

# Neutrino Properties

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[Neutrino Properties](#)

## $\bar{\nu}$ MASS (electron based)

Those limits given below are for the square root of  $m_{\nu_e}^{2(\text{eff})} \equiv \sum_i |U_{ei}|^2 m_{\nu_i}^2$ . Limits that come from the kinematics of  ${}^3\text{H}\beta^- \bar{\nu}$  decay are the square roots of the limits for  $m_{\nu_e}^{2(\text{eff})}$ . Obtained from the measurements reported in the Listings for “ $\bar{\nu}$  Mass Squared,” below.

| VALUE (eV)  | CL%   | DOCUMENT ID              | TECN | COMMENT                               |
|---|---|--------------------------|------|---------------------------------------|
| <b>&lt; 2</b>   | <b>OUR EVALUATION</b>   |                          |      |                                       |
| <b>&lt; 2.05</b>                                      | 95  | <sup>1</sup> ASEEV       | 11   | SPEC ${}^3\text{H} \beta$ decay       |
| < 2.3   | 95  | <sup>2</sup> KRAUS       | 05   | SPEC ${}^3\text{H} \beta$ decay       |
| • • •   | We do not use the following data for averages, fits, limits, etc. • • • |                          |      |                                       |
| < 5.8   | 95  | <sup>3</sup> PAGLIAROLI  | 10   | ASTR SN1987A                          |
| < 21.7  | 90  | <sup>4</sup> ARNABOLDI   | 03A  | BOLO ${}^{187}\text{Re} \beta$ -decay |
| < 5.7   | 95  | <sup>5</sup> LOREDO      | 02   | ASTR SN1987A                          |
| < 2.5   | 95  | <sup>6</sup> LOBASHEV    | 99   | SPEC ${}^3\text{H} \beta$ decay       |
| < 2.8   | 95  | <sup>7</sup> WEINHEIMER  | 99   | SPEC ${}^3\text{H} \beta$ decay       |
| < 4.35  | 95  | <sup>8</sup> BELESEV     | 95   | SPEC ${}^3\text{H} \beta$ decay       |
| < 12.4  | 95  | <sup>9</sup> CHING       | 95   | SPEC ${}^3\text{H} \beta$ decay       |
| < 92  | 95  | <sup>10</sup> HIDDEMANN  | 95   | SPEC ${}^3\text{H} \beta$ decay       |
| 15 $\begin{smallmatrix} +32 \\ -15 \end{smallmatrix}$ |   | HIDDEMANN                | 95   | SPEC ${}^3\text{H} \beta$ decay       |
| < 19.6  | 95  | KERNAN                   | 95   | ASTR SN 1987A                         |
| < 7.0   | 95  | <sup>11</sup> STOEFFL    | 95   | SPEC ${}^3\text{H} \beta$ decay       |
| < 7.2   | 95  | <sup>12</sup> WEINHEIMER | 93   | SPEC ${}^3\text{H} \beta$ decay       |
| < 11.7  | 95  | <sup>13</sup> HOLZSCHUH  | 92B  | SPEC ${}^3\text{H} \beta$ decay       |
| < 13.1  | 95  | <sup>14</sup> KAWAKAMI   | 91   | SPEC ${}^3\text{H} \beta$ decay       |
| < 9.3   | 95  | <sup>15</sup> ROBERTSON  | 91   | SPEC ${}^3\text{H} \beta$ decay       |
| < 14  | 95  | AVIGNONE                 | 90   | ASTR SN 1987A                         |
| < 16  |   | SPERGEL                  | 88   | ASTR SN 1987A                         |
| 17 to 40  |   | <sup>16</sup> BORIS      | 87   | SPEC ${}^3\text{H} \beta$ decay       |

<sup>1</sup> ASEEV 11 report the analysis of the entire beta endpoint data, taken with the Troitsk integrating electrostatic spectrometer between 1997 and 2002 (some of the earlier runs were rejected), using a windowless gaseous tritium source. The fitted value of  $m_{\nu}$ , based on the method of Feldman and Cousins, is obtained from the upper limit of the fit for  $m_{\nu}^2$ . Previous analysis problems were resolved by careful monitoring of the tritium gas column density. Supersedes LOBASHEV 99 and BELESEV 95.

<sup>2</sup> KRAUS 05 is a continuation of the work reported in WEINHEIMER 99. This result represents the final analysis of data taken from 1997 to 2001. Various sources of systematic uncertainties have been identified and quantified. The background has been reduced compared to the initial running period. A spectral anomaly at the endpoint, reported in LOBASHEV 99, was not observed.

- <sup>3</sup> PAGLIAROLI 10 is critical of the likelihood method used by LOREDO 02.
- <sup>4</sup> ARNABOLDI 03A *etal.* report kinematical neutrino mass limit using  $\beta$ -decay of  $^{187}\text{Re}$ . Bolometric  $\text{AgReO}_4$  micro-calorimeters are used. Mass bound is substantially weaker than those derived from tritium  $\beta$ -decays but has different systematic uncertainties.
- <sup>5</sup> LOREDO 02 updates LOREDO 89.
- <sup>6</sup> LOBASHEV 99 report a new measurement which continues the work reported in BELESEV 95. This limit depends on phenomenological fit parameters used to derive their best fit to  $m_\nu^2$ , making unambiguous interpretation difficult. See the footnote under " $\bar{\nu}$  Mass Squared."
- <sup>7</sup> WEINHEIMER 99 presents two analyses which exclude the spectral anomaly and result in an acceptable  $m_\nu^2$ . We report the most conservative limit, but the other is nearly the same. See the footnote under " $\bar{\nu}$  Mass Squared."
- <sup>8</sup> BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. A fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly) plus a monochromatic line 7–15 eV below the endpoint yields  $m_\nu^2 = -4.1 \pm 10.9 \text{ eV}^2$ , leading to this Bayesian limit.
- <sup>9</sup> CHING 95 quotes results previously given by SUN 93; no experimental details are given. A possible explanation for consistently negative values of  $m_\nu^2$  is given.
- <sup>10</sup> HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. Bayesian limit calculated from the weighted mean  $m_\nu^2 = 221 \pm 4244 \text{ eV}^2$  from the two runs listed below.
- <sup>11</sup> STOEFFL 95 (LLNL) result is the Bayesian limit obtained from the  $m_\nu^2$  errors given below but with  $m_\nu^2$  set equal to 0. The anomalous endpoint accumulation leads to a value of  $m_\nu^2$  which is negative by more than 5 standard deviations.
- <sup>12</sup> WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium  $\beta$  spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.
- <sup>13</sup> HOLZSCHUH 92B (Zurich) result is obtained from the measurement  $m_\nu^2 = -24 \pm 48 \pm 61$  ( $1\sigma$  errors), in  $\text{eV}^2$ , using the PDG prescription for conversion to a limit in  $m_\nu$ .
- <sup>14</sup> KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid. This result is the Bayesian limit obtained from the  $m_\nu^2$  limit with the errors combined in quadrature. This was also done in ROBERTSON 91, although the authors report a different procedure.
- <sup>15</sup> ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that  $m_\nu$  lies between 17 and 40 eV. However, the probability of a positive  $m^2$  is only 3% if statistical and systematic error are combined in quadrature.
- <sup>16</sup> See also comment in BORIS 87B and erratum in BORIS 88.

### $\bar{\nu}$ MASS SQUARED (electron based)

Given troubling systematics which result in improbably negative estimators of  $m_{\nu_e}^{2(\text{eff})} \equiv \sum_i |U_{ei}|^2 m_{\nu_i}^2$ , in many experiments, we use only KRAUS 05 and LOBASHEV 99 for our average.

| VALUE ( $\text{eV}^2$ )           | CL%                | DOCUMENT ID        | TECN | COMMENT                         |
|-----------------------------------|--------------------|--------------------|------|---------------------------------|
| – <b>0.6 <math>\pm</math> 1.9</b> | <b>OUR AVERAGE</b> |                    |      |                                 |
| – 0.67 $\pm$ 2.53                 |                    | <sup>1</sup> ASEEV | 11   | SPEC $^3\text{H}$ $\beta$ decay |
| – 0.6 $\pm$ 2.2 $\pm$ 2.1         |                    | <sup>2</sup> KRAUS | 05   | SPEC $^3\text{H}$ $\beta$ decay |

• • • We do not use the following data for averages, fits, limits, etc. • • •

|                   |                             |      |                        |
|-------------------|-----------------------------|------|------------------------|
| – 1.9 ± 3.4 ± 2.2 | <sup>3</sup> LOBASHEV 99    | SPEC | <sup>3</sup> H β decay |
| – 3.7 ± 5.3 ± 2.1 | <sup>4</sup> WEINHEIMER 99  | SPEC | <sup>3</sup> H β decay |
| – 22 ± 4.8        | <sup>5</sup> BELESEV 95     | SPEC | <sup>3</sup> H β decay |
| 129 ± 6010        | <sup>6</sup> HIDDEMANN 95   | SPEC | <sup>3</sup> H β decay |
| 313 ± 5994        | <sup>6</sup> HIDDEMANN 95   | SPEC | <sup>3</sup> H β decay |
| –130 ± 20 ± 15 95 | <sup>7</sup> STOEFFL 95     | SPEC | <sup>3</sup> H β decay |
| – 31 ± 75 ± 48    | <sup>8</sup> SUN 93         | SPEC | <sup>3</sup> H β decay |
| – 39 ± 34 ± 15    | <sup>9</sup> WEINHEIMER 93  | SPEC | <sup>3</sup> H β decay |
| – 24 ± 48 ± 61    | <sup>10</sup> HOLZSCHUH 92B | SPEC | <sup>3</sup> H β decay |
| – 65 ± 85 ± 65    | <sup>11</sup> KAWAKAMI 91   | SPEC | <sup>3</sup> H β decay |
| –147 ± 68 ± 41    | <sup>12</sup> ROBERTSON 91  | SPEC | <sup>3</sup> H β decay |

<sup>1</sup> ASEEV 11 report the analysis of the entire beta endpoint data, taken with the Troitsk integrating electrostatic spectrometer between 1997 and 2002, using a windowless gaseous tritium source. The analysis does not use the two additional fit parameters (see LOBASHEV 99) for a step-like structure near the endpoint. Using only the runs where the tritium gas column density was carefully monitored the need for such parameters was eliminated. Supersedes LOBASHEV 99 and BELESEV 95.

<sup>2</sup> KRAUS 05 is a continuation of the work reported in WEINHEIMER 99. This result represents the final analysis of data taken from 1997 to 2001. Problems with significantly negative squared neutrino masses, observed in some earlier experiments, have been resolved in this work.

