# $\nu_\mu$

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

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

## $\nu$ MASS

In the context of some models, it is possible that this weighted sum over mass eigenstates is the same as for the neutrinos produced in $\tau$ decay.

In some of the ASTR and 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 $\pi^+$ 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 the 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 $p_\mu$ from $\pi^+ \to \mu^+ \nu$ 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 $T_{\text{QCD}}$ 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, $\sim 1$ 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.

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

Test of *CPT* for a Dirac neutrino. (Not a very strong test.)

| *VALUE* (MeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<0.45$ | 90 | CLARK | 74 | ASPK | $K_{\mu 3}$ decay |

## $\nu$ (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. Most of these limits apply to any $\nu$ within the indicated mass range.

| *VALUE* (s/eV) | *CL%* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|
| **>15.4** | 90 | | [6] KRAKAUER | 91 | CNTR | $\nu_\mu, \overline{\nu}_\mu$ at LAMPF |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | | [7] BILLER | 98 | ASTR | $m_\nu$= 0.05–1 eV |
| $> 2.8 \times 10^{15}$ | | | [8,9] BLUDMAN | 92 | ASTR | $m_\nu < 50$ eV |
| none $10^{-12} - 5 \times 10^4$ | | | [10] DODELSON | 92 | ASTR | $m_\nu$=1–300 keV |
| $> 6.3 \times 10^{15}$ | | | [9,11] CHUPP | 89 | ASTR | $m_\nu < 20$ eV |
| $> 1.7 \times 10^{15}$ | | | [9] KOLB | 89 | ASTR | $m_\nu < 20$ eV |
| $> 3.3 \times 10^{14}$ | | | [12,13] VONFEILIT... | 88 | ASTR | |
| $> 0.11$ | 90 | 0 | [14] FRANK | 81 | CNTR | $\nu\overline{\nu}$ LAMPF |
| | | | [15] HENRY | 81 | ASTR | $m_\nu$= 16–20 eV |
| | | | [16] KIMBLE | 81 | ASTR | $m_\nu$= 10–100 eV |
| | | | [17] REPHAELI | 81 | ASTR | $m_\nu$= 30–150 eV |
| | | | [18] DERUJULA | 80 | ASTR | $m_\nu$= 10–100 eV |
| $> 2 \times 10^{21}$ | | | [19] STECKER | 80 | ASTR | $m_\nu$= 10–100 eV |
| $> 1.0 \times 10^{-2}$ | 90 | 0 | [14] BLIETSCHAU | 78 | HLBC | $\nu_\mu$, CERN GGM |
| $> 1.7 \times 10^{-2}$ | 90 | 0 | [14] BLIETSCHAU | 78 | HLBC | $\overline{\nu}_\mu$, CERN GGM |
| $> 2.2 \times 10^{-3}$ | 90 | 0 | [14] BARNES | 77 | DBC | $\nu$, ANL 12-ft |
| $> 3. \times 10^{-3}$ | 90 | 0 | [14] BELLOTTI | 76 | HLBC | $\nu$, CERN GGM |
| $> 1.3 \times 10^{-2}$ | 90 | 1 | [14] BELLOTTI | 76 | HLBC | $\overline{\nu}$, CERN GGM |

[6] 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 $a = -1$).

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

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

[9] Nonobservation of $\gamma$'s in coincidence with $\nu$'s from SN 1987A. Results should be divided by the $\nu \rightarrow \gamma X$ branching ratio.

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

[11] 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.
[12] Model-dependent theoretical analysis of SN 1987A neutrinos.
[13] Limit applies to $\nu_\tau$ also.
[14] These experiments look for $\nu_k \rightarrow \nu_j\gamma$ or $\overline{\nu}_k \rightarrow \overline{\nu}_j\gamma$.
[15] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.
[16] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–$10^{23}$ s.
[17] REPHAELI 81 consider the effect of radiative neutrino decay on neutral H in early universe based on M31 HI. They conclude $\tau > 10^{24}$ s.
[18] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.
[19] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

## $\nu$ CHARGE

| *VALUE* (units: electron charge) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2 \times 10^{-14}$ | [20] RAFFELT | 99 | ASTR | Red giant luminosity |
| $<6 \times 10^{-14}$ | [21] RAFFELT | 99 | ASTR | Solar cooling |

[20] This RAFFELT 99 limit applies to all neutrinos which are light enough (<5 kEV) to be emitted from globular-cluster red giants.
[21] This RAFFELT 99 limit is derived from the helioseismological limit on a new energy-loss channel of the Sun, and applies to all neutrinos which are light enough (<1 keV) to be emitted from the sun.

