# Massive Neutrinos – THIS IS PART 1 OF 3

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

PART 1


| | |
|---|---|
| 6 | (A) Heavy neutral leptons |
| 10 | (B) Sum of neutrino masses |
| 11 | (C) Searches for neutrinoless double-beta decay |
| 17 | (D) Other bounds from nuclear and particle decays |


PART 2


| | |
|---|---|
| 26 | (E) Solar nu Experiments |


PART 3


| | |
|---|---|
| 36 | (F) Astrophysical neutrino observations |
| 39 | (G) Reactor nubar(e) disappearance experiments |
| 41 | (H) Accelerator neutrino appearance experiments |
| 47 | (I) Disappearance experiments with accelerator & radioactive source neutrinos |
| 49 | References |

# Massive Neutrinos and Lepton Mixing, Searches for

## SEARCHES FOR MASSIVE NEUTRINOS

Revised April 1998 by D.E. Groom (LBNL).

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 $\overline{\nu}_e$ 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 section on $\nu_e$, $\nu_\mu$, or $\nu_\tau$. 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 current neutrino mass limits and the theory of mixing are given in the note on "Neutrino Mass" by Boris Kayser just before the $\nu_e$ 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 $\Delta M^2_{ij}$, *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 $\nu_e$ 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

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

where $|\Delta M^2|$ is in $\mathrm{eV}^2$ 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 $b \equiv 1.27 L/E$ has a Gaussian distribution with standard deviation $\sigma_b$ about a central value $b_0$. Then:

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

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.† 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 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($\mu/e$) for atmospheric neutrinos [3].

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* 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 $\sigma_b/b_0 = 0.08$.

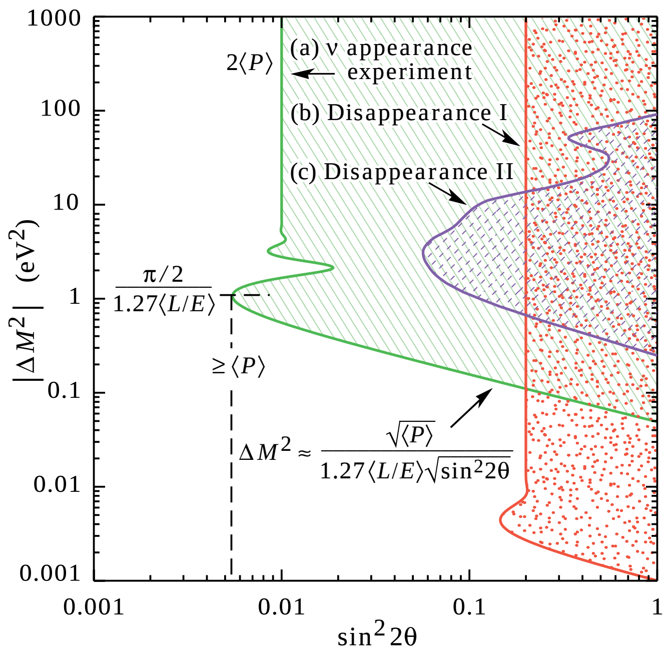


**Figure 1:** Neutrino oscillation parameter ranges excluded by two hypothetical experiments
(a and b) described by Eq. (2) and one real one (c). Parameters for the first two cases are given in the footnotes. In case (a) one searches for the appearance of neutrinos not expected in the beam. The probability 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 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 $\nu_k \not\to \nu_k$.) 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 $k$th and $j$th species with $P(\nu_k \to \nu_j)$ given by Eq. (1) or Eq. (2).

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 $\Delta M^2$ 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,

‡ 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.

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.

## References

1. G.J. Feldman and R.D. Cousins, Phys. Rev. **D3873** (1998).
2. C. Athanassopoulos *et al.*, Phys. Rev. **C54** (1996).
3. Y. Fukuda *et al.*, eprint `hep-ex/9803005`.
4. F. Dydak *et al.*, Phys. Lett. **134B** (1984).
5. M. Apollonio *et al.*, Phys. Lett. **B420**, 397 (1998).
6. N. Hata and P. Langacker, Phys. Rev. **D56**, 6107 (1997).

## (A) Heavy neutral leptons

### Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>45.0** | 95 | ABREU | 92B | DLPH | Dirac |
| **>39.5** | 95 | ABREU | 92B | DLPH | Majorana |
| >44.1 | 95 | ALEXANDER | 91F | OPAL | Dirac |
| >37.2 | 95 | ALEXANDER | 91F | OPAL | Majorana |
| none 3–100 | 90 | SATO | 91 | KAM2 | Kamiokande II |
| >42.8 | 95 | [1] ADEVA | 90S | L3 | Dirac |
| >34.8 | 95 | [1] ADEVA | 90S | L3 | Majorana |
| >42.7 | 95 | DECAMP | 90F | ALEP | Dirac |

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 >$ 6.2×10$^{-8}$ at $m_{L^0}$ = 20 GeV and $>$ 5.1×10$^{-10}$ for $m_{L^0}$ = 40 GeV.

## Neutral Heavy Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited neutral leptons, *i.e.* $\nu^* \to \nu\gamma$.

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| >69.8 | 95 | [2] ACKERSTAFF | 98C | OPAL | Majorana, coupling to $e$ |
| >79.1 | 95 | [2] ACKERSTAFF | 98C | OPAL | Dirac, coupling to $e$ |
| >68.7 | 95 | [2] ACKERSTAFF | 98C | OPAL | Majorana, coupling to $\mu$ |
| >78.5 | 95 | [2] ACKERSTAFF | 98C | OPAL | Dirac, coupling to $\mu$ |
| >54.4 | 95 | [2] ACKERSTAFF | 98C | OPAL | Majorana, coupling to $\tau$ |
| **>69.0** | 95 | [2] ACKERSTAFF | 98C | OPAL | Dirac, coupling to $\tau$ |
| >78.0 | 95 | [2] ACCIARRI | 97P | L3 | Dirac coupling to $e$ |
| >66.7 | 95 | [2] ACCIARRI | 97P | L3 | Majorana coupling to $e$ |
| >78.0 | 95 | [2] ACCIARRI | 97P | L3 | Dirac coupling to $\mu$ |
| >66.7 | 95 | [2] ACCIARRI | 97P | L3 | Majorana coupling to $\mu$ |
| >72.2 | 95 | [2] ACCIARRI | 97P | L3 | Dirac coupling to $\tau$ |
| **>58.2** | 95 | [2] ACCIARRI | 97P | L3 | Majorana coupling to $\tau$ |
| >63 | 95 | [3,4] BUSKULIC | 96S | ALEP | Dirac |
| >54.3 | 95 | [3,5] BUSKULIC | 96S | ALEP | Majorana |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >59.3 | 95 | ACCIARRI | 96G | L3 | Dirac coupling to $e$ |
| >57.9 | 95 | ACCIARRI | 96G | L3 | Dirac coupling to $\mu$ |
| >48.6 | 95 | ACCIARRI | 96G | L3 | Majorana coupling to $e$ |
| >47.2 | 95 | ACCIARRI | 96G | L3 | Majorana coupling to $\mu$ |
| >62.5 | 95 | ALEXANDER | 96P | OPAL | Dirac coupling to $e$ |
| >63.0 | 95 | ALEXANDER | 96P | OPAL | Dirac coupling to $\mu$ |
| >57.4 | 95 | ALEXANDER | 96P | OPAL | Dirac coupling to $\tau$ |
| >51.4 | 95 | ALEXANDER | 96P | OPAL | Majorana coupling to $e$ |
| >52.2 | 95 | ALEXANDER | 96P | OPAL | Majorana coupling to $\mu$ |
| >44.2 | 95 | ALEXANDER | 96P | OPAL | Majorana coupling to $\tau$ |
| >44.5 | 95 | [6] ABREU | 92B | DLPH | Dirac |
| >39.0 | 95 | [6] ABREU | 92B | DLPH | Majorana |
| none 2.5–50 | 95 | [7] ADRIANI | 92I | L3 | $\lvert U_{\tau \text{ or } \mu}\rvert^2 < 3\times10^{-4}$ |
| none 4–50 | 95 | [7] ADRIANI | 92I | L3 | $\lvert U_{\tau}\rvert^2 < 3\times10^{-4}$ |
| >46.4 | 95 | [8] ADEVA | 90S | L3 | Dirac |
| >45.1 | 95 | [8] ADEVA | 90S | L3 | Majorana |
| >46.5 | 95 | [9] AKRAWY | 90L | OPAL | Coupling to $e$ or $\mu$ |
| >45.7 | 95 | [9] AKRAWY | 90L | OPAL | Coupling to $\tau$ |
| >41 | 95 | [10,11] BURCHAT | 90 | MRK2 | Dirac, $\lvert U_{\ell j}\rvert^2 > 10^{-10}$ |
| >19.6 | 95 | [10,11] BURCHAT | 90 | MRK2 | Dirac, all $\lvert U_{\ell j}\rvert^2$ |

