Neutrino Properties

NEUTRINO PROPERTIES

Revised July 2023 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

The Neutrino Properties Listings concern measurements of various properties of neutrinos. Nearly all of the measurements, so far only limits, actually concern superpositions of the mass eigenstates ν_i, which are in turn related to the weak eigenstates ν_ℓ, via the neutrino mixing matrix

$$|\nu_\ell\rangle = \sum_i U_{\ell i} \, |\nu_i\rangle \ .$$

In the analogous case of quark mixing via the CKM matrix, the smallness of the off-diagonal terms (small mixing angles) permits a "dominant eigenstate" approximation. However, the results of neutrino oscillation searches show that the mixing matrix contains two large mixing angles and a third angle that is not exceedingly small. We cannot therefore associate any particular state $|\nu_i\rangle$ with any particular lepton label e, μ or τ. Nevertheless, note that in the standard labeling the $|\nu_1\rangle$ has the largest $|\nu_e\rangle$ component ($\sim 2/3$), $|\nu_2\rangle$ contains $\sim 1/3$ of the $|\nu_e\rangle$ component and $|\nu_3\rangle$ contains only a small $\sim 2.5\%$ $|\nu_e\rangle$ component.

Neutrinos are produced in weak decays with a definite lepton flavor, and are typically detected by the charged current weak interaction again associated with a specific lepton flavor. Hence, the listings for the neutrino mass that follow are separated into the three associated charged lepton categories. Other properties (mean lifetime, magnetic moment, charge and charge radius) are no longer separated this way. If needed, the associated lepton flavor is reported in the footnotes.

Measured quantities (mass-squared, magnetic moments, mean lifetimes, *etc.*) all depend upon the mixing parameters $|U_{\ell i}|^2$, but to some extent also on experimental conditions (e.g., on energy resolution). Many of these observables, in particular mass-squared, cannot distinguish between Dirac and Majorana neutrinos and are unaffected by CP phases.

Direct neutrino mass measurements are usually based on the analysis of the kinematics of charged particles (leptons, pions) emitted together with neutrinos (flavor states) in various weak decays. The most sensitive neutrino mass measurement to date, involving electron type antineutrinos, is based on fitting the shape of the beta spectrum. The quantity $m_{\nu_e}^{2(eff)} = \sum_i |U_{ei}|^2 m_{\nu_i}^2$ is determined or constrained, where the sum is over all mass eigenvalues m_{ν_i} that are too close together to be resolved experimentally. (The quantity $m_{\nu_e}^{eff} \equiv \sqrt{m_{\nu_e}^{2(eff)}}$ is often denoted $\langle m_\beta \rangle$ in the literature.) If the energy resolution is better than $\Delta m_{ij}^2 \equiv m_{\nu_i}^2 - m_{\nu_j}^2$, the corresponding heavier m_{ν_i} and mixing parameter could be determined by fitting the resulting spectral anomaly (step or kink).

The dependence of m_{ν_e} on the mass of the lightest neutrino is shown in Fig. 14.11 of the *Neutrino Masses, Mixing, and Oscillations* review. In the case of inverted ordering there is a minimum possible value of $m_{\nu_e}^{eff}$, approximately $\sqrt(\Delta m_{32}^2) \sim$ 50 meV. If $m_{\nu_e}^{eff}$ is found to be larger than this value, it is impossible, based on this information only, to decide which ordering is realized in nature. On the other hand, if the $m_{\nu_e}^{eff}$ is less than $\sim$50 meV, only the normal mass ordering is possible.

A limit on $m_{\nu_e}^{2(eff)}$ implies an upper limit on the minimum value m^2_{min} of $m^2_{\nu_i}$, independent of the mixing parameters U_{ei}: $m^2_{min} \leq m_{\nu_e}^{2(eff)}$. However, if and when the value of $m_{\nu_e}^{2(eff)}$ is determined then its combination with the results derived from neutrino oscillations that give us the values of the neutrino mass-squared differences $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, including eventually also their signs, and the mixing parameters $|U_{ei}|^2$, the individual neutrino mass squares $m^2_{\nu_j} = m_{\nu_e}^{2(eff)} - \sum_i |U_{ei}|^2 \Delta m^2_{ij}$ can be determined.

So far solar, reactor, atmospheric and accelerator neutrino oscillation experiments can be consistently described using three active neutrino flavors, i.e. two mass splittings and three mixing angles. However, several experiments with radioactive sources, reactors, and accelerators imply the possible existence of one or more non-interacting, i.e. sterile, neutrino species that might be observable since they couple, albeit weakly, to the flavor neutrinos $|\nu_l\rangle$. In that case, the neutrino mixing matrix would be $n \times n$ unitary matrix with $n > 3$.

Combined three neutrino analyses determine the squared mass differences and all three mixing angles to within reasonable accuracy. For given $|\Delta m^2_{ij}|$ a limit on $m_{\nu_e}^{2(eff)}$ from beta decay defines an upper limit on the maximum value m_{max} of m_{ν_i}: $m^2_{max} \leq m_{\nu_e}^{2(eff)} + \sum_{i<j} |\Delta m^2_{ij}|$. The analysis of the low energy beta decay of tritium, combined with the oscillation results, thus limits *all* active neutrino masses. Traditionally, experimental neutrino mass limits obtained from pion decay $\pi^+ \to \mu^+ + \nu_\mu$ or the shape of the spectrum of decay products of the τ lepton did not distinguish between flavor and mass eigenstates. These results are reported as limits of the μ and τ based neutrino mass. After the determination of the $|\Delta m^2_{ij}|$'s and the mixing

angles θ_{ij}, the corresponding neutrino mass limits are no longer competitive with those derived from low energy beta decays.

The spread of arrival times of the neutrinos from SN1987A, coupled with the measured neutrino energies, provided a time-of-flight limit on a quantity similar to $\langle m_\beta \rangle \equiv \sqrt{m_{\nu_e}^{2(eff)}}$. This statement, clothed in various degrees of sophistication, has been the basis for a very large number of papers. The resulting limits, however, are no longer comparable with the limits from tritium beta decay.

Constraint, or eventually a value, of the sum of the neutrino masses m_{tot} can be determined from the analysis of the cosmic microwave background anisotropy, combined with the galaxy redshift surveys and other data. These limits are reported in a separate table (Sum of Neutrino Masses, m_{tot}). Obviously, m_{tot} represents an upper limit for all m_i values. Note that many reported m_{tot} limits are considerably more stringent than the listed $m_{\nu_e}^{eff}$ limits. Discussion concerning the model dependence of the m_{tot} limit is continuing.

$\overline{\nu}$ MASS (electron based)

Those limits given below are for the square root of $m_{\nu_e}^{2(\mathrm{eff})} \equiv \sum_i |\mathrm{U}_{ei}|^2 m_{\nu_i}^2$. Limits that come from the kinematics of $^3\mathrm{H}\beta^-\overline{\nu}$ decay are the square roots of the limits for $m_{\nu_e}^{2(\mathrm{eff})}$. Obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.8	90	[1] AKER	22	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<155	90	[2] ESFAHANI	23	CRES	^{3}H β decay
< 1.1	90	[3] AKER	19	SPEC	^{3}H β decay
< 2.05	95	[4] ASEEV	11	SPEC	^{3}H β decay
< 5.8	95	[5] PAGLIAROLI	10	ASTR	SN1987A
< 2.3	95	[6] KRAUS	05	SPEC	^{3}H β decay
< 21.7	90	[7] ARNABOLDI	03A	BOLO	^{187}Re β decay

$<$ 5.7	95	[8] LOREDO	02	ASTR	SN1987A
$<$ 2.5	95	[9] LOBASHEV	99	SPEC	^{3}H β decay
$<$ 2.8	95	[10] WEINHEIMER	99	SPEC	^{3}H β decay
$<$ 4.35	95	[11] BELESEV	95	SPEC	^{3}H β decay
$<$ 12.4	95	[12] CHING	95	SPEC	^{3}H β decay
$<$ 92	95	[13] 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	[14] STOEFFL	95	SPEC	^{3}H β decay
$<$ 7.2	95	[15] WEINHEIMER	93	SPEC	^{3}H β decay
$<$ 11.7	95	[16] HOLZSCHUH	92B	SPEC	^{3}H β decay
$<$ 13.1	95	[17] KAWAKAMI	91	SPEC	^{3}H β decay
$<$ 9.3	95	[18] ROBERTSON	91	SPEC	^{3}H β decay
$<$ 14	95	AVIGNONE	90	ASTR	SN 1987A
$<$ 16		SPERGEL	88	ASTR	SN 1987A
17 to 40		[19] BORIS	87	SPEC	^{3}H β decay

[1] AKER 22 derive an upper limit on the kinematical neutrino mass using Tritium β-decay and the KATRIN spectrometer. The constraint is based on combining the first two science runs. Supersedes AKER 19.

[2] ESFAHANI 23 report the first continuous-spectrum measurement of ^{3}H β decay, using cyclotron radiation emission spectroscopy (CRES) and a small demonstration detector. The energy resolution at the endpoint is demonstrated using ^{83m}Kr and a kinematical neutrino mass limit derived from the spectral shape. A frequentist analysis obtained a limit of $<$152 eV.

[3] AKER 19 report a neutrino mass limit, derived from the first month of data collected by the KATRIN tritium endpoint experiment. The analysis of the electron kinematics shows no evidence for neutrino mass. The quoted result is based on a frequentist analysis of the data following the method described in LOKHOV 15. Using the method of Feldman and Cousins, the derived upper limit is $<$ 0.8 eV at 90% C.L. Superseded by AKER 22.

[4] ASEEV 11 report the analysis of the entire beta endpoint data, taken with the Troitsk integrating electrostatic spectrometer between 1997 and 2002 (some of the earlier runs were rejected), using a windowless gaseous tritium source. The fitted value of m_ν, based on the method of Feldman and Cousins, is obtained from the upper limit of the fit for m^2_ν. Previous analysis problems were resolved by careful monitoring of the tritium gas column density. Supersedes LOBASHEV 99 and BELESEV 95.

[5] PAGLIAROLI 10 is critical of the likelihood method used by LOREDO 02.

