# $\nu_e$

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

The following results are obtained using neutrinos associated with $e^+$ or $e^-$. See Note on "Electron, muon, and tau neutrinos."

## $\overline{\nu}$ MASS

Those limits given below for $\overline{\nu}$ mass that come from the kinematics of $^3\text{H}\beta^-\overline{\nu}$ decay are the square roots of limits for $m^{2(\text{eff})}_{\nu_e}$. These are obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

| *VALUE* (eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **< 3 OUR EVALUATION** | | | | | |
| < 5.7 | 95 | [1] LOREDO | 02 | ASTR | SN1987A |
| < 2.5 | 95 | [2] LOBASHEV | 99 | SPEC | $^3$H $\beta$ decay |
| < 2.8 | 95 | [3] WEINHEIMER | 99 | SPEC | $^3$H $\beta$ decay |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 4.35 | 95 | [4] BELESEV | 95 | SPEC | $^3$H $\beta$ decay |
| <12.4 | 95 | [5] CHING | 95 | SPEC | $^3$H$\beta$ decay |
| <92 | 95 | [6] 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 | [7] STOEFFL | 95 | SPEC | $^3$H $\beta$ decay |
| < 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 | $^3$H$\beta$ decay |

[1] LOREDO 02 updates LOREDO 89.

[2] 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 $m^2_\nu$, making unambiguous interpretation difficult. See the footnote under "$\overline{\nu}$ Mass Squared."

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

[4] 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 $m^2_\nu = -4.1 \pm 10.9$ eV$^2$, leading to this Bayesian limit.

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

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

[7] 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.

[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.

## $\overline{\nu}$ MASS SQUARED

Given troubling systematics which result in improbably negative estimators of $m_{\nu_e}^{2(\text{eff})}$ in many experiments, we use only WEINHEIMER 99 and LOBASHEV 99 for our average, as discussed above in the Note on the "Electron, muon, and tau neutrinos."

| *VALUE* (eV$^2$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **− 2.5± 3.3 OUR AVERAGE** | | | | | |
| − 1.9± 3.4± 2.2 | | [13] LOBASHEV | 99 | SPEC | $^3$H $\beta$ decay |
| − 3.7± 5.3± 2.1 | | [14] WEINHEIMER | 99 | SPEC | $^3$H $\beta$ decay |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| − 22 ± 4.8 | | [15] BELESEV | 95 | SPEC | $^3$H $\beta$ decay |
| 129 ±6010 | | [16] HIDDEMANN | 95 | SPEC | $^3$H $\beta$ decay |
| 313 ±5994 | | [16] HIDDEMANN | 95 | SPEC | $^3$H $\beta$ decay |
| −130 ± 20 ±15 | 95 | [17] STOEFFL | 95 | SPEC | $^3$H $\beta$ decay |
| − 31 ± 75 ±48 | | [18] SUN | 93 | SPEC | $^3$H$\beta$ decay |
| − 39 ± 34 ±15 | | [19] WEINHEIMER | 93 | SPEC | $^3$H $\beta$ decay |
| − 24 ± 48 ±61 | | [20] HOLZSCHUH | 92B | SPEC | $^3$H $\beta$ decay |
| − 65 ± 85 ±65 | | [21] KAWAKAMI | 91 | SPEC | $^3$H $\beta$ decay |
| −147 ± 68 ±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.

## $\nu$ MASS

These are measurement of $m_\nu$ (in contrast to $m_{\overline{\nu}}$, given above). The masses can be different for a Dirac neutrino in the absence of *CPT* invariance. The possible distinction between $\nu$ and $\overline{\nu}$ properties is usually ignored elsewhere in these Listings.

| *VALUE* (eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $<$ 460 | 68 | YASUMI | 94 | CNTR | $^{163}$Ho decay |
| $<$ 225 | 95 | SPRINGER | 87 | CNTR | $^{163}$Ho decay |
| • • • 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 | $^{22}$Na decay |

## $\nu$ 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 keV) 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.

