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# e

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

## *e* MASS (atomic mass units u)

The primary determination of an electron's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the electron in u; indeed, the recent improvements in the mass determination are not evident when the result is given in MeV. In this datablock we give the result in u, and in the following datablock in MeV.

| *VALUE* ($10^{-6}$ u) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **548.579909070±0.000000016** | MOHR | 16 | RVUE | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 548.57990946 ±0.00000022 | MOHR | 12 | RVUE | 2010 CODATA value |
| 548.57990943 ±0.00000023 | MOHR | 08 | RVUE | 2006 CODATA value |
| 548.57990945 ±0.00000024 | MOHR | 05 | RVUE | 2002 CODATA value |
| 548.5799092 ±0.0000004 | [1] BEIER | 02 | CNTR | Penning trap |
| 548.5799110 ±0.0000012 | MOHR | 99 | RVUE | 1998 CODATA value |
| 548.5799111 ±0.0000012 | [2] FARNHAM | 95 | CNTR | Penning trap |
| 548.579903 ±0.000013 | COHEN | 87 | RVUE | 1986 CODATA value |

[1] BEIER 02 compares Larmor frequency of the electron bound in a $^{12}C^{5+}$ ion with the cyclotron frequency of a single trapped $^{12}C^{5+}$ ion.

[2] FARNHAM 95 compares cyclotron frequency of trapped electrons with that of a single trapped $^{12}C^{6+}$ ion.

## *e* MASS

2010 CODATA (MOHR 12) gives the conversion factor from u (atomic mass units, see the above datablock) to MeV as 931.494 061 (21). Earlier values use the then-current conversion factor. The conversion error dominates the uncertainty of the masses given below.

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **0.5109989461±0.0000000031** | MOHR | 16 | RVUE | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.510998928 ±0.000000011 | MOHR | 12 | RVUE | 2010 CODATA value |
| 0.510998910 ±0.000000013 | MOHR | 08 | RVUE | 2006 CODATA value |
| 0.510998918 ±0.000000044 | MOHR | 05 | RVUE | 2002 CODATA value |
| 0.510998901 ±0.000000020 | [1,2] BEIER | 02 | CNTR | Penning trap |
| 0.510998902 ±0.000000021 | MOHR | 99 | RVUE | 1998 CODATA value |
| 0.510998903 ±0.000000020 | [1,3] FARNHAM | 95 | CNTR | Penning trap |
| 0.510998895 ±0.000000024 | [1] COHEN | 87 | RVUE | 1986 CODATA value |
| 0.5110034 ±0.0000014 | COHEN | 73 | RVUE | 1973 CODATA value |

[1] Converted to MeV using the 1998 CODATA value of the conversion constant, 931.494013 ± 0.000037 MeV/u.

[2] BEIER 02 compares Larmor frequency of the electron bound in a $^{12}C^{5+}$ ion with the cyclotron frequency of a single trapped $^{12}C^{5+}$ ion.
[3] FARNHAM 95 compares cyclotron frequency of trapped electrons with that of a single trapped $^{12}C^{6+}$ ion.

## $(m_{e^+} - m_{e^-})\ /\ m_{\mathrm{average}}$

A test of *CPT* invariance.

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **$<8 \times 10^{-9}$** | 90 | [1] FEE | 93 | CNTR | Positronium spectroscopy |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<4 \times 10^{-23}$ | 90 | [2] DOLGOV | 14 | | From photon mass limit |
| $<4 \times 10^{-8}$ | 90 | CHU | 84 | CNTR | Positronium spectroscopy |

[1] FEE 93 value is obtained under the assumption that the positronium Rydberg constant is exactly half the hydrogen one.
[2] DOLGOV 14 result is obtained under the assumption that any mass difference between electron and positron would lead to a non-zero photon mass. The PDG 12 limit of $1 \times 10^{-18}$ eV on the photon mass is in turn used to derive the value quoted here.

## $\left|q_{e^+} + q_{e^-}\right|/e$

A test of *CPT* invariance. See also similar tests involving the proton.

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **$<4 \times 10^{-8}$** | [1] HUGHES | 92 | RVUE | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2 \times 10^{-18}$ | [2] SCHAEFER | 95 | THEO | Vacuum polarization |
| $<1 \times 10^{-18}$ | [3] MUELLER | 92 | THEO | Vacuum polarization |

[1] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.
[2] SCHAEFER 95 removes model dependency of MUELLER 92.
[3] MUELLER 92 argues that an inequality of the charge magnitudes would, through higher-order vacuum polarization, contribute to the net charge of atoms.

