ν_μ

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

Not in general a mass eigenstate. See note on neutrinos in the ν_e section above.

ν_μ MASS

Applies to ν_2, the primary mass eigenstate in ν_μ. Would also apply to any other ν_j which mixes strongly in ν_μ and has sufficiently small mass that it can occur in the respective decays. (This would be nontrivial only for $j \geq 3$, given the ν_e mass limit above.) See also the Listings in the Neutrino Bounds from Astrophysics and Cosmology section.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.16		[1] ASSAMAGAN	94	SPEC	$m^2 = -0.022 \pm 0.023$
• • • 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
		MAMEDOV	92	RVUE	
<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
<0.27	90	[11] ABELA	84	SPEC	$m^2 = -0.097 \pm 0.072$
<0.50	90	ANDERHUB	82	SPEC	$m^2 = -0.14 \pm 0.20$
<0.52	90	[12] LU	80	CNTR	$m^2 = 0.102 \pm 0.119$
<0.65	90	CLARK	74	ASPK	$K_{\mu3}$ decay

[1] ASSAMAGAN 94 result is from a measurement of p_μ from $\pi^+ \to \mu^+ \nu_\mu$ at rest combined with JECKELMANN 94 Solution B pion mass. If Solution A is used, $m^2 = -0.148 \pm 0.024$ MeV^2.

[2] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below $T_{\rm QCD}$ for wrong-helicity Divac 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] 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 ν_τ 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] ABELA 84 used the PDG 84 value for $\pi^\pm$ mass, in conjunction with μ momentum measurement in $\pi \to \mu \nu_\mu$ decay to obtain $m < 0.25$ and $m^2 = -0.16 \pm 0.08$. The values shown here for mass and m^2 are corrected values obtained by JECKELMANN 86 from the ABELA 84 data using the more accurate $\pi^\pm$ mass of JECKELMANN 86.

[12] LU 80 combines DAUM 79 $\pi^+ \to \mu^+ \nu_\mu$ measurement with new LU 80 π^- mass and replaces DAUM 79. LU 80 is not independent of ABELA 84.

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

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	$K_{\mu3}$ decay

ν_2 (MEAN LIFE) / MASS

These limits often apply to ν_τ (ν_3) also.

VALUE (s/eV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>15.4	90		[13] KRAKAUER	91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$> 2.8 \times 10^{15}$			[14,15] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
none 10^{-12} – 5×10^4			[16] DODELSON	92	ASTR	m_ν=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
			[18,19] HATSUDA	88	ASTR	
$> 3.3 \times 10^{14}$			[20,21] VONFEILIT...	88	ASTR	
> 0.11	90	0	[22] FRANK	81	CNTR	$\nu\overline{\nu}$ LAMPF
			[23] HENRY	81	ASTR	m_ν= 16–20 eV
			[24] KIMBLE	81	ASTR	m_ν= 10–100 eV
			[25] REPHAELI	81	ASTR	m_ν= 30–150 eV
			[26] DERUJULA	80	ASTR	m_ν= 10–100 eV
$> 2 \times 10^{21}$			[27] STECKER	80	ASTR	m_ν= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[22] BLIETSCHAU	78	HLBC	ν_μ, CERN GGM
$> 1.7 \times 10^{-2}$	90	0	[22] BLIETSCHAU	78	HLBC	$\overline{\nu}_\mu$, CERN GGM
$> 2.2 \times 10^{-3}$	90	0	[22] BARNES	77	DBC	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[22] BELLOTTI	76	HLBC	ν, CERN GGM
$> 1.3 \times 10^{-2}$	90	1	[22] BELLOTTI	76	HLBC	$\overline{\nu}$, CERN GGM

[13] 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 $a = -1$).

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

[15] Nonobservation of γ's in coincidence with ν'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 ν's from the core of neutron star in SN 1987A decaying to ν'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.