[6] KRAUS 05 is a continuation of the work reported in WEINHEIMER 99. This result represents the final analysis of data taken from 1997 to 2001. Various sources of systematic uncertainties have been identified and quantified. The background has been reduced compared to the initial running period. A spectral anomaly at the endpoint, reported in LOBASHEV 99, was not observed.

[7] ARNABOLDI 03A *etal*. report kinematical neutrino mass limit using β-decay of ^{187}Re. Bolometric $AgReO_4$ micro-calorimeters are used. Mass bound is substantially weaker than those derived from tritium β-decays but has different systematic uncertainties.

[8] LOREDO 02 updates LOREDO 89.

[9] 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."

[10] WEINHEIMER 99 presents two analyses which exclude the spectral anomaly and result in an acceptable m_{ν}^2. We report the most conservative limit, but the other is nearly the same. See the footnote under "$\overline{\nu}$ Mass Squared."

[11] 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.

[12] CHING 95 quotes results previously given by SUN 93; no experimental details are given. A possible explanation for consistently negative values of m_{ν}^2 is given.

[13] 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.

[14] 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.

[15] 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.

[16] 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}.

[17] 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.

[18] 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.

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

$\overline{\nu}$ MASS SQUARED (electron based)

Given troubling systematics which result in improbably negative estimators of $m_{\nu_e}^{2(\text{eff})} \equiv \sum_i |U_{ei}|^2 \, m_{\nu_i}^2$, in many experiments, we use only KRAUS 05, LOBASHEV 99, and AKER 22 for our average.

VALUE (eV^2)	DOCUMENT ID		TECN	COMMENT
0.08 ± 0.30 OUR AVERAGE				
0.1 ± 0.3	[1] AKER	22	SPEC	^{3}H β decay
−0.67 ± 2.53	[2] ASEEV	11	SPEC	^{3}H β decay
−0.6 ± 2.2 ± 2.1	[3] KRAUS	05	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$-1.0^{+0.9}_{-1.1}$	[4] AKER	19	SPEC	^{3}H β decay
−1.9 ± 3.4 ± 2.2	[5] LOBASHEV	99	SPEC	^{3}H β decay
−3.7 ± 5.3 ± 2.1	[6] WEINHEIMER	99	SPEC	^{3}H β decay
−22 ± 4.8	[7] BELESEV	95	SPEC	^{3}H β decay

129	±6010		[8] HIDDEMANN	95	SPEC	^{3}H β decay
313	±5994		[8] HIDDEMANN	95	SPEC	^{3}H β decay
−130	± 20	±15	[9] STOEFFL	95	SPEC	^{3}H β decay
− 31	± 75	±48	[10] SUN	93	SPEC	^{3}H β decay
− 39	± 34	±15	[11] WEINHEIMER	93	SPEC	^{3}H β decay
− 24	± 48	±61	[12] HOLZSCHUH	92B	SPEC	^{3}H β decay
− 65	± 85	±65	[13] KAWAKAMI	91	SPEC	^{3}H β decay
−147	± 68	±41	[14] ROBERTSON	91	SPEC	^{3}H β decay

[1] AKER 22 report results from the analysis of the Tritium β spectrum using the combined data set collected by the KATRIN experiment in the first two science runs. Supersedes AKER 19.

[2] ASEEV 11 report the analysis of the entire beta endpoint data, taken with the Troitsk integrating electrostatic spectrometer between 1997 and 2002, using a windowless gaseous tritium source. The analysis does not use the two additional fit parameters (see LOBASHEV 99) for a step-like structure near the endpoint. Using only the runs where the tritium gas column density was carefully monitored the need for such parameters was eliminated. Supersedes LOBASHEV 99 and BELESEV 95.

[3] KRAUS 05 is a continuation of the work reported in WEINHEIMER 99. This result represents the final analysis of data taken from 1997 to 2001. Problems with significantly negative squared neutrino masses, observed in some earlier experiments, have been resolved in this work.

[4] AKER 19 use the first month of data collected by the KATRIN experiment to determine m^2_ν. The result is consistent with a neutrino mass of zero and is used to place a limit on m_ν. Superseded by AKER 22.

[5] 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 $m^2_\nu \approx -$(20–10) 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 $m^2_\nu = -1.9 \pm 3.4 \pm 2.2\,\mathrm{eV}^2$ which is used to derive a neutrino mass limit. However, the introduction of phenomenological fit parameters which are correlated with the derived m^2_ν limit makes unambiguous interpretation of this result difficult.

[6] 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^2_ν fits and are used to derive the neutrino mass limit published by the authors. We list the most conservative of the two.

[7] 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.

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

[9] 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^2_ν. The authors acknowledge

that "the negative value for the best fit of m^2_ν has no physical meaning" and discuss possible explanations for this effect.

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

[11] 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.

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

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

[14] 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_ν is only 3% if statistical and systematic error are combined in quadrature.

ν MASS (electron based)

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

ν MASS (muon based)

Limits given below are for the square root of $m^{2(\text{eff})}_{\nu_\mu} \equiv \sum_i |\text{U}_{\mu i}|^2\, m^2_{\nu_i}$.

In some of the COSM papers listed below, the authors did not distinguish between weak and mass eigenstates.

OUR EVALUATION is based on OUR AVERAGE for the $\pi^\pm$ mass and the ASSAMAGAN 96 value for the muon momentum for the π^+ decay at rest. The limit is calculated using the unified classical analysis of FELDMAN 98 for a Gaussian distribution near a physical boundary. WARNING: since $m^{2(\text{eff})}_{\nu_\mu}$ is calculated from the differences of large numbers, it and the corresponding limits are extraordinarily sensitive to small changes in the pion mass, the decay muon momentum, and their errors. For example, the limits obtained using JECKELMANN 94, LENZ 98, and the weighted averages are 0.15, 0.29, and 0.19 MeV, respectively.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.19 (CL = 90%) OUR EVALUATION					
<0.17	90	[1] ASSAMAGAN	96	SPEC	$m^2_\nu = -0.016 \pm 0.023$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15		[2] DOLGOV	95	COSM	Nucleosynthesis
<0.48		[3] ENQVIST	93	COSM	Nucleosynthesis

<0.3			[4] FULLER	91	COSM	Nucleosynthesis
<0.42			[4] LAM	91	COSM	Nucleosynthesis
<0.50	90		[5] ANDERHUB	82	SPEC	$m^2_\nu = -0.14 \pm 0.20$
<0.65	90		CLARK	74	ASPK	$K_{\mu 3}$ decay

[1] ASSAMAGAN 96 measurement of p_μ from $\pi^+ \rightarrow \mu^+ \nu$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m^2_\nu = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m^2_\nu = -0.143 \pm 0.024$ MeV^2. Replaces ASSAMAGAN 94.

[2] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits.

[3] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

[4] Assumes neutrino lifetime >1 s. For Dirac neutrinos only. See also ENQVIST 93.

[5] ANDERHUB 82 kinematics is insensitive to the pion mass.

ν MASS (tau based)

The limits given below are the square roots of limits for $m^{2(\mathrm{eff})}_{\nu_\tau} \equiv \sum_i |\mathrm{U}_{\tau i}|^2 \, m^2_{\nu_i}$.

In some of the ASTR and COSM papers listed below, the authors did not distinguish between weak and mass eigenstates.

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 18.2	95		[1] BARATE	98F	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 28	95		[2] ATHANAS	00	CLEO	$E^{ee}_{\mathrm{cm}} = 10.6$ GeV
< 27.6	95		[3] ACKERSTAFF	98T	OPAL	1990–1995 LEP runs
< 30	95	473	[4] AMMAR	98	CLEO	$E^{ee}_{\mathrm{cm}} = 10.6$ GeV
< 60	95		[5] ANASTASSOV	97	CLEO	$E^{ee}_{\mathrm{cm}} = 10.6$ GeV
< 0.37 or >22			[6] FIELDS	97	COSM	Nucleosynthesis
< 68	95		[7] SWAIN	97	THEO	m_τ, τ_τ, τ partial widths
< 29.9	95		[8] ALEXANDER	96M	OPAL	1990–1994 LEP runs
<149			[9] BOTTINO	96	THEO	π, μ, τ leptonic decays
<1 or >25			[10] HANNESTAD	96C	COSM	Nucleosynthesis
< 71	95		[11] SOBIE	96	THEO	m_τ, τ_τ, B($\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$)
< 24	95	25	[12] BUSKULIC	95H	ALEP	1991–1993 LEP runs
< 0.19			[13] DOLGOV	95	COSM	Nucleosynthesis
< 3			[14] SIGL	95	ASTR	SN 1987A
< 0.4 or > 30			[15] DODELSON	94	COSM	Nucleosynthesis

< 0.1 or > 50			[16] KAWASAKI	94	COSM	Nucleosynthesis
155–225			[17] PERES	94	THEO	π,K,μ,τ weak decays
< 32.6	95	113	[18] CINABRO	93	CLEO	$E^{ee}_{\rm cm} \approx$ 10.6 GeV
< 0.3 or > 35			[19] DOLGOV	93	COSM	Nucleosynthesis
< 0.74			[20] ENQVIST	93	COSM	Nucleosynthesis
< 31	95	19	[21] ALBRECHT	92M	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
< 0.3			[22] FULLER	91	COSM	Nucleosynthesis
< 0.5 or > 25			[23] KOLB	91	COSM	Nucleosynthesis
< 0.42			[22] LAM	91	COSM	Nucleosynthesis

[1] BARATE 98F result based on kinematics of 2939 $\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$ and 52 $\tau^- \rightarrow 3\pi^-2\pi^+(\pi^0)\nu_\tau$ decays. If possible 2.5% excited a_1 decay is included in 3-prong sample analysis, limit increases to 19.2 MeV.

[2] ATHANAS 00 bound comes from analysis of $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ decays.

[3] ACKERSTAFF 98T use $\tau \rightarrow 5\pi^\pm\nu_\tau$ decays to obtain a limit of 43.2 MeV (95%CL). They combine this with ALEXANDER 96M value using $\tau \rightarrow 3h^\pm\nu_\tau$ decays to obtain quoted limit.

[4] AMMAR 98 limit comes from analysis of $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \rightarrow 2\pi^-\pi^+2\pi^0\nu_\tau$ decay modes.

