ν_μ

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

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

ν 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 τ 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 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 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_μ 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_{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.

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

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

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. Most of these limits apply to any ν within the indicated mass range.

VALUE (s/eV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
>15.4	90		[6] KRAKAUER	91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[7] BILLER	98	ASTR	m_ν= 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_ν=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_ν= 16–20 eV
			[16] KIMBLE	81	ASTR	m_ν= 10–100 eV
			[17] REPHAELI	81	ASTR	m_ν= 30–150 eV
			[18] DERUJULA	80	ASTR	m_ν= 10–100 eV
$> 2 \times 10^{21}$			[19] STECKER	80	ASTR	m_ν= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[14] BLIETSCHAU	78	HLBC	ν_μ, 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	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[14] BELLOTTI	76	HLBC	ν, 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 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.

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

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

ν 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.

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

ν 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_ν 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. • • •					
< 37	95	[23] GRIFOLS	04	FIT	Solar ^{8}B ν (SNO NC)
< 3.6	90	[24] LIU	04	SKAM	Solar ν spectrum shape
< 1.1	90	[25] LIU	04	SKAM	Solar ν spectrum shape (LMA region)
< 2	90	[26] GRIMUS	02	FIT	solar + reactor (Majorana ν)
< 0.03		[27] RAFFELT	99	ASTR	Red giant luminosity
< 4		[28] RAFFELT	99	ASTR	Solar cooling
< 0.62		[29] ELMFORS	97	COSM	Depolarization in early universe plasma
< 30	90	VILAIN	95B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$
<100	95	[30] DORENBOS...	91	CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
< 8.5	90	AHRENS	90	CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
< 7.4	90	[31] KRAKAUER	90	CNTR	LAMPF $(\nu_\mu, \overline{\nu}_\mu) e$ elast.
< 0.02		[32] RAFFELT	90	ASTR	Red giant luminosity
< 0.1		[33] RAFFELT	89B	ASTR	Cooling helium stars
< 0.11		[33,34] FUKUGITA	87	ASTR	Cooling helium stars
< 0.0006		[35] NUSSINOV	87	ASTR	Cosmic EM backgrounds
< 0.85		[34] BEG	78	ASTR	Stellar plasmons
< 81		[36] KIM	74	RVUE	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
< 1		[37] BERNSTEIN	63	ASTR	Solar cooling

[22] 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.

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

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

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

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

[32] 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.

[33] Significant dependence on details of stellar properties.

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

[35] 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.

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

[37] 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	[38] HIRSCH	03		νe scat.
$< \lvert 0.6 \rvert$	90	VILAIN	95B	CHM2	νe elastic scat.
-1.1 ± 1.0		[39] AHRENS	90	CNTR	νe elastic scat.
-0.3 ± 1.5		[39] DORENBOS...	89	CHRM	νe elastic scat.

[38] 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 ν_μ charge radius it implies $\langle r_V^2 \rangle + \langle r_A^2 \rangle = (4.20 \pm 1.64) \times 10^{-33}$ cm^2.

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

ν_μ REFERENCES

GRIFOLS	04	PL B587 184	J.A. Grifols, E. Masso, S. Mohanty	(BARC, AHMED)
LIU	04	PRL 93 021802	D.W. Liu *et al.*	(Super-Kamiokande Collab.)
BERNABEU	03	hep-ph/0303202	J. Bernabeu, J. Papavassiliou, J. Vidal	
FUJIKAWA	03	hep-ph/0303188	K. Fujikawa, R. Shrock	
HIRSCH	03	PR D67 033005	M. Hirsch *et al.*	
BERNABEU	02	PRL 89 101802	J. Bernabeu, J. Papavassiliou, J. Vidal	
Also	02B	PRL 89 229902 (erratum)	J. Bernabeu, J. Papavassiliou, J. Vidal	
GRIMUS	02	NP B648 376	W. Grimus *et al.*	
AUERBACH	01	PR D63 112001	L.B. Auerbach *et al.*	(LSND Collab.)
BERNABEU	00	PR D62 113012	J. Bernabeu *et al.*	
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)
BLUDMAN	92	PR D45 4720	S.A. Bludman	(CFPA)
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)
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)
AHRENS	90	PR D41 3297	L.A. Ahrens *et al.*	(BNL, BROW, HIRO+)
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.)
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)
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+)