[19] HATSUDA 88 argues that previous bounds on radiative decays of neutrinos produced in supernovae explosions may not be valid (because $\nu_H \rightarrow \gamma\nu$ might be dominated by processes such as $\nu_H e \rightarrow \nu e$ if e number density is high enough), and that, in fact, a neutrino mean life/mass of 0.2–0.6 s/eV may be consistent with the data.

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

[21] Limit applies to ν_τ also.

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

[23] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.

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

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

[26] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.

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

$|(v - c) / c|$ ($v \equiv \nu_2$ 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 ν
<4.0	99	26	ALSPECTOR	76	SPEC	0	<5 GeV ν

ν_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_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_{\nu_2} < 0.27$ MeV, it follows that for the extended standard electroweak theory, $\mu(\nu_2) < 0.86\times10^{-13}\ \mu_B$.

VALUE (μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
$<8.5\times10^{-10}$	90	AHRENS	90	CNTR	$\nu_\mu e \to \nu_\mu e$
$<7.4\times10^{-10}$	90	[28] KRAKAUER	90	CNTR	LAMPF $(\nu_\mu, \overline{\nu}_\mu)e$ elast.
$<9.5\times10^{-10}$	90	ABE	87B	CNTR	$\nu_\mu e \to \nu_\mu e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1\times10^{-8}$	95	[29] DORENBOS...	91	CHRM	$\nu_\mu e \to \nu_\mu e$
$<2\times10^{-12}$	95	[30] RAFFELT	90	ASTR	Red giant luminosity
$<1\times10^{-11}$		[31] RAFFELT	89B	ASTR	Cooling helium stars
$<1.1\times10^{-11}$		[31,32] FUKUGITA	87	ASTR	Cooling helium stars
$<6\times10^{-14}$		[33] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<4\times10^{-11}$		LYNN	81	ASTR	
$<8.5\times10^{-11}$		[32] BEG	78	ASTR	Stellar plasmons
$<8.1\times10^{-9}$		[34] KIM	74	RVUE	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
$<1\times10^{-10}$		[35] BERNSTEIN	63	ASTR	Cooling white dwarfs

[28] KRAKAUER 90 experiment fully reported in ALLEN 93.
[29] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the ν_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 $\mu(\nu_\mu) = \mu(\overline{\nu}_\mu)$.
[30] 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 δM_c.
[31] Significant dependence on details of stellar properties.
[32] If $m_{\nu_2} < 10$ keV.
[33] For $m_{\nu_2} = 8$–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \to \nu_e$ and obtain $< 3\times10^{-15}$ for $m_{\nu_2} > 16$ eV and $< 6\times10^{-14}$ for $m_{\nu_2} > 4$ eV.
[34] KIM 74 is a theoretical analysis of $\overline{\nu}_\mu$ reaction data.
[35] 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)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
-1.1 ± 1.0	[36] AHRENS	90	CNTR	$\nu_\mu e$ elas scat
-0.3 ± 1.5	[36] DORENBOS...	89	CHRM	$\nu_\mu e$ elas scat

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

ν_μ REFERENCES

DOLGOV	95	PR D51 4129	+Kainulainen, Rothstein	(MICH, MINN, CERN)
ASSAMAGAN	94	PL B335 231	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
JECKELMANN	94	PL B335 326	+Goudsmit, Leisi	(WABRN, VILL)
ALLEN	93	PR D47 11	+Chen, Doe, Hausammann+	(UCI, LANL, ANL, UMD)
DOLGOV	93	PRL 71 476	+Rothstein	(MICH)
ENQVIST	93	PL B301 376	+Uibo	(NORD)
MAYLE	93	PL B317 119	+Schramm, Turner, Wilson	(LLNL, CHIC)
RAJPOOT	93	MPL A8 1179		(CSULB)
BLUDMAN	92	PR D45 4720		(CFPA)
BURROWS	92	PRL 68 3834	+Gandhi, Turner	(ARIZ, CHIC)
DODELSON	92	PRL 68 2572	+Frieman, Turner	(FNAL, CHIC)
MAMEDOV	92	SJPN 23 339 Translated from FECAY 23 767.		(JINR)