<sup>3</sup> LOBASHEV 99 report a new measurement which continues the work reported in BELESEV 95. The data were corrected for electron trapping effects in the source, eliminating the dependence of the fitted neutrino mass on the fit interval. The analysis assuming a pure beta spectrum yields significantly negative fitted  $m_\nu^2 \approx -(20-10) \text{ eV}^2$ . This problem is attributed to a discrete spectral anomaly of about  $6 \times 10^{-11}$  intensity with a time-dependent energy of 5–15 eV below the endpoint. The data analysis accounts for this anomaly by introducing two extra phenomenological fit parameters resulting in a best fit of  $m_\nu^2 = -1.9 \pm 3.4 \pm 2.2 \text{ eV}^2$  which is used to derive a neutrino mass limit. However, the introduction of phenomenological fit parameters which are correlated with the derived  $m_\nu^2$  limit makes unambiguous interpretation of this result difficult.

<sup>4</sup> WEINHEIMER 99 is a continuation of the work reported in WEINHEIMER 93. Using a lower temperature of the frozen tritium source eliminated the dewetting of the  $T_2$  film, which introduced a dependence of the fitted neutrino mass on the fit interval in the earlier work. An indication for a spectral anomaly reported in LOBASHEV 99 has been seen, but its time dependence does not agree with LOBASHEV 99. Two analyses, which exclude the spectral anomaly either by choice of the analysis interval or by using a particular data set which does not exhibit the anomaly, result in acceptable  $m_\nu^2$  fits and are used to derive the neutrino mass limit published by the authors. We list the most conservative of the two.

<sup>5</sup> BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. This value comes from a fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly), including the effects of an apparent peak 7–15 eV below the endpoint.

<sup>6</sup> HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. They quote measurements from two data sets.

<sup>7</sup> STOEFFL 95 (LLNL) uses a gaseous source of molecular tritium. An anomalous pileup of events at the endpoint leads to the negative value for  $m_\nu^2$ . The authors acknowledge that “the negative value for the best fit of  $m_\nu^2$  has no physical meaning” and discuss possible explanations for this effect.

<sup>8</sup> SUN 93 uses a tritiated hydrocarbon source. See also CHING 95.

- <sup>9</sup>WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium  $\beta$  spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.
- <sup>10</sup>HOLZSCHUH 92B (Zurich) source is a monolayer of tritiated hydrocarbon.
- <sup>11</sup>KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid.
- <sup>12</sup>ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that  $m_\nu$  lies between 17 and 40 eV. However, the probability of a positive  $m_\nu^2$  is only 3% if statistical and systematic error are combined in quadrature.

### $\nu$ MASS (electron based)

These are measurement of  $m_\nu$  (in contrast to  $m_{\bar{\nu}}$ , given above). The masses can be different for a Dirac neutrino in the absence of  $CPT$  invariance. The possible distinction between  $\nu$  and  $\bar{\nu}$  properties is usually ignored elsewhere in these Listings.

| VALUE (eV) | CL% | DOCUMENT ID | TECN | COMMENT                 |
|------------|-----|-------------|------|-------------------------|
| <460       | 68  | YASUMI 94   | CNTR | $^{163}\text{Ho}$ decay |
| <225       | 95  | SPRINGER 87 | CNTR | $^{163}\text{Ho}$ decay |

### $\nu$ MASS (muon based)

Limits given below are for the square root of  $m_{\nu\mu}^{2(\text{eff})} \equiv \sum_i |U_{\mu i}|^2 m_{\nu_i}^2$ .

In some of the 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 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.

### $\nu$ MASS (tau based)

The limits given below are the square roots of limits for  $m_{\nu_{\tau}}^{2(\text{eff})} \equiv \sum_i |U_{\tau i}|^2 m_{\nu_i}^2$ .

In some of the ASTR and COSM papers listed below, the authors did not distinguish between weak and mass eigenstates.

| VALUE (MeV)   | CL% | EVTs | DOCUMENT ID      | TECN | COMMENT   |
|---|-----|------|------------------|------|---|
| <b>&lt; 18.2</b>  | 95  |      | 1 BARATE 98F     | ALEP | 1991–1995 LEP runs  |
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |      |                  |      |   |
| < 28  | 95  |      | 2 ATHANAS 00     | CLEO | $E_{\text{cm}}^{ee} = 10.6 \text{ GeV}$                                   |
| < 27.6  | 95  |      | 3 ACKERSTAFF 98T | OPAL | 1990–1995 LEP runs  |
| < 30  | 95  | 473  | 4 AMMAR 98       | CLEO | $E_{\text{cm}}^{ee} = 10.6 \text{ GeV}$                                   |
| < 60  | 95  |      | 5 ANASTASSOV 97  | CLEO | $E_{\text{cm}}^{ee} = 10.6 \text{ GeV}$                                   |
| < 0.37 or > 22  |     |      | 6 FIELDS 97      | COSM | Nucleosynthesis   |
| < 68  | 95  |      | 7 SWAIN 97       | THEO | $m_{\tau}, \tau_{\tau}, \tau$ partial widths                              |
| < 29.9  | 95  |      | 8 ALEXANDER 96M  | OPAL | 1990–1994 LEP runs  |
| < 149   |     |      | 9 BOTTINO 96     | THEO | $\pi, \mu, \tau$ leptonic decays  |
| < 1 or > 25   |     |      | 10 HANNESTAD 96C | COSM | Nucleosynthesis   |
| < 71  | 95  |      | 11 SOBIE 96      | THEO | $m_{\tau}, \tau_{\tau}, B(\tau^- \rightarrow e^- \bar{\nu}_e \nu_{\tau})$ |
| < 24  | 95  | 25   | 12 BUSKULIC 95H  | ALEP | 1991–1993 LEP runs  |
| < 0.19  |     |      | 13 DOLGOV 95     | COSM | Nucleosynthesis   |
| < 3   |     |      | 14 SIGL 95       | ASTR | SN 1987A  |
| < 0.4 or > 30   |     |      | 15 DODELSON 94   | COSM | Nucleosynthesis   |
| < 0.1 or > 50   |     |      | 16 KAWASAKI 94   | COSM | Nucleosynthesis   |
| 155–225   |     |      | 17 PERES 94      | THEO | $\pi, K, \mu, \tau$ weak decays   |
| < 32.6  | 95  | 113  | 18 CINABRO 93    | CLEO | $E_{\text{cm}}^{ee} \approx 10.6 \text{ GeV}$                             |
| < 0.3 or > 35   |     |      | 19 DOLGOV 93     | COSM | Nucleosynthesis   |
| < 0.74  |     |      | 20 ENQVIST 93    | COSM | Nucleosynthesis   |
| < 31  | 95  | 19   | 21 ALBRECHT 92M  | ARG  | $E_{\text{cm}}^{ee} = 9.4\text{--}10.6 \text{ GeV}$                       |
| < 0.3   |     |      | 22 FULLER 91     | COSM | Nucleosynthesis   |
| < 0.5 or > 25   |     |      | 23 KOLB 91       | COSM | Nucleosynthesis   |
| < 0.42  |     |      | 22 LAM 91        | COSM | Nucleosynthesis   |

- <sup>1</sup> BARATE 98F result based on kinematics of 2939  $\tau^- \rightarrow 2\pi^- \pi^+ \nu_\tau$  and 52  $\tau^- \rightarrow 3\pi^- 2\pi^+ (\pi^0) \nu_\tau$  decays. If possible 2.5% excited  $a_1$  decay is included in 3-prong sample analysis, limit increases to 19.2 MeV.
- <sup>2</sup> ATHANAS 00 bound comes from analysis of  $\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$  decays.
- <sup>3</sup> ACKERSTAFF 98T use  $\tau \rightarrow 5\pi^\pm \nu_\tau$  decays to obtain a limit of 43.2 MeV (95%CL). They combine this with ALEXANDER 96M value using  $\tau \rightarrow 3h^\pm \nu_\tau$  decays to obtain quoted limit.
- <sup>4</sup> AMMAR 98 limit comes from analysis of  $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$  and  $\tau^- \rightarrow 2\pi^- \pi^+ 2\pi^0 \nu_\tau$  decay modes.
- <sup>5</sup> ANASTASSOV 97 derive limit by comparing their  $m_\tau$  measurement (which depends on  $m_{\nu_\tau}$ ) to BAI 96  $m_\tau$  threshold measurement.
- <sup>6</sup> FIELDS 97 limit for a Dirac neutrino. For a Majorana neutrino the mass region  $< 0.93$  or  $> 31$  MeV is excluded. These bounds assume  $N_\nu < 4$  from nucleosynthesis; a wider excluded region occurs with a smaller  $N_\nu$  upper limit.
- <sup>7</sup> SWAIN 97 derive their limit from the Standard Model relationships between the tau mass, lifetime, branching fractions for  $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ ,  $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ ,  $\tau^- \rightarrow \pi^- \nu_\tau$ , and  $\tau^- \rightarrow K^- \nu_\tau$ , and the muon mass and lifetime by assuming lepton universality and using world average values. Limit is reduced to 48 MeV when the CLEO  $\tau$  mass measurement (BALEST 93) is included; see CLEO's more recent  $m_{\nu_\tau}$  limit (ANASTASSOV 97).  
Consideration of mixing with a fourth generation heavy neutrino yields  $\sin^2 \theta_L < 0.016$  (95%CL).
- <sup>8</sup> ALEXANDER 96M bound comes from analyses of  $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$  and  $\tau^- \rightarrow h^- h^- h^+ \nu_\tau$  decays.
- <sup>9</sup> BOTTINO 96 assumes three generations of neutrinos with mixing, finds consistency with massless neutrinos with no mixing based on 1995 data for masses, lifetimes, and leptonic partial widths.
- <sup>10</sup> HANNESTAD 96C limit is on the mass of a Majorana neutrino. This bound assumes  $N_\nu < 4$  from nucleosynthesis. A wider excluded region occurs with a smaller  $N_\nu$  upper limit. This paper is the corrected version of HANNESTAD 96; see the erratum: HANNESTAD 96B.
- <sup>11</sup> SOBIE 96 derive their limit from the Standard Model relationship between the tau mass, lifetime, and leptonic branching fraction, and the muon mass and lifetime, by assuming lepton universality and using world average values.
- <sup>12</sup> BUSKULIC 95H bound comes from a two-dimensional fit of the visible energy and invariant mass distribution of  $\tau \rightarrow 5\pi(\pi^0) \nu_\tau$  decays. Replaced by BARATE 98F.
- <sup>13</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. DOLGOV 96 argues that a possible window near 20 MeV is excluded.
- <sup>14</sup> SIGL 95 exclude massive Dirac or Majorana neutrinos with lifetimes between  $10^{-3}$  and  $10^8$  seconds if the decay products are predominantly  $\gamma$  or  $e^+ e^-$ .
- <sup>15</sup> DODELSON 94 calculate constraints on  $\nu_\tau$  mass and lifetime from nucleosynthesis for 4 generic decay modes. Limits depend strongly on decay mode. Quoted limit is valid for all decay modes of Majorana neutrinos with lifetime greater than about 300 s. For Dirac neutrinos limits change to  $< 0.3$  or  $> 33$ .
- <sup>16</sup> KAWASAKI 94 excluded region is for Majorana neutrino with lifetime  $> 1000$  s. Other limits are given as a function of  $\nu_\tau$  lifetime for decays of the type  $\nu_\tau \rightarrow \nu_\mu \phi$  where  $\phi$  is a Nambu-Goldstone boson.
- <sup>17</sup> PERES 94 used PDG 92 values for parameters to obtain a value consistent with mixing. Reexamination by BOTTINO 96 which included radiative corrections and 1995 PDG parameters resulted in two allowed regions,  $m_3 < 70$  MeV and  $140 \text{ MeV} < m_3 < 149$  MeV.
- <sup>18</sup> CINABRO 93 bound comes from analysis of  $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$  and  $\tau^- \rightarrow 2\pi^- \pi^+ 2\pi^0 \nu_\tau$  decay modes.

