



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

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

## $\nu$ 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  $m_{\nu_\mu}^{2(\text{eff})}$  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
<b>&lt;0.19 (CL = 90%) OUR EVALUATION</b>				
<0.17	90	<sup>1</sup> ASSAMAGAN 96	SPEC	$m_\nu^2 = -0.016 \pm 0.023$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
<0.15		<sup>2</sup> DOLGOV	95 COSM	Nucleosynthesis
<0.48		<sup>3</sup> ENQVIST	93 COSM	Nucleosynthesis
<0.3		<sup>4</sup> FULLER	91 COSM	Nucleosynthesis
<0.42		<sup>4</sup> LAM	91 COSM	Nucleosynthesis
<0.50	90	<sup>5</sup> ANDERHUB 82	SPEC	$m_\nu^2 = -0.14 \pm 0.20$
<0.65	90	CLARK 74	ASPK	$K_{\mu 3}$ decay

<sup>1</sup> ASSAMAGAN 96 measurement of  $p_\mu$  from  $\pi^+ \rightarrow \mu^+ \nu$  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,  $m_\nu^2 = -0.143 \pm 0.024 \text{ MeV}^2$ . Replaces ASSAMAGAN 94.

<sup>2</sup> 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.

<sup>3</sup> 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,  $\sim 1 \text{ s}$ .

<sup>4</sup> Assumes neutrino lifetime  $> 1 \text{ s}$ . For Dirac neutrinos only. See also ENQVIST 93.

<sup>5</sup> ANDERHUB 82 kinematics is insensitive to the pion mass.

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

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  $[\sum |U_{\ell j}|^2 \Gamma_j m_j]^{-1}$ , 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
<b>&gt;15.4</b>	90		<sup>6</sup> KRAKAUER	91 CNTR	$\nu_\mu, \bar{\nu}_\mu$ at LAMPF
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
			<sup>7</sup> BILLER	98 ASTR	$m_\nu = 0.05-1$ eV
$> 2.8 \times 10^{15}$			<sup>8,9</sup> BLUDMAN	92 ASTR	$m_\nu < 50$ eV
none $10^{-12} - 5 \times 10^4$			<sup>10</sup> DODELSON	92 ASTR	$m_\nu = 1-300$ keV
$> 6.3 \times 10^{15}$			<sup>9,11</sup> CHUPP	89 ASTR	$m_\nu < 20$ eV
$> 1.7 \times 10^{15}$			<sup>9</sup> KOLB	89 ASTR	$m_\nu < 20$ eV
$> 3.3 \times 10^{14}$			<sup>12,13</sup> VONFEILIT...	88 ASTR	
$> 0.11$	90	0	<sup>14</sup> FRANK	81 CNTR	$\nu\bar{\nu}$ LAMPF
			<sup>15</sup> HENRY	81 ASTR	$m_\nu = 16-20$ eV
			<sup>16</sup> KIMBLE	81 ASTR	$m_\nu = 10-100$ eV
			<sup>17</sup> REPHAELI	81 ASTR	$m_\nu = 30-150$ eV
			<sup>18</sup> DERUJULA	80 ASTR	$m_\nu = 10-100$ eV
$> 2 \times 10^{21}$			<sup>19</sup> STECKER	80 ASTR	$m_\nu = 10-100$ eV
$> 1.0 \times 10^{-2}$	90	0	<sup>14</sup> BLIETSCHAU	78 HLBC	$\nu_\mu$ , CERN GGM
$> 1.7 \times 10^{-2}$	90	0	<sup>14</sup> BLIETSCHAU	78 HLBC	$\bar{\nu}_\mu$ , CERN GGM
$> 2.2 \times 10^{-3}$	90	0	<sup>14</sup> BARNES	77 DBC	$\nu$ , ANL 12-ft
$> 3. \times 10^{-3}$	90	0	<sup>14</sup> BELLOTTI	76 HLBC	$\nu$ , CERN GGM
$> 1.3 \times 10^{-2}$	90	1	<sup>14</sup> BELLOTTI	76 HLBC	$\bar{\nu}$ , CERN GGM

<sup>6</sup> KRAKAUER 91 quotes the limit  $\tau/m_{\nu_1} > (0.75a^2 + 21.65a + 26.3) \text{ s/eV}$ , 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  $a = -1$ ).

