

γ (photon)

$$I(J^{PC}) = 0,1(1^{--})$$

 γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: $1 \text{ eV} = 1.783 \times 10^{-33} \text{ g} = 1.957 \times 10^{-6} m_e$; $\hbar c = (1.973 \times 10^{-7} \text{ m}) \times (1 \text{ eV}/m_\gamma)$.

| VALUE (eV) | CL% | DOCUMENT ID | TECN | COMMENT |
|---|------|-------------------------|------|--|
| $<1 \times 10^{-18}$ | | ¹ RYUTOV | 07 | MHD of solar wind |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<2.3 \times 10^{-9}$ | 95 | ² EGOROV | 14 | COSM Lensed quasar position |
| | | ³ ACCIOLY | 10 | Anomalous mag. mom. |
| $<1 \times 10^{-26}$ | | ⁴ ADELBERGER | 07A | Proca galactic field |
| no limit feasible | | ⁴ ADELBERGER | 07A | γ as Higgs particle |
| $<1 \times 10^{-19}$ | | ⁵ TU | 06 | Torque on rotating magnetized toroid |
| $<1.4 \times 10^{-7}$ | | ACCIOLY | 04 | Dispersion of GHz radio waves by sun |
| $<2 \times 10^{-16}$ | | ⁶ FULLEKRUG | 04 | Speed of 5-50 Hz radiation in atmosphere |
| $<7 \times 10^{-19}$ | | ⁷ LUO | 03 | Torque on rotating magnetized toroid |
| $<1 \times 10^{-17}$ | | ⁸ LAKES | 98 | Torque on toroid balance |
| $<6 \times 10^{-17}$ | | ⁹ RYUTOV | 97 | MHD of solar wind |
| $<8 \times 10^{-16}$ | 90 | ¹⁰ FISCHBACH | 94 | Earth magnetic field |
| $<5 \times 10^{-13}$ | | ¹¹ CHERNIKOV | 92 | SQID Ampere-law null test |
| $<1.5 \times 10^{-9}$ | 90 | ¹² RYAN | 85 | Coulomb-law null test |
| $<3 \times 10^{-27}$ | | ¹³ CHIBISOV | 76 | Galactic magnetic field |
| $<6 \times 10^{-16}$ | 99.7 | ¹⁴ DAVIS | 75 | Jupiter magnetic field |
| $<7.3 \times 10^{-16}$ | | HOLLWEG | 74 | Alfven waves |
| $<6 \times 10^{-17}$ | | ¹⁵ FRANKEN | 71 | Low freq. res. cir. |
| $<2.4 \times 10^{-13}$ | | ¹⁶ KROLL | 71A | Dispersion in atmosphere |
| $<1 \times 10^{-14}$ | | ¹⁷ WILLIAMS | 71 | CNTR Tests Gauss law |
| $<2.3 \times 10^{-15}$ | | GOLDHABER | 68 | Satellite data |

¹ RYUTOV 07 extends the method of RYUTOV 97 to the radius of Pluto's orbit.

² EGOROV 14 studies chromatic dispersion of lensed quasar positions ("gravitational rainbows") that could be produced by any of several mechanisms, among them via photon mass. Limit not competitive but obtained on cosmological distance scales.

³ ACCIOLY 10 limits come from possible alterations of anomalous magnetic moment of electron and gravitational deflection of electromagnetic radiation. Reported limits are not "claimed" by the authors and in any case are not competitive.

⁴ When trying to measure m one must distinguish between measurements performed on large and small scales. If the photon acquires mass by the Higgs mechanism, the large-scale behavior of the photon might be effectively Maxwellian. If, on the other hand, one postulates the Proca regime for all scales, the very existence of the galactic field implies $m < 10^{-26} \text{ eV}$, as correctly calculated by YAMAGUCHI 59 and CHIBISOV 76.

⁵ TU 06 continues the work of LUO 03, with extended LAKES 98 method, reporting the improved limit $\mu^2 A = (0.7 \pm 1.7) \times 10^{-13} \text{ T/m}$ if $A = 0.2 \mu\text{G}$ out to 4×10^{22}