- <sup>19</sup> DOLGOV 93 assumes neutrino lifetime  $>100$  s. For Majorana neutrinos, the low mass limit is 0.5 MeV. KAWANO 92 points out that these bounds can be overcome for a Dirac neutrino if it possesses a magnetic moment. See also DOLGOV 96.
- <sup>20</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,  $\sim 1$  s.
- <sup>21</sup> ALBRECHT 92M reports measurement of a slightly lower  $\tau$  mass, which has the effect of reducing the  $\nu_\tau$  mass reported in ALBRECHT 88B. Bound is from analysis of  $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$  mode.
- <sup>22</sup> Assumes neutrino lifetime  $>1$  s. For Dirac neutrinos. See also ENQVIST 93.
- <sup>23</sup> KOLB 91 exclusion region is for Dirac neutrino with lifetime  $>1$  s; other limits are given.

See the related review(s):  
[Sum of Neutrino Masses](#)

### SUM OF THE NEUTRINO MASSES, $m_{\text{tot}}$

This is a sum of the neutrino masses,  $m_{\text{tot}}$ , as defined in the above note, of effectively stable neutrinos, i.e. those with mean lifetimes on cosmological scales. When necessary, we have generalized the results reported so they apply to  $m_{\text{tot}}$ . For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85. For more information see a note on "Neutrinos in Cosmology" in this *Review*.

| VALUE (eV)  | CL% | DOCUMENT ID                   | TECN | COMMENT               |
|---|-----|-------------------------------|------|-----------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                               |      |                       |
| < 0.152   | 95  | <sup>1</sup> CHOUDHURY 18     | COSM |                       |
| 0.064 $^{+0.061}_{-0.005}$  | 95  | <sup>2</sup> SIMPSON 17       | COSM |                       |
| < 0.151   | 95  | <sup>3</sup> VAGNOZZI 17      | COSM |                       |
| < 0.14  | 95  | <sup>4</sup> YECHE 17         | COSM | BOSS and XQ-100       |
| < 0.0926  | 90  | <sup>5</sup> DIVALENTINO 16   | COSM |                       |
| < 0.18  | 95  | <sup>6</sup> HUANG 16         | COSM | Normal mass hierarchy |
| < 0.14  | 95  | <sup>7</sup> ROSSI 15         | COSM |                       |
| < 0.23  | 95  | <sup>8</sup> ADE 14           | COSM | Planck                |
| 0.320 $\pm 0.081$   |     | <sup>9</sup> BATTYE 14        | COSM |                       |
| 0.35 $\pm 0.10$   |     | <sup>10</sup> BEUTLER 14      | COSM | BOSS                  |
| 0.22 $^{+0.09}_{-0.10}$   |     | <sup>11</sup> COSTANZI 14     | COSM |                       |
| < 0.22  | 95  | <sup>12</sup> GIUSARMA 14     | COSM |                       |
| 0.32 $\pm 0.11$   |     | <sup>13</sup> HOU 14          | COSM |                       |
| < 0.26  | 95  | <sup>14</sup> LEISTEDT 14     | COSM |                       |
| < 0.18  | 95  | <sup>15</sup> RIEMER-SOR...14 | COSM |                       |
| < 0.24  | 68  | <sup>16</sup> MORESCO 12      | COSM |                       |
| < 0.29  | 95  | <sup>17</sup> XIA 12          | COSM |                       |
| < 0.81  | 95  | <sup>18</sup> SAITO 11        | COSM | SDSS                  |
| < 0.44  | 95  | <sup>19</sup> HANNESTAD 10    | COSM |                       |
| < 0.6   | 95  | <sup>20</sup> SEKIGUCHI 10    | COSM |                       |
| < 0.28  | 95  | <sup>21</sup> THOMAS 10       | COSM |                       |
| < 1.1   |     | <sup>22</sup> ICHIKI 09       | COSM |                       |

|            |    |    |             |    |      |                        |
|------------|----|----|-------------|----|------|------------------------|
| < 1.3      | 95 | 23 | KOMATSU     | 09 | COSM | WMAP                   |
| < 1.2      |    | 24 | TERENO      | 09 | COSM |                        |
| < 0.33     |    | 25 | VIKHLININ   | 09 | COSM |                        |
| < 0.28     |    | 26 | BERNARDIS   | 08 | COSM |                        |
| < 0.17–2.3 |    | 27 | FOGLI       | 07 | COSM |                        |
| < 0.42     | 95 | 28 | KRISTIANSEN | 07 | COSM |                        |
| < 0.63–2.2 |    | 29 | ZUNCKEL     | 07 | COSM |                        |
| < 0.24     | 95 | 30 | CIRELLI     | 06 | COSM |                        |
| < 0.62     | 95 | 31 | HANNESTAD   | 06 | COSM |                        |
| < 1.2      |    | 32 | SANCHEZ     | 06 | COSM |                        |
| < 0.17     | 95 | 30 | SELJAK      | 06 | COSM |                        |
| < 2.0      | 95 | 33 | ICHIKAWA    | 05 | COSM |                        |
| < 0.75     |    | 34 | BARGER      | 04 | COSM |                        |
| < 1.0      |    | 35 | CROTTY      | 04 | COSM |                        |
| < 0.7      |    | 36 | SPERGEL     | 03 | COSM | WMAP                   |
| < 0.9      |    | 37 | LEWIS       | 02 | COSM |                        |
| < 4.2      |    | 38 | WANG        | 02 | COSM | CMB                    |
| < 2.7      |    | 39 | FUKUGITA    | 00 | COSM |                        |
| < 5.5      |    | 40 | CROFT       | 99 | ASTR | Ly $\alpha$ power spec |
| <180       |    |    | SZALAY      | 74 | COSM |                        |
| <132       |    |    | COWSIK      | 72 | COSM |                        |
| <280       |    |    | MARX        | 72 | COSM |                        |
| <400       |    |    | GERSHTEIN   | 66 | COSM |                        |

<sup>1</sup> CHOUDHURY 18 combines 2015 Planck CMB temperature data, information from the optical depth to reionization from Planck 2016 intermediate results together with baryon acoustic oscillation data from BOSS, MGS, and 6dFGS as well as supernovae Type Ia data from the Pantheon Sample. The limit is strengthened to 0.118 eV when high- $l$  CMB polarization data is also included.

<sup>2</sup> SIMPSON 17 uses a combination of laboratory and cosmological measurements to determine the light neutrino masses and argue that there is strong evidence for the normal mass ordering.

<sup>3</sup> Combines temperature anisotropies of the CMB from Planck with data on baryon acoustic oscillations and the optical depth to reionization. Limit is strengthened to 0.118 when high multipole polarization data is included. Updates GIUSARMA 16.

<sup>4</sup> Constrains the total mass of neutrinos using the Lyman-alpha forest power spectrum with BOSS (mid-resolution), XQ-100 (high-resolution) and CMB. Without the CMB data, the limit relaxes to 0.8 eV. Supersedes PALANQUE-DELABROUILLE 15A.

<sup>5</sup> Constrains the total mass of neutrinos from Planck CMB data combined with baryon acoustic oscillation and Planck cluster data.

<sup>6</sup> Constrains the total mass of neutrinos from BAO data from SDSS-III/BOSS combined with CMB data from Planck. Limit quoted for normal mass hierarchy. The limit for the inverted mass hierarchy is 0.20 eV and for the degenerate mass hierarchy it is 0.15 eV.

<sup>7</sup> ROSSI 15 sets limits on the sum of neutrino masses using BOSS Lyman alpha forest data combined with Planck CMB data and baryon acoustic oscillations.

<sup>8</sup> Constrains the total mass of neutrinos from Planck CMB data along with WMAP polarization, high  $L$ , and BAO data.

<sup>9</sup> Finite neutrino mass fit to resolve discrepancy between CMB and lensing measurements.

<sup>10</sup> Fit to the total mass of neutrinos from BOSS data along with WMAP CMB data and data from other BAO constraints and weak lensing.

<sup>11</sup> Fit to the total mass of neutrinos from Planck CMB data along with BAO.

<sup>12</sup> Constrains the total mass of neutrinos from Planck CMB data combined with baryon acoustic oscillation data from BOSS and HST data on the Hubble parameter.

<sup>13</sup> Fit based on the SPT-SZ survey combined with CMB, BAO, and  $H_0$  data.



