THE FUNDAMENTAL PHYSICAL CONSTANTS

The 1998 CODATA least-squares adjustment (the most recent carried out) has produced a new set of recommended values of the basic constants and conversion factors of physics and chemistry.

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The Committee on Data for Science and Technology (CODATA) was established in 1966 as an interdisciplinary committee of the International Council of Science (ICSU, formerly the International Council of Scientific Unions). Soon thereafter, in 1969, CODATA established the Task Group on Fundamental Constants (now the Task Group on Fundamental Physical Constants) to periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values of the basic constants and conversion factors of physics and chemistry. Under the auspices of this task group, we have recently completed a new least-squares adjustment of the values of the constants—termed the 1998 adjustment—that takes into account all relevant data available through 31 December 1998.[1] The accompanying tables give the 1998 CODATA recommended values resulting from that adjustment, with the exception of some specialized x-ray-related quantities and various natural and atomic units. The complete 1998 CODATA set of more than 300 recommended values, together with a covariance matrix of some of the more widely used values and a detailed description of the data and their analysis, are given in ref. 1. All of the values and all of their covariances (in the form of correlation coefficients) are available on the Web at http://physics.nist.gov/constants, in a searchable database provided by the Fundamental Constants Data Center of the NIST Physics Laboratory.

The 1998 CODATA set of recommended values replaces its immediate predecessor[2] issued by CODATA in 1986 and is a major step forward. The standard uncertainties (the estimated standard deviations) of many of the 1998 recommended values are about 1/5 to 1/12, and in the case of the Rydberg constant and some associated constants, 1/160 times the standard uncertainties of the corresponding 1986 values. Further, the absolute values of the differences between the 1986 values and the corresponding 1998 values are almost all less than twice the standard uncertainties of the 1986 values. The significant reduction of uncertainties and the relatively small shifts of values are apparent from the accompanying table, which compares the recommended values of a number of constants from the two adjustments.

The Newtonian constant of gravitation G is unique among the 1998 recommended values; its uncertainty is *larger* than that of the 1986 value by nearly a factor of 12. As explained in detail in ref. 1, for a number of reasons, but especially because of the existence of a value of G from a credible experiment that differs significantly from the 1986 value, the CODATA task group decided to retain the 1986 recommended value but to increase its relative uncertainty from $u_r = 1.3 \times 10^{-4}$ to 1.5×10^{-3}.

The Rydberg constant R_∞ with a shift of 2.7 times its 1986 uncertainty has the largest relative change in value of any constant. However, with a 1986 to 1998 uncertainty ratio of nearly 160, R_∞ has undergone the largest reduction in uncertainty of any constant. The large shift in value occurred because the 1986 recommended value of R_∞ is based mainly on a 1981 experimental result that turned out to be in error. The large uncertainty reduction is mainly due to the fact that, beginning in the early 1990s, optical frequency metrology replaced optical wavelength metrology in the measurement of transition frequencies in hydrogenic atoms, thereby significantly reducing the uncertainties of such measurements. Improvements in the theory of the energy levels of hydrogenic atoms also contributed to the uncertainty reduction.

The following experimental and theoretical advances made during the 13-year period between the 1986 and 1998 adjustments contributed to the reduction of the uncertainties for the fine-structure constant α, Planck constant h, and molar gas constant R. These constants are not only important in their own right, but, together with R_∞ and the relative atomic mass of the electron $A_r(e)$, they determine the recommended values of many other constants and conversion factors of prime interest.

▷ An improved experimental determination of the anomalous magnetic moment of the electron a_e obtained from measurements on a single electron confined in a Penning trap, combined with an improved theoretical expression for a_e calculated from quantum electrodynamics (QED), provides a value of α with $u_r = 3.8 \times 10^{-9}$. The 1998 recommended value of α with $u_r = 3.7 \times 10^{-9}$ is determined mainly by this result.

▷ The moving-coil watt balance, conceived in 1975 and first brought to a useful operational state in the late 1980s, provides two experimental values of $K_J^2 R_K = 4/h$,

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Comparison of the 1998 and 1986 CODATA recommended values of various constants

Quantity	1998 rel. std. uncert. u_r	1986 rel. std. uncert. u_r	Ratio 1986 u_r to 1998 u_r	D_r
α	3.7×10^{-9}	4.5×10^{-8}	12.2	–1.7
λ_C	7.3×10^{-9}	8.9×10^{-8}	12.2	–1.7
h	7.8×10^{-8}	6.0×10^{-7}	7.7	–1.7
N_A	7.9×10^{-8}	5.9×10^{-7}	7.5	1.5
e	3.9×10^{-8}	3.0×10^{-7}	7.8	–1.8
R	1.7×10^{-6}	8.4×10^{-6}	4.8	–0.5
k	1.7×10^{-6}	8.5×10^{-6}	4.8	–0.6
σ	7.0×10^{-6}	3.4×10^{-5}	4.8	–0.6
G	1.5×10^{-3}	1.3×10^{-4}	0.1	0.0
R_∞	7.6×10^{-12}	1.2×10^{-9}	157.1	2.7
m_e/m_p	2.1×10^{-9}	2.0×10^{-8}	9.5	0.9
$A_r(e)$	2.1×10^{-9}	2.3×10^{-8}	11.1	0.7

Note: The relative standard uncertainty of a quantity y is defined as $u_r(y) \equiv u(y)/|y|$, if $y \neq 0$, where $u(y)$ is the standard uncertainty of y. D_r is the 1998 value minus the 1986 value divided by the standard uncertainty of the 1986 value. The various constants are defined in subsequent tables.

one with $u_r = 8.7 \times 10^{-8}$ and the other with $u_r = 2.0 \times 10^{-7}$ ($K_J = 2e/h$ is the Josephson constant, characteristic of the Josephson effect, and $R_K = h/e^2$ is the von Klitzing constant, characteristic of the quantum Hall effect). The 1998 recommended value of h with $u_r = 7.8 \times 10^{-8}$ arises primarily from these two results.