## $\nu$ MEAN LIFE

Measures $\left[\sum |U_{\ell j}|^2\, \Gamma_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. In most cases the limit pertains to any decaying neutrino. See footnotes for qualifications and exceptions.

| *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 any radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/B_\gamma > 0.15 \times 10^{21}$ s at 0.05 eV, $> 1.2 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where $B_\gamma$ 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 $\nu_H \rightarrow \nu e e$ to be $\tau > 4 \times 10^{15}$ $\exp(-m/5\ \text{MeV})$ s.
[28] RAFFELT 89 uses KYULDJIEV 84 to obtain $\tau m^3 > 3 \times 10^{18}$ s eV$^3$ (based on $\overline{\nu} e^-$ 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.

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

Measures $\left[\sum |U_{ej}|^2\, \Gamma_j\, m_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. For many of the ASTR papers (RAFFELT 85 excepted), the limit applies to any $\nu$ in the indicated mass range.

| *VALUE* (s/eV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **> 300 (CL = 90%)** [$>7 \times 10^9$ s/eV OUR 2002 BEST LIMIT] | | | | | |
| **> 7 × 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. • • •

| | | | | | |
|---|---|---|---|---|---|
| $\geq$ 4200 | 90 | [35] DERBIN | 02B | CNTR | Solar $pp$ and Be $\nu$ |
| $>$ $2.8 \times 10^{-5}$ | 99 | [36] JOSHIPURA | 02B | FIT | nonradiative decay |
| $>$ $2.8 \times 10^{15}$ | | [37,38] BLUDMAN | 92 | ASTR | $m_\nu < 50$ eV |
| $>$ 6.4 | 90 | [39] KRAKAUER | 91 | CNTR | $\nu$ at LAMPF |
| $>$ $6.3 \times 10^{15}$ | | [38,40] CHUPP | 89 | ASTR | $m_\nu < 20$ eV |
| $>$ $1.7 \times 10^{15}$ | | [38] KOLB | 89 | ASTR | $m_\nu < 20$ eV |
| $>$ $8.3 \times 10^{14}$ | | [41] VONFEILIT... | 88 | ASTR | |
| $>$ 22 | 68 | [42] OBERAUER | 87 | | $\overline{\nu}_R$ (Dirac) |
| $>$ 38 | 68 | [42] OBERAUER | 87 | | $\overline{\nu}$ (Majorana) |
| $>$ 59 | 68 | [42] OBERAUER | 87 | | $\overline{\nu}_L$ (Dirac) |
| $>$ 30 | 68 | KETOV | 86 | CNTR | $\overline{\nu}$ (Dirac) |
| $>$ 20 | 68 | KETOV | 86 | CNTR | $\overline{\nu}$ (Majorana) |
| $>$ $2 \times 10^{21}$ | | [43] 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 $\nu$ 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 $\overline{\nu}$ 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] DERBIN 02B obtained this bound from the results of background measurements with Counting Test Facility (the prototype of the Borexiono detector). The laboratory gamma spectrum is given as $dN_\gamma/d\cos\theta = (1/2)\,(1 + \alpha\cos\theta)$ with $\alpha$=0 for a Majorana neutrino, and $\alpha$ varying to $-1$ to 1 for a Dirac neutrino. The listed bound is for the case of $\alpha$=0. The most conservative bound $1.5 \times 10^3$ s eV$^{-1}$ is obtained for the case of $\alpha = -1$.

[36] JOSHIPURA 02B derive a $\tau/m$ limit on the nonradiative decay of solar neutrinos using the total rates measured in all solar neutrino experiments. The exact limit depends on the specific solution of the solar neutrino problem. The quoted limit is for the LMA solution.

[37] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[38] Nonobservation of $\gamma$'s in coincidence with $\nu$'s from SN 1987A.

[39] KRAKAUER 91 quotes the limit $\tau/m_\nu > (0.3a^2 + 9.8a + 15.9)$ 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 $a = -1$).

[40] 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.

[41] Model-dependent theoretical analysis of SN 1987A neutrinos.

[42] OBERAUER 87 bounds are from comparison of observed and expected rate of reactor neutrinos.