## *e* MAGNETIC MOMENT ANOMALY

### $\mu_e/\mu_B - 1 = (g-2)/2$

| VALUE (units $10^{-6}$) | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|
| **1159.65218091±0.00000026** | MOHR | 16 | RVUE | | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 1159.65218076±0.00000027 | MOHR | 12 | RVUE | | 2010 CODATA value |
| 1159.65218073±0.00000028 | HANNEKE | 08 | MRS | | Single electron |
| 1159.65218111±0.00000074 | [1] MOHR | 08 | RVUE | | 2006 CODATA value |
| 1159.65218085±0.00000076 | [2] ODOM | 06 | MRS | − | Single electron |
| 1159.6521859 ±0.0000038 | MOHR | 05 | RVUE | | 2002 CODATA value |
| 1159.6521869 ±0.0000041 | MOHR | 99 | RVUE | | 1998 CODATA value |
| 1159.652193 ±0.000010 | COHEN | 87 | RVUE | | 1986 CODATA value |
| 1159.6521884 ±0.0000043 | VANDYCK | 87 | MRS | − | Single electron |
| 1159.6521879 ±0.0000043 | VANDYCK | 87 | MRS | + | Single positron |

[1] MOHR 08 average is dominated by ODOM 06.
[2] Superseded by HANNEKE 08 per private communication with Gerald Gabrielse.

## $(g_{e^+} - g_{e^-})\ /\ g_{\text{average}}$

A test of *CPT* invariance.

| VALUE (units $10^{-12}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **− 0.5± 2.1** | | [1] VANDYCK | 87 | MRS | Penning trap |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 12 | 95 | [2] VASSERMAN | 87 | CNTR | Assumes $m_{e^+} = m_{e^-}$ |
| 22 ±64 | | SCHWINBERG | 81 | MRS | Penning trap |

[1] VANDYCK 87 measured $(g_-/g_+)-1$ and we converted it.

[2] VASSERMAN 87 measured $(g_+ - g_-)/(g-2)$. We multiplied by $(g-2)/g = 1.2 \times 10^{-3}$.

## *e* ELECTRIC DIPOLE MOMENT (d)

A nonzero value is forbidden by both *T* invariance and *P* invariance.

| VALUE ($10^{-28}$ *e* cm) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **< 0.11** | 90 | [1] ANDREEV | 18 | CNTR | ThO molecules |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 1.3 | 90 | [2] CAIRNCROSS | 17 | ESR | $^{180}Hf^{19}F$ molecules |
| − 5570 ± 7980 ±120 | | KIM | 15 | CNTR | $Gd_3Ga_5O_{12}$ molecules |
| < 0.87 | 90 | [3] BARON | 14 | CNTR | ThO molecules |
| < 6050 | 90 | [4] ECKEL | 12 | CNTR | $Eu_{0.5}Ba_{0.5}TiO_3$ molecules |
| < 10.5 | 90 | [5] HUDSON | 11 | NMR | YbF molecules |
| 6.9 ± 7.4 | | REGAN | 02 | MRS | $^{205}Tl$ beams |
| 18 ± 12 ± 10 | | [6] COMMINS | 94 | MRS | $^{205}Tl$ beams |
| − 27 ± 83 | | [6] ABDULLAH | 90 | MRS | $^{205}Tl$ beams |
| − 1400 ± 2400 | | CHO | 89 | NMR | TlF molecules |
| − 150 ± 550 ±150 | | MURTHY | 89 | | Cs, no *B* field |
| − 5000 ±11000 | | LAMOREAUX | 87 | NMR | $^{199}Hg$ |
| 19000 ±34000 | 90 | SANDARS | 75 | MRS | Thallium |
| 7000 ±22000 | 90 | PLAYER | 70 | MRS | Xenon |
| < 30000 | 90 | WEISSKOPF | 68 | MRS | Cesium |

[1] ANDREEV 18 gives a measurement corresponding to this limit as $(4.3 \pm 3.1 \pm 2.6) \times 10^{-30}$ *e*cm.