[5] ANASTASSOV 97 derive limit by comparing their m_τ measurement (which depends on m_{ν_τ}) to BAI 96 m_τ threshold measurement.

[6] FIELDS 97 limit for a Dirac neutrino. For a Majorana neutrino the mass region < 0.93 or $>$31 MeV is excluded. These bounds assume $N_\nu <$4 from nucleosynthesis; a wider excluded region occurs with a smaller N_ν upper limit.

[7] SWAIN 97 derive their limit from the Standard Model relationships between the tau mass, lifetime, branching fractions for $\tau^- \rightarrow e^-\overline{\nu}_e\nu_\tau$, $\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau$, $\tau^- \rightarrow \pi^-\nu_\tau$, and $\tau^- \rightarrow K^-\nu_\tau$, and the muon mass and lifetime by assuming lepton universality and using world average values. Limit is reduced to 48 MeV when the CLEO τ mass measurement (BALEST 93) is included; see CLEO's more recent m_{ν_τ} limit (ANASTASSOV 97). Consideration of mixing with a fourth generation heavy neutrino yields $\sin^2\theta_L < 0.016$ (95%CL).

[8] ALEXANDER 96M bound comes from analyses of $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \rightarrow h^-h^-h^+\nu_\tau$ decays.

[9] BOTTINO 96 assumes three generations of neutrinos with mixing, finds consistency with massless neutrinos with no mixing based on 1995 data for masses, lifetimes, and leptonic partial widths.

[10] HANNESTAD 96C limit is on the mass of a Majorana neutrino. This bound assumes $N_\nu < 4$ from nucleosynthesis. A wider excluded region occurs with a smaller N_ν upper limit. This paper is the corrected version of HANNESTAD 96; see the erratum: HANNESTAD 96B.

[11] SOBIE 96 derive their limit from the Standard Model relationship between the tau mass, lifetime, and leptonic branching fraction, and the muon mass and lifetime, by assuming lepton universality and using world average values.

[12] BUSKULIC 95H bound comes from a two-dimensional fit of the visible energy and invariant mass distribution of $\tau \rightarrow 5\pi(\pi^0)\nu_\tau$ decays. Replaced by BARATE 98F.

[13] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below $T_{\rm QCD}$ for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits. DOLGOV 96 argues that a possible window near 20 MeV is excluded.

[14] SIGL 95 exclude massive Dirac or Majorana neutrinos with lifetimes between 10^{-3} and 10^{8} seconds if the decay products are predominantly γ or e^+e^-.

[15] DODELSON 94 calculate constraints on ν_τ mass and lifetime from nucleosynthesis for 4 generic decay modes. Limits depend strongly on decay mode. Quoted limit is valid for all decay modes of Majorana neutrinos with lifetime greater than about 300 s. For Dirac neutrinos limits change to < 0.3 or > 33.

[16] KAWASAKI 94 excluded region is for Majorana neutrino with lifetime $>$1000 s. Other limits are given as a function of ν_τ lifetime for decays of the type $\nu_\tau \rightarrow \nu_\mu \phi$ where ϕ is a Nambu-Goldstone boson.

[17] PERES 94 used PDG 92 values for parameters to obtain a value consistent with mixing. Reexamination by BOTTINO 96 which included radiative corrections and 1995 PDG parameters resulted in two allowed regions, $m_3 < 70$ MeV and 140 MeV $m_3 < 149$ MeV.

[18] CINABRO 93 bound comes from analysis of $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$ and $\tau^- \rightarrow 2\pi^- \pi^+ 2\pi^0 \nu_\tau$ decay modes.

[19] DOLGOV 93 assumes neutrino lifetime $>$100 s. For Majorana neutrinos, the low mass limit is 0.5 MeV. KAWANO 92 points out that these bounds can be overcome for a Dirac neutrino if it possesses a magnetic moment. See also DOLGOV 96.

[20] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.

[21] ALBRECHT 92M reports measurement of a slightly lower τ mass, which has the effect of reducing the ν_τ mass reported in ALBRECHT 88B. Bound is from analysis of $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$ mode.

[22] Assumes neutrino lifetime $>$1 s. For Dirac neutrinos. See also ENQVIST 93.

[23] KOLB 91 exclusion region is for Dirac neutrino with lifetime $>$1 s; other limits are given.

Revised August 2023 by K.A. Olive (University of Minnesota).

Neutrinos decouple from thermal equilibrium in the early universe at temperatures $\mathcal{O}(1)$ MeV. The limits on low mass ($m_\nu \lesssim 1$ MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu m_\nu \ .$$

Stable neutrinos in this mass range decouple from the thermal bath while still relativistic and make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu \simeq m_{\rm tot}(3/11)(3.045/3)^{3/4} n_\gamma \ ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons and the factor $(3.045/3)^{3/4}$ corrects for the fact that the effective number of neutrinos in the standard model is 3.045 when taking into account e^+e^- annihilation during neutrino decoupling. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where ρ_c is the critical energy density of the Universe, and using $n_\gamma = 410.7\ \mathrm{cm}^{-3}$, we have

$$\Omega_\nu h^2 \simeq m_{\mathrm{tot}}/(93\ \mathrm{eV})\ .$$

While an upper limit to the matter density of $\Omega_m h^2 < 0.12$ would constrain $m_{\mathrm{tot}} < 11$ eV, much stronger constraints are obtained from the observations of the CMB, combined with lensing and baryon acoustic oscillations data. These combine to give an upper limit of around 0.12 eV, and may, in the near future, be able to provide a lower bound on the sum of the neutrino masses. The current lower bound of $m_{\mathrm{tot}} > 0.06$ eV implies a lower limit of $\Omega_\nu h^2 > 6 \times 10^{-4}$. See our review on "Neutrinos in Cosmology" for more details.

SUM OF THE NEUTRINO MASSES, m_{tot}

This is a sum of the neutrino masses, m_{tot}, as defined in the above note, of effectively stable neutrinos, i.e. those with mean lifetimes on cosmological scales. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85. For more information see a note on "Neutrinos in Cosmology" in this *Review*.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.082	95	[1] BRIEDEN	22	COSM	BOSS, eBOSS, and CMB
< 0.116	95	[2] KUMAR	22	COMS	BOSS and CMB
< 0.14	95	[3] TANSERI	22	COSM	BOSS and CMB
< 0.13	95	[4] ABBOTT	21A	COSM	DES and Planck
< 0.12	95	[5] ALAM	21	COSM	
< 0.09	95	[6] DI-VALENT...	21	COSM	
< 0.16	95	[7] GARNY	21	COSM	
< 0.06–0.14	95	[8] STOCKER	21	COSM	Normal mass ordering
< 0.12	95	[9] AGHANIM	20	COSM	
< 0.15	95	[10] CHOUDHURY	20	COSM	Normal mass hierarchy

$<$ 0.16		95	[11] IVANOV	20	COSM	Planck and BOSS
$<$ 0.11		95	[12] PALANQUE-...	20	COSM	Lyman alpha and CMB
$<$ 0.26		95	[13] LOUREIRO	19	COSM	
$<$ 0.18		95	[14] UPADHYE	19	COSM	BOSS and CMB
$<$ 0.152		95	[15] CHOUDHURY	18	COSM	
0.064	$^{+0.061}_{-0.005}$	95	[16] SIMPSON	17	COSM	
$<$ 0.14		95	[17] YECHE	17	COSM	BOSS and XQ-100
$<$ 0.0926		90	[18] DIVALENTINO	16	COSM	
$<$ 0.18		95	[19] HUANG	16	COSM	Normal mass hierarchy
$<$ 0.14		95	[20] ROSSI	15	COSM	
$<$ 0.23		95	[21] ADE	14	COSM	Planck
0.320	$\pm$0.081		[22] BATTYE	14	COSM	
0.35	$\pm$0.10		[23] BEUTLER	14	COSM	BOSS
0.22	$^{+0.09}_{-0.10}$		[24] COSTANZI	14	COSM	
0.32	$\pm$0.11		[25] HOU	14	COSM	
$<$ 0.26		95	[26] LEISTEDT	14	COSM	
$<$ 0.18		95	[27] RIEMER-SOR...	14	COSM	
$<$ 0.24		68	[28] MORESCO	12	COSM	
$<$ 0.29		95	[29] XIA	12	COSM	
$<$ 0.81		95	[30] SAITO	11	COSM	SDSS
$<$ 0.44		95	[31] HANNESTAD	10	COSM	
$<$ 0.6		95	[32] SEKIGUCHI	10	COSM	
$<$ 0.28		95	[33] THOMAS	10	COSM	
$<$ 1.1			[34] ICHIKI	09	COSM	
$<$ 1.3		95	[35] KOMATSU	09	COSM	WMAP
$<$ 1.2			[36] TERENO	09	COSM	
$<$ 0.33			[37] VIKHLININ	09	COSM	
$<$ 0.28			[38] BERNARDIS	08	COSM	
$<$ 0.17–2.3			[39] FOGLI	07	COSM	
$<$ 0.42		95	[40] KRISTIANSEN	07	COSM	
$<$ 0.63–2.2			[41] ZUNCKEL	07	COSM	
$<$ 0.24		95	[42] CIRELLI	06	COSM	
$<$ 0.62		95	[43] HANNESTAD	06	COSM	
$<$ 1.2			[44] SANCHEZ	06	COSM	
$<$ 0.17		95	[42] SELJAK	06	COSM	
$<$ 2.0		95	[45] ICHIKAWA	05	COSM	
$<$ 0.75			[46] BARGER	04	COSM	
$<$ 1.0			[47] CROTTY	04	COSM	
$<$ 0.7			[48] SPERGEL	03	COSM	WMAP
$<$ 0.9			[49] LEWIS	02	COSM	
$<$ 4.2			[50] WANG	02	COSM	CMB
$<$ 2.7			[51] FUKUGITA	00	COSM	
$<$ 5.5			[52] CROFT	99	ASTR	Ly α power spec
$<$180			SZALAY	74	COSM	
$<$132			COWSIK	72	COSM	
$<$280			MARX	72	COSM	
$<$400			GERSHTEIN	66	COSM	

[1] BRIEDEN 22 combines redshift-space distortions and the shape of the matter power spectrum from BOSS and eBOSS data together with Planck CMB data. Absent the CMB data, the limit is 0.40 eV.