| | | | | | |
|---|---|---|---|---|---|
| none 25–45.7 | 95 | [10,12] DECAMP | 90F | ALEP | Dirac $\lvert U_{\ell j}\rvert^2 > 10^{-13}$ |
| none 8.2–26.5 | 95 | [13] SHAW | 89 | AMY | Dirac $L^0$, $\lvert U_{ej}\rvert^2 > 10^{-6}$ |
| none 8.3–22.4 | 95 | [13] SHAW | 89 | AMY | Majorana $L^0$, $\lvert U_{ej}\rvert^2 > 10^{-6}$ |
| none 8.1–24.9 | 95 | [13] SHAW | 89 | AMY | Majorana $L^0$, $\lvert U_{\mu j}\rvert^2 > 10^{-6}$ |
| none 1.8–6.7 | 90 | [14] AKERLOF | 88 | HRS | $\lvert U_{ej}\rvert^2$=1 |
| none 1.8–6.4 | 90 | [14] AKERLOF | 88 | HRS | $\lvert U_{\mu j}\rvert^2$=1 |
| none 2.5–6.3 | 80 | [14] AKERLOF | 88 | HRS | $\lvert U_{\tau j}\rvert^2$=1 |
| none 0.25–14 | 90 | [15] MISHRA | 87 | CNTR | $\lvert U_{\mu j}\rvert^2$=1. |
| none 0.25–10 | 90 | [15] MISHRA | 87 | CNTR | $\lvert U_{\mu j}\rvert^2$=0.1 |
| none 0.25–7.7 | 90 | [15] MISHRA | 87 | CNTR | $\lvert U_{\mu j}\rvert^2$=0.03 |
| none 1.–2. | 90 | [16] WENDT | 87 | MRK2 | $\lvert U_{e \text{ or } \mu j}\rvert^2$=0.1 |
| none 2.2–4. | 90 | [16] WENDT | 87 | MRK2 | $\lvert U_{e \text{ or } \mu j}\rvert^2$=0.001 |
| none 2.3–3. | 90 | [16] WENDT | 87 | MRK2 | $\lvert U_{\tau j}\rvert^2$=0.1 |
| none 3.2–4.8 | 90 | [16] WENDT | 87 | MRK2 | $\lvert U_{\tau j}\rvert^2$=0.001 |
| none 0.3–0.9 | 90 | [17] BADIER | 86 | CNTR | $\lvert U_{ej}\rvert^2$=0.8 |
| none 0.33–2.0 | 90 | [17] BADIER | 86 | CNTR | $\lvert U_{ej}\rvert^2$=0.03 |
| none 0.6–0.7 | 90 | [17] BADIER | 86 | CNTR | $\lvert U_{\mu j}\rvert^2$=0.8 |
| none 0.6–2.0 | 90 | [17] BADIER | 86 | CNTR | $\lvert U_{\mu j}\rvert^2$=0.01–0.001 |
| $>$ 1.2 | | MEYER | 77 | MRK1 | Neutral |

[2] The decay length of the heavy lepton is assumed to be $< 1$ cm, limiting the square of the mixing angle $\lvert U_{\ell j}\rvert^2$ to $10^{-12}$.

[3] BUSKULIC 96S requires the decay length of the heavy lepton to be $< 1$ cm, limiting the square of the mixing angle $\lvert U_{\ell j}\rvert^2$ to $10^{-10}$.

[4] BUSKULIC 96S limit for mixing with $\tau$. Mass is $>$ 63.6 GeV for mixing with $e$ or $\mu$.

[5] BUSKULIC 96S limit for mixing with $\tau$. Mass is $>$ 55.2 GeV for mixing with $e$ or $\mu$.

[6] ABREU 92B limit is for mixing matrix element $\approx 1$ for coupling to $e$ or $\mu$. Reduced somewhat for coupling to $\tau$, increased somewhat for smaller mixing matrix element. Replaces ABREU 91F.

[7] ADRIANI 92I is a search for isosinglet heavy lepton $N_\ell$ which might be produced from $Z \rightarrow \nu_\ell N_\ell$, then decay via a number of different channels. Limits are weaker for decay lengths longer than about 1 m.

[8] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $\lvert U_{1j}\rvert^2 + \lvert U_{2j}\rvert^2 + \lvert U_{3j}\rvert^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

[9] AKRAWY 90L limits valid if coupling strength is greater than a mass-dependent value, e.g., $4.9 \times 10^{-7}$ at $m_{L^0} = 20$ GeV, $3.5 \times 10^{-8}$ at 30 GeV, $4 \times 10^{-9}$ at 40 GeV.

[10] Limits apply for $\ell = e$, $\mu$, or $\tau$ and for $V-A$ decays of Dirac neutrinos.

[11] BURCHAT 90 searched for $Z$ decay to unstable $L^0$ pairs at SLC. It includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[12] For $25 < m_{L^0} < 42.7$ GeV, DECAMP 90F exclude an $L^0$ for all values of $\lvert U_{\ell j}\rvert^2$.

[13] SHAW 89 also excludes the mass region from 8.0 to 27.2 GeV for Dirac $L^0$ and from 8.1 to 23.6 GeV for Majorana $L^0$ with equal full-strength couplings to $e$ and $\mu$. SHAW 89 also gives correlated bounds on lepton mixing.

[14] AKERLOF 88 is PEP $e^+ e^-$ experiment at $E_{cm}$ = 29 GeV. The $L^0$ is assumed to decay via $V-A$ to $e$ or $\mu$ or $\tau$ plus a virtual $W$.

[15] MISHRA 87 is Fermilab neutrino experiment looking for either dimuon or double vertex events (hence long-lived).

[16] WENDT 87 is MARK-II search at PEP for heavy $\nu$ with decay length 1–20 cm (hence long-lived).

[17] BADIER 86 is a search for a long-lived penetrating sequential lepton produced in $\pi^-$ – nucleon collisions with lifetimes in the range from $5 \times 10^{-7} - 5 \times 10^{-11}$ s and decaying into at least two charged particles. $U_{ej}$ and $U_{m,j}$ are mixing angles to $\nu_e$ and $\nu_\mu$. See also the BADIER 86 entry in the section "Searches for Massive Neutrinos and Lepton Mixing".

## Astrophysical Limits on Neutrino MASS for $m_\nu$ > 1 GeV

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| none 60–115 | | [18] FARGION | 95 | ASTR | Dirac |
| none 9.2–2000 | | [19] GARCIA | 95 | COSM | Nucleosynthesis |
| none 26–4700 | | [19] BECK | 94 | COSM | Dirac |
| none 6 – hundreds | | [20,21] MORI | 92B | KAM2 | Dirac neutrino |
| none 24 – hundreds | | [20,21] MORI | 92B | KAM2 | Majorana neutrino |
| none 10–2400 | 90 | [22] REUSSER | 91 | CNTR | HPGe search |
| none 3–100 | 90 | SATO | 91 | KAM2 | Kamiokande II |
| | | [23] ENQVIST | 89 | COSM | |
| none 12–1400 | | [19] CALDWELL | 88 | COSM | Dirac $\nu$ |
| none 4–16 | 90 | [19,20] OLIVE | 88 | COSM | Dirac $\nu$ |
| none 4–35 | 90 | OLIVE | 88 | COSM | Majorana $\nu$ |
| >4.2 to 4.7 | | SREDNICKI | 88 | COSM | Dirac $\nu$ |
| >5.3 to 7.4 | | SREDNICKI | 88 | COSM | Majorana $\nu$ |
| none 20–1000 | 95 | [19] AHLEN | 87 | COSM | Dirac $\nu$ |
| >4.1 | | GRIEST | 87 | COSM | Dirac $\nu$ |

[18] FARGION 95 bound is sensitive to assumed $\nu$ concentration in the Galaxy. See also KONOPLICH 94.

[19] These results assume that neutrinos make up dark matter in the galactic halo.

[20] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

[21] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

[22] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[23] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

## (B) Sum of neutrino masses

Revised April 1998 by K.A. Olive (University of Minnesota).

The limits on low mass ($m_\nu \lesssim$ 1 MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu \ ,$$

where $g_\nu$ is the number of spin degrees of freedom for $\nu$ plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. Stable neutrinos in this mass range make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu = m_{\rm tot}(3/11) n_\gamma \ ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where $\rho_c$ is the critical energy density of the Universe, and using $n_\gamma = 412 \ {\rm cm}^{-3}$, we have

$$\Omega_\nu h^2 = m_{\rm tot}/(94 \ {\rm eV}) \ .$$

Therefore, a limit on $\Omega_\nu h^2$ such as $\Omega_\nu h^2 < 0.25$ gives the limit

$$m_{\rm tot} < 24 \ {\rm eV} \ .$$

The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

### Limit on Total $\nu$ MASS, $m_{\rm tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\rm tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

| *VALUE* (eV) | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| <180 | SZALAY | 74 | COSM |
| <132 | COWSIK | 72 | COSM |
| <280 | MARX | 72 | COSM |
| <400 | GERSHTEIN | 66 | COSM |

**Limits on MASSES of Light Stable Right-Handed $\nu$**
**(with necessarily suppressed interaction strengths)**

| *VALUE* (eV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| <100–200 | [24] OLIVE | 82 | COSM | Dirac $\nu$ |
| <200–2000 | [24] OLIVE | 82 | COSM | Majorana $\nu$ |

[24] Depending on interaction strength $G_R$ where $G_R < G_F$.

**Limits on MASSES of Heavy Stable Right-Handed $\nu$**
**(with necessarily suppressed interaction strengths)**

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| > 10 | [25] OLIVE | 82 | COSM | $G_R/G_F$ <0.1 |
| >100 | [25] OLIVE | 82 | COSM | $G_R/G_F$ <0.01 |

[25] These results apply to heavy Majorana neutrinos and are summarized by the equation: $m_\nu > 1.2$ GeV $(G_F/G_R)$. The bound saturates, and if $G_R$ is too small no mass range is allowed.