[2] CAIRNCROSS 17 gives a measurement corresponding to this limit as $(0.09 \pm 0.77 \pm 0.17) \times 10^{-28}$ *e*cm.

[3] BARON 14 gives a measurement corresponding to this limit as $(-0.21 \pm 0.37 \pm 0.25) \times 10^{-28}$ *e*cm.

[4] ECKEL 12 gives a measurement corresponding to this limit as $(-1.07 \pm 3.06 \pm 1.74) \times 10^{-25}$ *e*cm.

[5] HUDSON 11 gives a measurement corresponding to this limit as $(-2.4 \pm 5.7 \pm 1.5) \times 10^{-28}$ *e*cm.

[6] ABDULLAH 90, COMMINS 94, and REGAN 02 use the relativistic enhancement of a valence electron's electric dipole moment in a high-Z atom.

# $e^-$ MEAN LIFE / BRANCHING FRACTION

A test of charge conservation. See the "Note on Testing Charge Conservation and the Pauli Exclusion Principle" following this section in our 1992 edition (Physical Review **D45** S1 (1992), p. VI.10).

Most of these experiments are one of three kinds: Attempts to observe (a) the 255.5 keV gamma ray produced in $e^- \rightarrow \nu_e \gamma$, (b) the (K) shell x ray produced when an electron decays without additional energy deposit, e.g., $e^- \rightarrow \nu_e \overline{\nu}_e \nu_e$ ("disappearance" experiments), and (c) nuclear deexcitation gamma rays after the electron disappears from an atomic shell and the nucleus is left in an excited state. The last can include both weak boson and photon mediating processes. We use the best $e^- \rightarrow \nu_e \gamma$ limit for the Summary Tables.

Note that we use the mean life rather than the half life, which is often reported.

## $e \rightarrow \nu_e \gamma$ and astrophysical limits

| *VALUE* (yr) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>6.6 × 10^28** | 90 | AGOSTINI | 15B | BORX | $e^- \rightarrow \nu\gamma$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $>1.2 \times 10^{24}$ | 90 | ABGRALL | 17 | HPGE | electron decay to invisible |
| $>1.22 \times 10^{26}$ | 68 | [1] KLAPDOR-K... | 07 | CNTR | $e^- \rightarrow \nu\gamma$ |
| $>4.6 \times 10^{26}$ | 90 | BACK | 02 | BORX | $e^- \rightarrow \nu\gamma$ |
| $>3.4 \times 10^{26}$ | 68 | BELLI | 00B | DAMA | $e^- \rightarrow \nu\gamma$, liquid Xe |
| $>3.7 \times 10^{25}$ | 68 | AHARONOV | 95B | CNTR | $e^- \rightarrow \nu\gamma$ |
| $>2.35 \times 10^{25}$ | 68 | BALYSH | 93 | CNTR | $e^- \rightarrow \nu\gamma$, $^{76}$Ge detector |
| $>1.5 \times 10^{25}$ | 68 | AVIGNONE | 86 | CNTR | $e^- \rightarrow \nu\gamma$ |
| $>1 \times 10^{39}$ | | [2] ORITO | 85 | ASTR | Astrophysical argument |
| $>3 \times 10^{23}$ | 68 | BELLOTTI | 83B | CNTR | $e^- \rightarrow \nu\gamma$ |

[1] The authors of A. Derbin et al, arXiv:0704.2047v1 argue that this limit is overestimated by at least a factor of 5.

[2] ORITO 85 assumes that electromagnetic forces extend out to large enough distances and that the age of our galaxy is $10^{10}$ years.

## Disappearance and nuclear-de-excitation experiments

| *VALUE* (yr) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>6.4 × 10^24** | 68 | [1] BELLI | 99B | DAMA | De-excitation of $^{129}$Xe |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $>4.2 \times 10^{24}$ | 68 | BELLI | 99 | DAMA | Iodine L-shell disappearance |
| $>2.4 \times 10^{23}$ | 90 | [2] BELLI | 99D | DAMA | De-excitation of $^{127}$I (in NaI) |
| $>4.3 \times 10^{23}$ | 68 | AHARONOV | 95B | CNTR | Ge K-shell disappearance |
| $>2.7 \times 10^{23}$ | 68 | REUSSER | 91 | CNTR | Ge K-shell disappearance |
| $>2 \times 10^{22}$ | 68 | BELLOTTI | 83B | CNTR | Ge K-shell disappearance |

[1] BELLI 99B limit on charge nonconserving $e^-$ capture involving excitation of the 236.1 keV nuclear state of $^{129}$Xe; the 90% CL limit is $3.7 \times 10^{24}$ yr. Less stringent limits for other states are also given.