ALLEN	91	PR D43 R1	+Chen, Doe, Hausammann	(UCI, LANL, UMD)
DORENBOS...	91	ZPHY C51 142	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
FULLER	91	PR D43 3136	+Malaney	(UCSD)
GANDHI	91	PL B261 519E (erratum)	+Burrows	(ARIZ)
KRAKAUER	91	PR D44 R6	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
LAM	91	PR D44 3345	+Ng	(AST)
NATALE	91	PL B258 227		(SPIFT)
AHRENS	90	PR D41 3297	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
GANDHI	90	PL B246 149	+Burrows	(ARIZ)
Also	91	PL B261 519E (erratum)	Gandhi, Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	+Masso	(BARC, CERN)
KRAKAUER	90	PL B252 177	+Talaga, Allen, Chen+	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856		(MPIM)
CHUPP	89	PRL 62 505	+Vestrand, Reppin	(UNH, MPIM)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
GAEMERS	89	PR D40 309	+Gandhi, Lattimer	(ANIK, STON)
KOLB	89	PRL 62 509	+Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	+Dearborn, Silk	(UCB, LLL)
HATSUDA	88	PL B203 462	+Lim, Yoshimura	(KEK)
VONFEILIT...	88	PL B200 580	Von Feilitzsch, Oberauer	(MUNT)
ABE	87B	PRL 58 636	+	(BNL, BROW, HIRO, KEK, OSAK, PENN, STON)
FUKUGITA	87	PR D36 3817	+Yazaki	(KYOTY, TOKY)
NUSSINOV	87	PR D36 2278	+Rephaeli	(TELA)
JECKELMANN	86	PRL 56 1444	+Nakada, Beer+	(ETH, FRIB)
ABELA	84	PL 146B 431	+Daum, Eaton, Frosch, Jost, Kettle+	(SIN)
PDG	84	RMP 56 No. 2 Pt. II	Wohl, Cahn, Rittenberg+	(LBL, CIT, CERN)
ANDERHUB	82	PL 114B 76	+Boecklin, Hofer, Kottmann+	(ETH, SIN)
FRANK	81	PR D24 2001	+Burman+	(LASL, YALE, MIT, SACL, SIN+)
HENRY	81	PRL 47 618	+Feldman	(JHU)
KIMBLE	81	PRL 46 80	+Bowyer, Jakobsen	(UCB)
LYNN	81	PR D23 2151		(COLU)
REPHAELI	81	PL 106B 73	+Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	+Glashow	(MIT, HARV)
FUJIKAWA	80	PRL 45 963	+Shrock	(STON)
LU	80	PRL 45 1066	+Delker, Dugan, Wu, Caffrey+	(YALE, COLU, JHU)
STECKER	80	PRL 45 1460		(NASA)
DAUM	79	PR D20 2692	+Eaton, Frosch, Hirschmann+	(SIN)
Also	76	PL 60B 380	Daum, Dubal, Eaton, Frosch+	(SIN, ETH)
Also	78	PL 74B 126	Daum, Eaton, Frosch, Hirschmann+	(SIN)
KALBFLEISCH	79	PRL 43 1361	+Baggett, Fowler+	(FNAL, PURD, BELL)
BEG	78	PR D17 1395	+Marciano, Ruderman	(ROCK, COLU)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BARNES	77	PRL 38 1049	+Carmony, Dauwe, Fernandez+	(PURD, ANL)
LEE	77C	PR D16 1444	+Shrock	(STON)
ALSPECTOR	76	PRL 36 837	+	(BNL, PURD, CIT, FNAL, ROCK)
BELLOTTI	76	LNC 17 553	+Cavalli, Fiorini, Rollier	(MILA)
CLARK	74	PR D9 533	+Elioff, Frisch, Johnson, Kerth, Shen+	(LBL)
KIM	74	PR D9 3050	+Mather, Okubo	(ROCH)
BERNSTEIN	63	PR 132 1227	+Ruderman, Feinberg	(NYU, COLU)