- 14 Constrains the total mass of neutrinos (marginalizing over the effective number of neutrino species) from CMB, CMB lensing, BAO, and galaxy clustering data.
- 15 Constrains the total mass of neutrinos from Planck CMB data combined with baryon acoustic oscillation data from BOSS, 6dFGS, SDSS, WiggleZ data on the galaxy power spectrum, and HST data on the Hubble parameter. The limit is increased to 0.25 eV if a lower bound to the sum of neutrino masses of 0.04 eV is assumed.
- 16 Constrains the total mass of neutrinos from observational Hubble parameter data with seven-year WMAP data and the most recent estimate of  $H_0$ .
- 17 Constrains the total mass of neutrinos from the CFHTLS combined with seven-year WMAP data and a prior on the Hubble parameter. Limit is relaxed to 0.41 eV when small scales affected by non-linearities are removed.
- 18 Constrains the total mass of neutrinos from the Sloan Digital Sky Survey and the five-year WMAP data.
- 19 Constrains the total mass of neutrinos from the 7-year WMAP data including SDSS and HST data. Limit relaxes to 1.19 eV when CMB data is used alone. Supersedes HANNESTAD 06.
- 20 Constrains the total mass of neutrinos from a combination of CMB data, a recent measurement of  $H_0$  (SHOES), and baryon acoustic oscillation data from SDSS.
- 21 Constrains the total mass of neutrinos from SDSS MegaZ LRG DR7 galaxy clustering data combined with CMB, HST, supernovae and baryon acoustic oscillation data. Limit relaxes to 0.47 eV when the equation of state parameter,  $w \neq 1$ .
- 22 Constrains the total mass of neutrinos from weak lensing measurements when combined with CMB. Limit improves to 0.54 eV when supernovae and baryon acoustic oscillation observations are included. Assumes  $\Lambda$ CDM model.
- 23 Constrains the total mass of neutrinos from five-year WMAP data. Limit improves to 0.67 eV when supernovae and baryon acoustic oscillation observations are included. Limits quoted assume the  $\Lambda$ CDM model. Supersedes SPERGEL 07.
- 24 Constrains the total mass of neutrinos from weak lensing measurements when combined with CMB. Limit improves to  $0.03 < \Sigma m_\nu < 0.54$  eV when supernovae and baryon acoustic oscillation observations are included. The slight preference for massive neutrinos at the two-sigma level disappears when systematic errors are taken into account. Assumes  $\Lambda$ CDM model.
- 25 Constrains the total mass of neutrinos from recent Chandra X-ray observations of galaxy clusters when combined with CMB, supernovae, and baryon acoustic oscillation measurements. Assumes flat universe and constant dark-energy equation of state,  $w$ .
- 26 Constrains the total mass of neutrinos from recent CMB and SOSS LRG power spectrum data along with bias mass relations from SDSS, DEEP2, and Lyman-Break Galaxies. It assumes  $\Lambda$ CDM model. Limit degrades to 0.59 eV in a more general  $w$ CDM model.
- 27 Constrains the total mass of neutrinos from neutrino oscillation experiments and cosmological data. The most conservative limit uses only WMAP three-year data, while the most stringent limit includes CMB, large-scale structure, supernova, and Lyman-alpha data.
- 28 Constrains the total mass of neutrinos from recent CMB, large scale structure, SN1a, and baryon acoustic oscillation data. The limit relaxes to 1.75 when WMAP data alone is used with no prior. Paper shows results with several combinations of data sets. Supersedes KRISTIANSEN 06.
- 29 Constrains the total mass of neutrinos from the CMB and the large scale structure data. The most conservative limit is obtained when generic initial conditions are allowed.
- 30 Constrains the total mass of neutrinos from recent CMB, large scale structure, Lyman-alpha forest, and SN1a data.
- 31 Constrains the total mass of neutrinos from recent CMB and large scale structure data. See also GOOBAR 06. Superseded by HANNESTAD 10.
- 32 Constrains the total mass of neutrinos from the CMB and the final 2dF Galaxy Redshift Survey.
- 33 Constrains the total mass of neutrinos from the CMB experiments alone, assuming  $\Lambda$ CDM Universe. FUKUGITA 06 show that this result is unchanged by the 3-year WMAP data.

- <sup>34</sup> Constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the Sloan Digital Sky Survey and the 2dF galaxy redshift survey, WMAP and 27 other CMB experiments and measurements by the HST Key project.
- <sup>35</sup> Constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the Sloan Digital Sky Survey, the 2dF galaxy redshift survey, WMAP and ACBAR. The limit is strengthened to 0.6 eV when measurements by the HST Key project and supernovae data are included.
- <sup>36</sup> Constrains the fractional contribution of neutrinos to the total matter density in the Universe from WMAP data combined with other CMB measurements, the 2dfGRS data, and Lyman  $\alpha$  data. The limit does not noticeably change if the Lyman  $\alpha$  data are not used.
- <sup>37</sup> LEWIS 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB, HST Key project, 2dF galaxy redshift survey, supernovae type Ia, and BBN.
- <sup>38</sup> WANG 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB and other cosmological data sets such as galaxy clustering and the Lyman  $\alpha$  forest.
- <sup>39</sup> FUKUGITA 00 is a limit on neutrino masses from structure formation. The constraint is based on the clustering scale  $\sigma_8$  and the COBE normalization and leads to a conservative limit of 0.9 eV assuming 3 nearly degenerate neutrinos. The quoted limit is on the sum of the light neutrino masses.
- <sup>40</sup> CROFT 99 result based on the power spectrum of the Ly  $\alpha$  forest. If  $\Omega_{\text{matter}} < 0.5$ , the limit is improved to  $m_\nu < 2.4 (\Omega_{\text{matter}}/0.17-1)$  eV.

### Limits on MASSES of Light Stable Right-Handed $\nu$ (with necessarily suppressed interaction strengths)

| VALUE (eV)  | DOCUMENT ID        | TECN | COMMENT             |
|---|--------------------|------|---------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |                    |      |                     |
| <100–200  | <sup>1</sup> OLIVE | 82   | COSM Dirac $\nu$    |
| <200–2000   | <sup>1</sup> OLIVE | 82   | COSM Majorana $\nu$ |
| <sup>1</sup> Depending on interaction strength $G_R$ where $G_R < G_F$ .      |                    |      |                     |

### Limits on MASSES of Heavy Stable Right-Handed $\nu$ (with necessarily suppressed interaction strengths)

| VALUE (GeV)  | DOCUMENT ID        | TECN | COMMENT               |
|--|--------------------|------|-----------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●  |                    |      |                       |
| > 10   | <sup>1</sup> OLIVE | 82   | COSM $G_R/G_F < 0.1$  |
| >100   | <sup>1</sup> OLIVE | 82   | COSM $G_R/G_F < 0.01$ |
| <sup>1</sup> These results apply to heavy Majorana neutrinos and are summarized by the equation: $m_\nu > 1.2 \text{ GeV } (G_F/G_R)$ . The bound saturates, and if $G_R$ is too small no mass range is allowed. |                    |      |                       |

### $\nu$ CHARGE

| VALUE (units: electron charge)  | CL% | DOCUMENT ID              | TECN | COMMENT                   |
|---|-----|--------------------------|------|---------------------------|
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                          |      |                           |
| <3 $\times 10^{-8}$   | 95  | <sup>1</sup> DELLA-VALLE | 16   | LASR Magnetic dichroism   |
| <2.1 $\times 10^{-12}$  | 90  | <sup>2</sup> CHEN        | 14A  | TEXO Nuclear reactor      |
| <1.5 $\times 10^{-12}$  | 90  | <sup>3</sup> STUDENIKIN  | 14   | Nuclear reactor           |
| <3.7 $\times 10^{-12}$  | 90  | <sup>4</sup> GNINENKO    | 07   | RVUE Nuclear reactor      |
| <2 $\times 10^{-14}$  |     | <sup>5</sup> RAFFELT     | 99   | ASTR Red giant luminosity |

|                        |               |    |      |                               |
|------------------------|---------------|----|------|-------------------------------|
| <6 × 10 <sup>-14</sup> | 6 RAFFELT     | 99 | ASTR | Solar cooling                 |
| <4 × 10 <sup>-4</sup>  | 7 BABU        | 94 | RVUE | BEBC beam dump                |
| <3 × 10 <sup>-4</sup>  | 8 DAVIDSON    | 91 | RVUE | SLAC e <sup>-</sup> beam dump |
| <2 × 10 <sup>-15</sup> | 9 BARBIELLINI | 87 | ASTR | SN 1987A                      |
| <1 × 10 <sup>-13</sup> | 10 BERNSTEIN  | 63 | ASTR | Solar energy losses           |

- <sup>1</sup> DELLA-VALLE 16 obtain a limit on the charge of neutrinos valid for masses of less than 10 meV. For heavier neutrinos the limit increases as a power of mass, reaching 10<sup>-6</sup> e for  $m = 100$  meV.
- <sup>2</sup> CHEN 14A use the Multi-Configuration RRPA method to analyze reactor  $\bar{\nu}_e$  scattering on Ge atoms with 300 eV recoil energy threshold to obtain this limit.
- <sup>3</sup> STUDENIKIN 14 uses the limit on  $\mu_\nu$  from BEDA 13 and the 2.8 keV threshold of the electron recoil energy to obtain this limit.
- <sup>4</sup> GNINENKO 07 use limit on  $\bar{\nu}_e$  magnetic moment from LI 03B to derive this result. The limit is considerably weaker than the limits on the charge of  $\nu_e$  and  $\bar{\nu}_e$  from various astrophysics considerations.
- <sup>5</sup> This RAFFELT 99 limit applies to all neutrino flavors which are light enough (<5 keV) to be emitted from globular-cluster red giants.
- <sup>6</sup> 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.
- <sup>7</sup> BABU 94 use COOPER-SARKAR 92 limit on  $\nu$  magnetic moment to derive quoted result. It applies to  $\nu_\tau$ .
- <sup>8</sup> DAVIDSON 91 use data from early SLAC electron beam dump experiment to derive charge limit as a function of neutrino mass. It applies to  $\nu_\tau$ .
- <sup>9</sup> Exact BARBIELLINI 87 limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field. It applies to  $\nu_e$ .
- <sup>10</sup> The limit applies to all flavors.

### $\nu$ (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. Some of the limits constrain the radiative decay and are based on the limit of the corresponding photon flux. Other apply to the decay of a heavier neutrino into the lighter one and a Majoron or other invisible particle. Many of these limits apply to any  $\nu$  within the indicated mass range.

