# $\nu_e$

$J = \frac{1}{2}$

Not in general a mass eigenstate. See Note on "Neutrino Mass" above.

Revised April 2000 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

These limits apply to $\nu_1$, the primary mass eigenstate in $\nu_e$. They would also apply to any other $\nu_j$ which mixes strongly in $\nu_e$ and has sufficiently small mass that it can be emitted in the respective decay. (Note that the reactor $\overline{\nu}_e$ disappearance experiments show that the electron neutrino is not strongly coupled ($\sin^2 2\theta \lesssim 0.1$) to any other neutrino for $\Delta m^2 \gtrsim 10^{-3}$ eV$^2$.) The neutrino mass may be of a Dirac or Majorana type; the former conserves total lepton number while the latter violates it. Either could violate lepton family number, since the neutrino mass eigenstates do not need to coincide with the neutrino interaction eigenstates. For limits on a Majorana $\nu_e$ mass, see the section on "Searches for Massive Neutrinos and Lepton Mixing," part (C), entitled "Searches for Neutrinoless Double-$\beta$ Decay."

The square of the neutrino mass, $m^2_{\nu_e} = \sum |U_{ej}|^2 m^2_{\nu_j}$, where the sum is over the kinematically allowed range of the neutrino masses $m_{\nu_j}$, is measured in beta decay experiments by fitting the shape of the beta spectrum near the endpoint; results are given in one of the tables in this section. Low-energy tritium beta decays, delivering a high number of events near the kinematically interesting endpoint, are studied in a number of careful experiments. The most sensitive of these are reported in LOBASHEV 99 and WEINHEIMER 99. They both find that unknown effects cause an accumulation of events near the endpoint of the electron spectrum. If the fitting hypothesis or data selection does not account for this, unphysical negative values of $m^2_{\nu_e}$ are obtained. In WEINHEIMER 99, two analyses which exclude the spectral anomaly result in an acceptable $m^2_{\nu_e}$ and a mass limit of better than 3 eV. In LOBASHEV 99, the resulting mass limit is also less that 3 eV when the analysis includes an *a priori* form for the anomalous events near the endpoint. We take $m_{\nu_e} < 3$ eV as our evaluation.

The spread of arrival times of the neutrinos from SN1987A, coupled with the measured neutrino energies, provides a simple time-of-flight limit on $m_{\nu_e}$. This statement, clothed in various degrees of sophistication, has been the basis for a very large number of papers. The LOREDO 89 limit (23 eV) is among the most conservative and involves few assumptions; as such, it can be regarded as a safe limit.

## $\nu_e$ MASS

Most of the data from which these limits are derived are from $\beta^-$ decay experiments in which a $\overline{\nu}_e$ is produced, so that they really apply to $m_{\overline{\nu}_1}$. Assuming *CPT* invariance, a limit on $m_{\overline{\nu}_1}$ is the same as a limit on $m_{\nu_1}$. Results from studies of electron capture transitions, given below "$m_{\nu_1} - m_{\overline{\nu}_1}$", give limits on $m_{\nu_1}$ itself. But see the above Note on the "Electron Neutrino Mass."

| *VALUE* (eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **< 3 OUR EVALUATION** | | | | | |
| < 2.5 | 95 | [1] LOBASHEV | 99 | SPEC | $^3$H $\beta$ decay |
| < 2.8 | 95 | [2] WEINHEIMER | 99 | SPEC | $^3$H $\beta$ decay |
| < 23 | | LOREDO | 89 | ASTR | SN 1987A |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 4.35 | 95 | [3] BELESEV | 95 | SPEC | $^3$H $\beta$ decay |
| < 12.4 | 95 | [4] CHING | 95 | SPEC | $^3$H $\beta$ decay |
| < 92 | 95 | [5] HIDDEMANN | 95 | SPEC | $^3$H $\beta$ decay |
| $15^{+32}_{-15}$ | | HIDDEMANN | 95 | SPEC | $^3$H $\beta$ decay |
| < 19.6 | 95 | KERNAN | 95 | ASTR | SN 1987A |
| < 7.0 | 95 | [6] STOEFFL | 95 | SPEC | $^3$H $\beta$ decay |
| <460 | 68 | [7] YASUMI | 94 | CNTR | $e$ capture in $^{163}$Ho |
| < 7.2 | 95 | [8] WEINHEIMER | 93 | SPEC | $^3$H $\beta$ decay |
| < 11.7 | 95 | [9] HOLZSCHUH | 92B | SPEC | $^3$H $\beta$ decay |
| < 13.1 | 95 | [10] KAWAKAMI | 91 | SPEC | $^3$H $\beta$ decay |
| < 9.3 | 95 | [11] ROBERTSON | 91 | SPEC | $^3$H $\beta$ decay |
| < 14 | 95 | AVIGNONE | 90 | ASTR | SN 1987A |
| < 16 | | SPERGEL | 88 | ASTR | SN 1987A |
| 17 to 40 | | [12] BORIS | 87 | SPEC | $\overline{\nu}_e$, $^3$H $\beta$ decay |

