that the neutrino travels to its energy $E$ or

**Searches for Massive Neutrinos**

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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-$\beta$ decay (see the note by P. Vogel on “Searches for neutrinoless double-$\beta$ decay” preceding this section);
D. Other bounds from nuclear and particle decays;
E. Solar $\nu$ experiments (see the note on “Solar Neutrinos” by K. Nakamura preceding this section);
F. Astrophysical neutrino observations;
G. Reactor $\bar{\nu}_e$ disappearance experiments;
H. Accelerator neutrino appearance experiments;
I. Disappearance experiments with accelerator and radioactive source neutrinos.

Direct searches for masses of dominantly coupled neutrinos are listed in the appropriate sections on $\nu_e$, $\nu_\mu$, or $\nu_\tau$, where it is assumed that the mass eigenstates $\nu_1$, $\nu_2$, and $\nu_3$ predominate coupling to $\nu_e$, $\nu_\mu$, and $\nu_\tau$, respectively. Note that the assumptions made in these Listings, that $\nu_2$ predominate couples to $\nu_\mu$ and $\nu_\tau$ to $\nu_e$, may not be true. Searches for charge-lepton masses are listed elsewhere, and searches for the mixing of $(\mu^-e^+)$ and $(\mu^+e^-)$ are given in the muon Listings.

Discussion of the current neutrino mass limits and the theory of mixing are given in the note on “Neutrino Mass” by Boris Kayser just before the $\nu_\nu$ Listings.

In many of the following Listings (e.g. neutrino disappearance and appearance experiments), results are presented assuming that mixing occurs only between two neutrino species, such as $\nu_\tau \leftrightarrow \nu_\nu$. This assumption is also made for lepton-number violating mixing between two states, such as $\nu_e \leftrightarrow \tau_R$ or $\nu_\mu \leftrightarrow \tau_R$. As discussed in Kayser’s review, the assumption of mixing between only two states is valid if (a) all mixing angles are small or (b) there is a mass hierarchy such that one $\Delta M^2_{ij}$, e.g. $\Delta M^2_{21} = M^2_2 - M^2_1$, is small compared with the others, so that there is a region in $L/E$ (the ratio of the distance $L$ that the neutrino travels to its energy $E$) where $\Delta M^2_{21}L/E$ is negligible, but $\Delta M^2_{32}L/E$ is not.

In this case limits or results can be shown as allowed regions on a plot of $\Delta M^2$ as a function of $\sin^2 2\theta$. 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 $\nu_e$ interactions in a detector in a $\nu_\mu$ beam. For oscillation between two states, the probability that the “wrong” state will appear is given by Eq. 11 in Kayser’s review, which may be written as

$$P = \frac{1}{2} \sin^2 2\theta \sin^2 \left( \frac{1}{2} \Delta M^2 L/E \right) ,$$

where $|\Delta M^2|$ is in eV$^2$ and $L/E$ is in km/GeV or m/MeV. In a real experiment $L$ and $E$ have some spread, so that one must average $P$ over the distribution of $L/E$. As an example, let us make the somewhat unrealistic assumption that $b \equiv 1.27L/E$ has a Gaussian distribution with standard deviation $\sigma_b$ about a central value $b_0$. Then:

$$\langle P \rangle = \frac{1}{2} \sin^2 2\theta \sin^2 \left( \frac{1}{2} \Delta M^2 \frac{L}{E} \right) \exp \left( -2\sigma_b^2 \left( \frac{1}{2} \Delta M^2 \right)^2 \right)$$

(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. 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 (If $b$ is taken as much smaller than experimental resolution, Eq. (2) can be used in Monte Carlo calculations to avoid the pathology if Eq. (1) at large $\Delta m^2$);

(b) the maximum excursion of the curve to the left is $\sin^2 2\theta = \langle P \rangle$ with good resolution, with smaller excursion for worse resolution. This “bump” occurs at $|\Delta M^2| = \pi/2b_0$ eV$^2$;

(c) for large $\sin^2 2\theta$, $|\Delta M^2| \approx \langle P \rangle / \sin^2 2\theta$ and, consequently;

(d) the intercept at $\sin^2 2\theta = 1$ is $|\Delta M^2| = \langle P \rangle / b_0$. The intercept for large $|\Delta M^2|$ is a measure of running time and backgrounds, while the intercept at $\sin^2 2\theta = 1$ depends also on the mean value of $L/E$. The wiggles depend on experimental features such as the size of the source, the neutrino energy distribution, and detector and analysis features. Aside from such details, the two intercepts completely describe the exclusion region: For large $|\Delta M^2|$, $\sin^2 2\theta$ is constant and equal to $2\langle P \rangle$, and for large $\sin^2 2\theta$ the slope is known from the intercept. 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 is replaced by an allowed band or allowed regions. This is the case for the LSND experiment [2] and the SuperKamiokande analysis of $R(\mu/e)$ for atmospheric neutrinos [3].

In a “disappearance” experiment, one looks for the attenuation of the beam neutrinos (for example, $\nu_k$) by mixing with at least one other neutrino eigenstate. (We label such experiments as $\nu_k \leftrightarrow \nu_j$.) The probability that a neutrino remains the same neutrino from the production point to detector is given by

$$P(\nu_k \rightarrow \nu_k) = 1 - P(\nu_k \rightarrow \nu_j) ,$$

(3)

where mixing occurs between the $k$th and $j$th species with $P(\nu_k \rightarrow \nu_j)$ given by Eq. (1) or Eq. (2).
cannot establish small-probability (small sin$^2\theta$ fluctuations. For this reason, disappearance experiments usually go unobserved because of statistical disappearance of a few “right-flavor” neutrinos in a disappearance experiment, establishing mixing in an appearance experiment, 

\begin{equation}
\Delta M^2 = \frac{\sqrt{2}}{\sin^2\theta} \sqrt{1.27\langle L/E\rangle |\Delta M^2|}
\end{equation}

II. Those in which the beam neutrino flux is known, from theoretical or from other measurements. Examples are reactor $\bar{\nu}_e$ experiments and certain accelerator experiments. Although such experiments cannot establish very small-sin$^2\theta$ mixing, they can establish small limits on $\Delta M^2$ for large sin$^2\theta$ because $L/E$ can be very large. An example, based on the Chooz reactor measurements [5], is labeled “Disappearance I” in Fig. 1. \footnote{Curve generated with $\langle P \rangle = 0.005$, $\langle L/E \rangle = 1.11$, and $\sigma_p/b_0 = 0.08$.}

Finally, there are more complicated cases, such as analyses of solar neutrino data in terms of the MSW parameters [6]. For a variety of physical reasons, an irregular region in the $|\Delta M^2|$ vs sin$^2\theta$ plane is allowed. It is difficult to represent these graphical data adequately within the strictures of our tables.

Experimental two-neutrino mixing limits and positive signals are shown on the following page.

**Footnotes and References**

* A superior statistical analysis of confidence limits in the sin$^2\theta$ vs $|\Delta M^2|$ plane is given in Ref. 1.
\footnote{Curve parameters $\langle P \rangle = 0.1$, $\langle L/E \rangle = 237$, and $\sigma_p/b_0 = 0.5$. For the actual Chooz experiment [5], $\langle L/E \rangle \approx 300$ and the limit on $\langle P \rangle$ is 0.09.}

3. Y. Fukuda et al., eprint hep-ex/9803005.