[43] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

## $|(v - c)/c|$ ($v \equiv \nu$ 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 | [44] STODOLSKY | 88 | ASTR | SN 1987A |
| **<0.2** | | [45] LONGO | 87 | ASTR | SN 1987A |

[44] STODOLSKY 88 result based on <10 hr between $\overline{\nu}$ 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.

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

## $\nu$ MAGNETIC MOMENT

Must vanish for a purely chiral massless Dirac neutrino. A massive Dirac or Majorana neutrino can have a transition magnetic moment connecting one mass eigenstate to another one. The experimental limits below usually cannot distinguish between the true (diagonal, in mass) magnetic moment and a transition magnetic moment. 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 $m_\nu <$ 3 eV, it follows that for the extended standard electroweak theory, $\mu_\nu < 1 \times 10^{-18}$ $\mu_B$. 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 |
|---|---|---|---|---|---|
| **< 1.3 (CL = 90%)** | [<1.5 × $10^{-10}$ $\mu_B$ (CL = 90%) OUR 2002 BEST LIMIT] | | | | |
| **< 1.3** | 90 | [46] LI | 03B | CNTR | Reactor $\overline{\nu}_e$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 2 | 90 | [47] GRIMUS | 02 | FIT | solar + reactor (Majorana $\nu$) |
| < 0.01–0.04 | | [48] AYALA | 99 | ASTR | $\nu_L \rightarrow \nu_R$ in SN 1987A |
| < 1.5 | 90 | [49] BEACOM | 99 | SKAM | $\nu$ spectrum shape |
| < 0.03 | | [50] RAFFELT | 99 | ASTR | Red giant luminosity |
| < 4 | | [51] RAFFELT | 99 | ASTR | Solar cooling |
| < 0.62 | | [52] ELMFORS | 97 | COSM | Depolarization in early universe plasma |
| < 1.9 | 95 | [53] DERBIN | 93 | CNTR | Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$ |
| < 2.4 | 90 | [54] VIDYAKIN | 92 | CNTR | Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$ |
| <10.8 | 90 | [55] KRAKAUER | 90 | CNTR | LAMPF $\nu e \rightarrow \nu e$ |

| | | | | |
|---|---|---|---|---|
| < 0.02 | [56] RAFFELT | 90 | ASTR | Red giant luminosity |
| < 0.1 | [57] RAFFELT | 89B | ASTR | Cooling helium stars |
| | [58] FUKUGITA | 88 | COSM | Primordial magn. fields |
| ≤ .3 | [57] RAFFELT | 88B | ASTR | He burning stars |
| < 0.11 | [57] FUKUGITA | 87 | ASTR | Cooling helium stars |
| < 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 + degenerate dwarfs |
| < 1 | BERNSTEIN | 63 | ASTR | Solar cooling |
| <14 | COWAN | 57 | CNTR | Reactor $\overline{\nu}$ |

[46] LI 03B used Ge detector in active shield near nuclear reactor to test for nonstandard $\overline{\nu}_e$-$e$ scattering. Most stringent laboratory limit on magnetic moment.

[47] GRIMUS 02 obtain stringent bounds on all Majorana neutrino transition moments from a simultaneous fit of LMA-MSW oscillation parameters and transition moments to global solar neutrino data + reactor data. Using only solar neutrino data, a 90% CL bound of $6.3 \times 10^{-10} \mu_B$ is obtained.

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

[49] 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.

[50] 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.

[51] 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.

[52] 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.

[53] DERBIN 93 determine the cross section for 0.6–2.0 MeV electron energy as $(1.28 \pm 0.63) \times \sigma_{\text{weak}}$. However, the (reactor on – reactor off)/(reactor off) is only $\sim 1/100$.

[54] 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.

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

[56] 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 $\delta M_c$.

[57] Significant dependence on details of stellar models.

[58] 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.