[1] LOBASHEV 99 report a new measurement which continues the work reported in BELESEV 95. This limit depends on phenomonological fit parameters used to derive their best fit to $m_\nu^2$, making unambiguous interpretation difficult. See the footnote under "$m_\nu$ Mass Squared".

[2] WEINHEIMER 99 presents two analyses which exclude the spectral anomaly and result in an acceptable $m_\nu^2$. We report the most conservative limit, but the other ($< 2.7$ eV) is nearly the same. See the footnote under "$m_e$ Mass Squared."

[3] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. A fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly) plus a monochromatic line 7–15 eV below the endpoint yields $m_\nu^2 = -4.1 \pm 10.9$ eV$^2$, leading to this Bayesian limit.

[4] CHING 95 quotes results previously given by SUN 93; no experimental details are given. A possible explanation for consistently negative values of $m_\nu^2$ is given.

[5] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. Bayesian limit calculated from the weighted mean $m_\nu^2 = 221 \pm 4244$ eV$^2$ from the two runs listed below.

[6] STOEFFL 95 (LLNL) result is the Bayesian limit obtained from the $m_\nu^2$ errors given below but with $m_\nu^2$ set equal to 0. The anomalous endpoint accumulation leads to a value of $m_\nu^2$ which is negative by more than 5 standard deviations.

[7] The YASUMI 94 (KEK) limit results from their measurement $m_\nu$=$110^{+350}_{-110}$ eV.

[8] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium $\beta$ spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[9] HOLZSCHUH 92B (Zurich) result is obtained from the measurement $m_\nu^2 = -24 \pm 48 \pm 61$ ($1\sigma$ errors), in eV$^2$, using the PDG prescription for conversion to a limit in $m_\nu$.

[10] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid. This result is the Bayesian limit obtained from the $m_\nu^2$ limit with the errors combined in quadrature. This was also done in ROBERTSON 91, although the authors report a different procedure.

[11] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that $m_\nu$ lies between 17 and 40 eV. However, the probability of a positive $m^2$ is only 3% if statistical and systematic error are combined in quadrature.

[12] See also comment in BORIS 87B and erratum in BORIS 88.

## $\nu_e$ MASS SQUARED

The tritium experiments actually measure mass squared. A combined limit on mass should therefore be obtained from the weighted average of the results shown here. However, given troubling systematics which result in improbably negative estimators of $m_\nu^2$ in many experiments, we instead use WEINHEIMER 99 and LOBASHEV 99 for that estimate, as discussed above in the Note on the "Electron Neutrino Mass."

