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ν_μ

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

Not in general a mass eigenstate. Pending better understanding, it is assumed that ν_μ couples predominately with ν_2. See Note on "Neutrino Mass" 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.) 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 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 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_μ from $\pi^+ \rightarrow \mu^+ \nu_\mu$ 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_{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] 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] 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

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		[12] KRAKAUER 91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[13] BILLER 98	ASTR	m_ν= 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_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
$> 3.3 \times 10^{14}$			[18,19] VONFEILIT... 88	ASTR	
> 0.11	90	0	[20] FRANK 81	CNTR	$\nu\overline{\nu}$ LAMPF
			[21] HENRY 81	ASTR	m_ν= 16–20 eV
			[22] KIMBLE 81	ASTR	m_ν= 10–100 eV
			[23] REPHAELI 81	ASTR	m_ν= 30–150 eV
			[24] DERUJULA 80	ASTR	m_ν= 10–100 eV
$> 2 \times 10^{21}$			[25] STECKER 80	ASTR	m_ν= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[20] BLIETSCHAU 78	HLBC	ν_μ, 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	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[20] BELLOTTI 76	HLBC	ν, 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 γ-ray spectra to set limits on the mean life of a radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/\mathrm{B}_\gamma > 0.15 \times 10^{21}$ s at 0.05 eV, $> 1.2 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where B_γ is the branching ratio to photons.

[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 of SN 1987A neutrinos.

[19] Limit applies to ν_τ 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 $\tau > 1.1 \times 10^{25}$ s for radiative decay.

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

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

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

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

ν_2 CHARGE

VALUE (units: electron charge)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-14}$	[26] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$	[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.

$\left|(v - c)/c\right|$ ($v \equiv \nu_2$ 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 $m_{\nu_2} < 0.17$ 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	$\nu_\mu e \rightarrow \nu_\mu e$
$<$ 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. • • •

VALUE ($10^{-10}\ \mu_B$)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<$ 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	$\nu_\mu e \rightarrow \nu_\mu e$
$<$100	95	[32] DORENBOS...	91	CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
$<$ 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	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
$<$ 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 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 $\mu(\nu_\mu) = \mu(\overline{\nu}_\mu)$.

[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 δM_c.

[34] Significant dependence on details of stellar properties.

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

[36] For m_{ν_2} = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \to \nu_e$ 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 ± 1.0		[39] AHRENS	90	CNTR	$\nu_\mu e$ elas scat
-0.3 ± 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 σ errors.

ν_μ REFERENCES

RAFFELT	99	PRPL 320 319	G.G. Raffelt	
BILLER	98	PRL 80 2992	S.D. Biller *et al.*	(WHIPPLE Collab.)
FELDMAN	98	PR D57 3873	G.J. Feldman, R.D. Cousins	
LENZ	98	PL B416 50	S. Lenz *et al.*	
ELMFORS	97	NP B503 3	P. Elmfors *et al.*	
ASSAMAGAN	96	PR D53 6065	K.A. Assamagan *et al.*	(PSI, ZURI, VILL+)
DOLGOV	95	PR D51 4129	A.D. Dolgov, K. Kainulainen, I.Z. Rothstein	(MICH+)
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)
RAJPOOT	93	MPL A8 1179	S. Rajpoot	(CSULB)
BLUDMAN	92	PR D45 4720	S.A. Bludman	(CFPA)
BURROWS	92	PRL 68 3834	A. Burrows, R. Gandhi, M. Turner	(ARIZ, CHIC)
DODELSON	92	PRL 68 2572	S. Dodelson, J.A. Frieman, M.S. Turner	(FNAL+)
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)
GANDHI	91	PL B261 519E (erratum)	R. Gandhi, A. Burrows	(ARIZ)
KRAKAUER	91	PR D44 R6	D.A. Krakauer *et al.*	(LAMPF E225 Collab.)
LAM	91	PR D44 3345	W.P. Lam, K.W. Ng	(AST)
NATALE	91	PL B258 227	A.A. Natale	(SPIFT)
AHRENS	90	PR D41 3297	L.A. Ahrens *et al.*	(BNL, BROW, HIRO+)
GANDHI	90	PL B246 149	R. Gandhi, A. Burrows	(ARIZ)
Also	91	PL B261 519E (erratum)	R. Gandhi, A. Burrows	(ARIZ)
GRIFOLS	90B	PL B242 77	J.A. Grifols, E. Masso	(BARC, CERN)
KRAKAUER	90	PL B252 177	D.A. Krakauer *et al.*	(LAMPF E225 Collab.)

RAFFELT	90	PRL 64 2856	G.G. Raffelt	(MPIM)
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.)
GAEMERS	89	PR D40 309	K.J.F. Gaemers, R. Gandhi, J.M. Lattimer	(ANIK+)
KOLB	89	PRL 62 509	E.W. Kolb, M.S. Turner	(CHIC, FNAL)
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)
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.)
BARNES	77	PRL 38 1049	V.E. Barnes *et al.*	(PURD, ANL)
LEE	77C	PR D16 1444	B.W. Lee, R.E. Shrock	(STON)
ALSPECTOR	76	PRL 36 837	J. Alspector *et al.*	(BNL, PURD, CIT+)
BELLOTTI	76	LNC 17 553	E. Bellotti *et al.*	(MILA)
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)
BERNSTEIN	63	PR 132 1227	J. Bernstein, M. Ruderman, G. Feinberg	(NYU+)