ν_e

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

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

$\overline{\nu}$ MASS

Those limits given below for $\overline{\nu}$ mass that come from the kinematics of $^3\mathrm{H}\beta^-\overline{\nu}$ decay are the square roots of limits for $m^{2(\mathrm{eff})}_{\nu_e}$. 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 β decay
< 2.8	95	[3] WEINHEIMER	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<21.7	90	[4] ARNABOLDI	03A	BOLO	^{187}Re β-decay
< 4.35	95	[5] BELESEV	95	SPEC	^{3}H β decay
<12.4	95	[6] CHING	95	SPEC	^{3}Hβ decay
<92	95	[7] HIDDEMANN	95	SPEC	^{3}H β decay
$15\ ^{+32}_{-15}$		HIDDEMANN	95	SPEC	^{3}H β decay
<19.6	95	KERNAN	95	ASTR	SN 1987A
< 7.0	95	[8] STOEFFL	95	SPEC	^{3}H β decay
< 7.2	95	[9] WEINHEIMER	93	SPEC	^{3}H β decay
<11.7	95	[10] HOLZSCHUH	92B	SPEC	^{3}H β decay
<13.1	95	[11] KAWAKAMI	91	SPEC	^{3}H β decay
< 9.3	95	[12] ROBERTSON	91	SPEC	^{3}H β decay
<14	95	AVIGNONE	90	ASTR	SN 1987A
<16		SPERGEL	88	ASTR	SN 1987A
17 to 40		[13] BORIS	87	SPEC	^{3}Hβ 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 phenomenological fit parameters used to derive their best fit to m^2_ν, 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_ν. 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] ARNABOLDI 03A *etal*. report kinematical neutrino mass limit using β-decay of ^{187}Re. Bolometric $\mathrm{AgReO_4}$ micro-calorimeters are used. Mass bound is substantially weaker than those derived from tritium β-decays but has different systematic uncertainties.

[5] 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.

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

[7] 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.

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

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

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

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

[12] 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_ν 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.

[13] 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 neutrino listings."

VALUE (eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
− 2.5± 3.3 OUR AVERAGE					
− 1.9± 3.4± 2.2		[14] LOBASHEV	99	SPEC	^{3}H β decay
− 3.7± 5.3± 2.1		[15] WEINHEIMER	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
− 22 ± 4.8		[16] BELESEV	95	SPEC	^{3}H β decay
129 ±6010		[17] HIDDEMANN	95	SPEC	^{3}H β decay
313 ±5994		[17] HIDDEMANN	95	SPEC	^{3}H β decay
−130 ± 20 ±15	95	[18] STOEFFL	95	SPEC	^{3}H β decay
− 31 ± 75 ±48		[19] SUN	93	SPEC	^{3}Hβ decay
− 39 ± 34 ±15		[20] WEINHEIMER	93	SPEC	^{3}H β decay
− 24 ± 48 ±61		[21] HOLZSCHUH	92B	SPEC	^{3}H β decay
− 65 ± 85 ±65		[22] KAWAKAMI	91	SPEC	^{3}H β decay
−147 ± 68 ±41		[23] ROBERTSON	91	SPEC	^{3}H β decay

[14] 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 6×10^{-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_ν^2 limit makes unambiguous interpretation of this result difficult.

[15] 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_ν^2 fits and are used to derive the neutrino mass limit published by the authors. We list the most conservative of the two.

[16] 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.

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

[18] 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_ν^2. The authors acknowledge that "the negative value for the best fit of m_ν^2 has no physical meaning" and discuss possible explanations for this effect.

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

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

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

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

[23] 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_ν lies between 17 and 40 eV. However, the probability of a positive m_ν^2 is only 3% if statistical and systematic error are combined in quadrature.