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### (C) Searches for neutrinoless double-$\beta$ decay

## LIMITS FROM NEUTRINOLESS $\beta\beta$ DECAY

Revised 1995 by P. Vogel (Caltech).

Limits on an effective Majorana neutrino mass and a lepton-number violating current admixture can be obtained from lifetime limits on $0\nu\beta\beta$ nuclear decay. The derived quantities are model-dependent, so the half-life measurements are given first. Where possible we list the references for the matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the theory, results for this process are also given. As an indication of the spread among different ways of evaluating the matrix elements, we show in Fig. 1 some representative examples for the most popular nuclei. For further calculations, see, *e.g.,* Ref. 1

To define the limits on lepton-number violating right-handed current admixtures, we display the relevant part of a phenomenological current-current weak interaction Hamiltonian:

$$H_W = (G_F/\sqrt{2}) \times (J_L \cdot j_L^\dagger + \kappa J_R \cdot j_L^\dagger + \eta J_L \cdot j_R^\dagger + \lambda J_R \cdot j_R^\dagger) + \text{h.c.}$$

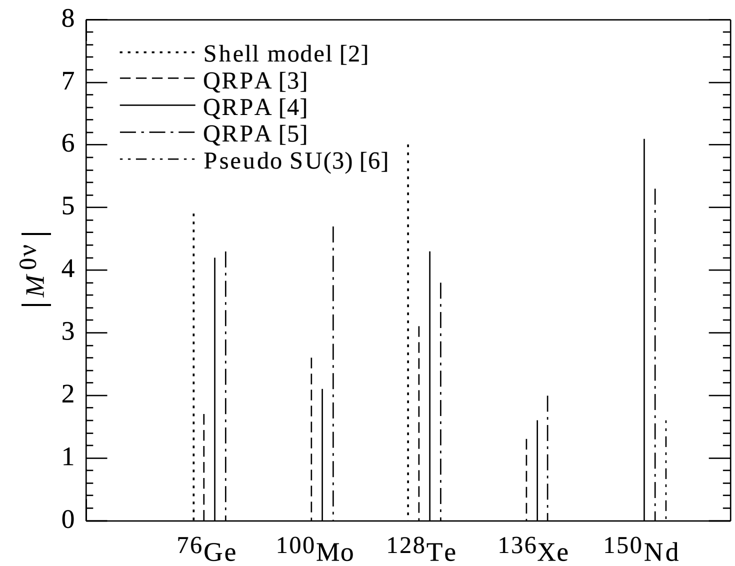


**Figure 1:** Nuclear matrix elements for $0\nu\beta\beta$ decay calculated by a subset of different methods and different authors for the most popular double-beta decay candidate nuclei. Recalculated from the published half-lives using consistent phase-space factors and $g_A = 1.25$. The QRPA [3] value is for $\alpha' = -390$ MeV fm$^3$.

where $j_L^\mu = \bar{e}_L \gamma^\mu \nu_{eL}$, $j_R^\mu = \bar{e}_R \gamma^\mu \nu_{eR}$, and $J_L^\mu$ and $J_R^\mu$ are left-handed and right-handed hadronic weak currents. Experiments are not sensitive to $\kappa$, but quote limits on quantities proportional to $\eta$ and $\lambda$.* In analogy to $\langle m_\nu \rangle$ (see Eq. 11 in the "Note on Neutrinos" at the beginning of the Neutrino Particle Listings), the quantities extracted from experiments are $\langle \eta \rangle = \eta \sum U_{1j} V_{1j}$ and $\langle \lambda \rangle = \lambda \sum U_{1j} V_{1j}$, where $V_{ij}$ is a matrix analogous to $U_{ij}$ (see Eq. 2 in the "Note on Neutrinos"), but describing the mixing among right-handed neutrinos. The quantities $\langle\eta\rangle$ and $\langle\lambda\rangle$ therefore vanish for massless or unmixed neutrinos. Also, as in the case of $\langle m_\nu\rangle$, cancellations are possible in $\langle\eta\rangle$ and $\langle\lambda\rangle$. The limits on $\langle\eta\rangle$ are of order $10^{-8}$ while the limits on $\langle\lambda\rangle$ are of order $10^{-6}$. The reader is warned that a number of earlier experiments did not distinguish between $\eta$ and $\lambda$. Because of evolving reporting conventions and matrix element calculations, we have not tabulated the admixture parameters for experiments published earlier than 1989.

See the section on Majoron searches for additional limits set by these experiments.

## Footnotes and References

* We have previously used a less accepted but more explicit notation in which $\eta_{RL} \equiv \kappa$, $\eta_{LR} \equiv \eta$, and $\eta_{RR} \equiv \lambda$.


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### Half-life Measurements and Limits for Double $\beta$ Decay

In all cases of double beta decay, (Z,A) $\rightarrow$ (Z+2,A) $+ 2\beta^- + (0 \text{ or } 2)\overline{\nu}_e$. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

| $t_{1/2}(10^{21}$ yr) | CL% | ISOTOPE | TRANSITION | | METHOD | DOCUMENT ID | |
|---|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| $(7.6^{+2.2}_{-1.4})$E18 | | $^{100}$Mo | $2\nu$ | | Si(Li) | [26] ALSTON-... | 97 |
| $>$ 0.19 | 90 | $^{92}$Mo | $0\nu+2\nu$ | $0^+ \rightarrow 0^+$ | $\gamma$ in HPGe | [27] BARABASH | 97 |
| $>$ 0.81 | 90 | $^{92}$Mo | $0\nu+2\nu$ | $0^+ \rightarrow 0^+_1$ | $\gamma$ in HPGe | [27] BARABASH | 97 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $>$ 0.89 | 90 | $^{92}$Mo | $0\nu$+$2\nu$ | $0^+ \to 2_1^+$ | $\gamma$ in HPGe | [27] BARABASH | 97 |
| $>$11000 | 90 | $^{76}$Ge | $0\nu$ | $0^+ \to 0^+$ | Enriched HPGe | [28] BAUDIS | 97 |
| $(6.82^{+0.38}_{-0.53} \pm 0.68)$E18 | | $^{100}$Mo | $2\nu$ | | TPC | [29] DESILVA | 97 |
| $(6.75^{+0.37}_{-0.42} \pm 0.68)$E18 | | $^{150}$Nd | $2\nu$ | | TPC | [30] DESILVA | 97 |
| $>$ 1.2 | 90 | $^{150}$Nd | $0\nu$ | | TPC | [31] DESILVA | 97 |
| $1.77 \pm 0.01^{+0.13}_{-0.11}$ | | $^{76}$Ge | $2\nu$ | | Enriched HPGe | [32] GUENTHER | 97 |
| $>$ 32.5 | 90 | $^{130}$Te | $0\nu$ | | Bolometer | [33] ALESSAND... | 96B |
| $(3.75 \pm 0.35 \pm 0.21)$E19 | | $^{116}$Cd | $2\nu$ | $0^+ \to 0^+$ | NEMO 2 | [34] ARNOLD | 96 |
| $0.043^{+0.024}_{-0.011} \pm 0.014$ | | $^{48}$Ca | $2\nu$ | | TPC | [35] BALYSH | 96 |
| $>$ 52 | 68 | $^{100}$Mo | $0\nu,\langle m_\nu\rangle$ | $0^+ \to 0^+$ | ELEGANT V | [36] EJIRI | 96 |
| $>$ 39 | 68 | $^{100}$Mo | $0\nu,\langle\lambda\rangle$ | $0^+ \to 0^+$ | ELEGANT V | [36] EJIRI | 96 |
| $>$ 51 | 68 | $^{100}$Mo | $0\nu,\langle\eta\rangle$ | $0^+ \to 0^+$ | ELEGANT V | [36] EJIRI | 96 |
| $0.79 \pm 0.10$ | | $^{130}$Te | $0\nu$+$2\nu$ | | Geochem | [37] TAKAOKA | 96 |
| $0.61^{+0.18}_{-0.11}$ | | $^{100}$Mo | $0\nu$+$2\nu$ | $0^+ \to 0_1^+$ | $\gamma$ in HPGe | [38] BARABASH | 95 |
| $>$ 0.00013 | 99 | $^{160}$Gd | $2\nu$ | $0^+ \to 0^+$ | $Gd_2SiO_5$:Ce scint | [39] BURACHAS | 95 |
| $>$ 0.00012 | 99 | $^{160}$Gd | $2\nu$ | $0^+ \to 2^+$ | $Gd_2SiO_5$:Ce scint | [39] BURACHAS | 95 |
| $>$ 0.014 | 90 | $^{160}$Gd | $0\nu$ | $0^+ \to 0^+$ | $Gd_2SiO_5$:Ce scint | [39] BURACHAS | 95 |
| $>$ 0.013 | 90 | $^{160}$Gd | $0\nu$ | $0^+ \to 2^+$ | $Gd_2SiO_5$:Ce scint | [39] BURACHAS | 95 |
| $(9.5 \pm 0.4 \pm 0.9)$E18 | | $^{100}$Mo | $2\nu$ | | NEMO 2 | DASSIE | 95 |
| $>$ 0.6 | 90 | $^{100}$Mo | $0\nu$ | $0^+ \to 0_1^+$ | NEMO 2 | DASSIE | 95 |
| $0.026^{+0.009}_{-0.005}$ | | $^{116}$Cd | $2\nu$ | $0^+ \to 0^+$ | ELEGANT IV | EJIRI | 95 |
| $>$ 29 | 90 | $^{116}$Cd | $0\nu$ | $0^+ \to 0^+$ | $^{116}CdWO_4$ scint | [40] GEORGADZE | 95 |
| $>$ 0.3 | 68 | $^{160}$Gd | $0\nu$ | | $Gd_2SiO_5$: Ce scint | KOBAYASHI | 95 |
| $>$ 2.37 | 90 | $^{116}$Cd | $0\nu$+$2\nu$ | $0^+ \to 2^+$ | $\gamma$ in HPGe | [41] PIEPKE | 94 |
| $>$ 2.05 | 90 | $^{116}$Cd | $0\nu$+$2\nu$ | $0^+ \to 0_1^+$ | $\gamma$ in HPGe | [41] PIEPKE | 94 |
| $>$ 2.05 | 90 | $^{116}$Cd | $0\nu$+$2\nu$ | $0^+ \to 0_2^+$ | $\gamma$ in HPGe | [41] PIEPKE | 94 |
| $0.017^{+0.010}_{-0.005} \pm 0.0035$ | | $^{150}$Nd | $2\nu$ | $0^+ \to 0^+$ | TPC | ARTEMEV | 93 |
| $0.039 \pm 0.009$ | | $^{96}$Mo | $0\nu$+$2\nu$ | | Geochem | KAWASHIMA | 93 |
| $>$ 340 | 90 | $^{136}$Xe | $0\nu$ | $0^+ \to 0^+$ | TPC | [42] VUILLEUMIER | 93 |
| $>$ 260 | 90 | $^{136}$Xe | $0\nu$ | $0^+ \to 0^+$ | TPC | [43] VUILLEUMIER | 93 |
| $>$ 0.21 | 90 | $^{136}$Xe | $2\nu$ | $0^+ \to 0^+$ | TPC | VUILLEUMIER | 93 |
| $>$ 430 | 90 | $^{76}$Ge | $0\nu$ | $0^+ \to 2^+$ | Enriched HPGe | BALYSH | 92 |
| $2.7 \pm 0.1$ | | $^{130}$Te | | | Geochem | BERNATOW... | 92 |
| $7200 \pm 400$ | | $^{128}$Te | | | Geochem | [44] BERNATOW... | 92 |
| $>$ 27 | 68 | $^{82}$Se | $0\nu$ | $0^+ \to 0^+$ | TPC | ELLIOTT | 92 |
| $0.108^{+0.026}_{-0.006}$ | | $^{82}$Se | $2\nu$ | $0^+ \to 0^+$ | TPC | ELLIOTT | 92 |
| $0.92^{+0.07}_{-0.04}$ | | $^{76}$Ge | $2\nu$ | $0^+ \to 0^+$ | Enriched HPGe | [45] AVIGNONE | 91 |
| $>$ 3.3 | 95 | $^{136}$Xe | $0\nu$ | $0^+ \to 2^+$ | Prop cntr | [46] BELLOTTI | 91 |
| $>$ 0.16 | 95 | $^{136}$Xe | $2\nu$ | | Prop cntr | BELLOTTI | 91 |
| $2.0 \pm 0.6$ | | $^{238}$U | | | Radiochem | [47] TURKEVICH | 91 |
| $>$ 9.5 | 76 | $^{48}$Ca | $0\nu$ | | $CaF_2$ scint. | YOU | 91 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $1.12^{+0.48}_{-0.26}$ | | $^{76}$Ge | $2\nu$ | $0^+ \to 0^+$ | HPGe | [48] MILEY | 90 |
| $0.9 \pm 0.1$ | | $^{76}$Ge | $2\nu$ | | Enriched Ge(Li) | VASENKO | 90 |
| $>$ 4.7 | 68 | $^{128}$Te | | $0^+ \to 2^+$ | Ge(Li) | [39] BELLOTTI | 87 |
| $>$ 4.5 | 68 | $^{130}$Te | | $0^+ \to 2^+$ | Ge(Li) | [39] BELLOTTI | 87 |
| $>$ 800 | 95 | $^{128}$Te | | | Geochem | [49] KIRSTEN | 83 |
| $2.60 \pm 0.28$ | | $^{130}$Te | | | Geochem | [49] KIRSTEN | 83 |