Limits on the radiative decay are either directly based on the limits of the corresponding photon flux, or are derived from the limits on the neutrino magnetic moments. In the later case the transition rate for  $\nu_i \rightarrow \nu_j + \gamma$

is constrained by  $\Gamma_{ij} = \frac{1}{\tau_{ij}} = \frac{(m_i^2 - m_j^2)^3}{m_i^3} \mu_{ij}^2$  where  $\mu_{ij}$  is the neutrino

transition moment in the mass eigenstates basis. Typically, the limits on lifetime based on the magnetic moments are many orders of magnitude more restrictive than limits based on the nonobservation of photons.

| VALUE (s/eV)                 | CL% | DOCUMENT ID | TECN | COMMENT                                |
|------------------------------|-----|-------------|------|--|
| > <b>15.4</b>                | 90  | 1 KRAKAUER  | 91   | CNTR $\nu_\mu, \bar{\nu}_\mu$ at LAMPF |
| > <b>7</b> × 10 <sup>9</sup> |     | 2 RAFFELT   | 85   | ASTR                                   |
| > <b>300</b>                 | 90  | 3 REINES    | 74   | CNTR $\bar{\nu}_e$                     |

• • • We do not use the following data for averages, fits, limits, etc. • • •

|                                   |    |       |              |     |      |   |
|-----------------------------------|----|-------|--------------|-----|------|---|
| $> 10^5 - 10^{10}$                | 95 | 4     | CECCHINI     | 11  | ASTR | $\nu_2 \rightarrow \nu_1$ radiative decay     |
|                                   | 90 | 5     | MIRIZZI      | 07  | CMB  | radiative decay                               |
|                                   | 90 | 6     | MIRIZZI      | 07  | CIB  | radiative decay                               |
|                                   |    | 7     | WONG         | 07  | CNTR | Reactor $\bar{\nu}_e$                         |
| $> 0.11$                          | 90 | 8     | XIN          | 05  | CNTR | Reactor $\nu_e$                               |
|                                   |    | 9     | XIN          | 05  | CNTR | Reactor $\nu_e$                               |
| $> 0.004$                         | 90 | 10    | AHARMIM      | 04  | SNO  | quasidegen. $\nu$ masses                      |
| $> 4.4 \times 10^{-5}$            | 90 | 10    | AHARMIM      | 04  | SNO  | hierarchical $\nu$ masses                     |
| $\gtrsim 100$                     | 95 | 11    | CECCHINI     | 04  | ASTR | Radiative decay for $\nu$<br>mass $> 0.01$ eV |
| $> 0.067$                         | 90 | 12    | EGUCHI       | 04  | KLND | quasidegen. $\nu$ masses                      |
| $> 1.1 \times 10^{-3}$            | 90 | 12    | EGUCHI       | 04  | KLND | hierarchical $\nu$ masses                     |
| $> 8.7 \times 10^{-5}$            | 99 | 13    | BANDYOPA...  | 03  | FIT  | nonradiative decay                            |
| $\geq 4200$                       | 90 | 14    | DERBIN       | 02B | CNTR | Solar $pp$ and Be $\nu$                       |
| $> 2.8 \times 10^{-5}$            | 99 | 15    | JOSHIPURA    | 02B | FIT  | nonradiative decay                            |
|                                   |    | 16    | DOLGOV       | 99  | COSM |   |
|                                   |    | 17    | BILLER       | 98  | ASTR | $m_\nu = 0.05-1$ eV                           |
| $> 2.8 \times 10^{15}$            |    | 18,19 | BLUDMAN      | 92  | ASTR | $m_\nu < 50$ eV                               |
| none $10^{-12} - 5 \times 10^4$   |    | 20    | DODELSON     | 92  | ASTR | $m_\nu = 1-300$ keV                           |
| $< 10^{-12}$ or $> 5 \times 10^4$ |    | 20    | DODELSON     | 92  | ASTR | $m_\nu = 1-300$ keV                           |
|                                   |    | 21    | GRANEK       | 91  | COSM | Decaying $L^0$                                |
| $> 6.4$                           | 90 | 22    | KRAKAUER     | 91  | CNTR | $\nu_e$ at LAMPF                              |
| $> 1.1 \times 10^{15}$            |    | 23    | WALKER       | 90  | ASTR | $m_\nu = 0.03 - \sim 2$ MeV                   |
| $> 6.3 \times 10^{15}$            |    | 19,24 | CHUPP        | 89  | ASTR | $m_\nu < 20$ eV                               |
| $> 1.7 \times 10^{15}$            |    | 19    | KOLB         | 89  | ASTR | $m_\nu < 20$ eV                               |
|                                   |    | 25    | RAFFELT      | 89  | RVUE | $\bar{\nu}$ (Dirac, Majorana)                 |
|                                   |    | 26    | RAFFELT      | 89B | ASTR |   |
| $> 8.3 \times 10^{14}$            |    | 27    | VONFEILIT... | 88  | ASTR |   |
| $> 22$                            | 68 | 28    | OBERAUER     | 87  |      | $\bar{\nu}_R$ (Dirac)                         |
| $> 38$                            | 68 | 28    | OBERAUER     | 87  |      | $\bar{\nu}$ (Majorana)                        |
| $> 59$                            | 68 | 28    | OBERAUER     | 87  |      | $\bar{\nu}_L$ (Dirac)                         |
| $> 30$                            | 68 |       | KETOV        | 86  | CNTR | $\bar{\nu}$ (Dirac)                           |
| $> 20$                            | 68 |       | KETOV        | 86  | CNTR | $\bar{\nu}$ (Majorana)                        |
|                                   |    | 29    | BINETRUY     | 84  | COSM | $m_\nu \sim 1$ MeV                            |
| $> 0.11$                          | 90 | 30    | FRANK        | 81  | CNTR | $\nu \bar{\nu}$ LAMPF                         |
| $> 2 \times 10^{21}$              |    | 31    | STECKER      | 80  | ASTR | $m_\nu = 10-100$ eV                           |
| $> 1.0 \times 10^{-2}$            | 90 | 30    | BLIETSCHAU   | 78  | HLBC | $\nu_{\mu'}$ , CERN GGM                       |
| $> 1.7 \times 10^{-2}$            | 90 | 30    | BLIETSCHAU   | 78  | HLBC | $\bar{\nu}_{\mu'}$ , CERN GGM                 |
| $< 3 \times 10^{-11}$             |    | 32    | FALK         | 78  | ASTR | $m_\nu < 10$ MeV                              |
| $> 2.2 \times 10^{-3}$            | 90 | 30    | BARNES       | 77  | DBC  | $\nu$ , ANL 12-ft                             |
|                                   |    | 33    | COWSIK       | 77  | ASTR |   |
| $> 3. \times 10^{-3}$             | 90 | 30    | BELLOTTI     | 76  | HLBC | $\nu$ , CERN GGM                              |
| $> 1.3 \times 10^{-2}$            | 90 | 30    | BELLOTTI     | 76  | HLBC | $\bar{\nu}$ , CERN GGM                        |

<sup>1</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>2</sup> RAFFELT 85 limit on the radiative decay is from solar  $x$ - and  $\gamma$ -ray fluxes. Limit depends on  $\nu$  flux from  $pp$ , now established from GALLEX and SAGE to be  $> 0.5$  of expectation.
- <sup>3</sup> REINES 74 looked for  $\nu$  of nonzero mass decaying radiatively to a neutral of lesser mass  $+ \gamma$ . Used liquid scintillator detector near fission reactor. Finds lab lifetime  $6 \times 10^7$  s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit  $6 \times 10^7$  s REINES 74 assumed that the full  $\bar{\nu}_e$  reactor flux could be responsible for yielding decays with photon energies in the interval 0.1 MeV – 0.5 MeV. This represents some overestimate so their lower limit is an over-estimate of the lab lifetime (VOGEL 84). If so, OBERAUER 87 may be comparable or better.
- <sup>4</sup> CECCHINI 11 search for radiative decays of solar neutrinos into visible photons during the 2006 total solar eclipse. The range of (mean life)/mass values corresponds to a range of  $\nu_1$  masses between  $10^{-4}$  and 0.1 eV.
- <sup>5</sup> MIRIZZI 07 determine a limit on the neutrino radiative decay from analysis of the maximum allowed distortion of the CMB spectrum as measured by the COBE/FIRAS. For the decay  $\nu_2 \rightarrow \nu_1$  the lifetime limit is  $\lesssim 4 \times 10^{20}$  s for  $m_{min} \lesssim 0.14$  eV. For transition with the  $|\Delta m_{31}|$  mass difference the lifetime limit is  $\sim 2 \times 10^{19}$  s for  $m_{min} \lesssim 0.14$  eV and  $\sim 5 \times 10^{20}$  s for  $m_{min} \gtrsim 0.14$  eV.
- <sup>6</sup> MIRIZZI 07 determine a limit on the neutrino radiative decay from analysis of the cosmic infrared background (CIB) using the Spitzer Observatory data. For transition with the  $|\Delta m_{31}|$  mass difference they obtain the lifetime limit  $\sim 10^{20}$  s for  $m_{min} \lesssim 0.14$  eV.
- <sup>7</sup> WONG 07 use their limit on the neutrino magnetic moment together with the assumed experimental value of  $\Delta m_{13}^2 \sim 2 \times 10^{-3}$  eV<sup>2</sup> to obtain  $\tau_{13}/m_1^3 > 3.2 \times 10^{27}$  s/eV<sup>3</sup> for the radiative decay in the case of the inverted mass hierarchy. Similarly to RAFFELT 89 this limit can be violated if electric and magnetic moments are equal to each other. Analogous, but numerically somewhat different limits are obtained for  $\tau_{23}$  and  $\tau_{21}$ .
- <sup>8</sup> XIN 05 search for the  $\gamma$  from radiative decay of  $\nu_e$  produced by the electron capture on <sup>51</sup>Cr. No events were seen and the limit on  $\tau/m_\nu$  was derived. This is a weaker limit on the decay of  $\nu_e$  than KRAKAUER 91.
- <sup>9</sup> XIN 05 use their limit on the neutrino magnetic moment of  $\nu_e$  together with the assumed experimental value of  $\Delta m_{1,3}^2 \sim 2 \times 10^{-3}$  eV<sup>2</sup> to obtain  $\tau_{13}/m_1^3 > 1 \times 10^{23}$  s/eV<sup>3</sup> for the radiative decay in the case of the inverted mass hierarchy. Similarly to RAFFELT 89 this limit can be violated if electric and magnetic moments are equal to each other. Analogous, but numerically somewhat different limits are obtained for  $\tau_{23}$  and  $\tau_{21}$ . Again, this limit is specific for  $\nu_e$ .
- <sup>10</sup> AHARMIM 04 obtained these results from the solar  $\bar{\nu}_e$  flux limit set by the SNO measurement assuming  $\nu_2$  decay through nonradiative process  $\nu_2 \rightarrow \bar{\nu}_1 X$ , where  $X$  is a Majoron or other invisible particle. Limits are given for the cases of quasidegenerate and hierarchical neutrino masses.
- <sup>11</sup> CECCHINI 04 obtained this bound through the observations performed on the occasion of the 21 June 2001 total solar eclipse, looking for visible photons from radiative decays of solar neutrinos. Limit is a  $\tau/m_{\nu_2}$  in  $\nu_2 \rightarrow \nu_1 \gamma$ . Limit ranges from  $\sim 100$  to  $10^7$  s/eV for  $0.01 < m_{\nu_1} < 0.1$  eV.
- <sup>12</sup> EGUCHI 04 obtained these results from the solar  $\bar{\nu}_e$  flux limit set by the KamLAND measurement assuming  $\nu_2$  decay through nonradiative process  $\nu_2 \rightarrow \bar{\nu}_1 X$ , where  $X$  is a Majoron or other invisible particle. Limits are given for the cases of quasidegenerate and hierarchical neutrino masses.
- <sup>13</sup> The ratio of the lifetime over the mass derived by BANDYOPADHYAY 03 is for  $\nu_2$ . They obtained this result using the following solar-neutrino data: total rates measured in Cl and Ga experiments, the Super-Kamiokande's zenith-angle spectra, and SNO's day and night spectra. They assumed that  $\nu_1$  is the lowest mass, stable or nearly stable neutrino state and  $\nu_2$  decays through nonradiative Majoron emission process,  $\nu_2 \rightarrow \bar{\nu}_1 + J$ , or through nonradiative process with all the final state particles being sterile. The best fit is obtained in the region of the LMA solution.