ν MASS

These are measurement of m_ν (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 ν 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. • • •					
$<$ 4.5×10^5	90	CLARK	74	ASPK	K_{e3} decay
$<$4100	67	BECK	68	CNTR	^{22}Na decay

ν CHARGE

VALUE (units: electron charge)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-14}$	[24] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$	[25] RAFFELT	99	ASTR	Solar cooling
$<2 \times 10^{-15}$	[26] BARBIELLINI	87	ASTR	SN 1987A
$<1 \times 10^{-13}$	BERNSTEIN	63	ASTR	Solar energy losses

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

[25] 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.

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

ν 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. • • •					
		[27] BILLER	98	ASTR	m_ν = 0.05–1 eV
		[28] COWSIK	89	ASTR	m_ν = 1–50 MeV
		[29] RAFFELT	89	RVUE	$\overline{\nu}$ (Dirac, Majorana)
		[30] RAFFELT	89B	ASTR	
>278	90	[31] LOSECCO	87B	IMB	
$> 1.1 \times 10^{25}$		[32] HENRY	81	ASTR	m_ν = 16–20 eV
$> 10^{22}$–10^{23}		[33] KIMBLE	81	ASTR	m_ν = 10–100 eV

[27] BILLER 98 use the observed TeV γ-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_γ is the branching ratio to photons.

[28] 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.

[29] 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.

[30] RAFFELT 89B analyze stellar evolution and exclude the region $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21}$ s eV^3.

[31] LOSECCO 87B assumes observed rate of 2.1 SNU (solar neutrino units) comes from sun while 7.0 ± 3.0 is theory.

[32] HENRY 81 uses UV flux from clusters of galaxies to find limit for radiative decay.

[33] KIMBLE 81 uses extreme UV flux limits.

ν (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 ν in the indicated mass range.

VALUE (s/eV)	CL%	DOCUMENT ID		TECN	COMMENT
$> 7 \times 10^{9}$		[34] RAFFELT	85	ASTR	
> 300	90	[35] REINES	74	CNTR	$\overline{\nu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.004	90	[36] AHARMIM	04	SNO	quasidegen. ν masses
$> 4.4 \times 10^{-5}$	90	[36] AHARMIM	04	SNO	hierarchical ν masses
$\gtrsim 100$	95	[37] CECCHINI	04	ASTR	Radiative decay for ν mass > 0.01 eV
> 0.067	90	[38] EGUCHI	04	KLND	quasidegen. ν masses
$> 1.1 \times 10^{-3}$	90	[38] EGUCHI	04	KLND	hierarchical ν masses
$> 8.7 \times 10^{-5}$	99	[39] BANDYOPA...	03	FIT	nonradiative decay
≥ 4200	90	[40] DERBIN	02B	CNTR	Solar pp and Be ν
$> 2.8 \times 10^{-5}$	99	[41] JOSHIPURA	02B	FIT	nonradiative decay
$> 2.8 \times 10^{15}$		[42,43] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
> 6.4	90	[44] KRAKAUER	91	CNTR	ν at LAMPF
$> 6.3 \times 10^{15}$		[43,45] CHUPP	89	ASTR	$m_\nu < 20$ eV
$> 1.7 \times 10^{15}$		[43] KOLB	89	ASTR	$m_\nu < 20$ eV
$> 8.3 \times 10^{14}$		[46] VONFEILIT...	88	ASTR	
> 22	68	[47] OBERAUER	87		$\overline{\nu}_R$ (Dirac)
> 38	68	[47] OBERAUER	87		$\overline{\nu}$ (Majorana)
> 59	68	[47] OBERAUER	87		$\overline{\nu}_L$ (Dirac)
> 30	68	KETOV	86	CNTR	$\overline{\nu}$ (Dirac)
> 20	68	KETOV	86	CNTR	$\overline{\nu}$ (Majorana)
$> 2 \times 10^{21}$		[48] STECKER	80	ASTR	m_ν= 10–100 eV

[34] RAFFELT 85 limit is from solar x- and γ-ray fluxes. Limit depends on ν flux from pp, now established from GALLEX and SAGE to be > 0.5 of expectation.

