# $\nu_\mu$

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

Not in general a mass eigenstate. Pending better understanding, it is assumed that $\nu_\mu$ couples predominately with $\nu_2$. See Note on "Neutrino Mass" above.

## $\nu_\mu$ MASS

Applies to $\nu_2$, the primary mass eigenstate in $\nu_\mu$. Would also apply to any other $\nu_j$ which mixes strongly in $\nu_\mu$ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the $\nu_e$ mass limit above.) Results based upon an obsolete pion mass are no longer shown; they were in any cass less restrive than ASSAMAGAN 96.

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 $m^2$ 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 | $m^2 = -0.016 \pm 0.023$ |
| • • • 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 |
| <0.003 | | [4,5] MAYLE | 93 | ASTR | SN 1987A cooling |
| < 0.025–0.030 | | [5,6] BURROWS | 92 | ASTR | SN 1987A cooling |
| <0.3 | | [7] FULLER | 91 | COSM | Nucleosynthesis |
| <0.42 | | [7] LAM | 91 | COSM | Nucleosynthesis |
| < 0.028–0.15 | | [8] NATALE | 91 | ASTR | SN 1987A |
| <0.028 | | [5] GANDHI | 90 | ASTR | SN 1987A |
| <0.014 | | [5,9] GRIFOLS | 90B | ASTR | SN 1987A |
| <0.06 | | [5,10] GAEMERS | 89 | | SN 1987A |
| <0.50 | 90 | [11] ANDERHUB | 82 | SPEC | $m^2 = -0.14 \pm 0.20$ |
| <0.65 | 90 | CLARK | 74 | ASPK | $K_{\mu 3}$ decay |

[1] ASSAMAGAN 96 measurement of $p_\mu$ from $\pi^+ \to \mu^+ \nu_\mu$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m_\nu^2 = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m_2 = -0.143 \pm 0.024$ MeV$^2$. Replaces ASSAMAGAN 94.

[2] 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.

[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] MAYLE 93 recalculates cooling rate enhancement by escape of wrong-helicity Dirac neutrinos using the Livermore Supernova Explosion Code, obtains more restrictive result than the "very conservative" BURROWS 92 limit because of higher core temperature.

[5] There would be an increased cooling rate if Dirac neutrino mass is included; this does not apply for Majorana neutrinos. Limit is on $\sqrt{m^2_{\nu_\mu}+m^2_{\nu_\tau}}$, and error becomes very large if $\nu_\tau$ is nonrelativistic, which occurs near the lab limit of 31 MeV. RAJPOOT 93 notes that limit could be evaded with new physics.

[6] BURROWS 92 limit for Dirac neutrinos only.

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

[8] NATALE 91 published result multiplied by $\sqrt{8}\sqrt{4}$ at the advice of the author.

[9] GRIFOLS 90B estimated error is a factor of 3.

[10] GAEMERS 89 published result ($< 0.03$) corrected via the GANDHI 91 erratum.

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

## $m_{\nu_2} - m_{\overline{\nu}_2}$

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 |

## $\nu_2$ (MEAN LIFE) / MASS

These limits often apply to $\nu_\tau$ ($\nu_3$) also.