[26] ALSTON-GARNJOST 97 report evidence for $2\nu$ decay of $^{100}$Mo. This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.

[27] BARABASH 97 measure limits for $\beta^+$, EC, and ECEC decay of $^{92}$Mo to the ground and excited states of $^{92}$Ru, respectively. Limits are not competive compared to $\beta^-\beta^-$ searches as far as sensitivity to $\langle m_\nu \rangle$ or RHC admixtures is concerned.

[28] BAUDIS 97 limit for $0\nu$ decay of enriched $^{76}$Ge using Ge calorimeters supersedes GUENTHER 97.

[29] DESILVA 97 result for $2\nu$ decay of $^{100}$Mo is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.

[30] DESILVA 97 result for $2\nu$ decay of $^{150}$Nd is in marginal agreement with ARTEMEV 93. It has smaller errors.

[31] DESILVA 97 do not explain whether their efficiency for $0\nu$ decay of $^{150}$Nd was calculated under the assumption of a $\langle m_\nu \rangle$, $\langle \lambda \rangle$, or $\langle \eta \rangle$ driven decay.

[32] GUENTHER 97 half-life for the $2\nu$ decay of $^{76}$Ge is not in good agreement with the previous measurements of BALYSH 94, AVIGNONE 91, and MILEY 90.

[33] ALESSANDRELLO 96B experiment can distinguish the $0\nu$ and $2\nu$ modes; it shows that the geochemical observation of $^{130}$Te decay (BERNATOWICZ 92, KIRSTEN 83, TAKAOKA 96) is dominanted by the $2\nu$ decay. Supersedes ALESSANDRELLO 94.

[34] ARNOLD 96 measure the $2\nu$ decay of $^{116}$Cd. This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.

[35] BALYSH 96 measure the $2\nu$ decay of $^{48}$Ca, using a passive source of enriched $^{48}$Ca in a TPC.

[36] EJIRI 96 use energy and angular correlations of the $2\,\beta$-rays in efficiency estimate to give limits for the $0\nu$ decay modes associated with $\langle m_\nu \rangle$, $\langle \lambda \rangle$, and $\langle \eta \rangle$, respectively. Enriched $^{100}$Mo source is used in tracking calorimeter. These are the best limits for $^{100}$Mo. Limit is more stringent than ALSTON-GARNJOST 97.

[37] TAKAOKA 96 measure the geochemical half-life of $^{130}$Te. Their value is in disagreemnt with the quoted values of BERNATOWICZ 92 and KIRSTEN 83; but agrees with several other unquoted determinations, e.g., MANUEL 91.

[38] BARABASH 95 cannot distinguish $0\nu$ and $2\nu$, but it is inferred indirectly that the $0\nu$ mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92).

[39] BELLOTTI 87 searches for $\gamma$ rays for $2^+$ state decays in corresponding Xe isotopes. Limit for $^{130}$Te case argues for dominant $0^+ \to 0^+$ transition in known decay of this isotope.

[40] GEORGADZE 95 result for this and other modes are also give in DANEVICH 95. Result for $2\nu$ decay omitted because of authors' caveats.

[41] In PIEPKE 94, the studied excited states of $^{116}$Sn have energies above the ground state of 1.2935 MeV for the $2^+$ state, 1.7568 MeV for the $0^+_1$ state, and 2.0273 for the $0^+_2$ state.

[42] Limit in the case of a transition induced by a Majorana mass.

[43] Limit for lepton-number violating right-handed current-induced (RHC) decay.

[44] BERNATOWICZ 92 finds $^{128}$Te/$^{130}$Te activity ratio from slope of $^{128}$Xe/$^{132}$Xe vs $^{130}$Xe/$^{132}$Xe ratios during extraction, and normalizes to lead-dated ages for the $^{130}$Te lifetime. The authors state that their results imply that "(a) the double beta decay of $^{128}$Te has been firmly established and its half-life has been determined . . . without any

ambiguity due to trapped Xe interferences... (b) Theoretical calculations ... underestimate the [long half-lives of $^{128}$Te $^{130}$Te] by 1 or 2 orders of magnitude, pointing to a real supression in the $2\nu$ decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models predict a *ratio* of $2\nu$ decay widths ... in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray $^{128}$Xe production corrections.

45 AVIGNONE 91 reports confirmation of the MILEY 90 and VASENKO 90 observations of $2\nu\beta\beta$ decay of $^{76}$Ge. Error is $2\sigma$.

46 BELLOTTI 91 uses difference between natural and enriched $^{136}$Xe runs to obtain $\beta\beta 0\nu$ limits, leading to "less stringent, but safer limits."