[35] REINES 74 looked for ν of nonzero mass decaying to a neutral of lesser mass + γ. Used liquid scintillator detector near fission reactor. Finds lab lifetime 6×10^7 s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit 6×10^7 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.

[36] AHARMIM 04 obtained these results from the solar $\overline{\nu}_e$ flux limit set by the SNO measurement assuming ν_2 decay through nonradiative process $\nu_2 \to \overline{\nu}_1 X$, where X is a Majoron or other invisible particle. Limits are given for the cases of quasidegenerate and hierarchical neutrino masses.

[37] CECCHINI 04 obtained this bound through the observations performed in the occasion of the 21 June 2001 total solar eclipse, looking for visible photons from radiative decays of solar neutrinos. Limit is a τ/m_{ν_2} in $\nu_2 \to \nu_1\gamma$. Limit ranges from $\sim$ 100 to 10^7 s/eV for $0.01 < m_{\nu_1} < 0.1$ eV.

[38] EGUCHI 04 obtained these results from the solar $\overline{\nu}_e$ flux limit set by the KamLAND measurement assuming ν_2 decay through nonradiative process $\nu_2 \to \overline{\nu}_1 X$, where X is a Majoron or other invisible particle. Limits are given for the cases of quasidegenerate and hierarchical neutrino masses.

[39] The ratio of the lifetime over the mass derived by BANDYOPADHYAY 03 is for ν_2. They obtained this result using the following solar-neutrino data: total rates measured in Cl and Ga experiments, the Super-Kamiokande's zenith-angle spectra, and SNO's day and night spectra. They assumed that ν_1 is the lowest mass, stable or nearly stable neutrino state and ν_2 decays through nonradiative Majoron emission process, $\nu_2 \rightarrow \overline{\nu}_1 + J$, or through nonradiative process with all the final state particles being sterile. The best fit is obtained in the region of the LMA solution.

[40] DERBIN 02B (also BACK 03B) obtained this bound from the results of background measurements with Counting Test Facility (the prototype of the Borexino detector). The laboratory gamma spectrum is given as $dN_\gamma/d\cos\theta = (1/2)\ (1 + \alpha\cos\theta)$ with α=0 for a Majorana neutrino, and α varying to -1 to 1 for a Dirac neutrino. The listed bound is for the case of α=0. The most conservative bound 1.5×10^3 s eV^{-1} is obtained for the case of $\alpha=-1$.

[41] The ratio of the lifetime over the mass derived by JOSHIPURA 02B is for ν_2. They obtained this result from the total rates measured in all solar neutrino experiments. They assumed that ν_1 is the lowest mass, stable or nearly stable neutrino state and ν_2 decays through nonradiative process like Majoron emission decay, $\nu_2 \rightarrow \nu'_1 + J$ where ν'_1 state is sterile. The exact limit depends on the specific solution of the solar neutrino problem. The quoted limit is for the LMA solution.

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

[43] Nonobservation of γ's in coincidence with ν's from SN 1987A.

[44] 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 $a = -1$).

[45] 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.

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

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

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

$|(\mathrm{v} - c)/c|$ ($\mathrm{v} \equiv \nu$ 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	[49] STODOLSKY	88	ASTR	SN 1987A
<0.2		[50] LONGO	87	ASTR	SN 1987A

[49] 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.

[50] LONGO 87 argues that uncertainty between light and neutrino transit times is ± 3 hr, ignoring Mont Blanc events.