| *VALUE* (s/eV) | *CL%* | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|
| **>15.4** | 90 | | [12] KRAKAUER | 91 | CNTR | $\nu_\mu$, $\overline{\nu}_\mu$ at LAMPF |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | | [13] BILLER | 98 | ASTR | $m_\nu = 0.05$–1 eV |
| $> 2.8 \times 10^{15}$ | | | [14,15] BLUDMAN | 92 | ASTR | $m_\nu < 50$ eV |
| none $10^{-12} - 5 \times 10^{4}$ | | | [16] DODELSON | 92 | ASTR | $m_\nu$=1–300 keV |
| $> 6.3 \times 10^{15}$ | | | [15,17] CHUPP | 89 | ASTR | $m_\nu < 20$ eV |
| $> 1.7 \times 10^{15}$ | | | [15] KOLB | 89 | ASTR | $m_\nu < 20$ eV |
| $> 3.3 \times 10^{14}$ | | | [18,19] VONFEILIT... | 88 | ASTR | |
| $> 0.11$ | 90 | 0 | [20] FRANK | 81 | CNTR | $\nu\overline{\nu}$ LAMPF |
| | | | [21] HENRY | 81 | ASTR | $m_\nu = 16$–20 eV |
| | | | [22] KIMBLE | 81 | ASTR | $m_\nu = 10$–100 eV |
| | | | [23] REPHAELI | 81 | ASTR | $m_\nu = 30$–150 eV |
| | | | [24] DERUJULA | 80 | ASTR | $m_\nu = 10$–100 eV |
| $> 2 \times 10^{21}$ | | | [25] STECKER | 80 | ASTR | $m_\nu = 10$–100 eV |
| $> 1.0 \times 10^{-2}$ | 90 | 0 | [20] BLIETSCHAU | 78 | HLBC | $\nu_\mu$, CERN GGM |
| $> 1.7 \times 10^{-2}$ | 90 | 0 | [20] BLIETSCHAU | 78 | HLBC | $\overline{\nu}_\mu$, CERN GGM |
| $> 2.2 \times 10^{-3}$ | 90 | 0 | [20] BARNES | 77 | DBC | $\nu$, ANL 12-ft |
| $> 3. \times 10^{-3}$ | 90 | 0 | [20] BELLOTTI | 76 | HLBC | $\nu$, CERN GGM |
| $> 1.3 \times 10^{-2}$ | 90 | 1 | [20] BELLOTTI | 76 | HLBC | $\overline{\nu}$, CERN GGM |

[12] 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 $a = -1$).

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

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

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

[16] 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.

[17] 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.

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

[19] Limit applies to $\nu_\tau$ also.

[20] These experiments look for $\nu_\mu \rightarrow \nu_e\gamma$ or $\overline{\nu}_\mu \rightarrow \overline{\nu}_e\gamma$.

[21] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1\times10^{25}$ s for radiative decay.

[22] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–$10^{23}$ s.

[23] REPHAELI 81 consider $\nu$ decay $\gamma$ effect on neutral $H$ in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.

[24] DERUJULA 80 finds $\tau > 3\times10^{23}$ s based on CDM neutrino decay contribution to UV background.

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

## $\nu_2$ CHARGE

| *VALUE* (units: electron charge) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2\times10^{-14}$ | [26] RAFFELT | 99 | ASTR | Red giant luminosity |
| $<6\times10^{-14}$ | [27] RAFFELT | 99 | ASTR | Solar cooling |

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

[27] 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.

## $|(v - c)/c|$ ($v \equiv \nu_2$ 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 $\nu$ |

## $\nu_2$ MAGNETIC MOMENT

Must vanish for Majorana neutrino or purely chiral massless Dirac neutrino. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2\times10^{-19})m_\nu\mu_B$ where $m_\nu$ is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_2} < 0.17$ MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_2) < 0.51\times10^{-13}\ \mu_B$.

| *VALUE* ($10^{-10}\ \mu_B$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $<$ 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. |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<$ 0.03 | | [29] RAFFELT | 99 | ASTR | Red giant luminosity |
| $<$ 4 | | [30] RAFFELT | 99 | ASTR | Solar cooling |
| $<$ 0.62 | | [31] ELMFORS | 97 | COSM | Depolarization in early universe plasma |
| $<$ 30 | 90 | VILAIN | 95B | CHM2 | $\nu_\mu e \to \nu_\mu e$ |
| $<$100 | 95 | [32] DORENBOS... | 91 | CHRM | $\nu_\mu e \to \nu_\mu e$ |
| $<$ 0.02 | | [33] RAFFELT | 90 | ASTR | Red giant luminosity |
| $<$ 0.1 | | [34] RAFFELT | 89B | ASTR | Cooling helium stars |
| $<$ 0.11 | | [34,35] FUKUGITA | 87 | ASTR | Cooling helium stars |
| $<$ 0.0006 | | [36] NUSSINOV | 87 | ASTR | Cosmic EM backgrounds |
| $<$ 0.4 | | LYNN | 81 | ASTR | |
| $<$ 0.85 | | [35] BEG | 78 | ASTR | Stellar plasmons |
| $<$ 81 | | [37] KIM | 74 | RVUE | $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ |
| $<$ 1 | | [38] BERNSTEIN | 63 | ASTR | Solar cooling |

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

[29] 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.

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

[31] 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.