| *VALUE* (eV$^2$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$-$ 2.5$\pm$ 3.3 OUR AVERAGE** | | | | | |
| $-$ 1.9$\pm$ 3.4$\pm$ 2.2 | | [13] LOBASHEV | 99 | SPEC | $^3$H $\beta$ decay |
| $-$ 3.7$\pm$ 5.3$\pm$ 2.1 | | [14] WEINHEIMER | 99 | SPEC | $^3$H $\beta$ decay |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | | | |
|---|---|---|---|---|---|---|
| $-22 \pm 4.8$ | | | [15] BELESEV | 95 | SPEC | $^3$H $\beta$ decay |
| $129 \pm 6010$ | | | [16] HIDDEMANN | 95 | SPEC | $^3$H $\beta$ decay |
| $313 \pm 5994$ | | | [16] HIDDEMANN | 95 | SPEC | $^3$H $\beta$ decay |
| $-130 \pm 20 \pm 15$ | 95 | | [17] STOEFFL | 95 | SPEC | $^3$H $\beta$ decay |
| $-31 \pm 75 \pm 48$ | | | [18] SUN | 93 | SPEC | $^3$H $\beta$ decay |
| $-39 \pm 34 \pm 15$ | | | [19] WEINHEIMER | 93 | SPEC | $^3$H $\beta$ decay |
| $-24 \pm 48 \pm 61$ | | | [20] HOLZSCHUH | 92B | SPEC | $^3$H $\beta$ decay |
| $-65 \pm 85 \pm 65$ | | | [21] KAWAKAMI | 91 | SPEC | $^3$H $\beta$ decay |
| $-147 \pm 68 \pm 41$ | | | [22] ROBERTSON | 91 | SPEC | $^3$H $\beta$ decay |

[13] LOBASHEV 99 report a new measurement which continues the work reported in BELESEV 95. The data were corrected for electron trapping effects in the source, eliminating the dependence of the fitted neutrino mass on the fit interval. The analysis assuming a pure beta spectrum yields significantly negative fitted $m_\nu^2 \approx -(20\text{–}10)$ eV$^2$. This problem is attributed to a discrete spectral anomaly of about $6 \times 10^{-11}$ intensity with a time-dependent energy of 5–15 eV below the endpoint. The data analysis accounts for this anomaly by introducing two extra phenomenological fit parameters resulting in a best fit of $m_\nu^2 = -1.9 \pm 3.4 \pm 2.2$ eV$^2$ which is used to derive a neutrino mass limit. However, the introduction of phenomenological fit parameters which are correlated with the derived $m_\nu^2$ limit makes unambiguous interpretation of this result difficult.

[14] WEINHEIMER 99 is a continuation of the work reported in WEINHEIMER 93 . Using a lower temperature of the frozen tritium source eliminated the dewetting of the $T_2$ film, which introduced a dependence of the fitted neutrino mass on the fit interval in the earlier work. An indication for a spectral anomaly reported in LOBASHEV 99 has been seen, but its time dependence does not agree with LOBASHEV 99. Two analyses, which exclude the spectral anomaly either by choice of the analysis interval or by using a particular data set which does not exhibit the anomaly, result in acceptable $m_\nu^2$ fits and are used to derive the neutrino mass limit published by the authors. We list the most conservative of the two.

[15] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. This value comes from a fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly), including the effects of an apparent peak 7–15 eV below the endpoint.

[16] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. They quote measurements from two data sets.

[17] STOEFFL 95 (LLNL) uses a gaseous source of molecular tritium. An anomalous pileup of events at the endpoint leads to the negative value for $m_\nu^2$. The authors acknowledge that "the negative value for the best fit of $m_\nu^2$ has no physical meaning" and discuss possible explanations for this effect.

[18] SUN 93 uses a tritiated hydrocarbon source. See also CHING 95.

[19] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium $\beta$ spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[20] HOLZSCHUH 92B (Zurich) source is a monolayer of tritiated hydrocarbon.

[21] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid.

[22] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that $m_\nu$ lies between 17 and 40 eV. However, the probability of a positive $m_\nu^2$ is only 3% if statistical and systematic error are combined in quadrature.

## $m_{\nu_1} - m_{\overline{\nu}_1}$

These are measurement of $m_{\nu_1}$ (in contrast to $m_{\overline{\nu}_1}$, given above). The masses can be different for a Dirac neutrino in the absense of $CPT$ invariance. The test is not very strong.

| VALUE (eV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| $<$ 225 | 95 | SPRINGER | 87 | CNTR | $\nu$, $^{163}$Ho |
| $<$ 550 | 68 | YASUMI | 86 | CNTR | $\nu$, $^{163}$Ho |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $< 4.5 \times 10^{5}$ | 90 | CLARK | 74 | ASPK | $K_{e3}$ decay |
| $<$4100 | 67 | BECK | 68 | CNTR | $\nu$, $^{22}$Na |

## $\nu_1$ CHARGE

| VALUE (units: electron charge) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2 \times 10^{-14}$ | [23] RAFFELT | 99 | ASTR | Red giant luminosity |
| $<6 \times 10^{-14}$ | [24] RAFFELT | 99 | ASTR | Solar cooling |
| $<2 \times 10^{-15}$ | [25] BARBIELLINI | 87 | ASTR | SN 1987A |
| $<1 \times 10^{-13}$ | BERNSTEIN | 63 | ASTR | Solar energy losses |

[23] This RAFFELT 99 limit applies to all neutrino flavors which are light enough ($<$5 kEe) to be emitted from globular-cluster red giants.