▷ A determination of the speed of sound in argon using a spherical acoustic resonator provides an experimental value of R with $u_r = 1.8 \times 10^{-6}$, about 1/5 times the uncertainty of the 1986 recommended value, which is based on a result obtained using a cylindrical acoustic interferometer. The new value is mainly responsible for the 1998 recommended value of R with $u_r = 1.7 \times 10^{-6}$.

Improved measurements and calculations of a number of other quantities also contributed to our better overall knowledge of the constants. Notable are the Penning-trap mass-ratio measurements that furnished more accurate values of the relative atomic masses of the electron, proton, deuteron, helion (nucleus of ^{3}He), and α particle; the crystal diffraction determination of the binding energy of the neutron in the deuteron that led to a more accurate value of the relative atomic mass of the neutron; and the Zeeman transition-frequency determination of the ground-state hyperfine splitting in muonium (μ^+e^- atom) $\Delta\nu_{Mu}$, together with a more accurate theoretical expression for $\Delta\nu_{Mu}$ calculated from QED, that led to a more accurate value of the electron–muon mass ratio m_e/m_μ.

The 1998 adjustment differs from its 1986 predecessor in several important respects. First, we abandoned the 1986 grouping of the input data into the two distinct categories, stochastic input data and auxiliary constants, where the latter were assumed to be exactly known. Instead, we treated all input data on an essentially equal footing, regardless of their uncertainties. This allowed all components of uncertainty and all correlations among the data to be properly taken into account, while at the same time it eliminated an arbitrary division of the data into two categories.

Second, we did not attempt to quantify the "uncertainty" of the uncertainty assigned each input datum as was done in 1986 in order to analyze the data using extended least-squares algorithms. The change was made after reviewing in detail literally hundreds of experimental and theoretical results and concluding that, because of the complexity of the measurements and calculations in the field of fundamental constants, it is difficult enough to evaluate their uncertainties in a meaningful way, let alone the "uncertainties" of those uncertainties. We therefore used the standard least-squares algorithm in our data analysis.

Third, in order to properly take into account the uncertainties of various theoretical expressions—for example, those for the energy levels of hydrogen (H) and deuterium (D) required to obtain R_∞ from measurements of transition frequencies in these atoms—we introduced in the 1998 adjustment an additive correction δ_i for each such expression. The δ's are included among the variables of the least-squares adjustment, and their estimated values are taken as input data. The best *a priori* estimate of each δ_i is assumed to be zero but with a standard uncertainty equal to the standard uncertainty of the theoretical expression. This approach enabled us to account for the uncertainties in the theory in a rigorous way, although it increased the number of variables that we had to deal with and the size of the matrices that we had to invert. Fortunately, modern computers have little difficulty with such inversions.

Fourth, we analyzed the data using the method of least squares for correlated input data. This means that the covariance matrix of the input data was not diagonal. Although the need to consider correlations among the input data in the evaluation of the fundamental constants was first emphasized half a century ago, the 1998 adjustment was the first time it was actually done.

Our analysis of the input data proceeded in multiple stages. First, we compared the various measured values of each quantity. Next, we compared measured values of different quantities by comparing values of a common inferred constant. Prominent among those inferred constants are R_∞, α, and h. Finally, we carried out a multivariate analysis of the data using the method of least squares as discussed above. Because the input data related to R_∞ are not strongly tied to the rest of the input data, various stages of the analysis were done independently on those two groups of data before the data were combined for final analysis. The focus of all of these investigations was the compatibility of the data and the extent to which a particular datum would contribute to the determination of the 1998 recommended values of the constants.

The final least-squares adjustment on which the 1998 recommended values are based used 93 of the 107 input data that were initially considered and 57 variables or adjusted constants. The 93 input data included values of 9 silicon lattice-spacing differences and 27 H and D transition frequencies and frequency differences. The 57 adjusted constants included 28 δ's, 8 {220} silicon lattice spacings, R_∞, α, h, R, $A_r(e)$, and the relative atomic masses of five other particles. Although a number of the 1998 recommended values are adjusted constants and hence were directly determined in the adjustment, most recommended values were subsequently calculated from the adjusted constants. For example, the elementary charge