[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. While the straight-forward definition of a neutrino charge radius has been proven to be gauge-dependent and, hence, unphysical (LEE 77C), there have been recent attempts to define a physically observable neutrino charge radius (BERNABEU 00, BERNABEU 02). The issue is still controversial (FUJIKAWA 03, BERNABEU 03). 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* |
|---|---|---|---|---|---|
| $-2.97$ to $4.14$ | 90 | [60] AUERBACH | 01 | LSND | $\nu_e e \rightarrow \nu_e e$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $0.9 \pm 2.7$ | | ALLEN | 93 | CNTR | LAMPF $\nu e \rightarrow \nu e$ |
| $< 2.3$ | 95 | MOURAO | 92 | ASTR | HOME/KAM2 $\nu$ rates |
| $< 7.3$ | 90 | [61] VIDYAKIN | 92 | CNTR | Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$ |
| $1.1 \pm 2.3$ | | ALLEN | 91 | CNTR | Repl. by ALLEN 93 |
| | | [62] GRIFOLS | 89B | ASTR | SN 1987A |

[60] AUERBACH 01 measure $\nu_e e$ elastic scattering with LSND detector. The cross section agrees with the Standard Model expectation, including the charge and neutral current interference. The 90% CL applies to the range shown.

[61] VIDYAKIN 92 limit is from a $e\overline{\nu}$ 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.

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

## $\nu_e$ REFERENCES


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|---|---|---|---|---|
| BERNABEU | 03 | hep-ph/0303202 | J. Bernabeu, J. Papavassiliou, J. Vidal | |
| FUJIKAWA | 03 | hep-ph/0303188 | K. Fujikawa, R. Shrock | |
| LI | 03B | PRL 90 131802 | H.B. Li *et al.* | (TEXONO Collab.) |
| BERNABEU | 02 | PRL 89 101802 | J. Bernabeu, J. Papavassiliou, J. Vidal | |
| Also | 02B | PRL 89 229902 (erratum) | J. Bernabeu, J. Papavassiliou, J. Vidal | |
| DERBIN | 02B | JETPL 76 409 | A.V. Derbin, O.Ju. Smirnov | |
| | | Translated from ZETFP 76 483. | | |
| GRIMUS | 02 | NP B648 376 | W. Grimus *et al.* | |
| JOSHIPURA | 02B | PR D66 113008 | A.S. Joshipura, E. Masso, S. Mohanty | |
| LOREDO | 02 | PR D65 063002 | T.J. Loredo, D.Q. Lamb | |
| AUERBACH | 01 | PR D63 112001 | L.B. Auerbach *et al.* | (LSND Collab.) |
| BERNABEU | 00 | PR D62 113912 | J. Bernabeu *et al.* | |
| AYALA | 99 | PR D59 111901 | A. Ayala, J.C. D'Olivo, M. Torres | |
| BEACOM | 99 | PRL 83 5222 | J.F. Beacom, P. Vogel | |
| LOBASHEV | 99 | PL B460 227 | V.M. Lobashev *et al.* | |
| RAFFELT | 99 | PRPL 320 319 | G.G. Raffelt | |
| WEINHEIMER | 99 | PL B460 219 | Ch. Weinheimer *et al.* | |
| Also | 99B | PL B464 352 (erratum) | Ch. Weinheimer *et al.* | |
| BILLER | 98 | PRL 80 2992 | S.D. Biller *et al.* | (WHIPPLE Collab.) |
| ELMFORS | 97 | NP B503 3 | P. Elmfors *et al.* | |
| BELESEV | 95 | PL B350 263 | A.I. Belesev *et al.* | (INRM, KIAE) |
| CHING | 95 | IJMP A10 2841 | C.R. Ching *et al.* | (CST, BEIJT, CIAE) |
| HIDDEMANN | 95 | JPG 21 639 | K.H. Hiddemann, H. Daniel, O. Schwentker | (MUNT) |
| KERNAN | 95 | NP B437 243 | P.J. Kernan, L.M. Krauss | (CASE) |
| STOEFFL | 95 | PRL 75 3237 | W. Stoeffl, D.J. Decman | (LLNL) |
| YASUMI | 94 | PL B334 229 | S. Yasumi *et al.* | (KEK, TSUK, KYOT+) |
| ALLEN | 93 | PR D47 11 | R.C. Allen *et al.* | (UCI, LANL, ANL+) |
| DERBIN | 93 | JETPL 57 768 | A.V. Derbin *et al.* | (PNPI) |
| | | Translated from ZETFP 57 755. | | |

