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 eV $= 1.783 \times 10^{-33}$ g $= 1.957 \times 10^{-6}$ m_e; $\lambda\!\!\!^{-}_C = (1.973 \times 10^{-7}$ m$)\times(1$ eV$/m_\gamma)$.

VALUE (eV)	CL%	DOCUMENT ID		COMMENT
$<1 \times 10^{-18}$		[1] RYUTOV	07	MHD of solar wind
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<4.9 \times 10^{-7}$		[2] MALTA	24	Shapiro effect in solar system
$<2.5 \times 10^{-18}$		[3] YAN	24A	Jovian magnetic field
$<2.1 \times 10^{-15}$	68	[4] WANG	23B	Fast Radio Bursts
$<2.5 \times 10^{-14}$		[5] MALTA	22	Schumann resonances in the Earth-ionosphere cavity
$<2.2 \times 10^{-14}$		[6] BONETTI	17	Fast Radio Bursts, FRB 121102
$<1.8 \times 10^{-14}$		[7] BONETTI	16	Fast Radio Bursts, FRB 150418
$<1.9 \times 10^{-15}$		[8] RETINO	16	Ampere's Law in solar wind
$<2.3 \times 10^{-9}$	95	[9] EGOROV	14	Lensed quasar position
		[10] ACCIOLY	10	Anomalous magn. mom.
$<1 \times 10^{-26}$		[11] ADELBERGER	07A	Proca galactic field
no limit feasible		[11] ADELBERGER	07A	γ as Higgs particle
$<1 \times 10^{-19}$		[12] TU	06	Torque on rotating magnetized toroid
$<1.4 \times 10^{-7}$		ACCIOLY	04	Dispersion of GHz radio waves by sun
$<2 \times 10^{-16}$		[13] FULLEKRUG	04	Speed of 5-50 Hz radiation in atmosphere
$<7 \times 10^{-19}$		[14] LUO	03	Torque on rotating magnetized toroid
$<1 \times 10^{-17}$		[15] LAKES	98	Torque on toroid balance
$<6 \times 10^{-17}$		[16] RYUTOV	97	MHD of solar wind
$<8 \times 10^{-16}$	90	[17] FISCHBACH	94	Earth magnetic field
$<5 \times 10^{-13}$		[18] CHERNIKOV	92	Ampere's Law null test
$<1.5 \times 10^{-9}$	90	[19] RYAN	85	Coulomb's Law null test
$<3 \times 10^{-27}$		[20] CHIBISOV	76	Galactic magnetic field
$<6 \times 10^{-16}$	99.7	[21] DAVIS	75	Jupiter's magnetic field
$<7.3 \times 10^{-16}$		HOLLWEG	74	Alfven waves
$<6 \times 10^{-17}$		[22] FRANKEN	71	Low freq. res. circuit
$<2.4 \times 10^{-13}$		[23] KROLL	71A	Dispersion in atmosphere
$<1 \times 10^{-14}$		[24] WILLIAMS	71	Tests Coulomb's 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] MALTA 24 gives an upper limit on the photon mass by analysing the gravitational time delay in a weak-field approximation using Doppler-tracking data from the Cassini mission.

[3] YAN 24A put constraints on the photon mass modelling non-zero-mass effects on the Jupiter magnetic field and using data of the JUNO Mission.

[4] WANG 23B use fast radio burst photon mass dependent dispersion relation to determine an upper limit of the photon mass.

[5] MALTA 22 consider the effect of a finite photon mass on Schumann resonances in the Earth-ionosphere cavity, improve limit by KROLL 71A by considering realistic conductivity profiles for the atmosphere.

[6] BONETTI 17 uses frequency-dependent time delays of repeating FRB with well-determined redshift, assuming the DM is caused by expected dispersion in IGM. There are several uncertainties, leading to mass limit 2.2×10^{-14} eV.

[7] BONETTI 16 uses frequency-dependent time delays of FRB, assuming the DM is caused by expected dispersion in IGM. There are several uncertainties, leading to mass limit 1.8×10^{-14} eV, if indeed the FRB is at the initially reported redshift.

[8] RETINO 16 looks for deviations from Ampere's law in the solar wind, using Cluster four spacecraft data. Authors quote a range of limits from 1.9×10^{-15} eV to 7.9×10^{-14} eV depending on the assumptions of the vector potential from the interplanetary magnetic field.

[9] 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.

[10] 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.

[11] 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 $m < 10^{-26}$ eV, as correctly calculated by YAMAGUCHI 59 and CHIBISOV 76.

[12] TU 06 continues the work of LUO 03, with extended LAKES 98 method, reporting the improved limit $\mu^2 A = (0.7 \pm 1.7) \times 10^{-13}$ T/m if $A = 0.2$ μG 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). While the results of the torsion balance method give a value for the local limit on $\mu^2 A$, the deduced limit on the photon mass μ is open to question. See the discussions in TU 05 and GOLDHABER 03.

[13] 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.

[14] LUO 03 extends LAKES 98 technique to set a limit on $\mu^2 A$, where μ^{-1} is the Compton wavelength $\lambda\!\!\!^{-}_C$ 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.

[15] LAKES 98 reports limits on torque on a toroid Cavendish balance, obtaining a limit on $\mu^2 A < 2 \times 10^{-9}$ Tm/m^2 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.