47 TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the $^{238}$U transition in the same range as deduced for $^{130}$Te and $^{76}$Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

48 MILEY 90 claims only "suggestive evidence" for the decay. Error is $2\sigma$.

49 KIRSTEN 83 reports "$2\sigma$" error. References are given to earlier determinations of the $^{130}$Te lifetime.

## $\langle m_\nu \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double $\beta$ Decay

$\langle m_\nu \rangle = |\Sigma\ U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to $n$ and where $n$ = number of neutrino generations, and $\nu_j$ is a Majorana neutrino. Note that $U^2_{1j}$, not $|U_{1j}|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

| *VALUE* (eV) | *CL%* | *ISOTOPE* | | *TRANSITION* | *METHOD* | *DOCUMENT ID* | |
|---|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| <9.3 | 68 | $^{100}$Mo | $0\nu$ | | Si(Li) | [50] ALSTON-... | 97 |
| <0.46 | 90 | $^{76}$Ge | $0\nu$ | $0^+ \to 0^+$ | Enriched HPGe | [51] BAUDIS | 97 |
| <2.2 | 68 | $^{100}$Mo | $0\nu$ | $0^+ \to 0^+$ | ELEGANT V | [52] EJIRI | 96 |
| <4.1 | 90 | $^{116}$Cd | $0\nu$ | | $^{116}CdWO_4$ scint | [53] DANEVICH | 95 |
| < 2.8–4.3 | 90 | $^{136}$Xe | $0\nu$ | $0^+ \to 0^+$ | TPC | [54] VUILLEUMIER | 93 |
| < 1.1–1.5 | | $^{128}$Te | | | Geochem | [55] BERNATOW... | 92 |
| <5 | 68 | $^{82}$Se | | | TPC | [56] ELLIOTT | 92 |
| <8.3 | 76 | $^{48}$Ca | $0\nu$ | | $CaF_2$ scint. | YOU | 91 |
| <5.6 | 95 | $^{128}$Te | | | Geochem | KIRSTEN | 83 |

50 ALSTON-GARNJOST 97 obtain the limit for $\langle m_\nu \rangle$ using the matrix elements of ENGEL 88. The limit supersedes ALSTON-GARNJOST 93.

51 BAUDIS 97 limit for $\langle m_\nu \rangle$ is based on the matrix elements of STAUDT 90. This is the most stringent bound on $\langle m_\nu \rangle$. It supersedes the limit of GUENTHER 97.

52 EJIRI 96 obtain the limit for $\langle m_\nu \rangle$ using the matrix elements of TOMODA 91.

53 DANEVICH 95 is identical to GEORGADZE 95.

54 VUILLEUMIER 93 mass range from parameter range in the Caltech calculations (ENGEL 88). On the basis of these calculations, the BALYSH 92 mass range would be < 2.2–4.4 eV.

55 BERNATOWICZ 92 finds these majoron mass limits assuming that the measured geochemical decay width is a limit on the $0\nu$ decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.

56 ELLIOTT 92 uses the matrix elements of HAXTON 84.

### Limits on Lepton-Number Violating ($V+A$) Current Admixture

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle\lambda\rangle = \lambda\sum U_{1j}V_{1j}$ and $\langle\eta\rangle = \eta\sum U_{1j}V_{1j}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

| $\langle\lambda\rangle$ ($10^{-6}$) | CL% | $\langle\eta\rangle$ ($10^{-8}$) | CL% | ISOTOPE | METHOD | DOCUMENT ID | |
|---|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| <1.1 | 90 | <0.64 | 90 | $^{76}$Ge | Enriched HPGe | [57] GUENTHER | 97 |
| <3.7 | 68 | <2.5 | 68 | $^{100}$Mo | Elegant V | [58] EJIRI | 96 |
| <5.3 | 90 | <5.9 | 90 | $^{116}$Cd | $^{116}CdWO_4$ scint | [59] DANEVICH | 95 |
| <4.4 | 90 | <2.3 | 90 | $^{136}$Xe | TPC | [60] VUILLEUMIER | 93 |
| | | <5.3 | | $^{128}$Te | Geochem | [61] BERNATOW... | 92 |

[57] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.
[58] EJIRI 96 obtain limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ using the matrix elements of TOMODA 91.
[59] DANEVICH 95 is identical to GEORGADZE 95.
[60] VUILLEUMIER 93 uses the matrix elements of MUTO 89.
[61] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the $0\nu$ width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on $\eta$. Further details of the experiment are given in BERNATOWICZ 93.

## (D) Other bounds from nuclear and particle decays

## Limits on $|U_{1j}|^2$ as Function of $m_{\nu_j}$

### Peak and kink search tests

Limits on $|U_{1j}|^2$ as function of $m_{\nu_j}$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<1 × 10$^{-7}$** | 90 | [62] BRITTON | 92B | CNTR | 50 MeV $< m_{\nu_j} <$ 130 MeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <5 × 10$^{-6}$ | 90 | DELEENER-... | 91 | | $m_{\nu_j}$ = 20 MeV |
| <5 × 10$^{-7}$ | 90 | DELEENER-... | 91 | | $m_{\nu_j}$ = 40 MeV |
| <3 × 10$^{-7}$ | 90 | DELEENER-... | 91 | | $m_{\nu_j}$ = 60 MeV |
| <1 × 10$^{-6}$ | 90 | DELEENER-... | 91 | | $m_{\nu_j}$ = 80 MeV |
| <1 × 10$^{-6}$ | 90 | DELEENER-... | 91 | | $m_{\nu_j}$ = 100 MeV |
| <5 × 10$^{-7}$ | 90 | AZUELOS | 86 | CNTR | $m_{\nu_j}$=60 MeV |
| <2 × 10$^{-7}$ | 90 | AZUELOS | 86 | CNTR | $m_{\nu_j}$=80 MeV |
| <3 × 10$^{-7}$ | 90 | AZUELOS | 86 | CNTR | $m_{\nu_j}$=100 MeV |
| <1 × 10$^{-6}$ | 90 | AZUELOS | 86 | CNTR | $m_{\nu_j}$=120 MeV |
| <2 × 10$^{-7}$ | 90 | AZUELOS | 86 | CNTR | $m_{\nu_j}$=130 MeV |
| <8 × 10$^{-6}$ | | DELEENER-... | 86 | CNTR | $m_{\nu_j}$=20 MeV |

| | | | | | |
|---|---|---|---|---|---|
| $<4 \times 10^{-7}$ | | DELEENER-... | 86 | CNTR | $m_{\nu_j}$=60 MeV |
| $<2 \times 10^{-6}$ | | DELEENER-... | 86 | CNTR | $m_{\nu_j}$=100 MeV |
| $<7 \times 10^{-6}$ | | DELEENER-... | 86 | CNTR | $m_{\nu_j}$=120 MeV |
| $<1 \times 10^{-4}$ | 90 | [63] BRYMAN | 83B | CNTR | $m_{\nu_j}$=5 MeV |
| $<1.5 \times 10^{-6}$ | 90 | BRYMAN | 83B | CNTR | $m_{\nu_j}$=53 MeV |
| $<1 \times 10^{-5}$ | 90 | BRYMAN | 83B | CNTR | $m_{\nu_j}$=70 MeV |
| $<1 \times 10^{-4}$ | 90 | BRYMAN | 83B | CNTR | $m_{\nu_j}$=130 MeV |
| $<1 \times 10^{-4}$ | 68 | [64] SHROCK | 81 | THEO | $m_{\nu_j}$=10 MeV |
| $<5 \times 10^{-6}$ | 68 | [64] SHROCK | 81 | THEO | $m_{\nu_j}$=60 MeV |
| $<1 \times 10^{-5}$ | 68 | [65] SHROCK | 80 | THEO | $m_{\nu_j}$=80 MeV |
| $<3 \times 10^{-6}$ | 68 | [65] SHROCK | 80 | THEO | $m_{\nu_j}$=160 MeV |

[62] BRITTON 92B is from a search for additional peaks in the $e^+$ spectrum from $\pi^+ \rightarrow e^+ \nu_e$ decay at TRIUMF. See also BRITTON 92.

[63] BRYMAN 83B obtain upper limits from both direct peak search and analysis of B($\pi \rightarrow e\nu$)/B($\pi \rightarrow \mu\nu$). Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).

[64] Analysis of $(\pi^+ \rightarrow e^+ \nu_e)/(\pi^+ \rightarrow \mu^+ \nu_\mu)$ and $(K^+ \rightarrow e^+ \nu_e)/(K^+ \rightarrow \mu^+ \nu_\mu)$ decay ratios.

[65] Analysis of $(K^+ \rightarrow e^+ \nu_e)$ spectrum.

## Kink search in nuclear $\beta$ decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)). Limits on $|U_{1j}|^2$ as a function of $m_{\nu_j}$. See WIETFELDT 96 for a comprehensive review.