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| SUN | 93 | CJNP 15 261 | H.C. Sun *et al.* | (CIAE, CST, BEIJT) |
| WEINHEIMER | 93 | PL B300 210 | C. Weinheimer *et al.* | (MANZ) |
| BLUDMAN | 92 | PR D45 4720 | S.A. Bludman | (CFPA) |
| HOLZSCHUH | 92B | PL B287 381 | E. Holzschuh, M. Fritschi, W. Kundig | (ZURI) |
| MOURAO | 92 | PL B285 364 | A.M. Mourao, J. Pulido, J.P. Ralston | (LISB, LISBT+) |
| VIDYAKIN | 92 | JETPL 55 206<br>Translated from ZETFP 55 212. | G.S. Vidyakin *et al.* | (KIAE) |
| ALLEN | 91 | PR D43 R1 | R.C. Allen *et al.* | (UCI, LANL, UMD) |
| KAWAKAMI | 91 | PL B256 105 | H. Kawakami *et al.* | (INUS, TOHOK, TINT+) |
| KRAKAUER | 91 | PR D44 R6 | D.A. Krakauer *et al.* | (LAMPF E225 Collab.) |
| ROBERTSON | 91 | PRL 67 957 | R.G.H. Robertson *et al.* | (LASL, LLL) |
| AVIGNONE | 90 | PR D41 682 | F.T. Avignone, J.I. Collar | (SCUC) |
| KRAKAUER | 90 | PL B252 177 | D.A. Krakauer *et al.* | (LAMPF E225 Collab.) |
| RAFFELT | 90 | PRL 64 2856 | G.G. Raffelt | (MPIM) |
| VOLOSHIN | 90 | NPBPS 19 433 | M. Voloshin | (ITEP) |
| Neutrino 90 Conference | | | | |
| CHUPP | 89 | PRL 62 505 | E.L. Chupp, W.T. Vestrand, C. Reppin | (UNH, MPIM) |
| COWSIK | 89 | PL B218 91 | R. Cowsik, D.N. Schramm, P. Hoflich | (WUSL, TATA+) |
| GRIFOLS | 89B | PR D40 3819 | J.A. Grifols, E. Masso | (BARC) |
| KOLB | 89 | PRL 62 509 | E.W. Kolb, M.S. Turner | (CHIC, FNAL) |
| LOREDO | 89 | ANYAS 571 601 | T.J. Loredo, D.Q. Lamb | (CHIC) |
| RAFFELT | 89 | PR D39 2066 | G.G. Raffelt | (PRIN, UCB) |
| RAFFELT | 89B | APJ 336 61 | G. Raffelt, D. Dearborn, J. Silk | (UCB, LLL) |
| BARBIERI | 88 | PRL 61 27 | R. Barbieri, R.N. Mohapatra | (PISA, UMD) |
| BORIS | 88 | PRL 61 245 erratum | S.D. Boris *et al.* | (ITEP, ASCI) |
| FUKUGITA | 88 | PRL 60 879 | M. Fukugita *et al.* | (KYOTU, MPIM, UCB) |
| GOLDMAN | 88 | PRL 60 1789 | I. Goldman *et al.* | (TELA) |
| LATTIMER | 88 | PRL 61 23 | J.M. Lattimer, J. Cooperstein | (STON, BNL) |
| Also | 88B | PRL 61 2633 erratum | J.M. Lattimer, J. Cooperstein | (STON, BNL) |
| NOTZOLD | 88 | PR D38 1658 | D. Notzold | (MPIM) |
| RAFFELT | 88B | PR D37 549 | G.G. Raffelt, D.S.P. Dearborn | (UCB, LLL) |
| SPERGEL | 88 | PL B200 366 | D.N. Spergel, J.N. Bahcall | (IAS) |
| STODOLSKY | 88 | PL B201 353 | L. Stodolsky | (MPIM) |