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CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
UNIVERSAL				
speed of light in vacuum	c, c_0	299 792 458	m s^{-1}	(exact)
magnetic constant	μ_0	$4\pi\times10^{-7}$	N A^{-2}	
		$=12.566\,370\,614\ldots\times10^{-7}$	N A^{-2}	(exact)
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817\ldots\times10^{-12}$	F m^{-1}	(exact)
characteristic impedance of vacuum $\sqrt{\mu_0/\epsilon_0}=\mu_0 c$	Z_0	$376.730\,313\,461\ldots$	Ω	(exact)
Newtonian constant of gravitation	G	$6.673(10)\times10^{-11}$	m^3 kg^{-1} s^{-2}	1.5×10^{-3}
	$G/\hbar c$	$6.707(10)\times10^{-39}$	$(\mathrm{GeV}/c^2)^{-2}$	1.5×10^{-3}
Planck constant	h	$6.626\,068\,76(52)\times10^{-34}$	J s	7.8×10^{-8}
in eV s		$4.135\,667\,27(16)\times10^{-15}$	eV s	3.9×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,596(82)\times10^{-34}$	J s	7.8×10^{-8}
in eV s		$6.582\,118\,89(26)\times10^{-16}$	eV s	3.9×10^{-8}
Planck mass $(\hbar c/G)^{1/2}$	m_P	$2.1767(16)\times10^{-8}$	kg	7.5×10^{-4}
Planck length $\hbar/m_P c=(\hbar G/c^3)^{1/2}$	l_P	$1.6160(12)\times10^{-35}$	m	7.5×10^{-4}
Planck time $l_P/c=(\hbar G/c^5)^{1/2}$	t_P	$5.3906(40)\times10^{-44}$	s	7.5×10^{-4}
ELECTROMAGNETIC				
elementary charge	e	$1.602\,176\,462(63)\times10^{-19}$	C	3.9×10^{-8}
	e/h	$2.417\,989\,491(95)\times10^{14}$	A J^{-1}	3.9×10^{-8}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,636(81)\times10^{-15}$	Wb	3.9×10^{-8}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,696(28)\times10^{-5}$	S	3.7×10^{-9}
inverse of conductance quantum	G_0^{-1}	$12\,906.403\,786(47)$	Ω	3.7×10^{-9}
Josephson constant[a] $2e/h$	K_J	$483\,597.898(19)\times10^{9}$	Hz V^{-1}	3.9×10^{-8}
von Klitzing constant[b] $h/e^2=\mu_0 c/2\alpha$	R_K	$25\,812.807\,572(95)$	Ω	3.7×10^{-9}
Bohr magneton $e\hbar/2m_e$	μ_B	$927.400\,899(37)\times10^{-26}$	J T^{-1}	4.0×10^{-8}
in eV T^{-1}		$5.788\,381\,749(43)\times10^{-5}$	eV T^{-1}	7.3×10^{-9}
	μ_B/h	$13.996\,246\,24(56)\times10^{9}$	Hz T^{-1}	4.0×10^{-8}
	μ_B/hc	$46.686\,4521(19)$	m^{-1} T^{-1}	4.0×10^{-8}
	μ_B/k	$0.671\,7131(12)$	K T^{-1}	1.7×10^{-6}
nuclear magneton $e\hbar/2m_p$	μ_N	$5.050\,783\,17(20)\times10^{-27}$	J T^{-1}	4.0×10^{-8}
in eV T^{-1}		$3.152\,451\,238(24)\times10^{-8}$	eV T^{-1}	7.6×10^{-9}
	μ_N/h	$7.622\,593\,96(31)$	MHz T^{-1}	4.0×10^{-8}
	μ_N/hc	$2.542\,623\,66(10)\times10^{-2}$	m^{-1} T^{-1}	4.0×10^{-8}
	μ_N/k	$3.658\,2638(64)\times10^{-4}$	K T^{-1}	1.7×10^{-6}
ATOMIC AND NUCLEAR **General**				
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,533(27)\times10^{-3}$		3.7×10^{-9}
inverse fine-structure constant	α^{-1}	$137.035\,999\,76(50)$		3.7×10^{-9}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	$10\,973\,731.568\,549(83)$	m^{-1}	7.6×10^{-12}
	$R_\infty c$	$3.289\,841\,960\,368(25)\times10^{15}$	Hz	7.6×10^{-12}
	$R_\infty hc$	$2.179\,871\,90(17)\times10^{-18}$	J	7.8×10^{-8}
$R_\infty hc$ in eV		$13.605\,691\,72(53)$	eV	3.9×10^{-8}
Bohr radius $\alpha/4\pi R_\infty=4\pi\epsilon_0\hbar^2/m_e e^2$	a_0	$0.529\,177\,2083(19)\times10^{-10}$	m	3.7×10^{-9}
Hartree energy $e^2/4\pi\epsilon_0 a_0=2R_\infty hc=\alpha^2 m_e c^2$	E_h	$4.359\,743\,81(34)\times10^{-18}$	J	7.8×10^{-8}
in eV		$27.211\,3834(11)$	eV	3.9×10^{-8}
quantum of circulation	$h/2m_e$	$3.636\,947\,516(27)\times10^{-4}$	m^2 s^{-1}	7.3×10^{-9}
	h/m_e	$7.273\,895\,032(53)\times10^{-4}$	m^2 s^{-1}	7.3×10^{-9}
Electroweak				
Fermi coupling constant[c]	$G_F/(\hbar c)^3$	$1.166\,39(1)\times10^{-5}$	GeV^{-2}	8.6×10^{-6}
weak mixing angle[d] θ_W (on-shell scheme)				
$\sin^2\theta_W=s^2_W\equiv1-(m_W/m_Z)^2$	$\sin^2\theta_W$	$0.2224(19)$		8.7×10^{-3}
Electron, e$^-$				
electron mass	m_e	$9.109\,381\,88(72)\times10^{-31}$	kg	7.9×10^{-8}
in u, $m_e=A_r(\mathrm{e})$ u (electron rel. atomic mass times u)		$5.485\,799\,110(12)\times10^{-4}$	u	2.1×10^{-9}
energy equivalent	$m_e c^2$	$8.187\,104\,14(64))\times10^{-14}$	J	7.9×10^{-8}
in MeV		$0.510\,998\,902(21)$	MeV	4.0×10^{-8}
electron–muon mass ratio	m_e/m_μ	$4.836\,332\,10(15)\times10^{-3}$		3.0×10^{-8}
electron–tau mass ratio	m_e/m_τ	$2.875\,55(47)\times10^{-4}$		1.6×10^{-4}
electron–proton mass ratio	m_e/m_p	$5.446\,170\,232(12)\times10^{-4}$		2.1×10^{-9}
electron–neutron mass ratio	m_e/m_n	$5.438\,673\,462(12)\times10^{-4}$		2.2×10^{-9}
electron–deuteron mass ratio	m_e/m_d	$2.724\,437\,1170(58)\times10^{-4}$		2.1×10^{-9}
electron to alpha particle mass ratio	m_e/m_α	$1.370\,933\,5611(29)\times10^{-4}$		2.1×10^{-9}
electron charge to mass quotient	$-e/m_e$	$-1.758\,820\,174(71)\times10^{11}$	C kg^{-1}	4.0×10^{-8}
electron molar mass $N_A m_e$	$M(\mathrm{e}), M_e$	$5.485\,799\,110(12)\times10^{-7}$	kg mol^{-1}	2.1×10^{-9}

CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
Compton wavelength $h/m_\mathrm{e}c$	λ_C	2.426 310 215(18)$\times 10^{-12}$	m	7.3×10^{-9}
$\lambda_\mathrm{C}/2\pi = \alpha a_0 = \alpha^2/4\pi R_\infty$	$\bar{\lambda}_\mathrm{C}$	386.159 2642(28)$\times 10^{-15}$	m	7.3×10^{-9}
classical electron radius $\alpha^2 a_0$	r_e	2.817 940 285(31)$\times 10^{-15}$	m	1.1×10^{-8}
Thomson cross section $(8\pi/3)r_\mathrm{e}^2$	σ_e	0.665 245 854(15)$\times 10^{-28}$	m^2	2.2×10^{-8}
electron magnetic moment	μ_e	–928.476 362(37)$\times 10^{-26}$	J T^{-1}	4.0×10^{-8}
to Bohr magneton ratio	$\mu_\mathrm{e}/\mu_\mathrm{B}$	–1.001 159 652 1869(41)		4.1×10^{-12}
to nuclear magneton ratio	$\mu_\mathrm{e}/\mu_\mathrm{N}$	–1 838.281 9660(39)		2.1×10^{-9}
electron magnetic moment anomaly $\lvert\mu_\mathrm{e}\rvert/\mu_\mathrm{B}-1$	a_e	1.159 652 1869(41)$\times 10^{-3}$		3.5×10^{-9}
electron *g*-factor $-2(1+a_\mathrm{e})$	g_e	–2.002 319 304 3737(82)		4.1×10^{-12}
electron–muon magnetic moment ratio	μ_e/μ_μ	206.766 9720(63)		3.0×10^{-8}
electron–proton magnetic moment ratio	$\mu_\mathrm{e}/\mu_\mathrm{p}$	–658.210 6875(66)		1.0×10^{-8}
electron to shielded proton magnetic moment ratio				
(H_2O, sphere, 25 °C)	$\mu_\mathrm{e}/\mu'_\mathrm{p}$	–658.227 5954(71)		1.1×10^{-8}
electron–neutron magnetic moment ratio	$\mu_\mathrm{e}/\mu_\mathrm{n}$	960.920 50(23)		2.4×10^{-7}
electron–deuteron magnetic moment ratio	$\mu_\mathrm{e}/\mu_\mathrm{d}$	–2 143.923 498(23)		1.1×10^{-8}
electron to shielded helion[e] magnetic moment ratio				
(gas, sphere, 25 °C)	$\mu_\mathrm{e}/\mu'_\mathrm{h}$	864.058 255(10)		1.2×10^{-8}
electron gyromagnetic ratio $2\lvert\mu_\mathrm{e}\rvert/\hbar$	γ_e	1.760 859 794(71)$\times 10^{11}$	s^{-1} T^{-1}	4.0×10^{-8}
	$\gamma_\mathrm{e}/2\pi$	28 024.9540(11)	MHz T^{-1}	4.0×10^{-8}
Muon, μ^-				
muon mass	m_μ	1.883 531 09(16)$\times 10^{-28}$	kg	8.4×10^{-8}
in u, $m_\mu = A_\mathrm{r}(\mu)$ u (muon rel. atomic mass times u)		0.113 428 9168(34)	u	3.0×10^{-8}
energy equivalent	$m_\mu c^2$	1.692 833 32(14)$\times 10^{-11}$	J	8.4×10^{-8}
in MeV		105.658 3568(52)	MeV	4.9×10^{-8}
muon–electron mass ratio	m_μ/m_e	206.768 2657(63)		3.0×10^{-8}
muon–tau mass ratio	m_μ/m_τ	5.945 72(97)$\times 10^{-2}$		1.6×10^{-4}
muon–proton mass ratio	m_μ/m_p	0.112 609 5173(34)		3.0×10^{-8}
muon–neutron mass ratio	m_μ/m_n	0.112 454 5079(34)		3.0×10^{-8}
muon molar mass $N_\mathrm{A}m_\mu$	$M(\mu)$, M_μ	0.113 428 9168(34)$\times 10^{-3}$	kg mol^{-1}	3.0×10^{-8}
muon Compton wavelength $h/m_\mu c$	$\lambda_{\mathrm{C},\mu}$	11.734 441 97(35)$\times 10^{-15}$	m	2.9×10^{-8}
$\lambda_{\mathrm{C},\mu}/2\pi$	$\bar{\lambda}_{\mathrm{C},\mu}$	1.867 594 444(55)$\times 10^{-15}$	m	2.9×10^{-8}
muon magnetic moment	μ_μ	–4.490 448 13(22)$\times 10^{-26}$	J T^{-1}	4.9×10^{-8}
to Bohr magneton ratio	μ_μ/μ_B	–4.841 970 85(15)$\times 10^{-3}$		3.0×10^{-8}
to nuclear magneton ratio	μ_μ/μ_N	–8.890 597 70(27)		3.0×10^{-8}
muon magnetic moment anomaly $\lvert\mu_\mu\rvert/(e\hbar/2m_\mu)-1$	a_μ	1.165 916 02(64)$\times 10^{-3}$		5.5×10^{-7}
muon *g*-factor $-2(1+a_\mu)$	g_μ	–2.002 331 8320(13)		6.4×10^{-10}
muon–proton magnetic moment ratio	μ_μ/μ_p	–3.183 345 39(10)		3.2×10^{-8}
Tau, τ^-				
tau mass[f]	m_τ	3.167 88(52)$\times 10^{-27}$	kg	1.6×10^{-4}
in u, $m_\tau = A_\mathrm{r}(\tau)$ u (tau rel. atomic mass times u)		1.907 74(31)	u	1.6×10^{-4}
energy equivalent	$m_\tau c^2$	2.847 15(46)$\times 10^{-10}$	J	1.6×10^{-4}
in MeV		1 777.05(29)	MeV	1.6×10^{-4}
tau–electron mass ratio	m_τ/m_e	3 477.60(57)		1.6×10^{-4}
tau–muon mass ratio	m_τ/m_μ	16.8188(27)		1.6×10^{-4}
tau–proton mass ratio	m_τ/m_p	1.893 96(31)		1.6×10^{-4}
tau–neutron mass ratio	m_τ/m_n	1.891 35(31)		1.6×10^{-4}
tau molar mass $N_\mathrm{A}m_\tau$	$M(\tau)$, M_τ	1.907 74(31)$\times 10^{-3}$	kg mol^{-1}	1.6×10^{-4}
tau Compton wavelength $h/m_\tau c$	$\lambda_{\mathrm{C},\tau}$	0.697 70(11)$\times 10^{-15}$	m	1.6×10^{-4}
$\lambda_{\mathrm{C},\tau}/2\pi$	$\bar{\lambda}_{\mathrm{C},\tau}$	0.111 042(18)$\times 10^{-15}$	m	1.6×10^{-4}
Proton, p				
proton mass	m_p	1.672 621 58(13)$\times 10^{-27}$	kg	7.9×10^{-8}
in u, $m_\mathrm{p} = A_\mathrm{r}(\mathrm{p})$ u (proton rel. atomic mass times u)		1.007 276 466 88(13)	u	1.3×10^{-10}
energy equivalent	$m_\mathrm{p} c^2$	1.503 277 31(12)$\times 10^{-10}$	J	7.9×10^{-8}
in MeV		938.271 998(38)	MeV	4.0×10^{-8}
proton–electron mass ratio	$m_\mathrm{p}/m_\mathrm{e}$	1 836.152 6675(39)		2.1×10^{-9}
proton–muon mass ratio	m_p/m_μ	8.880 244 08(27)		3.0×10^{-8}
proton–tau mass ratio	m_p/m_τ	0.527 994(86)		1.6×10^{-4}
proton–neutron mass ratio	$m_\mathrm{p}/m_\mathrm{n}$	0.998 623 478 55(58)		5.8×10^{-10}
proton charge to mass quotient	e/m_p	9.578 834 08(38)$\times 10^{7}$	C kg^{-1}	4.0×10^{-8}
proton molar mass $N_\mathrm{A}m_\mathrm{p}$	$M(\mathrm{p})$, M_p	1.007 276 466 88(13)$\times 10^{-3}$	kg mol^{-1}	1.3×10^{-10}
proton Compton wavelength $h/m_\mathrm{p} c$	$\lambda_{\mathrm{C},\mathrm{p}}$	1.321 409 847(10)$\times 10^{-15}$	m	7.6×10^{-9}
$\lambda_{\mathrm{C},\mathrm{p}}/2\pi$	$\bar{\lambda}_{\mathrm{C},\mathrm{p}}$	0.210 308 9089(16)$\times 10^{-15}$	m	7.6×10^{-9}

CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
proton magnetic moment	μ_p	$1.410\,606\,633(58)\times10^{-26}$	$\mathrm{J\,T^{-1}}$	4.1×10^{-8}
to Bohr magneton ratio	μ_p/μ_B	$1.521\,032\,203(15)\times10^{-3}$		1.0×10^{-8}
to nuclear magneton ratio	μ_p/μ_N	$2.792\,847\,337(29)$		1.0×10^{-8}
proton g-factor $2\mu_p/\mu_N$	g_p	$5.585\,694\,675(57)$		1.0×10^{-8}
proton–neutron magnetic moment ratio	μ_p/μ_n	$-1.459\,898\,05(34)$		2.4×10^{-7}
shielded proton magnetic moment				
(H_2O, sphere, 25 °C)	μ'_p	$1.410\,570\,399(59)\times10^{-26}$	$\mathrm{J\,T^{-1}}$	4.2×10^{-8}
to Bohr magneton ratio	μ'_p/μ_B	$1.520\,993\,132(16)\times10^{-3}$		1.1×10^{-8}
to nuclear magneton ratio	μ'_p/μ_N	$2.792\,775\,597(31)$		1.1×10^{-8}
proton magnetic shielding correction $1-\mu'_p/\mu_p$				
(H_2O, sphere, 25 °C)	σ'_p	$25.687(15)\times10^{-6}$		5.7×10^{-4}
proton gyromagnetic ratio $2\mu_p/\hbar$	γ_p	$2.675\,222\,12(11)\times10^{8}$	$\mathrm{s^{-1}\,T^{-1}}$	4.1×10^{-8}
	$\gamma_p/2\pi$	$42.577\,4825(18)$	$\mathrm{MHz\,T^{-1}}$	4.1×10^{-8}
shielded proton gyromagnetic ratio $2\mu'_p/\hbar$				
(H_2O, sphere, 25 °C)	γ'_p	$2.675\,153\,41(11)\times10^{8}$	$\mathrm{s^{-1}\,T^{-1}}$	4.2×10^{-8}
	$\gamma'_p/2\pi$	$42.576\,3888(18)$	$\mathrm{MHz\,T^{-1}}$	4.2×10^{-8}
Neutron, n				
neutron mass	m_n	$1.674\,927\,16(13)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_n=A_r(n)$ u (neutron rel. atomic mass times u)		$1.008\,664\,915\,78(55)$	u	5.4×10^{-10}
energy equivalent	m_nc^2	$1.505\,349\,46(12)\times10^{-10}$	J	7.9×10^{-8}
in MeV		$939.565\,330(38)$	MeV	4.0×10^{-8}
neutron–electron mass ratio	m_n/m_e	$1\,838.683\,6550(40)$		2.2×10^{-9}
neutron–muon mass ratio	m_n/m_μ	$8.892\,484\,78(27)$		3.0×10^{-8}
neutron–tau mass ratio	m_n/m_τ	$0.528\,722(86)$		1.6×10^{-4}
neutron–proton mass ratio	m_n/m_p	$1.001\,378\,418\,87(58)$		5.8×10^{-10}
neutron molar mass N_Am_n	$M(n)$, M_n	$1.008\,664\,915\,78(55)\times10^{-3}$	$\mathrm{kg\,mol^{-1}}$	5.4×10^{-10}
neutron Compton wavelengths h/m_nc	$\lambda_{C,n}$	$1.319\,590\,898(10)\times10^{-15}$	m	7.6×10^{-9}
$\lambda_{C,n}/2\pi$	$\bar{\lambda}_{C,n}$	$0.210\,019\,4142(16)\times10^{-15}$	m	7.6×10^{-9}
neutron magnetic moment	μ_n	$-0.966\,236\,40(23)\times10^{-26}$	$\mathrm{J\,T^{-1}}$	2.4×10^{-7}
to Bohr magneton ratio	μ_n/μ_B	$-1.041\,875\,63(25)\times10^{-3}$		2.4×10^{-7}
to nuclear magneton ratio	μ_n/μ_N	$-1.913\,042\,72(45)$		2.4×10^{-7}
neutron g-factor $2\mu_n/\mu_N$	g_n	$-3.826\,085\,45(90)$		2.4×10^{-7}
neutron–electron magnetic moment ratio	μ_n/μ_e	$1.040\,668\,82(25)\times10^{-3}$		2.4×10^{-7}
neutron–proton magnetic moment ratio	μ_n/μ_p	$-0.684\,979\,34(16)$		2.4×10^{-7}
neutron to shielded proton magnetic moment ratio				
(H_2O, sphere, 25 °C)	μ_n/μ'_p	$-0.684\,996\,94(16)$		2.4×10^{-7}
neutron gyromagnetic ratio $2\lvert\mu_n\rvert/\hbar$	γ_n	$1.832\,471\,88(44)\times10^{8}$	$\mathrm{s^{-1}\,T^{-1}}$	2.4×10^{-7}
	$\gamma_n/2\pi$	$29.164\,6958(70)$	$\mathrm{MHz\,T^{-1}}$	2.4×10^{-7}
Deuteron, d				
deuteron mass	m_d	$3.343\,583\,09(26)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_d=A_r(d)$ u (deuteron rel. atomic mass times u)		$2.013\,553\,212\,71(35)$	u	1.7×10^{-10}
energy equivalent	m_dc^2	$3.005\,062\,62(24)\times10^{-10}$	J	7.9×10^{-8}
in MeV		$1\,875.612\,762(75)$	MeV	4.0×10^{-8}
deuteron–electron mass ratio	m_d/m_e	$3\,670.482\,9550(78)$		2.1×10^{-9}
deuteron–proton mass ratio	m_d/m_p	$1.999\,007\,500\,83(41)$		2.0×10^{-10}
deuteron molar mass N_Am_d	$M(d)$, M_d	$2.013\,553\,212\,71(35)\times10^{-3}$	$\mathrm{kg\,mol^{-1}}$	1.7×10^{-10}
deuteron magnetic moment	μ_d	$0.433\,073\,457(18)\times10^{-26}$	$\mathrm{J\,T^{-1}}$	4.2×10^{-8}
to Bohr magneton ratio	μ_d/μ_B	$0.466\,975\,4556(50)\times10^{-3}$		1.1×10^{-8}
to nuclear magneton ratio	μ_d/μ_N	$0.857\,438\,2284(94)$		1.1×10^{-8}
deuteron–electron magnetic moment ratio	μ_d/μ_e	$-4.664\,345\,537(50)\times10^{-4}$		1.1×10^{-8}
deuteron–proton magnetic moment ratio	μ_d/μ_p	$0.307\,012\,2083(45)$		1.5×10^{-8}
deuteron–neutron magnetic moment ratio	μ_d/μ_n	$-0.448\,206\,52(11)$		2.4×10^{-7}
Helion, h				
helion mass[e]	m_h	$5.006\,411\,74(39)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_h=A_r(h)$ u (helion rel. atomic mass times u)		$3.014\,932\,234\,69(86)$	u	2.8×10^{-10}
energy equivalent	m_hc^2	$4.499\,538\,48(35)\times10^{-10}$	J	7.9×10^{-8}
in MeV		$2\,808.391\,32(11)$	MeV	4.0×10^{-8}
helion–electron mass ratio	m_h/m_e	$5\,495.885\,238(12)$		2.1×10^{-9}
helion–proton mass ratio	m_h/m_p	$2.993\,152\,658\,50(93)$		3.1×10^{-10}
helion molar mass N_Am_h	$M(h)$, M_h	$3.014\,932\,234\,69(86)\times10^{-3}$	$\mathrm{kg\,mol^{-1}}$	2.8×10^{-10}
shielded helion magnetic moment (gas, sphere, 25 °C)	μ'_h	$-1.074\,552\,967(45)\times10^{-26}$	$\mathrm{J\,T^{-1}}$	4.2×10^{-8}
to Bohr magneton ratio	μ'_h/μ_B	$-1.158\,671\,474(14)\times10^{-3}$		1.2×10^{-8}

CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
to nuclear magneton ratio	μ'_h/μ_N	$-2.127\ 497\ 718(25)$		1.2×10^{-8}
shielded helion to proton magnetic moment ratio (gas, sphere, 25 °C)	μ'_h/μ_p	$-0.761\ 766\ 563(12)$		1.5×10^{-8}
shielded helion to shielded proton magnetic moment ratio (gas/H_2O, spheres, 25 °C)	μ'_h/μ'_p	$-0.761\ 786\ 1313(33)$		4.3×10^{-9}
shielded helion gyromagnetic ratio $2\lvert\mu'_h\rvert/\hbar$ (gas, sphere, 25 °C)	γ'_h	$2.037\ 894\ 764(85)\times10^{8}$	$s^{-1}\ T^{-1}$	4.2×10^{-8}
	$\gamma'_h/2\pi$	$32.434\ 1025(14)$	MHz T^{-1}	4.2×10^{-8}
Alpha particle, α				
alpha particle mass	m_α	$6.644\ 655\ 98(52)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_\alpha=A_r(\alpha)$ u (alpha particle rel. atomic mass times u)		$4.001\ 506\ 1747(10)$	u	2.5×10^{-10}
energy equivalent	$m_\alpha c^2$	$5.971\ 918\ 97(47)\times10^{-10}$	J	7.9×10^{-8}
in MeV		$3\ 727.379\ 04(15)$	MeV	4.0×10^{-8}
alpha particle to electron mass ratio	m_α/m_e	$7\ 294.299\ 508(16)$		2.1×10^{-9}
alpha particle to proton mass ratio	m_α/m_p	$3.972\ 599\ 6846(11)$		2.8×10^{-10}
alpha particle molar mass $N_A m_\alpha$	$M(\alpha)$, M_α	$4.001\ 506\ 1747(10)\times10^{-3}$	kg mol^{-1}	2.5×10^{-10}
PHYSICOCHEMICAL				
Avogadro constant	N_A, L	$6.022\ 141\ 99(47)\times10^{23}$	mol^{-1}	7.9×10^{-8}
atomic mass constant				
$m_u=\frac{1}{12}m(^{12}C)=1\ u=10^{-3}$ kg mol^{-1}/N_A	m_u	$1.660\ 538\ 73(13)\times10^{-27}$	kg	7.9×10^{-8}
energy equivalent	$m_u c^2$	$1.492\ 417\ 78(12)\times10^{-10}$	J	7.9×10^{-8}
in MeV		$931.494\ 013(37)$	MeV	4.0×10^{-8}
Faraday constant[g] $N_A e$	F	$96\ 485.3415(39)$	C mol^{-1}	4.0×10^{-8}
molar Planck constant	$N_A h$	$3.990\ 312\ 689(30)\times10^{-10}$	J s mol^{-1}	7.6×10^{-9}
	$N_A hc$	$0.119\ 626\ 564\ 92(91)$	J m mol^{-1}	7.6×10^{-9}
molar gas constant	R	$8.314\ 472(15)$	J mol^{-1} K^{-1}	1.7×10^{-6}
Boltzmann constant R/N_A	k	$1.380\ 6503(24)\times10^{-23}$	J K^{-1}	1.7×10^{-6}
in eV K^{-1}		$8.617\ 342(15)\times10^{-5}$	eV K^{-1}	1.7×10^{-6}
	k/h	$2.083\ 6644(36)\times10^{10}$	Hz K^{-1}	1.7×10^{-6}
	k/hc	$69.503\ 56(12)$	m^{-1} K^{-1}	1.7×10^{-6}
molar volume of ideal gas RT/p				
$T=273.15$ K, $p=101.325$ kPa	V_m	$22.413\ 996(39)\times10^{-3}$	m^3 mol^{-1}	1.7×10^{-6}
Loschmidt constant N_A/V_m	n_0	$2.686\ 7775(47)\times10^{25}$	m^{-3}	1.7×10^{-6}
$T=273.15$ K, $p=100$ kPa	V_m	$22.710\ 981(40)\times10^{-3}$	m^3 mol^{-1}	1.7×10^{-6}
Sackur–Tetrode constant (absolute entropy constant)[h] $\frac{5}{2}+\ln[(2\pi m_u kT_1/h^2)^{3/2}kT_1/p_0]$				
$T_1=1$ K, $p_0=100$ kPa	S_0/R	$-1.151\ 7048(44)$		3.8×10^{-6}
$T_1=1$ K, $p_0=101.325$ kPa		$-1.164\ 8678(44)$		3.7×10^{-6}
Stefan–Boltzmann constant $(\pi^2/60)k^4/\hbar^3c^2$	σ	$5.670\ 400(40)\times10^{-8}$	W m^{-2} K^{-4}	7.0×10^{-6}
first radiation constant $2\pi hc^2$	c_1	$3.741\ 771\ 07(29)\times10^{-16}$	W m^2	7.8×10^{-8}
first radiation constant for spectral radiance $2hc^2$	c_{1L}	$1.191\ 042\ 722(93)\times10^{-16}$	W m^2 sr^{-1}	7.8×10^{-8}
second radiation constant hc/k	c_2	$1.438\ 7752(25)\times10^{-2}$	m K	1.7×10^{-6}
Wien displacement law constant $b=\lambda_{max}T=c_2/4.965\ 114\ 231\ldots$	b	$2.897\ 7686(51)\times10^{-3}$	m K	1.7×10^{-6}