[16] 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).

[17] 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).

[18] 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.

[19] 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).

[20] CHIBISOV 76 depends in critical way on assumptions such as applicability of virial theorem. Some of the arguments given only in unpublished references.

[21] DAVIS 75 analysis of Pioneer-10 data on Jupiter's magnetic field. "Secure limit, best by this method" (per GOLDHABER 10).

[22] FRANKEN 71 method is of dubious validity (KROLL 71A, JACKSON 99, GOLDHABER 10, and references therein).

[23] 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).

[24] 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. • • •					
$<1 \times 10^{-32}$	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 Ω_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.

γ REFERENCES

MALTA	24	PR D110 095017	P.C. Malta, C.A.D. Zarro	(UFRJ)
YAN	24A	JHEP 2406 028	S. Yan, L. Li, J.J. Fan	(BROW)
WANG	23B	JCAP 2309 025	B. Wang *et al.*	
MALTA	22	PR D106 116014	P.C. Malta, J.A. Helayel-Neto	
BONETTI	17	PL B768 326	L. Bonetti *et al.*	(ORLEANS, CERN)
BONETTI	16	PL B757 548	L. Bonetti *et al.*	
RETINO	16	ASP 82 49	A. Retino, A.D.A.M. Spallicci, A. Vaivads	(CURCP+)
EGOROV	14	MNRAS 437 L90	P. Egorov *et al.*	(MOSU, MIPT, INRM)
ACCIOLY	10	PR D82 065026	A. Accioly, J. Helayel-Neto, E. Scatena	(LABEX+)
GOLDHABER	10	RMP 82 939	A.S. Goldhaber, M.M. Nieto	(STON, LANL)
ADELBERGER	07A	PRL 98 010402	E. Adelberger, G. Dvali, A. Gruzinov	(WASH, NYU)
ALTSCHUL	07B	PRL 98 261801	B. Altschul	(IND)
Also		ASP 29 290	B. Altschul	(SCUC)
RYUTOV	07	PPCF 49 B429	D.D. Ryutov	(LLNL)
OKUN	06	APP B37 565	L.B. Okun	(ITEP)
TU	06	PL A352 267	L.-C. Tu *et al.*	
CAPRINI	05	JCAP 0502 006	C. Caprini, P.G. Ferreira	(GEVA, OXFTP)
KOBYCHEV	05	AL 31 147	V.V. Kobychev, S.B. Popov	(KIEV, PADO)
TU	05	RPP 68 77	L.-C. Tu, J. Luo, G.T. Gillies	
ACCIOLY	04	PR D69 107501	A. Accioly, R. Paszko	
FULLEKRUG	04	PRL 93 043901	M. Fullekrug	
GOLDHABER	03	PRL 91 149101	A.S. Goldhaber, M.M. Nieto	
LUO	03	PRL 90 081801	J. Luo *et al.*	
LUO	03B	PRL 91 149102	J. Luo *et al.*	
SEMERTZIDIS	03	PR D67 017701	Y.K. Semertzidis, G.T. Danby, D.M. Lazarus	
JACKSON	99	Classical Electrodynamics	J.D. Jackson	(3rd ed., J. Wiley and Sons (1999))
FELDMAN	98	PR D57 3873	G.J. Feldman, R.D. Cousins	
LAKES	98	PRL 80 1826	R. Lakes	(WISC)
RYUTOV	97	PPCF 39 A73	D.D. Ryutov	(LLNL)
SIVARAM	95	AJP 63 473	C. Sivaram	(BANG)
FISCHBACH	94	PRL 73 514	E. Fischbach *et al.*	(PURD, JHU+)
RAFFELT	94	PR D50 7729	G. Raffelt	(MPIM)
CHERNIKOV	92	PRL 68 3383	M.A. Chernikov *et al.*	(ETH)
Also		PRL 69 2999 (errat.)	M.A. Chernikov *et al.*	(ETH)
COCCONI	92	AJP 60 750	G. Cocconi	(CERN)
COCCONI	88	PL B206 705	G. Cocconi	(CERN)
RYAN	85	PR D32 802	J.J. Ryan, F. Accetta, R.H. Austin	(PRIN)
CHIBISOV	76	SPU 19 624	G.V. Chibisov	(LEBD)
		Translated from UFN 119 551.		
DAVIS	75	PRL 35 1402	L. Davis, A.S. Goldhaber, M.M. Nieto	(CIT, STON+)
HOLLWEG	74	PRL 32 961	J.V. Hollweg	(NCAR)
FRANKEN	71	PRL 26 115	P.A. Franken, G.W. Ampulski	(MICH)
GOLDHABER	71B	RMP 43 277	A.S. Goldhaber, M.M. Nieto	(STON, BOHR, UCSB)
KROLL	71	PRL 26 1395	N.M. Kroll	(SLAC)
KROLL	71A	PRL 27 340	N.M. Kroll	(SLAC)
PARK	71	PRL 26 1393	D. Park, E.R. Williams	(WILC)
WILLIAMS	71	PRL 26 721	E.R. Williams, J.E. Faller, H.A. Hill	(WESL)
GOLDHABER	68	PRL 21 567	A.S. Goldhaber, M.M. Nieto	(STON)
YAMAGUCHI	59	PTPS 11 37	Y. Yamaguchi	