[2] KUMAR 22 combine the reconstructed galaxy power spectrum from BOSS data with Planck CMB data.

[3] TANSERI 22 combines BOSS galaxy clustering data with measurements of CMB data. Updates VAGNOZZI 17.

[4] ABBOTT 21A combines Dark Energy Survey (DES) year 3 results with Planck CMB lensing measurements.

[5] ALAM 21 limit on the sum of neutrino masses by the eBOSS collaboration is based on galaxy, quasar, and Lyman-α 3D clustering data combined with Planck temperature and polarization CMB and supernovae data.

[6] DI-VALENTINO 21 combines CMB temperature and polarization, SNIa luminosity distances and baryon acoustic oscillations data.

[7] GARNY 21 employs a model for the Lyman-α flux power spectrum to set a limit using BOSS data. When combined with Planck CMB temperature and polarization data, a 95% CL range 0.10–0.13 eV is found.

[8] STOCKER 21 use terrestrial and cosmological experiments to set a 95% CL range on the sum of neutrino masses of 0.058–0.139 eV for normal ordering and 0.098–0.174 eV for inverse ordering. They also set an upper limit of 0.037 eV (NO) and 0.042 eV (IO) for the lightest neutrino mass.

[9] AGHANIM 20 limit on the sum of neutrino masses from Planck data combined with lensing and baryon acoustic oscillations (BAO). Without BAO, the limit relaxes to <0.24 eV. Several other limits are quoted based on different combinations of data.

[10] CHOUDHURY 20 combines 2018 Planck CMB temperature and polarization data plus lensing, together with baryon acoustic oscillation data from BOSS, MGS, and 6dFGS. Assumes ΛCDM model. The upper limit is 0.17 eV for the inverted hierarchy, and 0.12 eV for degenerate neutrinos. Limits are also derived for extended cosmological models.

[11] IVANOV 20 combines 2018 Planck CMB data with baryon acoustic oscillation data from BOSS. This study is based on a full-shape likelihood for the redshift-space galaxy power spectrum of the BOSS data.

[12] PALANQUE-DELABROUILLE 20 combine Lyman alpha and Planck temperature and polarization data. Limit improves to 0.09 eV when CMB lensing and baryon acoustic oscillation data are included.

[13] LOUREIRO 19 combines data from large scale structure, cosmic microwave background, type Ia supernovae and big bang nucleosynthesis using physically motivated neutrino mass models.

[14] UPADHYE 19 uses the shape of the BOSS redshift-space galaxy power spectrum in combination with the CMB, and supernovae data. Limit weakens to < 0.54 eV if the dark energy equation of state is allowed to vary.

[15] CHOUDHURY 18 combines 2015 Planck CMB temperature data, information from the optical depth to reionization from Planck 2016 intermediate results together with baryon acoustic oscillation data from BOSS, MGS, and 6dFGS as well as supernovae Type Ia data from the Pantheon Sample. The limit is strengthened to 0.118 eV when high-l CMB polarization data is also included.

[16] SIMPSON 17 uses a combination of laboratory and cosmological measurements to determine the light neutrino masses and argue that there is strong evidence for the normal mass ordering.

[17] Constrains the total mass of neutrinos using the Lyman-alpha forest power spectrum with BOSS (mid-resolution), XQ-100 (high-resolution) and CMB. Without the CMB data, the limit relaxes to 0.8 eV. Supersedes PALANQUE-DELABROUILLE 15A.

[18] Constrains the total mass of neutrinos from Planck CMB data combined with baryon acoustic oscillation and Planck cluster data.

[19] Constrains the total mass of neutrinos from BAO data from SDSS-III/BOSS combined with CMB data from Planck. Limit quoted for normal mass hierarchy. The limit for the inverted mass hierarchy is 0.20 eV and for the degenerate mass hierarchy it is 0.15 eV.

[20] ROSSI 15 sets limits on the sum of neutrino masses using BOSS Lyman alpha forest data combined with Planck CMB data and baryon acoustic oscillations.

[21] Constrains the total mass of neutrinos from Planck CMB data along with WMAP polarization, high L, and BAO data.

[22] Finite neutrino mass fit to resolve discrepancy between CMB and lensing measurements.

[23] Fit to the total mass of neutrinos from BOSS data along with WMAP CMB data and data from other BAO constraints and weak lensing.

[24] Fit to the total mass of neutrinos from Planck CMB data along with BAO.

[25] Fit based on the SPT-SZ survey combined with CMB, BAO, and H_0 data.

[26] Constraints the total mass of neutrinos (marginalizing over the effective number of neutrino species) from CMB, CMB lensing, BAO, and galaxy clustering data.

[27] Constrains the total mass of neutrinos from Planck CMB data combined with baryon acoustic oscillation data from BOSS, 6dFGS, SDSS, WiggleZ data on the galaxy power spectrum, and HST data on the Hubble parameter. The limit is increased to 0.25 eV if a lower bound to the sum of neutrino masses of 0.04 eV is assumed.

[28] Constrains the total mass of neutrinos from observational Hubble parameter data with seven-year WMAP data and the most recent estimate of H_0.

[29] Constrains the total mass of neutrinos from the CFHTLS combined with seven-year WMAP data and a prior on the Hubble parameter. Limit is relaxed to 0.41 eV when small scales affected by non-linearities are removed.

[30] Constrains the total mass of neutrinos from the Sloan Digital Sky Survey and the five-year WMAP data.

[31] Constrains the total mass of neutrinos from the 7-year WMAP data including SDSS and HST data. Limit relaxes to 1.19 eV when CMB data is used alone. Supersedes HANNESTAD 06.

[32] Constrains the total mass of neutrinos from a combination of CMB data, a recent measurement of H_0 (SHOES), and baryon acoustic oscillation data from SDSS.

[33] Constrains the total mass of neutrinos from SDSS MegaZ LRG DR7 galaxy clustering data combined with CMB, HST, supernovae and baryon acoustic oscillation data. Limit relaxes to 0.47 eV when the equation of state parameter, $w \neq 1$.

[34] Constrains the total mass of neutrinos from weak lensing measurements when combined with CMB. Limit improves to 0.54 eV when supernovae and baryon acoustic oscillation observations are included. Assumes ΛCDM model.

[35] Constrains the total mass of neutrinos from five-year WMAP data. Limit improves to 0.67 eV when supernovae and baryon acoustic oscillation observations are included. Limits quoted assume the ΛCDM model. Supersedes SPERGEL 07.

[36] Constrains the total mass of neutrinos from weak lensing measurements when combined with CMB. Limit improves to $0.03 < \Sigma m_{\nu} < 0.54$ eV when supernovae and baryon acoustic oscillation observations are included. The slight preference for massive neutrinos at the two-sigma level disappears when systematic errors are taken into account. Assumes ΛCDM model.

[37] Constrains the total mass of neutrinos from recent Chandra X-ray observations of galaxy clusters when combined with CMB, supernovae, and baryon acoustic oscillation measurements. Assumes flat universe and constant dark-energy equation of state, w.

[38] Constraints the total mass of neutrinos from recent CMB and SOSS LRG power spectrum data along with bias mass relations from SDSS, DEEP2, and Lyman-Break Galaxies. It assumes ΛCDM model. Limit degrades to 0.59 eV in a more general wCDM model.

[39] Constrains the total mass of neutrinos from neutrino oscillation experiments and cosmological data. The most conservative limit uses only WMAP three-year data, while the most stringent limit includes CMB, large-scale structure, supernova, and Lyman-alpha data.

[40] Constrains the total mass of neutrinos from recent CMB, large scale structure, SN1a, and baryon acoustic oscillation data. The limit relaxes to 1.75 when WMAP data alone is used with no prior. Paper shows results with several combinations of data sets. Supersedes KRISTIANSEN 06.

[41] Constrains the total mass of neutrinos from the CMB and the large scale structure data. The most conservative limit is obtained when generic initial conditions are allowed.

[42] Constrains the total mass of neutrinos from recent CMB, large scale structure, Lyman-alpha forest, and SN1a data.

[43] Constrains the total mass of neutrinos from recent CMB and large scale structure data. See also GOOBAR 06. Superseded by HANNESTAD 10.

[44] Constrains the total mass of neutrinos from the CMB and the final 2dF Galaxy Redshift Survey.

[45] Constrains the total mass of neutrinos from the CMB experiments alone, assuming ΛCDM Universe. FUKUGITA 06 show that this result is unchanged by the 3-year WMAP data.

[46] Constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the Sloan Digital Sky Survey and the 2dF galaxy redshift survey, WMAP and 27 other CMB experiments and measurements by the HST Key project.

[47] Constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the Sloan Digital Sky Survey, the 2dF galaxy redshift survey, WMAP and ACBAR. The limit is strengthened to 0.6 eV when measurements by the HST Key project and supernovae data are included.

[48] Constrains the fractional contribution of neutrinos to the total matter density in the Universe from WMAP data combined with other CMB measurements, the 2dfGRS data, and Lyman α data. The limit does not noticeably change if the Lyman α data are not used.

[49] LEWIS 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB, HST Key project, 2dF galaxy redshift survey, supernovae type Ia, and BBN.

[50] WANG 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB and other cosmological data sets such as galaxy clustering and the Lyman α forest.

[51] FUKUGITA 00 is a limit on neutrino masses from structure formation. The constraint is based on the clustering scale σ_8 and the COBE normalization and leads to a conservative limit of 0.9 eV assuming 3 nearly degenerate neutrinos. The quoted limit is on the sum of the light neutrino masses.

[52] CROFT 99 result based on the power spectrum of the Ly α forest. If $\Omega_{\text{matter}} < 0.5$, the limit is improved to $m_\nu < 2.4$ (Ω_{matter}/0.17–1) eV.

Limits on MASSES of Light Stable Right-Handed ν (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	[1] OLIVE	82	COSM	Dirac ν
<200–2000	[1] OLIVE	82	COSM	Majorana ν

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

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 10	[1] OLIVE	82	COSM	G_R/G_F <0.1
>100	[1] OLIVE	82	COSM	G_R/G_F <0.01

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

ν CHARGE

e = electron charge is the unit of values listed below.