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[a] See the "Internationally Adopted Values" table for the conventional value for realizing representations of the volt using the Josephson effect.

[b] See the "Internationally Adopted Values" table for the conventional value for realizing representations of the ohm using the quantum Hall effect.

[c] Value recommended by the Particle Data Group [C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998)].

[d] Based on the ratio of the masses of the W and Z bosons m_W/m_Z recommended by the Particle Data Group [C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998)]. The value for $\sin^2\theta_W$ they recommend, which is based on a particular variant of the modified minimal subtraction ($\overline{MS}$) scheme, is $\sin^2\hat{\theta}_W(M_Z)=0.231\ 24(24)$.

[e] The helion, symbol h, is the nucleus of the ^{3}He atom.

[f] This and all other values involving m_τ are based on the value of $m_\tau c^2$ in MeV recommended by the Particle Data Group [C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998)], but with a standard uncertainty of 0.29 MeV rather than the quoted uncertainty of −0.26 MeV, +0.29 MeV.

[g] The numerical value of F to be used in coulometric chemical measurements is 96 485.3432(76) [7.9×10^{-8}] when the relevant current is measured in terms of representations of the volt and ohm based on the Josephson and quantum Hall effects and the conventional values of the Josephson and von Klitzing constants K_{J-90} and R_{K-90} given in the "Internationally Adopted Values" table.

[h] The entropy of an ideal monoatomic gas of relative atomic mass A_r is given by $S=S_0+\frac{3}{2}R\ln A_r-R\ln(p/p_0)+\frac{5}{2}R\ln(T/K)$.

Internationally Adopted Values of Various Quantities

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
molar mass of ^{12}C	$M(^{12}\mathrm{C})$	12×10^{-3}	kg mol^{-1}	(exact)
molar mass constant[a] $M(^{12}\mathrm{C})/12$	M_u	1×10^{-3}	kg mol^{-1}	(exact)
conventional value of Josephson constant[b]	K_{J-90}	483 597.9	GHz V^{-1}	(exact)
conventional value of von Klitzing constant[c]	R_{K-90}	25 812.807	Ω	(exact)
standard atmosphere		101 325	Pa	(exact)
standard acceleration of gravity	g_n	9.806 65	m s^{-2}	(exact)

[a] The relative atomic mass $A_r(X)$ of particle X with mass $m(X)$ is defined by $A_r(X) = m(X)/m_u$, where $m_u = m(^{12}\mathrm{C})/12 = M_u/N_A = 1$ u is the atomic mass constant, N_A is the Avogadro constant, and u is the (unified) atomic mass unit. Thus the mass of particle X is $m(X) = A_r(X)$ u and the molar mass of X is $M(X) = A_r(X)M_u$.