| *VALUE* (units $10^{-3}$) | *CL%* | $m_{\nu_j}$ (keV) | *ISOTOPE* | *METHOD* | *DOCUMENT ID* | |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $< 1 \times 10^{-2}$ | 95 | 1 | $^3$H | SPEC | [66] HIDDEMANN | 95 |
| $< 6 \times 10^{-3}$ | 95 | 2 | $^3$H | SPEC | [66] HIDDEMANN | 95 |
| $< 2 \times 10^{-3}$ | 95 | 3 | $^3$H | SPEC | [66] HIDDEMANN | 95 |
| $< 2 \times 10^{-3}$ | 95 | 4 | $^3$H | SPEC | [66] HIDDEMANN | 95 |
| $0.3 \pm 1.5 \pm 0.8$ | | 17 | $^{35}$S | Mag spect | [67] BERMAN | 93 |
| $<$ 2.8 | 99 | 17 | $^3$H | Prop chamber | [68] KALBFLEISCH | 93 |
| $<$ 1 | 99 | 14.4–15.2 | $^3$H | Prop chamber | [68] KALBFLEISCH | 93 |
| $<$ 0.7 | 99 | 16.3–16.6 | $^3$H | Prop chamber | [68] KALBFLEISCH | 93 |
| $<$ 2 | 95 | 13–40 | $^{35}$S | Si(Li) | [69] MORTARA | 93 |
| $<$ 0.73 | 95 | 17 | $^{63}$Ni | Mag spect | OHSHIMA | 93 |
| $<$ 1.5 | 95 | 10.5–25.0 | $^{63}$Ni | Mag spect | [70] OHSHIMA | 93 |
| $<$ 6 | 95 | 5–25 | $^{55}$Fe | IBEC in Ge | [71] WIETFELDT | 93 |
| $<$ 2 | 90 | 17 | $^{35}$S | Mag spect. | [72] CHEN | 92 |
| $<$ 0.95 | 95 | 17 | $^{63}$Ni | Mag spect | [73] KAWAKAMI | 92 |
| $<$ 1.0 | 95 | 10–24 | $^{63}$Ni | Mag spect | KAWAKAMI | 92 |
| $<$ 10 | 90 | 16–35 | $^{125}$I | IBEC; $\gamma$ det | [74] BORGE | 86 |

| | | | | | | |
|---|---|---|---|---|---|---|
| < 7.5 | 99 | 5–50 | $^{35}$S | Mag spect | ALTZITZOG... | 85 |
| < 8 | 90 | 80 | $^{35}$S | Mag spect | [75] APALIKOV | 85 |
| < 1.5 | 90 | 60 | $^{35}$S | Mag spect | APALIKOV | 85 |
| < 8 | 90 | 30 | $^{35}$S | Mag spect | APALIKOV | 85 |
| < 3 | 90 | 17 | $^{35}$S | Mag spect | APALIKOV | 85 |
| < 45 | 90 | 4 | $^{35}$S | Mag spect | APALIKOV | 85 |
| < 10 | 90 | 5–30 | $^{35}$S | Si(Li) | DATAR | 85 |
| < 3.0 | 90 | 5–50 | | Mag spect | MARKEY | 85 |
| < 0.62 | 90 | 48 | $^{35}$S | Si(Li) | OHI | 85 |
| < 0.90 | 90 | 30 | $^{35}$S | Si(Li) | OHI | 85 |
| < 1.30 | 90 | 20 | $^{35}$S | Si(Li) | OHI | 85 |
| < 1.50 | 90 | 17 | $^{35}$S | Si(Li) | OHI | 85 |
| < 3.30 | 90 | 10 | $^{35}$S | Si(Li) | OHI | 85 |
| < 25 | 90 | 30 | $^{64}$Cu | Mag spect | [76] SCHRECK... | 83 |
| < 4 | 90 | 140 | $^{64}$Cu | Mag spect | [76] SCHRECK... | 83 |
| < 8 | 90 | 440 | $^{64}$Cu | Mag spect | [76] SCHRECK... | 83 |
| < 1 | 95 | 0.1 | | | [77] SIMPSON | 81B |
| <4E−3 | 95 | 10 | | | [77] SIMPSON | 81B |
| <100 | 90 | 0.1–3000 | | THEO | [78] SHROCK | 80 |
| < 0.1 | 68 | 80 | | THEO | [79] SHROCK | 80 |

[66] In the beta spectrum from tritium $\beta$ decay nonvanishing or mixed $m_{\overline{\nu}_1}$ state in the mass region 0.01–4 keV. For $m_{\nu_j}$ <1 keV, their upper limit on $|U_{1j}|^2$ becomes less

[67] BERMAN 93 uses an iron-free intermediate-image magnetic spectrometer to measure $^{35}$S$\beta$ decay over a large portion of the spectrum. Paper reports (0.01 ± 0.15)%; above result revised by author on basis of analysis refinements.

[68] KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of $^3$H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{1j}|^2$ as a function of $m_{\nu_j}$ in the range from 13.5 keV to 17.5 keV. Typical upper limits are listed above. They report that this experiment in combination with BAHRAN 92 gives an upper limit of $2.4 \times 10^{-3}$ at the 99% CL. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

[69] MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that "The sensitivity to neutrino mass is verified by measurement with a mixed source of $^{35}$S and $^{14}$C, which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino."

[70] OHSHIMA 93 is the full data analysis from this experiment. The above limit on the mixing strength for a 17 keV neutrino is obtained from the measurement $|U_{1j}|^2 = (-0.11 \pm 0.33 \pm 0.30) \times 10^{-3}$ by taking zero as the best estimate and ignoring physical boundaries; see discussion in HOLZSCHUH 92B for a comparison of methods. An earlier report of this experiment was given in KAWAKAMI 92.

[71] WIETFELDT 93 is an extension of the NORMAN 91 experiment. However, whereas NORMAN 91 reported indications for the emission of a neutrino with mass $m_{\nu_j}$ = 21 ± 2 keV and coupling strength = 0.0085 ± 0.0045, the present experiment states that "We find no evidence for emission of a neutrino in the mass range 5–25 keV. In particular, a 17 keV neutrino with $\sin^2\theta$ ($|U_{1j}|^2$ in our notation) = 0.008 is excluded at the 7$\sigma$ level." The listed limits can be obtained from the paper's Fig. 4. The authors acknowledge that this conclusion contradicts the one reported in NORMAN 91, based on a smaller data sample. In further tests, WIETFELDT 95 have shown that "the observed

distortion was most likely caused by systematic effects... A new measurement with a smaller data sample shows no sign of this distortion."

[72] CHEN 92 is a continuation and improvement of the Boehm *et al.* Caltech iron-free magnetic spectrometer experiment searching for emission of massive neutrinos in $^{35}$S decay (MARKEY 85). The upper limit on $|U_{1j}|^2$ for $m_{\nu_j}$ = 17 keV comes from the measurement $|U_{1j}|^2 = (-0.5 \pm 1.4) \times 10^{-3}$. The authors state that their results "rule out, at the $6\sigma$ level, a 17 keV neutrino admixed at 0.85% (*i.e.* with $|U_{1j}|^2 = 0.85 \times 10^{-2}$," the level claimed by Hime and Jelly in HIME 91. They also state that "our data show no evidence for a heavy neutrino with a mass between 12 and 22 keV" with substantial admixture in the weak admixture in the weak eigenstate $\nu_e$; see their Fig. 4 for a graphical set of measured values of $|U_{1j}|^2$ for various hypothetical values of $m_{\nu_j}$ in this range.

[73] KAWAKAMI 92 experiment final results are given in OHSHIMA 93. The upper limit is improved to $0.73 \times 10^{-3}$, based on $|U_{1j}|^2 = (-0.11 \pm 0.33 \pm 0.30) \times 10^{-3}$. Ohshima notes that the result is $22\sigma$ away from the value $|U_{1j}|^2 = 1\%$.

[74] BORGE 86 results originally presented as evidence against the SIMPSON 85 claim of a 17 keV antineutrino emitted with $|U_{1j}|^2 = 0.03$ in $^3$H decay.

[75] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of $1.7 \times 10^{-3}$ at CL = 90%.

[76] SCHRECKENBACH 83 is a combined measurement of the $\beta^+$ and $\beta^-$ spectrum.

[77] Application of kink search test to tritium $\beta$ decay Kurie plot.

[78] SHROCK 80 was a retroactive analysis of data on several superallowed $\beta$ decays to search for kinks in the Kurie plot.

[79] Application of test to search for kinks in $\beta$ decay Kurie plots.

## Searches for Decays of Massive $\nu$

Limits on $|U_{1j}|^2$ as function of $m_{\nu_j}$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<2 \times 10^{-5}$ | 95 | [80] ABREU | 97I | DLPH | $m_{\nu_j}$=6 GeV |
| $<3 \times 10^{-5}$ | 95 | [80] ABREU | 97I | DLPH | $m_{\nu_j}$=50 GeV |
| $<1.8 \times 10^{-3}$ | 90 | [81] HAGNER | 95 | MWPC | $m_{\nu_h}$ = 1.5 MeV |
| $<2.5 \times 10^{-4}$ | 90 | [81] HAGNER | 95 | MWPC | $m_{\nu_h}$ = 4 MeV |
| $<4.2 \times 10^{-3}$ | 90 | [81] HAGNER | 95 | MWPC | $m_{\nu_h}$ = 9 MeV |
| $<1 \times 10^{-5}$ | 90 | [82] BARANOV | 93 | | $m_{\nu_j}$= 100 MeV |
| $<1 \times 10^{-6}$ | 90 | [82] BARANOV | 93 | | $m_{\nu_j}$= 200 MeV |
| $<3 \times 10^{-7}$ | 90 | [82] BARANOV | 93 | | $m_{\nu_j}$= 300 MeV |
| $<2 \times 10^{-7}$ | 90 | [82] BARANOV | 93 | | $m_{\nu_j}$= 400 MeV |
| $<6.2 \times 10^{-8}$ | 95 | ADEVA | 90S | L3 | $m_{\nu_j}$ = 20 GeV |
| $<5.1 \times 10^{-10}$ | 95 | ADEVA | 90S | L3 | $m_{\nu_j}$ = 40 GeV |
| all values ruled out | 95 | [83] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ < 19.6 GeV |
| $<1 \times 10^{-10}$ | 95 | [83] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ = 22 GeV |
| $<1 \times 10^{-11}$ | 95 | [83] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ = 41 GeV |