VALUE (e)	CL%	DOCUMENT ID		TECN	COMMENT
<4 $\times 10^{-35}$	95	[1] CAPRINI	05	COSM	charge neutral universe
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.24 \times 10^{-13}$	90	[2] AALBERS	23A	LZ	Solar ν spectrum
$<1.5 \times 10^{-13}$	90	[3] ATZORI-COR...	23	FIT	solar neutrinos
$<3.3 \times 10^{-12}$	90	[4] BONET	22A	CONU	nuclear reactor
$<5.4 \times 10^{-12}$	90	[5] ABE	20E	XMAS	solar neutrinos
$1.7–2.3 \times 10^{-12}$	68	[6] KHAN	20		spectral fit of XENON1T
$<3 \times 10^{-8}$	95	[7] DELLA-VALLE	16	LASR	magnetic dichroism
$<2.1 \times 10^{-12}$	90	[8] CHEN	14A	TEXO	nuclear reactor
$<1.5 \times 10^{-12}$	90	[9] STUDENIKIN	14		nuclear reactor
$<3.7 \times 10^{-12}$	90	[10] GNINENKO	07	RVUE	nuclear reactor
$<2 \times 10^{-14}$		[11] RAFFELT	99	ASTR	red giant luminosity
$<6 \times 10^{-14}$		[12] RAFFELT	99	ASTR	solar cooling
$<4 \times 10^{-4}$		[13] BABU	94	RVUE	BEBC beam dump
$<3 \times 10^{-4}$		[14] DAVIDSON	91	RVUE	SLAC e^- beam dump
$<2 \times 10^{-15}$		[15] BARBIELLINI	87	ASTR	SN 1987A
$<1 \times 10^{-13}$		[16] BERNSTEIN	63	ASTR	solar energy losses

[1] CAPRINI 05 limit derived from the lack of a charge asymmetry in the universe. Limit assumes that charge asymmetries between particles are not anti-correlated.

[2] AALBERS 23A utilize the first 60 days of data collected by the LZ dark matter search to place a limit on the electric charge of solar neutrinos. Low energy electron-recoil events are utilized. This LZ-collaboration analysis supersedes that of the external authors in ATZORI-CORONA 23 because of a more complete treatment of experiment uncertainties.

[3] ATZORI-CORONA 23 use LUX-ZEPLIN dark matter search data published by AALBERS 23 to place a limit on neutrino millicharge.

[4] BONET 22A use data collected by four low-threshold Ge detectors, placed 17.1 m from one of the cores of the nuclear reactors at Brokdorf to derive this limit. A spectral analysis is performed on reactor on and off data.

[5] ABE 20E obtains this result by assuming that the low-energy excess events in the XMASS detector are produced by neutrino millicharge which is common for all three neutrino flavors.

[6] KHAN 20 performed a constrained spectral fit analysis of the excess observed in the electron recoil energy spectrum by the XENON1T experiment. This range of neutrino

millicharge values is one of the possible interpretations of these excess events. For the individual flavor constraints at 90% C.L. see the original reference.

[7] DELLA-VALLE 16 obtain a limit on the charge of neutrinos valid for masses of less than 10 meV. For heavier neutrinos the limit increases as a power of mass, reaching 10^{-6} e for $m = 100$ meV.

[8] CHEN 14A use the Multi-Configuration RRPA method to analyze reactor $\overline{\nu}_e$ scattering on Ge atoms with 300 eV recoil energy threshold to obtain this limit.

[9] STUDENIKIN 14 uses the limit on μ_ν from BEDA 13 and the 2.8 keV threshold of the electron recoil energy to obtain this limit.

[10] GNINENKO 07 use limit on $\overline{\nu}_e$ magnetic moment from LI 03B to derive this result. The limit is considerably weaker than the limits on the charge of ν_e and $\overline{\nu}_e$ from various astrophysics considerations.

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

[12] 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.

[13] BABU 94 use COOPER-SARKAR 92 limit on ν magnetic moment to derive quoted result. It applies to ν_τ.

[14] DAVIDSON 91 use data from early SLAC electron beam dump experiment to derive charge limit as a function of neutrino mass. It applies to ν_τ.

[15] Exact BARBIELLINI 87 limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field. It applies to ν_e.

[16] The limit applies to all flavors.

ν (MEAN LIFE) / MASS

Measures $\left[\sum |U_{\ell j}|^2 \; \Gamma_j \; m_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. Some of the limits constrain the radiative decay and are based on the limit of the corresponding photon flux. Other apply to the decay of a heavier neutrino into the lighter one and a Majoron or other invisible particle. Many of these limits apply to any ν within the indicated mass range.

Limits on the radiative decay are either directly based on the limits of the corresponding photon flux, or are derived from the limits on the neutrino magnetic moments. In the later case the transition rate for $\nu_i \to \nu_j + \gamma$ is constrained by $\Gamma_{ij} = \frac{1}{\tau_{ij}} = \frac{(m_i^2 - m_j^2)^3}{m_i^3} \mu_{ij}^2$ where μ_{ij} is the neutrino transition moment in the mass eigenstates basis. Typically, the limits on lifetime based on the magnetic moments are many orders of magnitude more restrictive than limits based on the nonobservation of photons.

VALUE (s/eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 15.4	90	[1] KRAKAUER	91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
> 7 × 10^{9}		[2] RAFFELT	85	ASTR	
> 300	90	[3] REINES	74	CNTR	$\overline{\nu}_e$

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

$>$ 1.2 $\times 10^{5}$	90	[4] IVANEZ-BAL...	23	ASTR	SN1987A, nonradiative decay
$>$ 8.08 $\times 10^{-5}$	90	[5] AHARMIM	19	SNO	ν_2 invisible nonradiative decay
$>$ 1.92 $\times 10^{-3}$	90	[6] AHARMIM	19	FIT	ν_2 invisible nonradiative decay
6–26 $\times 10^{9}$	95	[7] ESCUDERO	19	COSM	Invisible decay $m_\nu \geq$ 0.05 eV
$> 10^5 - 10^{10}$	95	[8] CECCHINI	11	ASTR	$\nu_2 \rightarrow \nu_1$ radiative decay
		[9] MIRIZZI	07	CMB	radiative decay
		[10] MIRIZZI	07	CIB	radiative decay
		[11] WONG	07	CNTR	Reactor $\overline{\nu}_e$
$>$ 0.11	90	[12] XIN	05	CNTR	Reactor ν_e
		[13] XIN	05	CNTR	Reactor ν_e
$>$ 0.004	90	[14] AHARMIM	04	SNO	quasidegen. ν masses
$>$ 4.4 $\times 10^{-5}$	90	[14] AHARMIM	04	SNO	hierarchical ν masses
$\gtrsim$ 100	95	[15] CECCHINI	04	ASTR	Radiative decay for ν mass $>$ 0.01 eV
$>$ 0.067	90	[16] EGUCHI	04	KLND	quasidegen. ν masses
$>$ 1.1 $\times 10^{-3}$	90	[16] EGUCHI	04	KLND	hierarchical ν masses
$>$ 8.7 $\times 10^{-5}$	99	[17] BANDYOPA...	03	FIT	nonradiative decay
$\geq$ 4200	90	[18] DERBIN	02B	CNTR	Solar pp and Be ν
$>$ 2.8 $\times 10^{-5}$	99	[19] JOSHIPURA	02B	FIT	nonradiative decay
		[20] DOLGOV	99	COSM	
		[21] BILLER	98	ASTR	m_ν= 0.05–1 eV
$>$ 2.8 $\times 10^{15}$		[22,23] BLUDMAN	92	ASTR	$m_\nu <$ 50 eV
none 10^{-12} – 5×10^4		[24] DODELSON	92	ASTR	m_ν=1–300 keV
$<$ 10^{-12} or $>$ 5×10^4		[24] DODELSON	92	ASTR	m_ν=1–300 keV
		[25] GRANEK	91	COSM	Decaying L^0
$>$ 6.4	90	[26] KRAKAUER	91	CNTR	ν_e at LAMPF
$>$ 1.1 $\times 10^{15}$		[27] WALKER	90	ASTR	m_ν= 0.03 – $\sim$ 2 MeV
$>$ 6.3 $\times 10^{15}$		[23,28] CHUPP	89	ASTR	$m_\nu <$ 20 eV
$>$ 1.7 $\times 10^{15}$		[23] KOLB	89	ASTR	$m_\nu <$ 20 eV
		[29] RAFFELT	89	RVUE	$\overline{\nu}$ (Dirac, Majorana)
		[30] RAFFELT	89B	ASTR	
$>$ 8.3 $\times 10^{14}$		[31] VONFEILIT...	88	ASTR	
$>$ 22	68	[32] OBERAUER	87		$\overline{\nu}_R$ (Dirac)
$>$ 38	68	[32] OBERAUER	87		$\overline{\nu}$ (Majorana)
$>$ 59	68	[32] OBERAUER	87		$\overline{\nu}_L$ (Dirac)
$>$ 30	68	KETOV	86	CNTR	$\overline{\nu}$ (Dirac)
$>$ 20	68	KETOV	86	CNTR	$\overline{\nu}$ (Majorana)
		[33] BINETRUY	84	COSM	$m_\nu \sim$ 1 MeV
$>$ 0.11	90	[34] FRANK	81	CNTR	$\nu\overline{\nu}$ LAMPF
$>$ 2 $\times 10^{21}$		[35] STECKER	80	ASTR	m_ν= 10–100 eV
$>$ 1.0 $\times 10^{-2}$	90	[34] BLIETSCHAU	78	HLBC	ν_μ, CERN GGM
$>$ 1.7 $\times 10^{-2}$	90	[34] BLIETSCHAU	78	HLBC	$\overline{\nu}_\mu$, CERN GGM
$<$ 3 $\times 10^{-11}$		[36] FALK	78	ASTR	m_ν <10 MeV
$>$ 2.2 $\times 10^{-3}$	90	[34] BARNES	77	DBC	ν, ANL 12-ft
		[37] COWSIK	77	ASTR	

>	$3. \times 10^{-3}$	90	[34] BELLOTTI	76	HLBC	ν, CERN GGM
>	1.3×10^{-2}	90	[34] BELLOTTI	76	HLBC	$\overline{\nu}$, CERN GGM

[1] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.75a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ The parameter $a = 0$ 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 $a = -1$).