- 14 DERBIN 02B (also BACK 03B) obtained this bound for the radiative decay from the results of background measurements with Counting Test Facility (the prototype of the Borexino detector). The laboratory gamma spectrum is given as  $dN_\gamma/d\cos\theta = (1/2)(1 + \alpha\cos\theta)$  with  $\alpha=0$  for a Majorana neutrino, and  $\alpha$  varying to  $-1$  to  $1$  for a Dirac neutrino. The listed bound is for the case of  $\alpha=0$ . The most conservative bound  $1.5 \times 10^3 \text{ s eV}^{-1}$  is obtained for the case of  $\alpha=-1$ .
- 15 The ratio of the lifetime over the mass derived by JOSHIPURA 02B is for  $\nu_2$ . They obtained this result from the total rates measured in all solar neutrino experiments. They assumed that  $\nu_1$  is the lowest mass, stable or nearly stable neutrino state and  $\nu_2$  decays through nonradiative process like Majoron emission decay,  $\nu_2 \rightarrow \nu'_1 + J$  where  $\nu'_1$  state is sterile. The exact limit depends on the specific solution of the solar neutrino problem. The quoted limit is for the LMA solution.
- 16 DOLGOV 99 places limits in the (Majorana)  $\tau$ -associated  $\nu$  mass-lifetime plane based on nucleosynthesis. Results would be considerably modified if neutrino oscillations exist.
- 17 BILLER 98 use the observed TeV  $\gamma$ -ray spectra to set limits on the mean life of any 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.
- 18 BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.
- 19 Limit on the radiative decay based on nonobservation of  $\gamma$ 's in coincidence with  $\nu$ 's from SN 1987A.
- 20 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.
- 21 GRANEK 91 considers heavy neutrino decays to  $\gamma\nu_L$  and  $3\nu_L$ , where  $m_{\nu_L} < 100 \text{ keV}$ . Lifetime is calculated as a function of heavy neutrino mass, branching ratio into  $\gamma\nu_L$ , and  $m_{\nu_L}$ .
- 22 KRAKAUER 91 quotes the limit for  $\nu_e$ ,  $\tau/m_\nu > (0.3a^2 + 9.8a + 15.9) \text{ s/eV}$ , where  $a$  is a parameter describing the asymmetry in the radiative neutrino decay defined as  $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$   $a=0$  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  $a = -1$ ).
- 23 WALKER 90 uses SN 1987A  $\gamma$  flux limits after 289 days.
- 24 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.
- 25 RAFFELT 89 uses KYULDJIEV 84 to obtain  $\tau m^3 > 3 \times 10^{18} \text{ s eV}^3$  (based on  $\bar{\nu}_e e^-$  cross sections). The bound for the radiative decay is not valid if electric and magnetic transition moments are equal for Dirac neutrinos.
- 26 RAFFELT 89B analyze stellar evolution and exclude the region  $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21} \text{ s eV}^3$ .
- 27 Model-dependent theoretical analysis of SN 1987A neutrinos. Quoted limit is for  $[\sum_j |U_{\ell j}|^2 \Gamma_j m_j]^{-1}$ , where  $\ell = \mu, \tau$ . Limit is  $3.3 \times 10^{14} \text{ s/eV}$  for  $\ell = e$ .
- 28 OBERAUER 87 looks for photons and  $e^+e^-$  pairs from radiative decays of reactor neutrinos.
- 29 BINETRUY 84 finds  $\tau < 10^8 \text{ s}$  for neutrinos in a radiation-dominated universe.
- 30 These experiments look for  $\nu_k \rightarrow \nu_j \gamma$  or  $\bar{\nu}_k \rightarrow \bar{\nu}_j \gamma$ .
- 31 STECKER 80 limit based on UV background; result given is  $\tau > 4 \times 10^{22} \text{ s}$  at  $m_\nu = 20 \text{ eV}$ .
- 32 FALK 78 finds lifetime constraints based on supernova energetics.
- 33 COWSIK 77 considers variety of scenarios. For neutrinos produced in the big bang, present limits on optical photon flux require  $\tau > 10^{23} \text{ s}$  for  $m_\nu \sim 1 \text{ eV}$ . See also COWSIK 79 and GOLDMAN 79.

## $\nu$ MAGNETIC MOMENT

The coupling of neutrinos to an electromagnetic field is characterized by a  $3 \times 3$  matrix  $\lambda$  of the magnetic ( $\mu$ ) and electric ( $d$ ) dipole moments ( $\lambda = \mu - id$ ). For Majorana neutrinos the matrix  $\lambda$  is antisymmetric and only transition moments are allowed, while for Dirac neutrinos  $\lambda$  is a general  $3 \times 3$  matrix. In the standard electroweak theory extended to include neutrino masses (see FUJIKAWA 80)  $\mu_\nu = 3eG_F m_\nu / (8\pi^2 \sqrt{2}) = 3.2 \times 10^{-19} (m_\nu / \text{eV}) \mu_B$ , i.e. it is unobservably small given the known small neutrino masses. In more general models there is no longer a proportionality between neutrino mass and its magnetic moment, even though only massive neutrinos have nonvanishing magnetic moments without fine tuning.

Laboratory bounds on  $\lambda$  are obtained via elastic  $\nu$ - $e$  scattering, where the scattered neutrino is not observed. The combinations of matrix elements of  $\lambda$  that are constrained by various experiments depend on the initial neutrino flavor and on its propagation between source and detector (e.g., solar  $\nu_e$  and reactor  $\bar{\nu}_e$  do not constrain the same combinations). The listings below therefore identify the initial neutrino flavor.

Other limits, e.g. from various stellar cooling processes, apply to all neutrino flavors. Analogous flavor independent, but weaker, limits are obtained from the analysis of  $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$  collider experiments.

| VALUE ( $10^{-10} \mu_B$ )  | CL% | DOCUMENT ID        | TECN | COMMENT                                    |
|---|-----|--------------------|------|--|
| < 0.28  | 90  | 1 AGOSTINI 17A     | BORX | Solar $\nu$ spectrum                       |
| < <b>0.29</b>   | 90  | 2 BEDA 13          | CNTR | Reactor $\bar{\nu}_e$                      |
| < <b>6.8</b>  | 90  | 3 AUERBACH 01      | LSND | $\nu_e e, \nu_\mu e$ scattering            |
| < <b>3900</b>   | 90  | 4 SCHWIENHO...01   | DONU | $\nu_\tau e^- \rightarrow \nu_\tau e^-$    |
| ● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ● |     |                    |      |  |
| < 0.022   | 90  | 5 ARCEO-DIAZ 15    | ASTR | Red giants                                 |
| < 0.1   | 95  | 6 CORSICO 14       | ASTR |  |
| < 0.05  | 95  | 7 MILLER-BER...14B | ASTR |  |
| < 0.045   | 95  | 8 VIAUX 13A        | ASTR | Globular cluster M5                        |
| < 0.32  | 90  | 9 BEDA 10          | CNTR | Reactor $\bar{\nu}_e$                      |
| < 2.2   | 90  | 10 DENIZ 10        | TEXO | Reactor $\bar{\nu}_e$                      |
| < 0.011–0.027   |     | 11 KUZNETSOV 09    | ASTR | $\nu_L \rightarrow \nu_R$ in SN1987A       |
| < 0.54  | 90  | 12 ARPESELLA 08A   | BORX | Solar $\nu$ spectrum                       |
| < 0.58  | 90  | 13 BEDA 07         | CNTR | Reactor $\bar{\nu}_e$                      |
| < 0.74  | 90  | 14 WONG 07         | CNTR | Reactor $\bar{\nu}_e$                      |
| < 0.9   | 90  | 15 DARAKTCH... 05  |      | Reactor $\bar{\nu}_e$                      |
| < 130   | 90  | 16 XIN 05          | CNTR | Reactor $\nu_e$                            |
| < 37  | 95  | 17 GRIFOLS 04      | FIT  | Solar $^8\text{B}$ $\nu$ (SNO NC)          |
| < 3.6   | 90  | 18 LIU 04          | SKAM | Solar $\nu$ spectrum                       |
| < 1.1   | 90  | 19 LIU 04          | SKAM | Solar $\nu$ spectrum (LMA region)          |
| < 5.5   | 90  | 20 BACK 03B        | CNTR | Solar $pp$ and Be $\nu$                    |
| < 1.0   | 90  | 21 DARAKTCH... 03  |      | Reactor $\bar{\nu}_e$                      |
| < 1.3   | 90  | 22 LI 03B          | CNTR | Reactor $\bar{\nu}_e$                      |
| < 2   | 90  | 23 GRIMUS 02       | FIT  | solar + reactor (Majorana $\nu$ )          |
| < 80000   | 90  | 24 TANIMOTO 00     | RVUE | $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ |

|             |    |    |             |     |      |   |
|-------------|----|----|-------------|-----|------|---|
| < 0.01–0.04 |    | 25 | AYALA       | 99  | ASTR | $\nu_L \rightarrow \nu_R$ in SN 1987A             |
| < 1.5       | 90 | 26 | BEACOM      | 99  | SKAM | Solar $\nu$ spectrum                              |
| < 0.03      |    | 27 | RAFFELT     | 99  | ASTR | Red giant luminosity                              |
| < 4         |    | 28 | RAFFELT     | 99  | ASTR | Solar cooling                                     |
| <44000      | 90 |    | ABREU       | 97J | DLPH | $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ at LEP |
| <33000      | 90 | 29 | ACCIARRI    | 97Q | L3   | $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ at LEP |
| < 0.62      |    | 30 | ELMFORS     | 97  | COSM | Depolarization in early universe plasma           |
| <27000      | 95 | 31 | ESCRIBANO   | 97  | RVUE | $\Gamma(Z \rightarrow \nu \nu)$ at LEP            |
| < 30        | 90 |    | VILAIN      | 95B | CHM2 | $\nu_\mu e \rightarrow \nu_\mu e$                 |
| <55000      | 90 |    | GOULD       | 94  | RVUE | $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ at LEP |
| < 1.9       | 95 | 32 | DERBIN      | 93  | CNTR | Reactor $\bar{\nu} e \rightarrow \bar{\nu} e$     |
| < 5400      | 90 | 33 | COOPER-...  | 92  | BEBC | $\nu_\tau e^- \rightarrow \nu_\tau e^-$           |
| < 2.4       | 90 | 34 | VIDYAKIN    | 92  | CNTR | Reactor $\bar{\nu} e \rightarrow \bar{\nu} e$     |
| <56000      | 90 |    | DESHPANDE   | 91  | RVUE | $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$        |
| < 100       | 95 | 35 | DORENBOS... | 91  | CHRM | $\nu_\mu e \rightarrow \nu_\mu e$                 |
| < 8.5       | 90 |    | AHRENS      | 90  | CNTR | $\nu_\mu e \rightarrow \nu_\mu e$                 |
| < 10.8      | 90 | 36 | KRAKAUER    | 90  | CNTR | LAMPF $\nu e \rightarrow \nu e$                   |
| < 7.4       | 90 | 36 | KRAKAUER    | 90  | CNTR | LAMPF $(\nu_\mu, \bar{\nu}_\mu) e$ elast.         |
| < 0.02      |    | 37 | RAFFELT     | 90  | ASTR | Red giant luminosity                              |
| < 0.1       |    | 38 | RAFFELT     | 89B | ASTR | Cooling helium stars                              |
|             |    | 39 | FUKUGITA    | 88  | COSM | Primordial magn. fields                           |
| <40000      | 90 | 40 | GROTCH      | 88  | RVUE | $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$        |
| $\leq$ .3   |    | 38 | RAFFELT     | 88B | ASTR | He burning stars                                  |
| < 0.11      |    | 38 | FUKUGITA    | 87  | ASTR | Cooling helium stars                              |
| < 0.0006    |    | 41 | NUSSINOV    | 87  | ASTR | Cosmic EM back-grounds                            |
| < 0.1–0.2   |    |    | MORGAN      | 81  | COSM | $^4\text{He}$ abundance                           |
| < 0.85      |    |    | BEG         | 78  | ASTR | Stellar plasmons                                  |
| < 0.6       |    | 42 | SUTHERLAND  | 76  | ASTR | Red giants + degenerate dwarfs                    |
| < 81        |    | 43 | KIM         | 74  | RVUE | $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$     |
| < 1         |    |    | BERNSTEIN   | 63  | ASTR | Solar cooling                                     |
| < 14        |    |    | COWAN       | 57  | CNTR | Reactor $\bar{\nu}$                               |

<sup>1</sup> AGOSTINI 17A obtained this limit using the shape of the recoil electron energy spectrum from the Borexino Phase-II 1291.5 live days of solar neutrino data and the constraints on the sum of the solar neutrino fluxes from the radiochemical gallium experiments SAGE, Gallex, and GNO. Without radiochemical constraints, the 90% C.L. limit of  $< 4.0 \times 10^{-11} \mu_B$  is obtained.

<sup>2</sup> BEDA 13 report  $\bar{\nu}_e e^-$  scattering results, using the Kalinin Nuclear Power Plant and a shielded Ge detector. The recoil electron spectrum is analyzed between 2.5 and 55 keV. Supersedes BEDA 07. Supersedes BEDA 10. This is the most stringent limit on the magnetic moment of reactor  $\bar{\nu}_e$ .

<sup>3</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>4</sup> SCHWIENHORST 01 quote an experimental sensitivity of  $4.9 \times 10^{-7}$ .

<sup>5</sup> ARCEO-DIAZ 15 constrains the neutrino magnetic moment from observation of the tip of the red giant branch in the globular cluster  $\omega$ -Centauri.

<sup>6</sup> CORSICO 14 constrains the neutrino magnetic moment from observations of white dwarf pulsations.



- 7 MILLER-BERTOLAMI 14B constrains the neutrino magnetic moment from observations of the white dwarf luminosity function of the Galactic disk.
- 8 VIAUX 13A constrains the neutrino magnetic moment from observations of the globular cluster M5.
- 9 BEDA 10 report  $\bar{\nu}_e e^-$  scattering results, using the Kalinin Nuclear Power Plant and a shielded Ge detector. The recoil electron spectrum is analyzed between 2.9 and 45 keV. Supersedes BEDA 07. Superseded by BEDA 13.
- 10 DENIZ 10 observe reactor  $\bar{\nu}_e e$  scattering with recoil kinetic energies 3–8 MeV using CsI(Tl) detectors. The observed rate and spectral shape are consistent with the Standard Model prediction, leading to the reported constraint on  $\bar{\nu}_e$  magnetic moment.
- 11 KUZNETSOV 09 obtain a limit on the flavor averaged magnetic moment of Dirac neutrinos from the time averaged neutrino signal of SN1987A. Improves and supersedes the analysis of BARBIERI 88 and AYALA 99.
- 12 ARPESELLA 08A obtained this limit using the shape of the recoil electron energy spectrum from the Borexino 192 live days of solar neutrino data.
- 13 BEDA 07 performed search for electromagnetic  $\bar{\nu}_e$ -e scattering at Kalininskaya nuclear reactor. A Ge detector with active and passive shield was used and the electron recoil spectrum between 3.0 and 61.3 keV analyzed. Superseded by BEDA 10.
- 14 WONG 07 performed search for non-standard  $\bar{\nu}_e$ -e scattering at the Kuo-Sheng nuclear reactor. Ge detector equipped with active anti-Compton shield is used. Most stringent laboratory limit on magnetic moment of reactor  $\bar{\nu}_e$ . Supersedes LI 03B.
- 15 DARAKTCHIEVA 05 present the final analysis of the search for non-standard  $\bar{\nu}_e$ -e scattering component at Bugey nuclear reactor. Full kinematical event reconstruction of both the kinetic energy above 700 keV and scattering angle of the recoil electron, by use of TPC. Most stringent laboratory limit on magnetic moment. Supersedes DARAKTCHIEVA 03.
- 16 XIN 05 evaluated the  $\nu_e$  flux at the Kuo-Sheng nuclear reactor and searched for non-standard  $\nu_e$ -e scattering. Ge detector equipped with active anti-Compton shield was used. This laboratory limit on magnetic moment is considerably less stringent than the limits for reactor  $\bar{\nu}_e$ , but is specific to  $\nu_e$ .
- 17 GRIFOLS 04 obtained this bound using the SNO data of the solar  $^8\text{B}$  neutrino flux measured with deuteron breakup. This bound applies to  $\mu_{\text{eff}} = (\mu_{21}^2 + \mu_{22}^2 + \mu_{23}^2)^{1/2}$ .
- 18 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.
- 19 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.
- 20 BACK 03B obtained this bound from the results of background measurements with Counting Test Facility (the prototype of the Borexino detector). Standard Solar Model flux was assumed. This  $\mu_{\nu}$  can be different from the reactor  $\mu_{\nu}$  in certain oscillation scenarios (see BEACOM 99).
- 21 DARAKTCHIEVA 03 searched for non-standard  $\bar{\nu}_e$ -e scattering component at Bugey nuclear reactor. Full kinematical event reconstruction by use of TPC. Superseded by DARAKTCHIEVA 05.
- 22 LI 03B used Ge detector in active shield near nuclear reactor to test for nonstandard  $\bar{\nu}_e$ -e scattering.
- 23 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.
- 24 TANIMOTO 00 combined  $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$  data from VENUS, TOPAZ, and AMY.
- 25 AYALA 99 improves the limit of BARBIERI 88.

- 26 BEACOM 99 obtain the limit using the shape, but not the absolute magnitude which is affected by oscillations, of the solar neutrino spectrum obtained by Superkamiokande (825 days). This  $\mu_\nu$  can be different from the reactor  $\mu_\nu$  in certain oscillation scenarios.
- 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 ACCIARRI 97Q result applies to both direct and transition magnetic moments and for  $q^2=0$ .
- 30 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.
- 31 Applies to absolute value of magnetic moment.
- 32 DERBIN 93 determine the cross section for 0.6–2.0 MeV electron energy as  $(1.28 \pm 0.63) \times \sigma_{\text{weak}}$ . However, the (reactor on – reactor off)/(reactor off) is only  $\sim 1/100$ .
- 33 COOPER-SARKAR 92 assume  $f_{D_s}/f_\pi = 2$  and  $D_s, \bar{D}_s$  production cross section =  $2.6 \mu\text{b}$  to calculate  $\nu$  flux.
- 34 VIDYAKIN 92 limit is from a  $e\bar{\nu}_e$  elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was  $1/10$ . The limit uses  $\sin^2\theta_W = 0.23$  as input.
- 35 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  $\mu(\nu) = \mu(\bar{\nu})$ .
- 36 KRAKAUER 90 experiment fully reported in ALLEN 93.
- 37 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  $\delta M_C$ .
- 38 Significant dependence on details of stellar models.
- 39 FUKUGITA 88 find magnetic dipole moments of any two neutrino species are bounded by  $\mu < 10^{-16} [10^{-9} G/B_0]$  where  $B_0$  is the present-day intergalactic field strength.
- 40 GROTCHE 88 combined data from MAC, ASP, CELLO, and Mark J.
- 41 For  $m_\nu = 8\text{--}200$  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.
- 42 We obtain above limit from SUTHERLAND 76 using their limit  $f < 1/3$ .
- 43 KIM 74 is a theoretical analysis of  $\bar{\nu}_\mu$  reaction data.