ν 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_ν 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 μ_ν, ... 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*
< 1.0	90	[51] DARAKTCH...	03		Reactor $\overline{\nu}_e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<37	95	[52] GRIFOLS	04	FIT	Solar ^{8}B ν (SNO NC)
< 3.6	90	[53] LIU	04	SKAM	Solar ν spectrum shape
< 1.1	90	[54] LIU	04	SKAM	Solar ν spectrum shape (LMA region)
< 5.5	90	[55] BACK	03B	CNTR	Solar pp and Be ν
< 1.3	90	[56] LI	03B	CNTR	Reactor $\overline{\nu}_e$
< 2	90	[57] GRIMUS	02	FIT	solar + reactor (Majorana ν)
< 0.01–0.04		[58] AYALA	99	ASTR	$\nu_L \rightarrow \nu_R$ in SN 1987A
< 1.5	90	[59] BEACOM	99	SKAM	ν spectrum shape
< 0.03		[60] RAFFELT	99	ASTR	Red giant luminosity
< 4		[61] RAFFELT	99	ASTR	Solar cooling
< 0.62		[62] ELMFORS	97	COSM	Depolarization in early universe plasma
< 1.9	95	[63] DERBIN	93	CNTR	Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$
< 2.4	90	[64] VIDYAKIN	92	CNTR	Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$
<10.8	90	[65] KRAKAUER	90	CNTR	LAMPF $\nu e \rightarrow \nu e$
< 0.02		[66] RAFFELT	90	ASTR	Red giant luminosity
< 0.1		[67] RAFFELT	89B	ASTR	Cooling helium stars
		[68] FUKUGITA	88	COSM	Primordial magn. fields
≤ .3		[67] RAFFELT	88B	ASTR	He burning stars
< 0.11		[67] 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		[69] SUTHERLAND	76	ASTR	Red giants + degenerate dwarfs
< 1		BERNSTEIN	63	ASTR	Solar cooling
<14		COWAN	57	CNTR	Reactor $\overline{\nu}$

[51] Search for non-standard $\overline{\nu}_e$-e scattering component at Bugey nuclear reactor. Full kinematical event reconstruction by use of TPC. Most stringent laboratory limit on magnetic moment.

[52] GRIFOLS 04 obtained this bound using the SNO data of the solar ^{8}B neutrino flux measured with deuteron breakup. This bound applies to $\mu_{\text{eff}} = (\mu_{21}^2 + \mu_{22}^2 + \mu_{23}^2)^{1/2}$.

[53] LIU 04 obtained this limit using the shape of the recoil electron energy spectrum from the Super-Kamiokande-I 1496 days of solar neutrino data. Neutrinos are assumed to have only diagonal magnetic moments, $\mu_{\nu 1} = \mu_{\nu 2}$. This limit corresponds to the oscillation parameters in the vacuum oscillation region.

[54] LIU 04 obtained this limit using the shape of the recoil electron energy spectrum from the Super-Kamiokande-I 1496 live-day solar neutrino data, by limiting the oscillation parameter region in the LMA region allowed by solar neutrino experiments plus KamLAND. $\mu_{\nu 1} = \mu_{\nu 2}$ is assumed. In the LMA region, the same limit would be obtained even if neutrinos have off-diagonal magnetic moments.

[55] BACK 03B obtained this bound from the results of background measurements with Counting Test Facility (the prototype of the Borexino detector). Standard Solar Model flux was assumed. This μ_ν can be different from the reactor μ_ν in certain oscillation scenarios (see BEACOM 99).

[56] LI 03B used Ge detector in active shield near nuclear reactor to test for nonstandard $\overline{\nu}_e$-e scattering.

[57] 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.

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

[59] 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 μ_ν can be different from the reactor μ_ν in certain oscillation scenarios.

[60] 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.

[61] RAFFELT 99 is essentially 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.

[62] 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.

[63] 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 $\sim 1/100$.

[64] 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.

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

[66] 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 δM_c.

[67] Significant dependence on details of stellar models.

[68] 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.

[69] 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	[70] AUERBACH	01	LSND	$\nu_e e \rightarrow \nu_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.9 ± 2.7		ALLEN	93	CNTR	LAMPF $\nu e \rightarrow \nu e$
<2.3	95	MOURAO	92	ASTR	HOME/KAM2 ν rates
<7.3	90	[71] VIDYAKIN	92	CNTR	Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$
1.1 ± 2.3		ALLEN	91	CNTR	Repl. by ALLEN 93
		[72] GRIFOLS	89B	ASTR	SN 1987A

[70] 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.

[71] 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.

[72] 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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