[2] BELLI 99D limit on charge nonconserving $e^-$ capture involving excitation of the 57.6 keV nuclear state of $^{127}$I. Less stringent limits for the other states and for the state of $^{23}$Na are also given.

## LIMITS ON LEPTON-FLAVOR VIOLATION IN PRODUCTION

Forbidden by lepton family number conservation.

This section was added for the 2008 edition of this *Review* and is not complete. For a list of further measurements see references in the papers listed below.

### $\sigma(e^+e^- \to e^\pm\tau^\mp) / \sigma(e^+e^- \to \mu^+\mu^-)$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<8.9 × 10$^{-6}$** | 95 | AUBERT | 07P | BABR | $e^+e^-$ at $E_{cm}$ = 10.58 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<1.8 \times 10^{-3}$ | 95 | GOMEZ-CAD... | 91 | MRK2 | $e^+e^-$ at $E_{cm}$ = 29 GeV |

### $\sigma(e^+e^- \to \mu^\pm\tau^\mp) / \sigma(e^+e^- \to \mu^+\mu^-)$

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<4.0 × 10$^{-6}$** | 95 | AUBERT | 07P | BABR | $e^+e^-$ at $E_{cm}$ = 10.58 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<6.1 \times 10^{-3}$ | 95 | GOMEZ-CAD... | 91 | MRK2 | $e^+e^-$ at $E_{cm}$ = 29 GeV |

## *e* REFERENCES


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| ABGRALL | 17 | PRL 118 161801 | N. Abgrall *et al.* | (MAJORANA Collab.) |
| CAIRNCROSS | 17 | PRL 119 153001 | W.B. Cairncross *et al.* | (NIST,COLO) |
| MOHR | 16 | RMP 88 035009 | P.J. Mohr, D.B. Newell, B.N. Taylor | (NIST) |
| AGOSTINI | 15B | PRL 115 231802 | M. Agostini *et al.* | (Borexino Collab.) |
| KIM | 15 | PR D91 102004 | Y.J. Kim *et al.* | (IND, YALE, LANL) |
| BARON | 14 | SCIENCE 343 269 | J. Baron *et al.* | (ACME Collab.) |
| DOLGOV | 14 | PL B732 244 | A.D. Dolgov, V.A. Novikov | |
| ECKEL | 12 | PRL 109 193003 | S. Eckel, A.O. Sushkov, S.K. Lamoreaux | (YALE) |
| MOHR | 12 | RMP 84 1527 | P.J. Mohr, B.N. Taylor, D.B. Newell | (NIST) |
| PDG | 12 | PR D86 010001 | J. Beringer *et al.* | (PDG Collab.) |
| HUDSON | 11 | NAT 473 493 | J.J. Hadson *et al.* | (LOIC) |
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| MOHR | 08 | RMP 80 633 | P.J. Mohr, B.N. Taylor, D.B. Newell | (NIST) |
| AUBERT | 07P | PR D75 031103 | B. Aubert *et al.* | (BABAR Collab.) |
| KLAPDOR-K... | 07 | PL B644 109 | H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, I.V. Titkova | |
| ODOM | 06 | PRL 97 030801 | B. Odom *et al.* | (HARV) |
| MOHR | 05 | RMP 77 1 | P.J. Mohr, B.N. Taylor | (NIST) |
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| | | | | |
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| CHO | 89 | PRL 63 2559 | D. Cho, K. Sangster, E.A. Hinds | (YALE) |
| MURTHY | 89 | PRL 63 965 | S.A. Murthy *et al.* | (AMHT) |
| COHEN | 87 | RMP 59 1121 | E.R. Cohen, B.N. Taylor | (RISC, NBS) |
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| AVIGNONE | 86 | PR D34 97 | F.T. Avignone *et al.* | (PNL, SCUC) |
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| CHU | 84 | PRL 52 1689 | S. Chu, A.P. Mills, J.L. Hall | (BELL, NBS, COLO) |
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| WEISSKOPF | 68 | PRL 21 1645 | M.C. Weisskopf *et al.* | (BRAN) |