<sup>7</sup> 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  $\tau_\nu/B_\gamma > 0.15 \times 10^{21} \text{ s}$  at 0.05 eV,  $> 1.2 \times 10^{21} \text{ s}$  at 0.17 eV,  $> 3 \times 10^{21} \text{ s}$  at 1 eV, where  $B_\gamma$  is the branching ratio to photons.

<sup>8</sup> BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

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

<sup>10</sup> 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.

- <sup>11</sup> 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.  
<sup>12</sup> Model-dependent theoretical analysis of SN 1987A neutrinos.  
<sup>13</sup> Limit applies to  $\nu_\tau$  also.  
<sup>14</sup> These experiments look for  $\nu_k \rightarrow \nu_j \gamma$  or  $\bar{\nu}_k \rightarrow \bar{\nu}_j \gamma$ .  
<sup>15</sup> HENRY 81 uses UV flux from clusters of galaxies to find  $\tau > 1.1 \times 10^{25}$  s for radiative decay.  
<sup>16</sup> KIMBLE 81 uses extreme UV flux limits to find  $\tau > 10^{22-10^{23}}$  s.  
<sup>17</sup> 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.  
<sup>18</sup> DERUJULA 80 finds  $\tau > 3 \times 10^{23}$  s based on CDM neutrino decay contribution to UV background.  
<sup>19</sup> STECKER 80 limit based on UV background; result given is  $\tau > 4 \times 10^{22}$  s at  $m_\nu = 20$  eV.

### $\nu$ CHARGE

<u>VALUE (units: electron charge)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
$< 2 \times 10^{-14}$	<sup>20</sup> RAFFELT	99 ASTR	Red giant luminosity
$< 6 \times 10^{-14}$	<sup>21</sup> RAFFELT	99 ASTR	Solar cooling
<sup>20</sup> This RAFFELT 99 limit applies to all neutrinos which are light enough ( $< 5$ keV) to be emitted from globular-cluster red giants.			
<sup>21</sup> 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.

<u>VALUE (units <math>10^{-4}</math>)</u>	<u>CL%</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>CHG</u>	<u>COMMENT</u>
● ● ● 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  $SU(2) \times U(1)$  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
< <b>6.8</b>	90	22 AUERBACH	01 LSND	$\nu_e e$ scatt.
< 8.5	90	AHRENS	90 CNTR	$\nu_\mu e \rightarrow \nu_\mu e$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
< 0.03		23 RAFFELT	99 ASTR	Red giant luminosity
< 4		24 RAFFELT	99 ASTR	Solar cooling
< 0.62		25 ELMFORS	97 COSM	Depolarization in early universe plasma
< 30	90	VILAIN	95B CHM2	$\nu_\mu e \rightarrow \nu_\mu e$
<100	95	26 DORENBOS...	91 CHRM	$\nu_\mu e \rightarrow \nu_\mu e$
< 7.4	90	27 KRAKAUER	90 CNTR	LAMPF ( $\nu_\mu, \bar{\nu}_\mu$ )e elast.
< 0.02		28 RAFFELT	90 ASTR	Red giant luminosity
< 0.1		29 RAFFELT	89B ASTR	Cooling helium stars
< 0.11		29,30 FUKUGITA	87 ASTR	Cooling helium stars
< 0.0006		31 NUSSINOV	87 ASTR	Cosmic EM backgrounds
< 0.85		30 BEG	78 ASTR	Stellar plasmons
< 81		32 KIM	74 RVUE	$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
< 1		33 BERNSTEIN	63 ASTR	Solar cooling

<sup>22</sup> 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.

<sup>23</sup> 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.

