1.2.3 Atomic constants

The values of *e, h,* N_A etc., given in this section are based on the values of Cohen and Taylor (1987).

The best values of constants such as the mass and charge of the electron are not found by measuring each separately (e.g. as in Millikan's oil-drop experiment). The values recommended in the above paper were obtained by a weighted 'least-squares' statistical treatment of selected experimental data. The values depend on comparatively few (22) experimental results and the number of 'unknowns' was reduced by treating certain combinations of the constants as being exact (or auxiliary constants) for the purposes of the evaluation. This group included quantities such as the Rydberg constant $\mu_0 c^3 m_e e^4/8h^3$, the ratio μ'_p/μ_B between the proton magnetic moment (in water) μ'_p and the Bohr magneton μ_B (= $eh/4\pi m_e$), the Josephson effect value of $2e/h$ in terms of the maintained representation of the volt, and set numerical functional relationships between *e, h,* and m_e. The unknowns included the spectroscopic fine-structure constant α $((\mu_0 c^2/4\pi)e^2/h)$, the ratio K_Ω of the maintained representation of the ohm to the SI ohm, the ratio K_V of the BIPM maintained representation of the volt to the SI volt, d_{220} the (220) lattice spacing of a perfect crystal of pure silicon at 22.5 °C in vacuum and μ_μ/μ_p the ratio of the magnetic moment of the muon to that of the proton. Some of the experimental data can only be interpreted in terms of α, etc. by invoking very sophisticated quantum electrodynamic calculations and so, as time passes, improved values are obtained for α as higher order terms are taken into account.

After the 1973 evaluation by Cohen and Taylor it became apparent that the 1973 recommended value of K_V was in error by about eight parts per million. In addition there were further accurate measurements such as the gravitational constant, the gas constant, the Avogadro constant, and the Rydberg constant. The advent of ion traps led to increased accuracy of measurement of the electron magnetic moment anomaly $g_c - 2$, and of the ratio of the proton to electron mass. Better direct realizations were made of the ampere, watt, and ohm, while the quantized Hall resistance in MOSFET semi-conductors at low temperatures provided information concerning K_Ω and α.

As a result of the method of evaluation there are correlations between the output values, so that the full variance and co-variance matrix should be used for computing values that are not given in the table. Although the accuracy is normally well ahead of user requirements, it is always important to specify which evaluation one has used and also to ensure that they come from a consistent set of constants. (Results from different evaluations may differ and consequently should not be mixed, otherwise the constants will not form a consistent set.) For the most part, more accurate measurements since 1987 have confirmed the correctness of the 1987 set within their assigned uncertainties. A more accurate evaluation will be made when sufficient experimental data are available.

Values accepted formerly. Other conventional values of *e*, *h*, etc. may be encountered in books, and some of these earlier values are given below. The first is essentially Millikan's oil-drop value of *e*, 4.77 × 10^{-10} esu, and the second the 'X-ray grating' value 4.802. The numbers in brackets are standard errors. It will be seen that the accuracies claimed have sometimes appeared over-optimistic in retrospect, and that besides the supposed random errors of observation some unsuspected systematic error has been present. (In Millikan's value of e, accepted from 1917 to 1935, it was an inaccuracy in the assumed viscosity of air.) Consequently, it may be thought prudent to regard the standard errors given here with caution. Although the accuracy has improved over the years there is no sustained evidence for any systematic time dependence of these constants, and increasing reliance is placed on them for metrological purposes.

Author of discussion	$e \times 10^{19}$/C	$h \times 10^{34}$/(J s)	*Kaye and Laby*
Birge, 1929.	1.591 1	6.547	7th ed.
	(0.002 4)	(0.012)	
Birge, 1942.	1.602 03	6.624 2	10th ed.
	(0.000 50)	(0.003 5)	
Dumond and Cohen, 1963. .	1.602 10	6.625 6	13th ed.
	(0.000 02)	(0.000 16)	
Taylor et al., 1969.	1.602 192	6.626 20	14th ed.
	(0.000 007)	(0.000 05)	
Cohen and Taylor, 1973. . .	1.602 189 2	6.626 176	15th ed. (1986)
	(0.000 004 6)	(0.000 036)	
Cohen and Taylor, 1987. . .	1.602 177 3	6.626 075 5	15th ed. (1991
	(0.000 000 49)	(0.000 004 0)	reprint)

Table of fundamental constants

These are the recommended values of Mohr and Taylor (2004). These are known as the 2002 best values and are based on the published data to about December 2002; they may be superseded by a more accurate set if sufficient new data are available. They will be available on the NIST Web Site at http://physics.nist.gov/cuu/Constants/

				SI unit	*Standard error* (parts in 10^6)
Principal constants					
Speed of light in vacuum . .	*c*	2.997 924 580	$\times 10^{8}$	m s^{-1}	exact
Planck constant	*h*	6.626 0693	$\times 10^{-34}$	J s	0.17