| | | | | | | |
|---|---|---|---|---|---|---|
| all values ruled out | 95 | | DECAMP | 90F | ALEP | $m_{\nu_j}$= 25.0–42.7 GeV |
| $<1 \times 10^{-13}$ | 95 | | DECAMP | 90F | ALEP | $m_{\nu_j}$= 42.7–45.7 GeV |
| $<5 \times 10^{-3}$ | 90 | | AKERLOF | 88 | HRS | $m_{\nu_j}$=1.8 GeV |
| $<2 \times 10^{-5}$ | 90 | | AKERLOF | 88 | HRS | $m_{\nu_j}$=4 GeV |
| $<3 \times 10^{-6}$ | 90 | | AKERLOF | 88 | HRS | $m_{\nu_j}$=6 GeV |
| $<1.2 \times 10^{-7}$ | 90 | | BERNARDI | 88 | CNTR | $m_{\nu_j}$=100 MeV |
| $<1 \times 10^{-8}$ | 90 | | BERNARDI | 88 | CNTR | $m_{\nu_j}$=200 MeV |
| $<2.4 \times 10^{-9}$ | 90 | | BERNARDI | 88 | CNTR | $m_{\nu_j}$=300 MeV |
| $<2.1 \times 10^{-9}$ | 90 | | BERNARDI | 88 | CNTR | $m_{\nu_j}$=400 MeV |
| $<2 \times 10^{-2}$ | 68 | [84] | OBERAUER | 87 | | $m_{\nu_j}$=1.5 MeV |
| $<8 \times 10^{-4}$ | 68 | [84] | OBERAUER | 87 | | $m_{\nu_j}$=4.0 MeV |
| $<8 \times 10^{-3}$ | 90 | | BADIER | 86 | CNTR | $m_{\nu_j}$=400 MeV |
| $<8 \times 10^{-5}$ | 90 | | BADIER | 86 | CNTR | $m_{\nu_j}$=1.7 GeV |
| $<8 \times 10^{-8}$ | 90 | | BERNARDI | 86 | CNTR | $m_{\nu_j}$=100 MeV |
| $<4 \times 10^{-8}$ | 90 | | BERNARDI | 86 | CNTR | $m_{\nu_j}$=200 MeV |
| $<6 \times 10^{-9}$ | 90 | | BERNARDI | 86 | CNTR | $m_{\nu_j}$=400 MeV |
| $<3 \times 10^{-5}$ | 90 | | DORENBOS... | 86 | CNTR | $m_{\nu_j}$=150 MeV |
| $<1 \times 10^{-6}$ | 90 | | DORENBOS... | 86 | CNTR | $m_{\nu_j}$=500 MeV |
| $<1 \times 10^{-7}$ | 90 | | DORENBOS... | 86 | CNTR | $m_{\nu_j}$=1.6 GeV |
| $<7 \times 10^{-7}$ | 90 | [85] | COOPER-... | 85 | HLBC | $m_{\nu_j}$=0.4 GeV |
| $<8 \times 10^{-8}$ | 90 | [85] | COOPER-... | 85 | HLBC | $m_{\nu_j}$=1.5 GeV |
| $<1 \times 10^{-2}$ | 90 | [86] | BERGSMA | 83B | CNTR | $m_{\nu_j}$=10 MeV |
| $<1 \times 10^{-5}$ | 90 | [86] | BERGSMA | 83B | CNTR | $m_{\nu_j}$=110 MeV |
| $<6 \times 10^{-7}$ | 90 | [86] | BERGSMA | 83B | CNTR | $m_{\nu_j}$=410 MeV |
| $<1 \times 10^{-5}$ | 90 | | GRONAU | 83 | | $m_{\nu_j}$=160 MeV |
| $<1 \times 10^{-6}$ | 90 | | GRONAU | 83 | | $m_{\nu_j}$=480 MeV |

[80] ABREU 97I long-lived $\nu_j$ analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[81] HAGNER 95 obtain limits on heavy neutrino admixture from the decay $\nu_h \rightarrow \nu_e e^+ e^-$ at a nuclear reactor for the $\nu_h$ mass range 2–9 MeV.

[82] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

[83] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[84] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' e e$ decay mode using reactor (anti)neutrinos.

[85] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for $\nu_\tau$ flux. We do not list these. Note that for this bound to be nontrivial, $j$ is not equal to 3, i.e. $\nu_j$ cannot be the dominant mass eigenstate in $\nu_\tau$ since $m_{\nu_3}$ <70 MeV (ALBRECHT 85I). Also, of course, $j$ is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[86] BERGSMA 83B also quote limits on $|U_{13}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the $\tau$. Those limits were based on assumptions about the $D_s$ mass and $D_s \rightarrow \tau \nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

## Limits on $|U_{2j}|^2$ as Function of $m_{\nu_j}$

### Peak search test

Limits on $|U_{2j}|^2$ as function of $m_{\nu_j}$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $< 1–10 \times 10^{-4}$ | | [87] BRYMAN | 96 | CNTR | $m_{\nu_x}$ = 30–33.91 MeV |
| $>10^{-16}$ | | [88] ARMBRUSTER | 95 | KARM | $m_{\nu_x}$ = 33.9 MeV |
| $< 4 \times 10^{-7}$ | 95 | [89] BILGER | 95 | LEPS | $m_{\overline{\nu}_x}$ = 33.9 MeV |
| $< 7 \times 10^{-8}$ | 95 | [89] BILGER | 95 | LEPS | $m_{\nu_x}$ = 33.9 MeV |
| $< 2.6 \times 10^{-8}$ | 95 | [89] DAUM | 95B | TOF | $m_{\nu_x}$ = 33.9 MeV |
| $< 2 \times 10^{-2}$ | 90 | DAUM | 87 | | $m_{\nu_j}$=1 MeV |
| $< 1 \times 10^{-3}$ | 90 | DAUM | 87 | | $m_{\nu_j}$=2 MeV |
| $< 6 \times 10^{-5}$ | 90 | DAUM | 87 | | 3 MeV $< m_{\nu_j} <$ 19.5 MeV |
| $< 3 \times 10^{-2}$ | 90 | [90] MINEHART | 84 | | $m_{\nu_j}$=2 MeV |
| $< 1 \times 10^{-3}$ | 90 | [90] MINEHART | 84 | | $m_{\nu_j}$=4 MeV |
| $< 3 \times 10^{-4}$ | 90 | [90] MINEHART | 84 | | $m_{\nu_j}$=10 MeV |
| $< 5 \times 10^{-6}$ | 90 | [91] HAYANO | 82 | | $m_{\nu_j}$=330 MeV |
| $< 1 \times 10^{-4}$ | 90 | [91] HAYANO | 82 | | $m_{\nu_j}$=70 MeV |
| $< 9 \times 10^{-7}$ | 90 | [91] HAYANO | 82 | | $m_{\nu_j}$=250 MeV |
| $< 1 \times 10^{-1}$ | 90 | [90] ABELA | 81 | | $m_{\nu_j}$=4 MeV |
| $< 7 \times 10^{-5}$ | 90 | [90] ABELA | 81 | | $m_{\nu_j}$=10.5 MeV |
| $< 2 \times 10^{-4}$ | 90 | [90] ABELA | 81 | | $m_{\nu_j}$=11.5 MeV |
| $< 2 \times 10^{-5}$ | 90 | [90] ABELA | 81 | | $m_{\nu_j}$=16–30 MeV |
| $< 2 \times 10^{-5}$ | 95 | [91] ASANO | 81 | | $m_{\nu_j}$=170 MeV |
| $< 3 \times 10^{-6}$ | 95 | [91] ASANO | 81 | | $m_{\nu_j}$=210 MeV |
| $< 3 \times 10^{-6}$ | 95 | [91] ASANO | 81 | | $m_{\nu_j}$=230 MeV |
| $< 6 \times 10^{-6}$ | 95 | [92] ASANO | 81 | | $m_{\nu_j}$=240 MeV |
| $< 5 \times 10^{-7}$ | 95 | [92] ASANO | 81 | | $m_{\nu_j}$=280 MeV |
| $< 6 \times 10^{-6}$ | 95 | [92] ASANO | 81 | | $m_{\nu_j}$=300 MeV |
| $< 1 \times 10^{-2}$ | 95 | [90] CALAPRICE | 81 | | $m_{\nu_j}$=7 MeV |
| $< 3 \times 10^{-3}$ | 95 | [90] CALAPRICE | 81 | | $m_{\nu_j}$=33 MeV |
| $< 1 \times 10^{-4}$ | 68 | [93] SHROCK | 81 | THEO | $m_{\nu_j}$=13 MeV |
| $< 3 \times 10^{-5}$ | 68 | [93] SHROCK | 81 | THEO | $m_{\nu_j}$=33 MeV |
| $< 6 \times 10^{-3}$ | 68 | [94] SHROCK | 81 | THEO | $m_{\nu_j}$=80 MeV |
| $< 5 \times 10^{-3}$ | 68 | [94] SHROCK | 81 | THEO | $m_{\nu_j}$=120 MeV |

[87] BRYMAN 96 search for massive unconventional neutrinos of mass $m_{\nu_x}$ in $\pi^+$ decay. The reported value is the upper limit for the branching ratio, $< 4–6 \times 10^{-5}$ (90%CL). They interpret the result as an upper limit for the admixture of a heavy sterile or otherwise unconventional neutrino.

[88] ARMBRUSTER 95 study the reactions $^{12}C(\nu_e,e^-)\,^{12}N$ and $^{12}C(\nu,\nu')\,^{12}C^*$ induced by neutrinos from $\pi^+$ and $\mu^+$ decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay $\pi^+ \rightarrow \mu^+ \nu_x$, where $\nu_x$ is a neutral weakly interacting particle with mass $\approx$ 33.9 MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few $\times 10^{-16}$ for $\tau_x \sim 5$ s.