## $|(v - c)/c|$ ($v \equiv \nu$ VELOCITY)

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

| *VALUE* (units $10^{-4}$) | *CL%* | *EVTS* | *DOCUMENT ID* | | *TECN* | *CHG* | *COMMENT* |
|---|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| <0.4 | 95 | 9800 | KALBFLEISCH | 79 | SPEC | | |
| <2.0 | 99 | 77 | ALSPECTOR | 76 | SPEC | 0 | >5 GeV $\nu$ |
| <4.0 | 99 | 26 | ALSPECTOR | 76 | SPEC | 0 | <5 GeV $\nu$ |

## $\nu$ MAGNETIC MOMENT

Must vanish for a purely chiral massless Dirac neutrino. A massive Dirac or Majorana neutrino can have a transition magnetic moment connecting one mass eigenstate to another one. The experimental limits below usually cannot distinguish between the true (diagonal, in mass) magnetic moment and a transition magnetic moment. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2})$ $= (3.2 \times 10^{-19})m_\nu\mu_B$ where $m_\nu$ is in eV and $\mu_B = e\hbar/2m_e$ is the

Bohr magneton. Given the upper bound $m_\nu < 0.19$ MeV, it follows that for the extended standard electroweak theory, $\mu_\nu < 6 \times 10^{-14}\ \mu_B$.

| *VALUE* ($10^{-10}\ \mu_B$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **< 6.8** | 90 | [22] AUERBACH | 01 | LSND | $\nu_e$ e scatt. |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 2 | 90 | [23] GRIMUS | 02 | FIT | solar + reactor (Majorana $\nu$) |
| < 0.03 | | [24] RAFFELT | 99 | ASTR | Red giant luminosity |
| < 4 | | [25] RAFFELT | 99 | ASTR | Solar cooling |
| < 0.62 | | [26] ELMFORS | 97 | COSM | Depolarization in early universe plasma |
| < 30 | 90 | VILAIN | 95B | CHM2 | $\nu_\mu e \to \nu_\mu e$ |
| <100 | 95 | [27] DORENBOS... | 91 | CHRM | $\nu_\mu e \to \nu_\mu e$ |
| < 8.5 | 90 | AHRENS | 90 | CNTR | $\nu_\mu e \to \nu_\mu e$ |
| < 7.4 | 90 | [28] KRAKAUER | 90 | CNTR | LAMPF $(\nu_\mu, \overline{\nu}_\mu) e$ elast. |
| < 0.02 | | [29] RAFFELT | 90 | ASTR | Red giant luminosity |
| < 0.1 | | [30] RAFFELT | 89B | ASTR | Cooling helium stars |
| < 0.11 | | [30,31] FUKUGITA | 87 | ASTR | Cooling helium stars |
| < 0.0006 | | [32] NUSSINOV | 87 | ASTR | Cosmic EM backgrounds |
| < 0.85 | | [31] BEG | 78 | ASTR | Stellar plasmons |
| < 81 | | [33] KIM | 74 | RVUE | $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ |
| < 1 | | [34] BERNSTEIN | 63 | ASTR | Solar cooling |

[22] AUERBACH 01 limit is based on the LSND $\nu_e$ and $\nu_\mu$ electron scattering measurements. The limit is slightly more stringent than KRAKAUER 90.

[23] 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.

[24] 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.

[25] 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.

[26] 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.

[27] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the $\nu$ 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 $\mu(\nu) = \mu(\overline{\nu})$.

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

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

[30] Significant dependence on details of stellar properties.

[31] If $m_\nu < 10$ keV.

[32] For $m_\nu$ = 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.

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

[34] If $m_\nu < 1$ keV.

## 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* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<0.68, > -0.53$ | 90 | [35] HIRSCH | 03 | | $\nu e$ scat. |
| $< \|0.6\|$ | 90 | VILAIN | 95B | CHM2 | $\nu e$ elastic scat. |
| $-1.1 \pm 1.0$ | | [36] AHRENS | 90 | CNTR | $\nu e$ elastic scat. |
| $-0.3 \pm 1.5$ | | [36] DORENBOS... | 89 | CHRM | $\nu e$ elastic scat. |

[35] Based on analysis of CCFR 98 results. Limit is on $\langle r_V^2 \rangle + \langle r_A^2 \rangle$. 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 $\nu_\mu$ charge radius it implies $\langle r_V^2 \rangle + \langle r_A^2 \rangle = (4.20 \pm 1.64) \times 10^{-33}$ cm$^2$.

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

## $\nu_\mu$ REFERENCES


| | | | | |
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| FUJIKAWA | 03 | hep-ph/0303188 | K. Fujikawa, R. Shrock | |
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| BERNABEU | 00 | PR D62 113012 | J. Bernabeu *et al.* | |
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| FELDMAN | 98 | PR D57 3873 | G.J. Feldman, R.D. Cousins | |
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| RAFFELT | 89B | APJ 336 61 | G. Raffelt, D. Dearborn, J. Silk | (UCB, LLL) |
| VONFEILIT... | 88 | PL B200 580 | F. von Feilitzsch, L. Oberauer | (MUNT) |
| FUKUGITA | 87 | PR D36 3817 | M. Fukugita, S. Yazaki | (KYOTU, TOKY) |
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| FRANK | 81 | PR D24 2001 | J.S. Frank *et al.* | (LASL, YALE, MIT+) |
| HENRY | 81 | PRL 47 618 | R.C. Henry, P.D. Feldman | (JHU) |
| KIMBLE | 81 | PRL 46 80 | R. Kimble, S. Bowyer, P. Jakobsen | (UCB) |
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