- m. Reported result $\mu = (0.9 \pm 1.5) \times 10^{-52}$ g reduces to the frequentist mass limit 1.2×10^{-19} eV (FELDMAN 98).
- ⁶ FULLEKRUG 04 adopted KROLL 71A method with newer and better Schumann resonance data. Result questionable because assumed frequency shift with photon mass is assumed to be linear. It is quadratic according to theorem by GOLDHABER 71B, KROLL 71, and PARK 71.
- ⁷ LUO 03 extends LAKES 98 technique to set a limit on $\mu^2 A$, where μ^{-1} is the Compton wavelength λ_C of the massive photon and A is the ambient vector potential. The important departure is that the apparatus rotates, removing sensitivity to the direction of A . They take $A = 10^{12}$ Tm, due to “cluster level fields.” But see comment of GOLDHABER 03 and reply by LUO 03B.
- ⁸ LAKES 98 reports limits on torque on a toroid Cavendish balance, obtaining a limit on $\mu^2 A < 2 \times 10^{-9}$ Tm/m² via the Maxwell-Proca equations, where μ^{-1} is the characteristic length associated with the photon mass and A is the ambient vector potential in the Lorentz gauge. Assuming $A \approx 1 \times 10^{12}$ Tm due to cluster fields he obtains $\mu^{-1} > 2 \times 10^{10}$ m, corresponding to $\mu < 1 \times 10^{-17}$ eV. A more conservative limit, using $A \approx (1 \mu\text{G}) \times (600 \text{ pc})$ based on the galactic field, is $\mu^{-1} > 1 \times 10^9$ m or $\mu < 2 \times 10^{-16}$ eV.
- ⁹ RYUTOV 97 uses a magnetohydrodynamics argument concerning survival of the Sun’s field to the radius of the Earth’s orbit. “To reconcile observations to theory, one has to reduce [the photon mass] by approximately an order of magnitude compared with” per DAVIS 75. “Secure limit, best by this method” (per GOLDHABER 10).
- ¹⁰ FISCHBACH 94 analysis is based on terrestrial magnetic fields; approach analogous to DAVIS 75. Similar result based on a much smaller planet probably follows from more precise B field mapping. “Secure limit, best by this method” (per GOLDHABER 10).
- ¹¹ CHERNIKOV 92, motivated by possibility that photon exhibits mass only below some unknown critical temperature, searches for departure from Ampere’s Law at 1.24 K. See also RYAN 85.
- ¹² RYAN 85, motivated by possibility that photon exhibits mass only below some unknown critical temperature, sets mass limit at $< (1.5 \pm 1.4) \times 10^{-42}$ g based on Coulomb’s Law departure limit at 1.36 K. We report the result as frequentist 90% CL (FELDMAN 98).
- ¹³ CHIBISOV 76 depends in critical way on assumptions such as applicability of virial theorem. Some of the arguments given only in unpublished references.
- ¹⁴ DAVIS 75 analysis of Pioneer-10 data on Jupiter’s magnetic field. “Secure limit, best by this method” (per GOLDHABER 10).
- ¹⁵ FRANKEN 71 method is of dubious validity (KROLL 71A, JACKSON 99, GOLDHABER 10, and references therein).
- ¹⁶ KROLL 71A used low frequency Schumann resonances in cavity between the conducting earth and resistive ionosphere, overcoming objections to resonant-cavity methods (JACKSON 99, GOLDHABER 10, and references therein). “Secure limit, best by this method” (per GOLDHABER 10).
- ¹⁷ WILLIAMS 71 is landmark test of Coulomb’s law. “Secure limit, best by this method” (per GOLDHABER 10).

γ CHARGE

OKUN 06 has argued that schemes in which all photons are charged are inconsistent. He says that if a neutral photon is also admitted to avoid this problem, then other problems emerge, such as those connected with the emission and absorption of charged photons by charged particles. He concludes that in the absence of a self-consistent phenomenological basis, interpretation of experimental data is at best difficult.

| VALUE (e) | CHARGE | DOCUMENT ID | TECN | COMMENT |
|----------------------|---------------|-----------------------|----------|----------------------|
| $<1 \times 10^{-46}$ | mixed | ¹ ALTSCHUL | 07B VLBI | Aharonov-Bohm effect |
| $<1 \times 10^{-35}$ | single | ² CAPRINI | 05 CMB | Isotropy constraint |

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

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|------------------------|--------|--------------------------|-----|------|--|
| $<1 \times 10^{-32}$ | single | ¹ ALTSCHUL | 07B | VLBI | Aharonov-Bohm effect |
| $<3 \times 10^{-33}$ | mixed | ³ KOBYCHEV | 05 | VLBI | Smear as function of $B \cdot E_\gamma$ |
| $<4 \times 10^{-31}$ | single | ³ KOBYCHEV | 05 | VLBI | Deflection as function of $B \cdot E_\gamma$ |
| $<8.5 \times 10^{-17}$ | | ⁴ SEMERTZIDIS | 03 | | Laser light deflection in B-field |
| $<3 \times 10^{-28}$ | single | ⁵ SIVARAM | 95 | CMB | For $\Omega_M = 0.3$, $h^2 = 0.5$ |
| $<5 \times 10^{-30}$ | | ⁶ RAFFELT | 94 | TOF | Pulsar $f_1 - f_2$ |
| $<2 \times 10^{-28}$ | | ⁷ COCCONI | 92 | | VLBA radio telescope resolution |
| $<2 \times 10^{-32}$ | | COCCONI | 88 | TOF | Pulsar $f_1 - f_2$ TOF |

¹ ALTSCHUL 07B looks for Aharonov-Bohm phase shift in addition to geometric phase shift in radio interference fringes (VSOP mission).

² CAPRINI 05 uses isotropy of the cosmic microwave background to place stringent limits on possible charge asymmetry of the Universe. Charge limits are set on the photon, neutrino, and dark matter particles. Valid if charge asymmetries produced by different particles are not anticorrelated.

³ KOBYCHEV 05 considers a variety of observable effects of photon charge for extragalactic compact radio sources. Best limits if source observed through a foreground cluster of galaxies.

⁴ SEMERTZIDIS 03 reports the first laboratory limit on the photon charge in the last 30 years. Straightforward improvements in the apparatus could attain a sensitivity of $10^{-20} e$.

⁵ SIVARAM 95 requires that CMB photon charge density not overwhelm gravity. Result scales as $\Omega_M h^2$.

⁶ RAFFELT 94 notes that COCCONI 88 neglects the fact that the time delay due to dispersion by free electrons in the interstellar medium has the same photon energy dependence as that due to bending of a charged photon in the magnetic field. His limit is based on the assumption that the entire observed dispersion is due to photon charge. It is a factor of 200 less stringent than the COCCONI 88 limit.

⁷ See COCCONI 92 for less stringent limits in other frequency ranges. Also see RAFFELT 94 note.

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