<sup>24</sup> 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.

<sup>25</sup> 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.

<sup>26</sup> 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  $\bar{\nu} e$  elastic scattering and assume  $\mu(\nu) = \mu(\bar{\nu})$ .

<sup>27</sup> KRAKAUER 90 experiment fully reported in ALLEN 93.

<sup>28</sup> 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  $\delta M_C$ .

<sup>29</sup> Significant dependence on details of stellar properties.

<sup>30</sup> If  $m_\nu < 10$  keV.

<sup>31</sup> 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.

<sup>32</sup> KIM 74 is a theoretical analysis of  $\bar{\nu}_\mu$  reaction data.

<sup>33</sup> If  $m_\nu < 1$  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.

<u>VALUE</u> ( $10^{-32}$ cm <sup>2</sup> )	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$<  0.6 $	90	VILAIN	95B CHM2	$\nu e$ elastic scat.
$-1.1 \pm 1.0$		<sup>34</sup> AHRENS	90 CNTR	$\nu e$ elastic scat.
$-0.3 \pm 1.5$		<sup>34</sup> DORENBOS...	89 CHRМ	$\nu e$ elastic scat.
<sup>34</sup> Result is obtained from reanalysis given in ALLEN 91, followed by our reduction to obtain $1\sigma$ errors.				

## $\nu_\mu$ REFERENCES

AUERBACH 01	PR D63 112001	L.B. Auerbach <i>et al.</i>	(LSND Collab.)
RAFFELT 99	PRPL 320 319	G.G. Raffelt	
BILLER 98	PRL 80 2992	S.D. Biller <i>et al.</i>	(WHIPPLE Collab.)
FELDMAN 98	PR D57 3873	G.J. Feldman, R.D. Cousins	
LENZ 98	PL B416 50	S. Lenz <i>et al.</i>	
ELMFORS 97	NP B503 3	P. Elmfors <i>et al.</i>	
ASSAMAGAN 96	PR D53 6065	K.A. Assamagan <i>et al.</i>	(PSI, ZURI, VILL+)
DOLGOV 95	PR D51 4129	A.D. Dolgov, K. Kainulainen, I.Z. Rothstein	(MICH+)
VILAIN 95B	PL B345 115	P. Vilain <i>et al.</i>	(CHARM II Collab.)
ASSAMAGAN 94	PL B335 231	K.A. Assamagan <i>et al.</i>	(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 <i>et al.</i>	(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 <i>et al.</i>	(UCI, LANL, UMD)
DORENBOS... 91	ZPHY C51 142	J. Dorenbosch <i>et al.</i>	(CHARM Collab.)
FULLER 91	PR D43 3136	G.M. Fuller, R.A. Malaney	(UCSD)
KRAKAUER 91	PR D44 R6	D.A. Krakauer <i>et al.</i>	(LAMPF E225 Collab.)
LAM 91	PR D44 3345	W.P. Lam, K.W. Ng	(AST)
AHRENS 90	PR D41 3297	L.A. Ahrens <i>et al.</i>	(BNL, BROW, HIRO+)
KRAKAUER 90	PL B252 177	D.A. Krakauer <i>et al.</i>	(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 <i>et al.</i>	(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 <i>et al.</i>	(ETH, SIN)
FRANK 81	PR D24 2001	J.S. Frank <i>et al.</i>	(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 <i>et al.</i>	(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 <i>et al.</i>	(Gargamelle Collab.)

BARNES	77	PRL 38 1049	V.E. Barnes <i>et al.</i>	(PURD, ANL)
LEE	77C	PR D16 1444	B.W. Lee, R.E. Shrock	(STON)
ALSPECTOR	76	PRL 36 837	J. Alspector <i>et al.</i>	(BNL, PURD, CIT+)
BELLOTTI	76	LNC 17 553	E. Bellotti <i>et al.</i>	(MILA)
CLARK	74	PR D9 533	A.R. Clark <i>et al.</i>	(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+)

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