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-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. Solar ν experiments (see the note on "Solar Neutrinos" by K. Nakamura preceding this section);
F. Astrophysical neutrino observations;
G. Reactor $\overline{\nu}_e$ 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 ν_e, ν_μ, or ν_τ, where it is assumed that the mass eigenstates ν_1, ν_2, and ν_3 predominately couple to ν_e, ν_μ, and ν_τ, respectively. Note that the assumptions made in these Listings, that ν_2 predominately couples to ν_μ and ν_3 to ν_τ, may not be true. Searches for massive charged leptons 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 ν_e 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 $\nu_\tau \leftrightarrow \nu_e$. This assumption is also made for lepton-number violating mixing between two states, such as $\nu_e \leftrightarrow \overline{\nu}_\mu$ or $\nu_\mu \leftrightarrow \overline{\nu}_\mu$. 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 ΔM^2_{ij}, *e.g.* $\Delta M^2_{21} = M^2_{\nu_2} - M^2_{\nu_1}$, 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 ν_e interactions in a detector in a ν_μ 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

$$P = \sin^2 2\theta \, \sin^2(1.27 \Delta M^2 L/E) \ , \tag{1}$$

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 σ_b about a central value b_0. Then:

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

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 Δm^2);
(b) the maximum excursion of the curve to the left is to $\sin^2 2\theta = \langle P \rangle$ with good resolution, with smaller excursion for worse resolution. This "bump" occurs at $|\Delta M^2| = \pi/2b_0$ eV^2;
(c) for large $\sin^2 2\theta$, $\Delta M^2 \approx (\langle P \rangle / \sin^2 2\theta)^{1/2}/b_0$; and, consequently,
(d) the intercept at $\sin^2 2\theta = 1$ is at $\Delta M^2 = \sqrt{\langle P \rangle}/b_0$.

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(μ/e) for atmospheric neutrinos [3].

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 $\nu_k \not\to \nu_k$.) The probability that a neutrino remains the same neutrino from the production point to detector is given by

$$P(\nu_k \to \nu_k) = 1 - P(\nu_k \to \nu_j) \ , \tag{3}$$

where mixing occurs between the kth and jth species with $P(\nu_k \to \nu_j)$ given by Eq. (1) or Eq. (2).

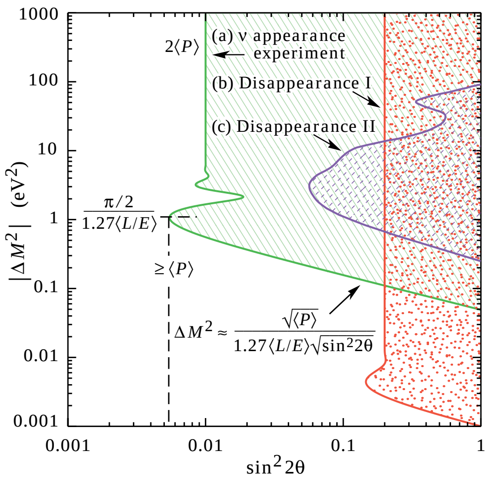

Figure 1: Neutrino oscillation parameter ranges excluded by two hypothetical experiments
(a and b) described by Eq. (2) and one real one (c). Parameters for the first two cases are given in the footnotes. In case (a) one searches for the appearance of neutrinos not expected in the beam. The probability 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. Case (b) represents a disappearance experiment in which the flux is known in the absence of mixing. In case (c), the information comes from measured fluxes at two distances from the target [4].

In contrast to the detection of even a few "wrong-flavor" neutrinos establishing mixing in an appearance experiment, the disappearance of a few "right-flavor" neutrinos in a disappearance experiment goes unobserved because of statistical fluctuations. For this reason, disappearance experiments usually cannot establish small-probability (small $\sin^2 2\theta$) mixing.

Disappearance experiments fall into two general classes:

I. Those in which the beam neutrino flux is known, from theory or from other measurements. Examples are reactor $\overline{\nu}_e$ experiments and certain accelerator experiments. Although such experiments cannot establish very small-$\sin^2 2\theta$ mixing, they can establish small limits on ΔM^2 for large $\sin^2 2\theta$ because L/E can be very large. An example, based on the Chooz reactor measurements [5], is labeled "Disappearance I" in Fig. 1.[‡]

II. Those in which attenuation or oscillation of the beam neutrino flux is measured in the apparatus itself (two detectors, or a "long" detector). 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 can be seen by the curve labeled "Disappearance II" in Fig. 1 [4]. Such experiments have not been competititive for a long time. However, a new generation of long-baseline experiments with a "near" detector and a "far" detector with very large L, *e.g.*, MINOS, will be able to use this strategy to advantage.

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 $\sin^2 2\theta$ 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 $\sin^2 2\theta$–$|\Delta M^2|$ plane is given in Ref. 1.

† Curve generated with $\langle P\rangle = 0.005$, $\langle L/E\rangle = 1.11$, and $\sigma_b/b_0 = 0.08$.

‡ Curve parameters $\langle P\rangle = 0.1$, $\langle L/E\rangle = 237$, and $\sigma_b/b_0 = 0.5$. For the actual Chooz experiment [5], $\langle L/E\rangle \approx 300$ and the limit on $\langle P\rangle$ is 0.09.

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