[24] This RAFFELT 99 limit is derived from the helioseismological limit on a new energy-loss channel of the Sun, and applies to all neutrino flavors which are light enough ($<$1 keV) to be emitted from the sun.

[25] Precise BARBIELLINI 87 limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field.

## $\nu_1$ MEAN LIFE

| VALUE (s) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [26] BILLER | 98 | ASTR | $m_\nu$= 0.05–1 eV |
| | | [27] COWSIK | 89 | ASTR | $m_\nu$ = 1–50 MeV |
| | | [28] RAFFELT | 89 | RVUE | $\overline{\nu}$ (Dirac, Majorana) |
| | | [29] RAFFELT | 89B | ASTR | |
| $>$278 | 90 | [30] LOSECCO | 87B | IMB | |
| $> 1.1 \times 10^{25}$ | | [31] HENRY | 81 | ASTR | $m_\nu$= 16–20 eV |
| $> 10^{22}$–$10^{23}$ | | [32] KIMBLE | 81 | ASTR | $m_\nu$= 10–100 eV |

[26] BILLER 98 use the observed TeV $\gamma$-ray spectra to set limits on the mean life of a radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/\mathrm{B}_\gamma > 0.15 \times 10^{21}$ s at 0.05 eV, $> 1.2 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where $\mathrm{B}_\gamma$ is the branching ratio to photons.

[27] COWSIK 89 use observations of supernova SN 1987A to set the limit for the lifetime of a neutrino with $1 < m < 50$ MeV decaying through $\nu_H \rightarrow \nu_1 e e$ to be $\tau > 4 \times 10^{15}$ $\exp(-m/5$ MeV) s.

[28] RAFFELT 89 uses KYULDJIEV 84 to obtain $\tau m^3 > 3 \times 10^{18}$ s eV$^3$ (based on $\overline{\nu}_e e^-$ cross sections). The bound is not valid if electric and magnetic transition moments are equal for Dirac neutrinos.

[29] RAFFELT 89B analyze stellar evolution and exclude the region $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21}$ s eV$^3$.
[30] LOSECCO 87B assumes observed rate of 2.1 SNU (solar neutrino units) comes from sun while 7.0 ± 3.0 is theory.
[31] HENRY 81 uses UV flux from clusters of galaxies to find limit for radiative decay.
[32] KIMBLE 81 uses extreme UV flux limits.

## $\nu_1$ (MEAN LIFE) / MASS

| *VALUE* (s/eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$> 7 \times 10^9$** | | [33] RAFFELT | 85 | ASTR | |
| **$>300$** | 90 | [34] REINES | 74 | CNTR | $\overline{\nu}$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $> 2.8 \times 10^{15}$ | | [35,36] BLUDMAN | 92 | ASTR | $m_\nu < 50$ eV |
| $> 6.4$ | 90 | [37] KRAKAUER | 91 | CNTR | $\overline{\nu}$ at LAMPF |
| $> 6.3 \times 10^{15}$ | | [36,38] CHUPP | 89 | ASTR | $m_\nu < 20$ eV |
| $> 1.7 \times 10^{15}$ | | [36] KOLB | 89 | ASTR | $m_\nu < 20$ eV |
| $> 8.3 \times 10^{14}$ | | [39] VONFEILIT... | 88 | ASTR | |
| $> 22$ | 68 | [40] OBERAUER | 87 | | $\overline{\nu}_R$ (Dirac) |
| $> 38$ | 68 | [40] OBERAUER | 87 | | $\overline{\nu}$ (Majorana) |
| $> 59$ | 68 | [40] OBERAUER | 87 | | $\overline{\nu}_L$ (Dirac) |
| $> 30$ | 68 | KETOV | 86 | CNTR | $\overline{\nu}$ (Dirac) |
| $> 20$ | 68 | KETOV | 86 | CNTR | $\overline{\nu}$ (Majorana) |
| $> 2 \times 10^{21}$ | | [41] STECKER | 80 | ASTR | $m_\nu$= 10–100 eV |