[2] RAFFELT 85 limit on the radiative decay 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.

[3] REINES 74 looked for ν of nonzero mass decaying radiatively to a neutral of lesser mass $+ \gamma$. 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 $\overline{\nu}_e$ 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.

[4] IVANEZ-BALLESTEROS 23 reports a limit on the lifetime-to-mass ratio of the mass eigenstates ν_1 and ν_2 for inverted mass ordering. No limit was obtained in the case of normal mass ordering.

[5] AHARMIM 19 quotes the limit τ/m_{ν_2} for invisible nonradiative decay of ν_2. They obtained this result by analyzing the entire SNO dataset, allowing for the decay of ν_2 which would cause an energy-dependent distortion of the survival probability of electron-type solar neutrinos.

[6] AHARMIM 19 quotes the limit τ/m_{ν_2} for invisible nonradiative decay of ν_2. They obtained this result by combining the τ/m_{ν_2} measurements from SNO and other solar neutrino experiments (Super-Kamiokande, KamLAND, and Borexino ^{8}B results; Borexino and KamLAND ^{7}Be results; the combined gallium interaction rate from GNO, GALLEX, and SAGE; and the chlorine interaction rate from Homestake). The quoted limit at 99% CL is $> 1.04 \times 10^{-3}$.

[7] ESCUDERO 19 sets limits on invisible neutrino decays using Planck 2018 data of $\tau > 1.3$–0.3×10^9 s at 95% C.L. Values in the range $\tau = 2$–16×10^9 s are preferred at 95% C.L. when Planck polarization data is included. Limits scale as $(m_\nu/0.05\ \text{eV})^3$.

[8] CECCHINI 11 search for radiative decays of solar neutrinos into visible photons during the 2006 total solar eclipse. The range of (mean life)/mass values corresponds to a range of ν_1 masses between 10^{-4} and 0.1 eV.

[9] MIRIZZI 07 determine a limit on the neutrino radiative decay from analysis of the maximum allowed distortion of the CMB spectrum as measured by the COBE/FIRAS. For the decay $\nu_2 \rightarrow \nu_1$ the lifetime limit is $\lesssim 4 \times 10^{20}$ s for $m_{min} \lesssim 0.14$ eV. For transition with the $|\Delta m_{31}|$ mass difference the lifetime limit is $\sim 2 \times 10^{19}$ s for $m_{min} \lesssim 0.14$ eV and $\sim 5 \times 10^{20}$ s for $m_{min} \gtrsim 0.14$ eV.

[10] MIRIZZI 07 determine a limit on the neutrino radiative decay from analysis of the cosmic infrared background (CIB) using the Spitzer Observatory data. For transition with the $|\Delta m_{31}|$ mass difference they obtain the lifetime limit $\sim 10^{20}$ s for $m_{min} \lesssim 0.14$ eV.

[11] WONG 07 use their limit on the neutrino magnetic moment together with the assumed experimental value of $\Delta m^2_{13} \sim 2 \times 10^{-3}$ eV^2 to obtain $\tau_{13}/m_1^3 > 3.2 \times 10^{27}$ s/eV^3 for the radiative decay in the case of the inverted mass hierarchy. Similarly to RAFFELT 89 this limit can be violated if electric and magnetic moments are equal to each other. Analogous, but numerically somewhat different limits are obtained for τ_{23} and τ_{21}.

[12] XIN 05 search for the γ from radiative decay of ν_e produced by the electron capture on ^{51}Cr. No events were seen and the limit on τ/m_ν was derived. This is a weaker limit on the decay of ν_e than KRAKAUER 91.

[13] XIN 05 use their limit on the neutrino magnetic moment of ν_e together with the assumed experimental value of $\Delta m^2_{1,3} \sim 2\times10^{-3}$ eV^2 to obtain $\tau_{13}/m_1^3 > 1\times10^{23}$ s/eV^3 for the radiative decay in the case of the inverted mass hierarchy. Similarly to RAFFELT 89 this limit can be violated if electric and magnetic moments are equal to each other. Analogous, but numerically somewhat different limits are obtained for τ_{23} and τ_{21}. Again, this limit is specific for ν_e.

[14] 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 $\nu_2 \rightarrow \overline{\nu}_1 X$, where X is a Majoron or other invisible particle. Limits are given for the cases of quasidegenerate and hierarchical neutrino masses.

[15] CECCHINI 04 obtained this bound through the observations performed on 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 $\nu_2 \rightarrow \nu_1\gamma$. Limit ranges from $\sim$ 100 to 10^7 s/eV for $0.01 < m_{\nu_1} < 0.1$ eV.

[16] 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 $\nu_2 \rightarrow \overline{\nu}_1 X$, where X is a Majoron or other invisible particle. Limits are given for the cases of quasidegenerate and hierarchical neutrino masses.

[17] 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.

[18] DERBIN 02B (also BACK 03B) obtained this bound for the radiative decay 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 $\alpha=0$ for a Majorana neutrino, and α varying to -1 to 1 for a Dirac neutrino. The listed bound is for the case of $\alpha=0$. The most conservative bound 1.5×10^3 s eV^{-1} is obtained for the case of $\alpha=-1$.

[19] 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.

[20] DOLGOV 99 places limits in the (Majorana) τ-associated ν mass-lifetime plane based on nucleosynthesis. Results would be considerably modified if neutrino oscillations exist.

[21] 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 $\tau_\nu/\mathrm{B}_\gamma > 0.15\times10^{21}$ s at 0.05 eV, $> 1.2\times10^{21}$ s at 0.17 eV, $> 3\times10^{21}$ s at 1 eV, where B_γ is the branching ratio to photons.

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

[23] Limit on the radiative decay based on nonobservation of γ's in coincidence with ν's from SN 1987A.

[24] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.

[25] GRANEK 91 considers heavy neutrino decays to $\gamma\nu_L$ and $3\nu_L$, where m_{ν_L} <100 keV. Lifetime is calculated as a function of heavy neutrino mass, branching ratio into $\gamma\nu_L$, and m_{ν_L}.

[26] KRAKAUER 91 quotes the limit for ν_e, $\tau/m_\nu > (0.3a^2 + 9.8a + 15.9)$ s/eV, where a is a parameter describing the asymmetry in the radiative 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 $a = -1$).

[27] WALKER 90 uses SN 1987A γ flux limits after 289 days.

[28] 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.

[29] 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 for the radiative decay 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] Model-dependent theoretical analysis of SN 1987A neutrinos. Quoted limit is for $\left[\sum_j |U_{\ell j}|^2\, \Gamma_j\, m_j\right]^{-1}$, where $\ell=\mu$, τ. Limit is 3.3×10^{14} s/eV for $\ell=e$.

[32] OBERAUER 87 looks for photons and e^+e^- pairs from radiative decays of reactor neutrinos.

[33] BINETRUY 84 finds $\tau < 10^8$ s for neutrinos in a radiation-dominated universe.

[34] These experiments look for $\nu_k \to \nu_j\gamma$ or $\overline{\nu}_k \to \overline{\nu}_j\gamma$.

[35] STECKER 80 limit based on UV background; result given is $\tau > 4\times10^{22}$ s at m_ν=20 eV.

[36] FALK 78 finds lifetime constraints based on supernova energetics.

[37] COWSIK 77 considers variety of scenarios. For neutrinos produced in the big bang, present limits on optical photon flux require $\tau > 10^{23}$ s for $m_\nu \sim 1$ eV. See also COWSIK 79 and GOLDMAN 79.

ν MAGNETIC MOMENT

The coupling of neutrinos to an electromagnetic field is a characterized by a 3×3 matrix λ of the magnetic (μ) and electric (d) dipole moments ($\lambda = \mu$ - id). For Majorana neutrinos the matrix λ is antisymmetric and only transition moments are allowed, while for Dirac neutrinos λ is a general 3×3 matrix. In the standard electroweak theory extended to include neutrino masses (see FUJIKAWA 80) $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = 3.2 \times 10^{-19}(m_\nu/\text{eV})\mu_B$, i.e. it is unobservably small given the known small neutrino masses. In more general models there is no longer a proportionality between neutrino mass and its magnetic moment, even though only massive neutrinos have nonvanishing magnetic moments without fine tuning.

Laboratory bounds on λ are obtained via elastic ν-e scattering, where the scattered neutrino is not observed. The combinations of matrix elements of λ that are constrained by various experiments depend on the initial neutrino flavor and on its propagation between source and detector (e.g., solar ν_e and reactor $\overline{\nu}_e$ do not constrain the same combinations). The listings below therefore identify the initial neutrino flavor.

Other limits, e.g. from various stellar cooling processes, apply to all neutrino flavors. Analogous flavor independent, but weaker, limits are obtained from the analysis of $e^+ e^- \to \nu\overline{\nu}\gamma$ collider experiments.