[32] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the $\nu_2$ magnetic moment is $< 1\times10^{-9}$ at the 95%CL. DORENBOSCH 89 measures both $\nu_\mu e$ and $\overline{\nu}_\mu e$ elastic scattering and assume $\mu(\nu_\mu) = \mu(\overline{\nu}_\mu)$.

[33] 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 $< 1.4\times10^{-12}$. Limit at 95%CL obtained from $\delta M_c$.

[34] Significant dependence on details of stellar properties.

[35] If $m_{\nu_2} < 10$ keV.

[36] For $m_{\nu_2}$ = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for $m_{\nu_2} > 16$ eV and $< 6 \times 10^{-14}$ for $m_{\nu_2} > 4$ eV.

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

[38] If $m_{\nu_2} < 1$ keV.

## NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

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

| *VALUE* ($10^{-32}$ cm$^2$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $< \lvert 0.6 \rvert$ | 90 | VILAIN | 95B | CHM2 | $\nu_\mu e$ elas scat |
| $-1.1 \pm 1.0$ | | [39] AHRENS | 90 | CNTR | $\nu_\mu e$ elas scat |
| $-0.3 \pm 1.5$ | | [39] DORENBOS... | 89 | CHRM | $\nu_\mu e$ elas scat |

[39] 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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| FELDMAN | 98 | PR D57 3873 | G.J. Feldman, R.D. Cousins | |
| LENZ | 98 | PL B416 50 | S. Lenz *et al.* | |
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| ASSAMAGAN | 96 | PR D53 6065 | K.A. Assamagan *et al.* | (PSI, ZURI, VILL+) |
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| VILAIN | 95B | PL B345 115 | P. Vilain *et al.* | (CHARM II Collab.) |
| ASSAMAGAN | 94 | PL B335 231 | K.A. Assamagan *et al.* | (PSI, ZURI, VILL+) |
| JECKELMANN | 94 | PL B335 326 | B. Jeckelmann, P.F.A. Goudsmit, H.J. Leisi | (WABRN+) |
| ALLEN | 93 | PR D47 11 | R.C. Allen *et al.* | (UCI, LANL, ANL+) |
| DOLGOV | 93 | PRL 71 476 | A.D. Dolgov, I.Z. Rothstein | (MICH) |
| ENQVIST | 93 | PL B301 376 | K. Enqvist, H. Uibo | (NORD) |
| MAYLE | 93 | PL B317 119 | R. Mayle *et al.* | (LLNL, CHIC) |
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| BLUDMAN | 92 | PR D45 4720 | S.A. Bludman | (CFPA) |
| BURROWS | 92 | PRL 68 3834 | A. Burrows, R. Gandhi, M. Turner | (ARIZ, CHIC) |
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| ALLEN | 91 | PR D43 R1 | R.C. Allen *et al.* | (UCI, LANL, UMD) |
| DORENBOS... | 91 | ZPHY C51 142 | J. Dorenbosch *et al.* | (CHARM Collab.) |
| FULLER | 91 | PR D43 3136 | G.M. Fuller, R.A. Malaney | (UCSD) |
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| GANDHI | 90 | PL B246 149 | R. Gandhi, A. Burrows | (ARIZ) |
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| | | | | |
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| CHUPP | 89 | PRL 62 505 | E.L. Chupp, W.T. Vestrand, C. Reppin | (UNH, MPIM) |
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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) |
| NUSSINOV | 87 | PR D36 2278 | S. Nussinov, Y. Rephaeli | (TELA) |
| ANDERHUB | 82 | PL 114B 76 | H.B. Anderhub *et al.* | (ETH, SIN) |
| 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) |
| LYNN | 81 | PR D23 2151 | B.W. Lynn | (COLU) |
| REPHAELI | 81 | PL 106B 73 | Y. Rephaeli, A.S. Szalay | (UCSB, CHIC) |
| DERUJULA | 80 | PRL 45 942 | A. De Rujula, S.L. Glashow | (MIT, HARV) |
| FUJIKAWA | 80 | PRL 45 963 | K. Fujikawa, R. Shrock | (STON) |
| STECKER | 80 | PRL 45 1460 | F.W. Stecker | (NASA) |
| KALBFLEISCH | 79 | PRL 43 1361 | G.R. Kalbfleisch *et al.* | (FNAL, PURD, BELL) |
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| 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) |
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