Planck constant ($h/2\pi$) . . .	$\hbar$	1.054 571 68	$\times10^{-34}$	J s	0.17
Elementary charge	e	1.602 176 53	$\times10^{-19}$	C	0.085
Mass of electron	m_e	9.109 3826	$\times10^{-31}$	kg	0.17
Mass of electron in atomic mass units		5.485 799 0945	$\times10^{-4}$	u	0.00044
Avogadro constant	N_A, L	6.022 14145	$\times10^{23}$	mol^{-1}	0.17
Atomic mass unit, 10^{-3} kg mol^{-1} N_A^{-1}	u	1.660 540 2	$\times10^{-27}$	kg	0.17
Faraday constant	F ($= N_A e$)	9.648 533 83	$\times10^{4}$	C mol^{-1}	0.086
Newtonian constant of gravitation	G	6.6742	$\times10^{-11}$	N m^2 Kg^{-2}	150
Spectroscopy and atoms					
Planck constant	h	4.135 667 43	$\times10^{-15}$	eV s	0.085
Planck constant ($h/2\pi$) . . .	$\hbar$	6.582 119 15	$\times10^{-16}$	eV s	0.085
Charge/mass ratio of electron .	$-e/m_e$	−1.758 820 12	$\times10^{11}$	C kg^{-1}	0.086
Fine structure constant .	α	7.297 352 568	$\times10^{-3}$		0.0033
Fine structure constant, reciprocal	α^{-1}	137.035 999 11			0.0033
Rydberg constant (fixed nucleus) .	R_∞	10 973 731.568 525		m^{-1}	0.0000066
Bohr radius $(4\pi/\mu_0 c^2)\hbar^2/m_e e^2$.	a_0	5.291 772 108	$\times10^{-11}$	m	0.00333
Compton wavelength of electron .	λ_c	2.426 310 238	$\times10^{-12}$	m	0.0067
Compton wavelength of electron ÷ 2π	$\hbar/m_e c$	3.861 592 678	$\times10^{-13}$	m	0.0067
Classical 'radius' of electron $(\mu_0 c^2/4\pi)e^2/mc^2$	r_e	2.817 940 325	$\times10^{-15}$	m	0.01
Thomson cross-section $8\pi r_e{}^2/3$	σ_e	6.652 458 73	$\times10^{-29}$	m	0.02
Zeeman effect,	μ_B/hc	46.686 4507		m^{-1} T^{-1}	0.086
Bohr magneton $e\hbar/2m_e$ . .	μ_B	9.274 015 4	$\times10^{-24}$	J T^{-1}	0.086
Nuclear magneton $e\hbar/2m_p$ . .	μ_N	5.050 783 43	$\times10^{-27}$	J T^{-1}	0.086
Ratio of masses proton/electron	m_p/m_e	1 836.152 672 61			0.00046
Gyromagnetic ratio of proton .	$\gamma_p = \mu_p / \frac{1}{2}\hbar$	2.675 222 05	$\times10^{8}$	s^{-1} T^{-1}	0.086
in H_2O, sph., 25 ºC . . .	γ'_p	2.675 153 33	$\times10^{8}$	s^{-1} T^{-1}	0.086
in H_2O (cycles), sph., 25 ºC .	$\gamma'_p/2\pi$	4.257 638 75	$\times10^{7}$	Hz T^{-1}	0.086
Conversion factors for mass, energy and wavelength					
Energy and mass					
Electron volt		1.602 176 53	$\times10^{-19}$	J	0.17
Atomic mass unit		931.494 043		MeV	0.086

1 MeV		1.073 544 171	$\times 10^{-3}$	u	0.0086
Rest-mass of electron . . .		0.510 998 9186		MeV	0.17
1 eV per molecule		9.648 533 83	$\times 10^{7}$	J $kmol^{-1}$	0.086
Frequency, wavelength and energy					
Quantum energy ÷ wave number		1.986 445 61	$\times 10^{-25}$	J m	0.18
Energy × wavelength . . .		1.239 841 91	$\times 10^{-6}$	eV m	0.0085
Wave number ÷ energy . .		8.065 544 45	$\times 10^{5}$	eV^{-1} m^{-1}	0.085
Quantum energy ÷ frequency .		4.135 667 43	$\times 10^{-15}$	eV Hz^{-1}	0.0.085
Frequency ÷ energy . . .		2.417 989 40	$\times 10^{14}$	Hz eV^{-1}	0.085
Thermal constants					
Molar gas constant . . .	R	8.314 472		J mol^{-1} K^{-1}	1.7
Loschmidt constant (number of molecules in 1 m^3 of ideal gas at stp) . .	n_0	2.686 7773	$\times 10^{25}$	m^{-3}	1.8
Boltzmann constant R/N_A . .	k	1.380 6505	$\times 10^{-23}$	J K^{-1}	1.8
Boltzmann constant . . .		8.617 343	$\times 10^{-5}$	eV K^{-1}	1.8
Stefan-Boltzmann constant (σ)† . . .	$2\pi^5 k^4/15c^2h^3$	5.670 400	$\times 10^{-8}$	Wm^{-2} K^{-4}	7
Constant in Planck formula (c_1)† .	$2\pi hc^2$	3.741 771 38	$\times 10^{-16}$	W m^2	0.17
Constant in Planck formula (c_2)† .	hc/k	1.438 7752	$\times 10^{-2}$	m K	1.7

† see also section 2.5.2.

Note: Magnetic moments are defined so that mechanical energy = $-\mu . \boldsymbol{B}$; the unit is 1 J T^{-1} = 1 J Wb^{-1} m^2 = 1 A m^2 (1 tesla = 1 weber m^{-2} ≡ 10^4 gauss).

*Standard values**

Von Klitzing constant R_{K-90} 25 812.807 (1 ± 0.2 × 10^{-6}) Ω

Josephson constant K_{J-90} 483 579.9 (1 ± 0.4 × 10^{-6}) GHz/V

* These standard values were recommended by the CCE in 1989 for adoption from 1.1.1990. The CCE considered later data than were available to Cohen and Taylor (1987) and they are not necessarily identical with h/e^2 and $2e/h$ respectively. They were defined by the CCE in order to help ensure global uniformity of standards of resistance and emf. (The suffix −90 is used here to indicate that they may be revised at a later date, although it is usually omitted.)

Reference

P. J Mohr and B. N. Taylor, Rev. Mod Phys., **76**, no 4(Oct 2004)

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