[33] RAFFELT 85 limit is from solar x- and $\gamma$-ray fluxes. Limit depends on $\nu$ flux from $pp$, now established from GALLEX and SAGE to be > 0.5 of expectation.
[34] REINES 74 looked for $\nu_e$ of nonzero mass decaying to a neutral of lesser mass + $\gamma$. Used liquid scintillator detector near fission reactor. Finds lab lifetime $6. \times 10^7$ s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit $6. \times 10^7$ s REINES 74 assumed that the full $\overline{\nu}_e$ reactor flux could be responsible for yielding decays with photon energies in the interval 0.1 MeV – 0.5 MeV. This represents some overestimate so their lower limit is an over-estimate of the lab lifetime (VOGEL 84). If so, OBERAUER 87 may be comparable or better.
[35] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.
[36] Nonobservation of $\gamma$'s in coincidence with $\nu$'s from SN 1987A.
[37] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.3a^2 + 9.8a + 15.9)$ s/eV, where $a$ is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ $a = 0$ for a Majorana neutrino, but can vary from $-1$ to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).
[38] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.
[39] Model-dependent theoretical analysis of SN 1987A neutrinos.
[40] OBERAUER 87 bounds are from comparison of observed and expected rate of reactor neutrinos.
[41] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

## $\left|(v - c)/c\right|$ ($v \equiv \nu_1$ VELOCITY)

Expected to be zero for massless neutrino, but tests also whether photons and neutrinos have the same limiting velocity in vacuum.

| *VALUE* (units $10^{-8}$) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| <1 | 17 | [42] STODOLSKY | 88 | ASTR | SN 1987A |
| **<0.2** | | [43] LONGO | 87 | ASTR | SN 1987A |

[42] STODOLSKY 88 result based on <10 hr between $\overline{\nu}_e$ detection in IMB and KAMI detectors and beginning of light signal. Inclusion of the problematic 5 neutrino events from Mont Blanc (four hours later) does not change the result.

[43] LONGO 87 argues that uncertainty between light and neutrino transit times is $\pm 3$ hr, ignoring Mont Blanc events.

## $\nu_1$ MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where $m_\nu$ is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_1} < 7.3$ eV, it follows that for the extended standard electroweak theory, $\mu(\nu_1) < 2.3 \times 10^{-18}\ \mu_B$. Current experiments are not yet challenging this limit. There is considerable controversy over the validity of many of the claimed upper limits on the magnetic moment from the astrophysical data. For example, VOLOSHIN 90 states that "in connection with the astrophysical limits on $\mu_\nu$, ... there is by now a general consensus that contrary to the initial claims (BARBIERI 88, LATTIMER 88, GOLDMAN 88, NOTZOLD 88), essentially no better than quoted limits (from previous constraints) can be derived from detection of the neutrino flux from the supernova SN1987A." See VOLOSHIN 88 and VOLOSHIN 88C.

| *VALUE* ($10^{-10}\ \mu_B$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **< 1.5** | 90 | [44] BEACOM | 99 | SKAM | $\nu$ spectrum shape |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 0.01–0.04 | | [45] AYALA | 99 | ASTR | $\nu_L \to \nu_R$ in SN 1987A |
| < 0.03 | | [46] RAFFELT | 99 | ASTR | Red giant luminosity |
| < 4 | | [47] RAFFELT | 99 | ASTR | Solar cooling |
| < 0.62 | | [48] ELMFORS | 97 | COSM | Depolarization in early universe plasma |
| < 0.003–0.0005 | | [49] GOYAL | 95 | | SN 1987A |
| < 1.9 | 95 | [50] DERBIN | 93 | CNTR | Reactor $\overline{\nu}_e e \to \overline{\nu}_e e$ |
| < 2.4 | 90 | [51] VIDYAKIN | 92 | CNTR | Reactor $\overline{\nu}_e e \to \overline{\nu}_e e$ |
| <10.8 | 90 | [52] KRAKAUER | 90 | CNTR | LAMPF $\nu_e e \to \nu_e e$ |
| < 0.02 | | [53] RAFFELT | 90 | ASTR | Red giant luminosity |
| < 0.1 | | [54] RAFFELT | 89B | ASTR | Cooling helium stars |
| | | [55] FUKUGITA | 88 | COSM | Primordial magn. fields |