## NEUTRINO CHARGE RADIUS SQUARED

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.

| <u>VALUE (<math>10^{-32} \text{ cm}^2</math>)</u> | <u>CL%</u> | <u>DOCUMENT ID</u> | <u>TECN</u> | <u>COMMENT</u>          |
|---|------------|--------------------|-------------|-------------------------|
| <b>–2.1 to 3.3</b>                                | 90         | <sup>1</sup> DENIZ | 10 TEXO     | Reactor $\bar{\nu}_e e$ |

• • • We do not use the following data for averages, fits, limits, etc. • • •

|               |    |                          |     |  |
|---------------|----|--------------------------|-----|--|
| −4 to 5.5     | 90 | <sup>2</sup> CAEDDU      | 18  | $\nu_\mu$ coherent scat. on Csl                      |
| −0.53 to 0.68 | 90 | <sup>3</sup> HIRSCH      | 03  | $\nu_\mu e$ scat.                                    |
| −8.2 to 9.9   | 90 | <sup>4</sup> HIRSCH      | 03  | anomalous $e^+ e^- \rightarrow \nu \bar{\nu} \gamma$ |
| −2.97 to 4.14 | 90 | <sup>5</sup> AUERBACH    | 01  | LSND $\nu_e e \rightarrow \nu_e e$                   |
| −0.6 to 0.6   | 90 | VILAIN                   | 95B | CHM2 $\nu_\mu e$ elastic scat.                       |
| 0.9 ± 2.7     |    | ALLEN                    | 93  | CNTR LAMPF $\nu e \rightarrow \nu e$                 |
| < 2.3         | 95 | MOURAO                   | 92  | ASTR HOME/KAM2 $\nu$ rates                           |
| < 7.3         | 90 | <sup>6</sup> VIDYAKIN    | 92  | CNTR Reactor $\bar{\nu} e \rightarrow \bar{\nu} e$   |
| 1.1 ± 2.3     |    | ALLEN                    | 91  | CNTR Repl. by ALLEN 93                               |
| −1.1 ± 1.0    |    | <sup>7</sup> AHRENS      | 90  | CNTR $\nu_\mu e$ elastic scat.                       |
| −0.3 ± 1.5    |    | <sup>7</sup> DORENBOS... | 89  | CHRM $\nu_\mu e$ elastic scat.                       |
|               |    | <sup>8</sup> GRIFOLS     | 89B | ASTR SN 1987A  |

<sup>1</sup> DENIZ 10 observe reactor  $\bar{\nu}_e e$  scattering with recoil kinetic energies 3–8 MeV using Csl(Tl) detectors. The observed rate and spectral shape are consistent with the Standard Model prediction, leading to the reported constraint on  $\bar{\nu}_e$  charge radius.

<sup>2</sup> CAEDDU 18 use the data of the COHERENT experiment, AKIMOV 18. The limit is  $\langle r_\nu^2 \rangle$  for  $\nu_\mu$  obtained from the time-dependent data. Weaker limits were obtained for charge radii of  $\nu_e$  and for transition charge radii. The published value was divided by 2 to conform to the convention of this table.

<sup>3</sup> 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  $\nu_\mu$  charge radius it implies  $\langle r_V^2 \rangle + \langle r_A^2 \rangle = (4.20 \pm 1.64) \times 10^{-33} \text{ cm}^2$ .

<sup>4</sup> Results of LEP-2 are interpreted as limits on the axial-vector charge radius squared of a Majorana  $\nu_\tau$ . Slightly weaker limits for both vector and axial-vector charge radius squared are obtained for the Dirac case, and somewhat weaker limits are obtained from the analysis of lower energy data (LEP-1.5 and TRISTAN).

<sup>5</sup> AUERBACH 01 measure  $\nu_e e$  elastic scattering with LSND detector. The cross section agrees with the Standard Model expectation, including the charge and neutral current interference. The 90% CL applies to the range shown.

<sup>6</sup> VIDYAKIN 92 limit is from a  $e\bar{\nu}$  elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses  $\sin^2 \theta_W = 0.23$  as input.

<sup>7</sup> Result is obtained from reanalysis given in ALLEN 91, followed by our reduction to obtain  $1\sigma$  errors.

<sup>8</sup> GRIFOLS 89B sets a limit of  $\langle r^2 \rangle < 0.2 \times 10^{-32} \text{ cm}^2$  for right-handed neutrinos.

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| ALBRECHT     | 88B | PL B202 149            | H. Albrecht <i>et al.</i>                        | (ARGUS Collab.)      |
| BARBIERI     | 88  | PRL 61 27              | R. Barbieri, R.N. Mohapatra                      | (PISA, UMD)          |
| BORIS        | 88  | PRL 61 245 (erratum)   | S.D. Boris <i>et al.</i>                         | (ITEP, ASCI)         |
| FUKUGITA     | 88  | PRL 60 879             | M. Fukugita <i>et al.</i>                        | (KYOTU, MPIM, UCB)   |
| GROTCH       | 88  | ZPHY C39 553           | H. Grotch, R.W. Robinett                         | (PSU)                |
| RAFFELT      | 88B | PR D37 549             | G.G. Raffelt, D.S.P. Dearborn                    | (UCB, LLL)           |
| SPERGEL      | 88  | PL B200 366            | D.N. Spergel, J.N. Bahcall                       | (IAS)                |
| VONFEILIT... | 88  | PL B200 580            | F. von Feilitzsch, L. Oberauer                   | (MUNT)               |
| BARBIELLINI  | 87  | NAT 329 21             | G. Barbiellini, G. Cocconi                       | (CERN)               |
| BORIS        | 87  | PRL 58 2019            | S.D. Boris <i>et al.</i>                         | (ITEP, ASCI)         |
| Also         |     | PRL 61 245 (erratum)   | S.D. Boris <i>et al.</i>                         | (ITEP, ASCI)         |
| BORIS        | 87B | JETPL 45 333           | S.D. Boris <i>et al.</i>                         | (ITEP)               |
| FUKUGITA     | 87  | PR D36 3817            | M. Fukugita, S. Yazaki                           | (KYOTU, TOKY)        |
| NUSSINOV     | 87  | PR D36 2278            | S. Nussinov, Y. Rephaeli                         | (TELA)               |
| OBERAUER     | 87  | PL B198 113            | L.F. Oberauer, F. von Feilitzsch, R.L. Mossbauer |                      |
| SPRINGER     | 87  | PR A35 679             | P.T. Springer <i>et al.</i>                      | (LLNL)               |
| KETOV        | 86  | JETPL 44 146           | S.N. Ketov <i>et al.</i>                         | (KIAE)               |
| COWSIK       | 85  | PL 151B 62             | R. Cowsik  | (TATA)               |
| RAFFELT      | 85  | PR D31 3002            | G.G. Raffelt                                     | (MPIM)               |
| BINETRUY     | 84  | PL 134B 174            | P. Binetruy, G. Girardi, P. Salati               | (LAPP)               |
| FREESE       | 84  | NP B233 167            | K. Freese, D.N. Schramm                          | (CHIC, FNAL)         |
| KYULDJIEV    | 84  | NP B243 387            | A.V. Kyuldjiev                                   | (SOFI)               |
| SCHRAMM      | 84  | PL 141B 337            | D.N. Schramm, G. Steigman                        | (FNAL, BART)         |
| VOGEL        | 84  | PR D30 1505            | P. Vogel   |                      |
| ANDERHUB     | 82  | PL 114B 76             | H.B. Anderhub <i>et al.</i>                      | (ETH, SIN)           |
| OLIVE        | 82  | PR D25 213             | K.A. Olive, M.S. Turner                          | (CHIC, UCSB)         |
| BERNSTEIN    | 81  | PL 101B 39             | J. Bernstein, G. Feinberg                        | (STEV, COLU)         |
| FRANK        | 81  | PR D24 2001            | J.S. Frank <i>et al.</i>                         | (LASL, YALE, MIT+)   |
| MORGAN       | 81  | PL 102B 247            | J.A. Morgan                                      | (SUSS)               |
| FUJIKAWA     | 80  | PRL 45 963             | K. Fujikawa, R. Shrock                           | (STON)               |
| LUBIMOV      | 80  | PL 94B 266             | V.A. Lyubimov <i>et al.</i>                      | (ITEP)               |
| STECKER      | 80  | PRL 45 1460            | F.W. Stecker                                     | (NASA)               |
| COWSIK       | 79  | PR D19 2219            | R. Cowsik  | (TATA)               |
| GOLDMAN      | 79  | PR D19 2215            | T. Goldman, G.J. Stephenson                      | (LASL)               |
| 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.) |
| FALK         | 78  | PL 79B 511             | S.W. Falk, D.N. Schramm                          | (CHIC)               |
| BARNES       | 77  | PRL 38 1049            | V.E. Barnes <i>et al.</i>                        | (PURD, ANL)          |
| COWSIK       | 77  | PRL 39 784             | R. Cowsik  | (MPIM, TATA)         |
| LEE          | 77C | PR D16 1444            | B.W. Lee, R.E. Shrock                            | (STON)               |

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|------------|----|-------------------------------|--|-------------------|
| VYSOTSKY   | 77 | JETPL 26 188                  | M.I. Vysotsky, A.D. Dolgov, Y.B. Zeldovich | (ITEP)            |
|            |    | Translated from ZETFP 26 200. |  |                   |
| BELLOTTI   | 76 | LNC 17 553                    | E. Bellotti <i>et al.</i>                  | (MILA)            |
| SUTHERLAND | 76 | PR D13 2700                   | P. Sutherland <i>et al.</i>                | (PENN, COLU, NYU) |
| SZALAY     | 76 | AA 49 437                     | A.S. Szalay, G. Marx                       | (EOTV)            |
| 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)            |
| REINES     | 74 | PRL 32 180                    | F. Reines, H.W. Sobel, H.S. Gurr           | (UCI)             |
| SZALAY     | 74 | APAH 35 8                     | A.S. Szalay, G. Marx                       | (EOTV)            |
| COWSIK     | 72 | PRL 29 669                    | R. Cowsik, J. McClelland                   | (UCB)             |
| MARX       | 72 | Nu Conf. Budapest             | G. Marx, A.S. Szalay                       | (EOTV)            |
| GERSHTEIN  | 66 | JETPL 4 120                   | S.S. Gershtein, Y.B. Zeldovich             | (KIAM)            |
|            |    | Translated from ZETFP 4 189.  |  |                   |
| BERNSTEIN  | 63 | PR 132 1227                   | J. Bernstein, M. Ruderman, G. Feinberg     | (NYU+)            |
| COWAN      | 57 | PR 107 528                    | C.L. Cowan, F. Reines                      | (LANL)            |

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