta m^2|$ limit and the slope of the lower part of the curve are independent of the experiment. In a disappearance experiment, high-$|\Delta m^2|$ sensitivity is lost unless the incident flux is known. These two possibilities are shown qualitatively by the dashed lines marked "Disappearance A" and "Disappearance B."