VALUE (10^{-10} μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.064	90	[1] APRILE	22B	XENT	Solar ν spectrum
< 0.29	90	[2] BEDA	13	CNTR	Reactor $\overline{\nu}_e$
< 6.8	90	[3] AUERBACH	01	LSND	$\nu_e e$, $\nu_\mu e$ scattering
< 3900	90	[4] SCHWIENHO...	01	DONU	$\nu_\tau e^- \to \nu_\tau e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.136	90	[5] AALBERS	23A	LZ	Solar ν spectrum
< 0.11	90	[6] ATZORI-COR...	23	FIT	Solar ν spectrum
< 0.75	90	[7] BONET	22A	CONU	Reactor $\overline{\nu}_e$
< 2.8	90	[8] COLOMA	22	CNTR	Reactor $\overline{\nu}_e$
< 1.8	90	[9] ABE	20E	XMAS	Solar ν spectrum
0.14–0.29	90	[10] APRILE	20	XE1T	Solar ν spectrum
< 0.012	95	[11] CAPOZZI	20	ASTR	Tip of the Red-Giant Branch
0.2–0.4	68	[12] KHAN	20		Spectral fit of XENON1T
< 0.28	90	[13] AGOSTINI	17A	BORX	Solar ν spectrum
< 0.022	90	[14] ARCEO-DIAZ	15	ASTR	Red giants
< 0.1	95	[15] CORSICO	14	ASTR	
< 0.05	95	[16] MILLER-BER...	14B	ASTR	
< 0.045	95	[17] VIAUX	13A	ASTR	Globular cluster M5
< 0.32	90	[18] BEDA	10	CNTR	Reactor $\overline{\nu}_e$
< 2.2	90	[19] DENIZ	10	TEXO	Reactor $\overline{\nu}_e$
< 0.011–0.027		[20] KUZNETSOV	09	ASTR	$\nu_L \to \nu_R$ in SN1987A
< 0.54	90	[21] ARPESELLA	08A	BORX	Solar ν spectrum
< 0.58	90	[22] BEDA	07	CNTR	Reactor $\overline{\nu}_e$
< 0.74	90	[23] WONG	07	CNTR	Reactor $\overline{\nu}_e$
< 0.9	90	[24] DARAKTCH...	05		Reactor $\overline{\nu}_e$
< 130	90	[25] XIN	05	CNTR	Reactor ν_e
< 37	95	[26] GRIFOLS	04	FIT	Solar ^{8}B ν (SNO NC)
< 3.6	90	[27] LIU	04	SKAM	Solar ν spectrum
< 1.1	90	[28] LIU	04	SKAM	Solar ν spectrum (LMA region)
< 5.5	90	[29] BACK	03B	CNTR	Solar pp and Be ν
< 1.0	90	[30] DARAKTCH...	03		Reactor $\overline{\nu}_e$
< 1.3	90	[31] LI	03B	CNTR	Reactor $\overline{\nu}_e$
< 2	90	[32] GRIMUS	02	FIT	solar + reactor (Majorana ν)
<80000	90	[33] TANIMOTO	00	RVUE	$e^+ e^- \to \nu\overline{\nu}\gamma$
< 0.01–0.04		[34] AYALA	99	ASTR	$\nu_L \to \nu_R$ in SN 1987A
< 1.5	90	[35] BEACOM	99	SKAM	Solar ν spectrum
< 0.03		[36] RAFFELT	99	ASTR	Red giant luminosity
< 4		[37] RAFFELT	99	ASTR	Solar cooling
<44000	90	ABREU	97J	DLPH	$e^+ e^- \to \nu\overline{\nu}\gamma$ at LEP
<33000	90	[38] ACCIARRI	97Q	L3	$e^+ e^- \to \nu\overline{\nu}\gamma$ at LEP

$<$ 0.62		[39] ELMFORS	97	COSM	Depolarization in early universe plasma
$<$27000	95	[40] ESCRIBANO	97	RVUE	$\Gamma(Z \rightarrow \nu\nu)$ at LEP
$<$ 30	90	VILAIN	95B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$
$<$55000	90	GOULD	94	RVUE	$e^+ e^- \rightarrow \nu\overline{\nu}\gamma$ at LEP
$<$ 1.9	95	[41] DERBIN	93	CNTR	Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$
$<$ 5400	90	[42] COOPER-...	92	BEBC	$\nu_\tau e^- \rightarrow \nu_\tau e^-$
$<$ 2.4	90	[43] VIDYAKIN	92	CNTR	Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$
$<$56000	90	DESHPANDE	91	RVUE	$e^+ e^- \rightarrow \nu\overline{\nu}\gamma$
$<$ 100	95	[44] DORENBOS...	91	CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
$<$ 8.5	90	AHRENS	90	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
$<$ 10.8	90	[45] KRAKAUER	90	CNTR	LAMPF $\nu e \rightarrow \nu e$
$<$ 7.4	90	[45] KRAKAUER	90	CNTR	LAMPF $(\nu_\mu, \overline{\nu}_\mu) e$ elast.
$<$ 0.02		[46] RAFFELT	90	ASTR	Red giant luminosity
$<$ 0.1		[47] RAFFELT	89B	ASTR	Cooling helium stars
		[48] FUKUGITA	88	COSM	Primordial magn. fields
$<$40000	90	[49] GROTCH	88	RVUE	$e^+ e^- \rightarrow \nu\overline{\nu}\gamma$
$\leq$ .3		[47] RAFFELT	88B	ASTR	He burning stars
$<$ 0.11		[47] FUKUGITA	87	ASTR	Cooling helium stars
$<$ 0.0006		[50] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<$ 0.1–0.2		MORGAN	81	COSM	^{4}He abundance
$<$ 0.85		BEG	78	ASTR	Stellar plasmons
$<$ 0.6		[51] SUTHERLAND	76	ASTR	Red giants + degenerate dwarfs
$<$ 81		[52] KIM	74	RVUE	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
$<$ 1		BERNSTEIN	63	ASTR	Solar cooling
$<$ 14		COWAN	57	CNTR	Reactor $\overline{\nu}$

[1] APRILE 22B use data collected with the XENONnT dark matter detector to place a limit on an enhanced magnetic moment of solar neutrinos. Supersedes APRILE 20.

[2] BEDA 13 report $\overline{\nu}_e e^-$ scattering results, using the Kalinin Nuclear Power Plant and a shielded Ge detector. The recoil electron spectrum is analyzed between 2.5 and 55 keV. Supersedes BEDA 07. Supersedes BEDA 10. This is the most stringent limit on the magnetic moment of reactor $\overline{\nu}_e$.

[3] AUERBACH 01 limit is based on the LSND ν_e and ν_μ electron scattering measurements. The limit is slightly more stringent than KRAKAUER 90.

[4] SCHWIENHORST 01 quote an experimental sensitivity of 4.9×10^{-7}.

[5] AALBERS 23A utilize the first 60 days of data collected by the LZ dark matter search to place a limit on the magnetic moment of solar neutrinos. Low energy electron-recoil events are utilized. This LZ-collaboration analysis supersedes that of the external authors in ATZORI-CORONA 23 because of a more complete treatment of experiment uncertainties.

[6] ATZORI-CORONA 23 use LUX-ZEPLIN dark matter search data published by AALBERS 23 to place a limit on an enhanced magnetic moment of solar neutrinos.

[7] BONET 22A use data collected by four low-threshold Ge detectors, placed 17.1 m from one of the cores of the nuclear reactors at Brokdorf to derive this limit. A spectral analysis is performed on reactor on and off data.

[8] COLOMA 22 present a re-analysis of data taken by the COHERENT and Dresden-II experiments. The combination of both experiments is used to place a limit on the magnetic moment of electron-type neutrinos. The presented value is one-sided limit as recommended by the authors; the two-sided limit is $< 3.2 \times 10^{-10} \mu_B$ at 90% C.L. Results based on Fef and YBe quenching models are reported in the paper. The authors are not part of either collaboration.

[9] ABE 20E observed an excess of low-energy events in the XMASS detector, which could be interpreted as a signal produced by a neutrino magnetic moment with this magnitude.

[10] APRILE 20 observed an excess of low-energy events in the XENON1T detector, which could be interpreted as a signal produced by a neutrino magnetic moment with this magnitude.

[11] CAPOZZI 20 obtains a limit on the neutrino dipole moment from the brightness of the tip of the red-giant branch in ω Centauri. A similar limit of $\mu_\nu < 1.5 \times 10^{-12} \mu_B$ is obtained in NGC 4258.

[12] KHAN 20 performed a constrained spectral fit analysis of the excess observed in the electron recoil energy spectrum by the XENON1T experiment. This range of the μ_B values is one of the possible interpretations of these excess events. For the individual flavor constraints at 90% C.L. see the original reference.

[13] AGOSTINI 17A obtained this limit using the shape of the recoil electron energy spectrum from the Borexino Phase-II 1291.5 live days of solar neutrino data and the constraints on the sum of the solar neutrino fluxes from the radiochemical gallium experiments SAGE, Gallex, and GNO. Without radiochemical constraints, the 90% C.L. limit of $<$ $4.0 \times 10^{-11} \mu_B$ is obtained.

[14] ARCEO-DIAZ 15 constrains the neutrino magnetic moment from observation of the tip of the red giant branch in the globular cluster ω-Centauri.

[15] CORSICO 14 constrains the neutrino magnetic moment from observations of white drarf pulsations.

[16] MILLER-BERTOLAMI 14B constrains the neutrino magnetic moment from observations of the white dwarf luminosity function of the Galactic disk.

[17] VIAUX 13A constrains the neutrino magnetic moment from observations of the globular cluster M5.

[18] BEDA 10 report $\overline{\nu}_e e^-$ scattering results, using the Kalinin Nuclear Power Plant and a shielded Ge detector. The recoil electron spectrum is analyzed between 2.9 and 45 keV. Supersedes BEDA 07. Superseded by BEDA 13.

[19] DENIZ 10 observe reactor $\overline{\nu}_e e$ scattering with recoil kinetic energies 3–8 MeV using CsI(Tl) detectors. The observed rate and spectral shape are consistent with the Standard Model prediction, leading to the reported constraint on $\overline{\nu}_e$ magnetic moment.

[20] KUZNETSOV 09 obtain a limit on the flavor averaged magnetic moment of Dirac neutrinos from the time averaged neutrino signal of SN1987A. Improves and supersedes the analysis of BARBIERI 88 and AYALA 99.

[21] ARPESELLA 08A obtained this limit using the shape of the recoil electron energy spectrum from the Borexino 192 live days of solar neutrino data.

[22] BEDA 07 performed search for electromagnetic $\overline{\nu}_e$-e scattering at Kalininskaya nuclear reactor. A Ge detector with active and passive shield was used and the electron recoil spectrum between 3.0 and 61.3 keV analyzed. Superseded by BEDA 10.

[23] WONG 07 performed search for non-standard $\overline{\nu}_e$-e scattering at the Kuo-Sheng nuclear reactor. Ge detector equipped with active anti-Compton shield is used. Most stringent laboratory limit on magnetic moment of reactor $\overline{\nu}_e$. Supersedes LI 03B.

[24] DARAKTCHIEVA 05 present the final analysis of the search for non-standard $\overline{\nu}_e$-e scattering component at Bugey nuclear reactor. Full kinematical event reconstruction of both the kinetic energy above 700 keV and scattering angle of the recoil electron, by

use of TPC. Most stringent laboratory limit on magnetic moment. Supersedes DARAKTCHIEVA 03.