[89] From experiments of $\pi^+$ and $\pi^-$ decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).

[90] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[91] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[92] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \overline{\nu}_x$ decay.

[93] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.

[94] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu, \nu_\mu$ decay.

## Peak Search in Muon Capture

Limits on $|U_{2j}|^2$ as function of $m_{\nu_j}$

| VALUE | DOCUMENT ID | | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $<1 \times 10^{-1}$ | DEUTSCH | 83 | $m_{\nu_j}$=45 MeV |
| $<7 \times 10^{-3}$ | DEUTSCH | 83 | $m_{\nu_j}$=70 MeV |
| $<1 \times 10^{-1}$ | DEUTSCH | 83 | $m_{\nu_j}$=85 MeV |

## Searches for Decays of Massive $\nu$

Limits on $|U_{2j}|^2$ as function of $m_{\nu_j}$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<2 \times 10^{-5}$ | 95 | [95] ABREU | 97I | DLPH | $m_{\nu_j}$=6 GeV |
| $<3 \times 10^{-5}$ | 95 | [95] ABREU | 97I | DLPH | $m_{\nu_j}$=50 GeV |
| $<3 \times 10^{-6}$ | 90 | GALLAS | 95 | CNTR | $m_{\nu_j}$ = 1 GeV |
| $<3 \times 10^{-5}$ | 90 | [96] VILAIN | 95C | CHM2 | $m_{\nu_j}$ = 2 GeV |
| $<6.2 \times 10^{-8}$ | 95 | ADEVA | 90S | L3 | $m_{\nu_j}$ = 20 GeV |
| $<5.1 \times 10^{-10}$ | 95 | ADEVA | 90S | L3 | $m_{\nu_j}$ = 40 GeV |
| all values ruled out | 95 | [97] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ < 19.6 GeV |
| $<1 \times 10^{-10}$ | 95 | [97] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ = 22 GeV |
| $<1 \times 10^{-11}$ | 95 | [97] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ = 41 GeV |
| all values ruled out | 95 | DECAMP | 90F | ALEP | $m_{\nu_j}$= 25.0–42.7 GeV |
| $<1 \times 10^{-13}$ | 95 | DECAMP | 90F | ALEP | $m_{\nu_j}$= 42.7–45.7 GeV |
| $<5 \times 10^{-4}$ | 90 | [98] KOPEIKIN | 90 | CNTR | $m_{\nu_j}$ = 5.2 MeV |
| $<5 \times 10^{-3}$ | 90 | AKERLOF | 88 | HRS | $m_{\nu_j}$=1.8 GeV |

| | | | | | |
|---|---|---|---|---|---|
| $<2 \times 10^{-5}$ | 90 | AKERLOF | 88 | HRS | $m_{\nu_j}$=4 GeV |
| $<3 \times 10^{-6}$ | 90 | AKERLOF | 88 | HRS | $m_{\nu_j}$=6 GeV |
| $<1 \times 10^{-7}$ | 90 | BERNARDI | 88 | CNTR | $m_{\nu_j}$=200 MeV |
| $<3 \times 10^{-9}$ | 90 | BERNARDI | 88 | CNTR | $m_{\nu_j}$=300 MeV |
| $<4 \times 10^{-4}$ | 90 | [99] MISHRA | 87 | CNTR | $m_{\nu_j}$=1.5 GeV |
| $<4 \times 10^{-3}$ | 90 | [99] MISHRA | 87 | CNTR | $m_{\nu_j}$=2.5 GeV |
| $<0.9 \times 10^{-2}$ | 90 | [99] MISHRA | 87 | CNTR | $m_{\nu_j}$=5 GeV |
| $<0.1$ | 90 | [99] MISHRA | 87 | CNTR | $m_{\nu_j}$=10 GeV |
| $<8 \times 10^{-4}$ | 90 | BADIER | 86 | CNTR | $m_{\nu_j}$=600 MeV |
| $<1.2 \times 10^{-5}$ | 90 | BADIER | 86 | CNTR | $m_{\nu_j}$=1.7 GeV |
| $<3 \times 10^{-8}$ | 90 | BERNARDI | 86 | CNTR | $m_{\nu_j}$=200 MeV |
| $<6 \times 10^{-9}$ | 90 | BERNARDI | 86 | CNTR | $m_{\nu_j}$=350 MeV |
| $<1 \times 10^{-6}$ | 90 | DORENBOS... | 86 | CNTR | $m_{\nu_j}$=500 MeV |
| $<1 \times 10^{-7}$ | 90 | DORENBOS... | 86 | CNTR | $m_{\nu_j}$=1600 MeV |
| $<0.8 \times 10^{-5}$ | 90 | [100] COOPER-... | 85 | HLBC | $m_{\nu_j}$=0.4 GeV |
| $<1.0 \times 10^{-7}$ | 90 | [100] COOPER-... | 85 | HLBC | $m_{\nu_j}$=1.5 GeV |

[95] ABREU 97I long-lived $\nu_j$ analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[96] VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.

[97] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[98] KOPEIKIN 90 find no $m_{\nu_j}$ in the interval 1–6.3 MeV at 90%CL for maximal mixing.

[99] See also limits on $|U_{3j}|$ from WENDT 87.

[100] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for $\nu_\tau$ flux. We do not list these. Note that for this bound to be nontrivial, $j$ is not equal to 3, i.e. $\nu_j$ cannot be the dominant mass eigenstate in $\nu_\tau$ since $m_{\nu_3}$ <70 MeV (ALBRECHT 85I). Also, of course, $j$ is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

## Limits on $|U_{3j}|^2$ as a Function of $m_{\nu_j}$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<2 \times 10^{-5}$ | 95 | [101] ABREU | 97I | DLPH | $m_{\nu_j}$=6 GeV |
| $<3 \times 10^{-5}$ | 95 | [101] ABREU | 97I | DLPH | $m_{\nu_j}$=50 GeV |
| $<6.2 \times 10^{-8}$ | 95 | ADEVA | 90S | L3 | $m_{\nu_j}$ = 20 GeV |
| $<5.1 \times 10^{-10}$ | 95 | ADEVA | 90S | L3 | $m_{\nu_j}$ = 40 GeV |
| all values ruled out | 95 | [102] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ < 19.6 GeV |
| $<1 \times 10^{-10}$ | 95 | [102] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ = 22 GeV |

| | | | | | |
|---|---|---|---|---|---|
| $<1 \times 10^{-11}$ | 95 | [102] BURCHAT | 90 | MRK2 | $m_{\nu_j}$ = 41 GeV |
| all values ruled out | 95 | DECAMP | 90F | ALEP | $m_{\nu_j}$= 25.0–42.7 GeV |
| $<1 \times 10^{-13}$ | 95 | DECAMP | 90F | ALEP | $m_{\nu_j}$= 42.7–45.7 GeV |
| $<5 \times 10^{-2}$ | 80 | AKERLOF | 88 | HRS | $m_{\nu_j}$=2.5 GeV |
| $<9 \times 10^{-5}$ | 80 | AKERLOF | 88 | HRS | $m_{\nu_j}$=4.5 GeV |

[101] ABREU 97I long-lived $\nu_j$ analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity.

[102] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

## Limits on $|U_{aj}|^2$

Where $a$ = 1, 2 from $\rho$ parameter in $\mu$ decay.

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<1 \times 10^{-2}$ | 68 | SHROCK | 81B | THEO | $m_{\nu_j}$=10 MeV |
| $<2 \times 10^{-3}$ | 68 | SHROCK | 81B | THEO | $m_{\nu_j}$=40 MeV |
| $<4 \times 10^{-2}$ | 68 | SHROCK | 81B | THEO | $m_{\nu_j}$=70 MeV |

## Limits on $|U_{1j} \times U_{2j}|$ as Function of $m_{\nu_j}$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<3 \times 10^{-5}$ | 90 | [103] BARANOV | 93 | | $m_{\nu_j}$= 80 MeV |
| $<3 \times 10^{-6}$ | 90 | [103] BARANOV | 93 | | $m_{\nu_j}$= 160 MeV |
| $<6 \times 10^{-7}$ | 90 | [103] BARANOV | 93 | | $m_{\nu_j}$= 240 MeV |
| $<2 \times 10^{-7}$ | 90 | [103] BARANOV | 93 | | $m_{\nu_j}$= 320 MeV |
| $<9 \times 10^{-5}$ | 90 | BERNARDI | 86 | CNTR | $m_{\nu_j}$=25 MeV |
| $<3.6 \times 10^{-7}$ | 90 | BERNARDI | 86 | CNTR | $m_{\nu_j}$=100 MeV |
| $<3 \times 10^{-8}$ | 90 | BERNARDI | 86 | CNTR | $m_{\nu_j}$=200 MeV |
| $<6 \times 10^{-9}$ | 90 | BERNARDI | 86 | CNTR | $m_{\nu_j}$=350 MeV |
| $<1 \times 10^{-2}$ | 90 | BERGSMA | 83B | CNTR | $m_{\nu_j}$=10 MeV |
| $<1 \times 10^{-5}$ | 90 | BERGSMA | 83B | CNTR | $m_{\nu_j}$=140 MeV |
| $<7 \times 10^{-7}$ | 90 | BERGSMA | 83B | CNTR | $m_{\nu_j}$=370 MeV |

[103] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.