| VOLOSHIN | 88 | PL B209 360 | M.B. Voloshin | (ITEP) |
| Also | 88B | JETPL 47 501<br>Translated from ZETFP 47 421. | M.B. Voloshin | (ITEP) |
| VOLOSHIN | 88C | JETPL 68 690 | M.B. Voloshin | (ITEP) |
| VONFEILIT... | 88 | PL B200 580 | F. von Feilitzsch, L. Oberauer | (MUNT) |
| BARBIELLINI | 87 | NAT 329 21 | G. Barbiellini, G. Cocconi | (CERN) |
| BORIS | 87 | PRL 58 2019 | S.D. Boris *et al.* | (ITEP, ASCI) |
| Also | 88 | PRL 61 245 erratum | S.D. Boris *et al.* | (ITEP, ASCI) |
| BORIS | 87B | JETPL 45 333<br>Translated from ZETFP 45 267. | S.D. Boris *et al.* | (ITEP) |
| FUKUGITA | 87 | PR D36 3817 | M. Fukugita, S. Yazaki | (KYOTU, TOKY) |
| LONGO | 87 | PR D36 3276 | M.J. Longo | (MICH) |
| LOSECCO | 87B | PR D35 2073 | J.M. LoSecco *et al.* | (IMB Collab.) |
| OBERAUER | 87 | PL B198 113 | L.F. Oberauer, F. von Feilitzsch, R.L. Mossbauer | |
| SPRINGER | 87 | PR A35 679 | P.T. Springer *et al.* | (LLNL) |
| KETOV | 86 | JETPL 44 146<br>Translated from ZETFP 44 114. | S.N. Ketov *et al.* | (KIAE) |
| RAFFELT | 85 | PR D31 3002 | G.G. Raffelt | (MPIM) |
| KYULDJIEV | 84 | NP B243 387 | A.V. Kyuldjiev | (SOFI) |
| VOGEL | 84 | PR D30 1505 | P. Vogel | |
| HENRY | 81 | PRL 47 618 | R.C. Henry, P.D. Feldman | (JHU) |
| KIMBLE | 81 | PRL 46 80 | R. Kimble, S. Bowyer, P. Jakobsen | (UCB) |
| MORGAN | 81 | PL 102B 247 | J.A. Morgan | (SUSS) |
| FUJIKAWA | 80 | PRL 45 963 | K. Fujikawa, R. Shrock | (STON) |
| LUBIMOV | 80 | PL 94B 266 | V.A. Lyubimov *et al.* | (ITEP) |
| Also | 80 | SJNP 32 154<br>Translated from YAF 32 301. | V.S. Kozik *et al.* | (ITEP) |
| Also | 81 | JETP 54 616<br>Translated from ZETF 81 1158. | V.A. Lyubimov *et al.* | (ITEP) |
| STECKER | 80 | PRL 45 1460 | F.W. Stecker | (NASA) |
| BEG | 78 | PR D17 1395 | M.A.B. Beg, W.J. Marciano, M. Ruderman | (ROCK+) |
| LEE | 77C | PR D16 1444 | B.W. Lee, R.E. Shrock | (STON) |
| SUTHERLAND | 76 | PR D13 2700 | P. Sutherland *et al.* | (PENN, COLU, NYU) |
| CLARK | 74 | PR D9 533 | A.R. Clark *et al.* | (LBL) |
| REINES | 74 | PRL 32 180 | F. Reines, H.W. Sobel, H.S. Gurr | (UCI) |
| Also | 78 | Private Comm. | V.E. Barnes | (PURD) |
| BECK | 68 | ZPHY 216 229 | E. Beck, H. Daniel | (MPIH) |
| BERNSTEIN | 63 | PR 132 1227 | J. Bernstein, M. Ruderman, G. Feinberg | (NYU+) |
| COWAN | 57 | PR 107 528 | C.L. Cowan, F. Reines | (LANL) |