[25] XIN 05 evaluated the ν_e flux at the Kuo-Sheng nuclear reactor and searched for non-standard ν_e-e scattering. Ge detector equipped with active anti-Compton shield was used. This laboratory limit on magnetic moment is considerably less stringent than the limits for reactor $\overline{\nu}_e$, but is specific to ν_e.

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

[27] 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.

[28] 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.

[29] 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).

[30] DARAKTCHIEVA 03 searched for non-standard $\overline{\nu}_e$-e scattering component at Bugey nuclear reactor. Full kinematical event reconstruction by use of TPC. Superseded by DARAKTCHIEVA 05.

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

[32] 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.

[33] TANIMOTO 00 combined $e^+ e^- \rightarrow \nu \overline{\nu} \gamma$ data from VENUS, TOPAZ, and AMY.

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

[35] 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.

[36] 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.

[37] 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.

[38] ACCIARRI 97Q result applies to both direct and transition magnetic moments and for q^2=0.

[39] 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.

[40] Applies to absolute value of magnetic moment.

[41] 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 $\sim 1/100$.

[42] COOPER-SARKAR 92 assume $f_{D_s}/f_\pi = 2$ and D_s, $\overline{D}_s$ production cross section $=$ 2.6 μb to calculate ν flux.

[43] 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.

[44] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the ν magnetic moment is $< 1 \times 10^{-9}$ at the 95%CL. DORENBOSCH 89 measures both $\nu_\mu e$ and $\overline{\nu} e$ elastic scattering and assume $\mu(\nu) = \mu(\overline{\nu})$.

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

[46] 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.

[47] Significant dependence on details of stellar models.

[48] 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.

[49] GROTCH 88 combined data from MAC, ASP, CELLO, and Mark J.

[50] For m_ν = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m_\nu > 16$ eV and $< 6 \times 10^{-14}$ for $m_\nu > 4$ eV.

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

[52] KIM 74 is a theoretical analysis of $\overline{\nu}_\mu$ reaction data.

NEUTRINO CHARGE RADIUS SQUARED

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*
− 2.1 to 3.3	90	[1] DENIZ	10	TEXO	Reactor $\overline{\nu}_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−27.5 to 3	90	[2] CADEDDU	18		ν_μ coherent scat. on CsI
− 0.53 to 0.68	90	[3] HIRSCH	03		$\nu_\mu e$ scat.
− 8.2 to 9.9	90	[4] HIRSCH	03		anomalous $e^+ e^- \rightarrow \nu\overline{\nu}\gamma$
− 2.97 to 4.14	90	[5] AUERBACH	01	LSND	$\nu_e e \rightarrow \nu_e e$
− 0.6 to 0.6	90	VILAIN	95B	CHM2	$\nu_\mu e$ elastic scat.
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	[6] VIDYAKIN	92	CNTR	Reactor $\overline{\nu} e \rightarrow \overline{\nu} e$

1.1 $\pm$2.3	ALLEN	91	CNTR	Repl. by ALLEN 93
$-$ 1.1 $\pm$1.0	[7] AHRENS	90	CNTR	$\nu_\mu e$ elastic scat.
$-$ 0.3 $\pm$1.5	[7] DORENBOS...	89	CHRM	$\nu_\mu e$ elastic scat.
	[8] GRIFOLS	89B	ASTR	SN 1987A

[1] DENIZ 10 observe reactor $\overline{\nu}_e e$ scattering with recoil kinetic energies 3–8 MeV using CsI(Tl) detectors. The observed rate and spectral shape are consistent with the Standard Model prediction, leading to the reported constraint on $\overline{\nu}_e$ charge radius.

[2] CADEDDU 18 use the data of the COHERENT experiment, AKIMOV 18. The limit is $\langle r^2_\nu \rangle$ for ν_μ obtained from the time-dependent data. Weaker limits were obtained for charge radii of ν_e and for transition charge radii. The published value was divided by 2 to conform to the convention of this table.

[3] Based on analysis of CCFR 98 results. Limit is on $\langle r^2_V \rangle + \langle r^2_A \rangle$. The CHARM II and E734 at BNL results are reanalyzed, and weaker bounds on the charge radius squared than previously published are obtained. The NuTeV result is discussed; when tentatively interpreted as ν_μ charge radius it implies $\langle r^2_V \rangle + \langle r^2_A \rangle = (4.20 \pm 1.64) \times 10^{-33}$ cm^2.

[4] Results of LEP-2 are interpreted as limits on the axial-vector charge radius squared of a Majorana ν_τ. Slightly weaker limits for both vector and axial-vector charge radius squared are obtained for the Dirac case, and somewhat weaker limits are obtained from the analysis of lower energy data (LEP-1.5 and TRISTAN).

[5] 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.

[6] 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.

[7] Result is obtained from reanalysis given in ALLEN 91, followed by our reduction to obtain $1\,\sigma$ errors.

[8] 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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LAM	91	PR D44 3345	W.P. Lam, K.W. Ng	(AST)
ROBERTSON	91	PRL 67 957	R.G.H. Robertson *et al.*	(LASL, LLL)
AHRENS	90	PR D41 3297	L.A. Ahrens *et al.*	(BNL, BROW, HIRO+)
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)
WALKER	90	PR D41 689	T.P. Walker	(HARV)
CHUPP	89	PRL 62 505	E.L. Chupp, W.T. Vestrand, C. Reppin	(UNH, MPIM)
DORENBOS...	89	ZPHY C41 567	J. Dorenbosch *et al.*	(CHARM Collab.)
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)
ALBRECHT	88B	PL B202 149	H. Albrecht *et al.*	(ARGUS Collab.)
BARBIERI	88	PRL 61 27	R. Barbieri, R.N. Mohapatra	(PISA, UMD)
BORIS	88	PRL 61 245 (errat.)	S.D. Boris *et al.*	(ITEP, ASCI)
FUKUGITA	88	PRL 60 879	M. Fukugita *et al.*	(KYOTU, MPIM, UCB)
GROTCH	88	ZPHY C39 553	H. Grotch, R.W. Robinett	(PSU)
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)
VONFEILIT...	88	PL B200 580	F. von Feilitzsch, L. Oberauer	(TUM)
BARBIELLINI	87	NAT 329 21	G. Barbiellini, G. Cocconi	(CERN)
BORIS	87	PRL 58 2019	S.D. Boris *et al.*	(ITEP, ASCI)
Also		PRL 61 245 (errat.)	S.D. Boris *et al.*	(ITEP, ASCI)
BORIS	87B	JETPL 45 333	S.D. Boris *et al.*	(ITEP)
		Translated from ZETFP 45 267.		
FUKUGITA	87	PR D36 3817	M. Fukugita, S. Yazaki	(KYOTU, TOKY)
NUSSINOV	87	PR D36 2278	S. Nussinov, Y. Rephaeli	(TELA)
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	S.N. Ketov *et al.*	(KIAE)
		Translated from ZETFP 44 114.		
COWSIK	85	PL 151B 62	R. Cowsik	(TATA)
RAFFELT	85	PR D31 3002	G.G. Raffelt	(MPIM)
BINETRUY	84	PL 134B 174	P. Binetruy, G. Girardi, P. Salati	(LAPP)
FREESE	84	NP B233 167	K. Freese, D.N. Schramm	(CHIC, FNAL)
KYULDJIEV	84	NP B243 387	A.V. Kyuldjiev	(SOFI)
SCHRAMM	84	PL 141B 337	D.N. Schramm, G. Steigman	(FNAL, BART)
VOGEL	84	PR D30 1505	P. Vogel	
ANDERHUB	82	PL 114B 76	H.B. Anderhub *et al.*	(ETH, SIN)
OLIVE	82	PR D25 213	K.A. Olive, M.S. Turner	(CHIC, UCSB)
BERNSTEIN	81	PL 101B 39	J. Bernstein, G. Feinberg	(STEV, COLU)
FRANK	81	PR D24 2001	J.S. Frank *et al.*	(LASL, YALE, MIT+)
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)
STECKER	80	PRL 45 1460	F.W. Stecker	(NASA)
COWSIK	79	PR D19 2219	R. Cowsik	(TATA)
GOLDMAN	79	PR D19 2215	T. Goldman, G.J. Stephenson	(LASL)
BEG	78	PR D17 1395	M.A.B. Beg, W.J. Marciano, M. Ruderman	(ROCK+)
BLIETSCHAU	78	NP B133 205	J. Blietschau *et al.*	(Gargamelle Collab.)
FALK	78	PL 79B 511	S.W. Falk, D.N. Schramm	(CHIC)
BARNES	77	PRL 38 1049	V.E. Barnes *et al.*	(PURD, ANL)
COWSIK	77	PRL 39 784	R. Cowsik	(MPIM, TATA)
LEE	77C	PR D16 1444	B.W. Lee, R.E. Shrock	(STON)
VYSOTSKY	77	JETPL 26 188	M.I. Vysotsky, A.D. Dolgov, Y.B. Zeldovich	(ITEP)
		Translated from ZETFP 26 200.		
BELLOTTI	76	LNC 17 553	E. Bellotti *et al.*	(MILA)
SUTHERLAND	76	PR D13 2700	P. Sutherland *et al.*	(PENN, COLU, NYU)
SZALAY	76	AA 49 437	A.S. Szalay, G. Marx	(EOTV)
CLARK	74	PR D9 533	A.R. Clark *et al.*	(LBL)
KIM	74	PR D9 3050	J.E. Kim, V.S. Mathur, S. Okubo	(ROCH)
REINES	74	PRL 32 180	F. Reines, H.W. Sobel, H.S. Gurr	(UCI)
SZALAY	74	APAH 35 8	A.S. Szalay, G. Marx	(EOTV)
COWSIK	72	PRL 29 669	R. Cowsik, J. McClelland	(UCB)
MARX	72	Nu Conf. Budapest	G. Marx, A.S. Szalay	(EOTV)
GERSHTEIN	66	JETPL 4 120	S.S. Gershtein, Y.B. Zeldovich	(KIAM)
		Translated from ZETFP 4 189.		
BERNSTEIN	63	PR 132 1227	J. Bernstein, M. Ruderman, G. Feinberg	(NYU+)
COWAN	57	PR 107 528	C.L. Cowan, F. Reines	(LANL)