| | | | | |
|---|---|---|---|---|
| $<$ 0.01 | [56,57,58] GOLDMAN | 88 | ASTR | SN 1987A |
| $<$ 0.005 | [54,58] LATTIMER | 88 | ASTR | SN 1987A |
| $\leq$ 0.015 | [54,58] NOETZOLD | 88 | ASTR | SN 1987A |
| $\leq$ .3 | [54] RAFFELT | 88B | ASTR | He burning stars |
| $<$ 0.11 | [54] FUKUGITA | 87 | ASTR | Cooling helium stars |
| $<$ 0.4 | LYNN | 81 | ASTR | |
| $<$ 0.1–0.2 | MORGAN | 81 | COSM | $^4$He abundance |
| $<$ 0.85 | BEG | 78 | ASTR | Stellar plasmons |
| $<$ 0.6 | [59] SUTHERLAND | 76 | ASTR | Red giants + degen. dwarfs |
| $<$ 1 | BERNSTEIN | 63 | ASTR | Solar cooling |
| $<$14 | COWAN | 57 | CNTR | Reactor $\overline{\nu}_e$ |

[44] BEACOM 99 obtain the limit using the shape, but not the absolute magnitude which is affected by oscillations, of the solar neutrino spectrum obtained by Superkamiokande (825 days). This $\mu_\nu$ can be different from the reactor $\mu_\nu$ in certain oscillation scenarios.

[45] AYALA 99 improves the limit of BARBIERI 88.

[46] RAFFELT 99 is an update of RAFFELT 90. This limit applies to all neutrino flavors which are light enough ($<$ 5 keV) to be emitted from globular-cluster red giants. This limit pertains equally to electric dipole moments and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

[47] RAFFELT 99 is essenitally an update of BERNSTEIN 63, but is derived from the helioseismological limit on a new energy-loss channel of the Sun. This limit applies to all neutrino flavors which are light enough ($<$1 keV) to be emitted from the Sun. This limit pertains equally to electric dipole and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

[48] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[49] GOYAL 95 assume that helicity flip via $\mu_\nu$ would result in faster cooling and hence shorter burst from SN1987A. Limit is based on the assumed presence of a pion condensate or quark core in the remanant.

[50] DERBIN 93 updated in review DERBIN 94.

[51] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[52] KRAKAUER 90 experiment fully reported in ALLEN 93.

[53] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from $\delta M_c$.

[54] Significant dependence on details of stellar models.

[55] FUKUGITA 88 find magnetic dipole moments of any two neutrino species are bounded by $\mu < 10^{-16}$ $[10^{-9}\ G/B_0]$ where $B_0$ is the present-day intergalactic field strength.

[56] A limit of $10^{-13}$ is obtained with even more model-dependence.

[57] Some dependence on details of stellar models.

[58] These papers have assumed that the right-handed neutrino is inert; see BARBIERI 88B.

[59] We obtain above limit from SUTHERLAND 76 using their limit $f < 1/3$.

## NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared in this section. This quantity is not an observable, physical quantity and this is reflected in the fact that it is gauge dependent (see LEE 77C). It is not necessarily positive. A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

| *VALUE* ($10^{-32}$ cm$^2$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **0.9±2.7** | | ALLEN | 93 | CNTR | LAMPF $\nu_e e \to \nu_e e$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <2.3 | 95 | MOURAO | 92 | ASTR | HOME/KAM2 $\nu$ rates |
| <7.3 | 90 | [60] VIDYAKIN | 92 | CNTR | Reactor $\overline{\nu}_e e \to \overline{\nu}_e e$ |
| 1.1±2.3 | | ALLEN | 91 | CNTR | Repl. by ALLEN 93 |
| | | [61] GRIFOLS | 89B | ASTR | SN 1987A |

[60] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[61] GRIFOLS 89B sets a limit of $\langle r^2 \rangle < 0.2 \times 10^{-32}$ cm$^2$ for right-handed neutrinos.

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