[b] This is the value adopted internationally for realizing representations of the volt using the Josephson effect.

[c] This is the value adopted internationally for realizing representations of the ohm using the quantum Hall effect.

CODATA Recommended Values of Energy Equivalents – 1998

	Relevant unit			
	J	**kg**	**m^{-1}**	**Hz**
1 J	$(1\ \mathrm{J}) =$ 1 J	$(1\ \mathrm{J})/c^2 =$ $1.112\ 650\ 056\times10^{-17}$ kg	$(1\ \mathrm{J})/hc =$ $5.034\ 117\ 62(39)\times10^{24}$ m^{-1}	$(1\ \mathrm{J})/h =$ $1.509\ 190\ 50(12)\times10^{33}$ Hz
1 kg	$(1\ \mathrm{kg})c^2 =$ $8.987\ 551\ 787\times10^{16}$ J	$(1\ \mathrm{kg}) =$ 1 kg	$(1\ \mathrm{kg})c/h =$ $4.524\ 439\ 29(35)\times10^{41}$ m^{-1}	$(1\ \mathrm{kg})c^2/h =$ $1.356\ 392\ 77(11)\times10^{50}$ Hz
1 m^{-1}	$(1\ \mathrm{m}^{-1})hc =$ $1.986\ 445\ 44(16)\times10^{-25}$ J	$(1\ \mathrm{m}^{-1})h/c =$ $2.210\ 218\ 63(17)\times10^{-42}$ kg	$(1\ \mathrm{m}^{-1}) =$ 1 m^{-1}	$(1\ \mathrm{m}^{-1})c =$ 299 792 458 Hz
1 Hz	$(1\ \mathrm{Hz})h =$ $6.626\ 068\ 76(52)\times10^{-34}$ J	$(1\ \mathrm{Hz})h/c^2 =$ $7.372\ 495\ 78(58)\times10^{-51}$ kg	$(1\ \mathrm{Hz})/c =$ $3.335\ 640\ 952\times10^{-9}$ m^{-1}	$(1\ \mathrm{Hz}) =$ 1 Hz
1 K	$(1\ \mathrm{K})k =$ $1.380\ 6503(24)\times10^{-23}$ J	$(1\ \mathrm{K})k/c^2 =$ $1.536\ 1807(27)\times10^{-40}$ kg	$(1\ \mathrm{K})k/hc =$ $69.503\ 56(12)$ m^{-1}	$(1\ \mathrm{K})k/h =$ $2.083\ 6644(36)\times10^{10}$ Hz
1 eV	$(1\ \mathrm{eV}) =$ $1.602\ 176\ 462(63)\times10^{-19}$ J	$(1\ \mathrm{eV})/c^2 =$ $1.782\ 661\ 731(70)\times10^{-36}$ kg	$(1\ \mathrm{eV})/hc =$ $8.065\ 544\ 77(32)\times10^{5}$ m^{-1}	$(1\ \mathrm{eV})/h =$ $2.417\ 989\ 491(95)\times10^{14}$ Hz
1 u	$(1\ \mathrm{u})c^2 =$ $1.492\ 417\ 78(12)\times10^{-10}$ J	$(1\ \mathrm{u}) =$ $1.660\ 538\ 73(13)\times10^{-27}$ kg	$(1\ \mathrm{u})c/h =$ $7.513\ 006\ 658(57)\times10^{14}$ m^{-1}	$(1\ \mathrm{u})c^2/h =$ $2.252\ 342\ 733(17)\times10^{23}$ Hz
1 E_h	$(1\ E_h) =$ $4.359\ 743\ 81(34)\times10^{-18}$ J	$(1\ E_h)/c^2 =$ $4.850\ 869\ 19(38)\times10^{-35}$ kg	$(1\ E_h)/hc =$ $2.194\ 746\ 313\ 710(17)\times10^{7}$ m^{-1}	$(1\ E_h)/h =$ $6.579\ 683\ 920\ 735(50)\times10^{15}$ Hz

CODATA Recommended Values of Energy Equivalents – 1998

	Relevant unit			
	K	**eV**	**u**	**E_h**
1 J	$(1\ \mathrm{J})/k =$ $7.242\ 964(13)\times10^{22}$ K	$(1\ \mathrm{J}) =$ $6.241\ 509\ 74(24)\times10^{18}$ eV	$(1\ \mathrm{J})/c^2 =$ $6.700\ 536\ 62(53)\times10^{9}$ u	$(1\ \mathrm{J}) =$ $2.293\ 712\ 76(18)\times10^{17}\ E_h$
1 kg	$(1\ \mathrm{kg})c^2/k =$ $6.509\ 651(11)\times10^{39}$ K	$(1\ \mathrm{kg})c^2 =$ $5.609\ 589\ 21(22)\times10^{35}$ eV	$(1\ \mathrm{kg}) =$ $6.022\ 141\ 99(47)\times10^{26}$ u	$(1\ \mathrm{kg})c^2 =$ $2.061\ 486\ 22(16)\times10^{34}\ E_h$
1 m^{-1}	$(1\ \mathrm{m}^{-1})hc/k =$ $1.438\ 7752(25)\times10^{-2}$ K	$(1\ \mathrm{m}^{-1})hc =$ $1.239\ 841\ 857(49)\times10^{-6}$ eV	$(1\ \mathrm{m}^{-1})h/c =$ $1.331\ 025\ 042(10)\times10^{-15}$ u	$(1\ \mathrm{m}^{-1})hc =$ $4.556\ 335\ 252\ 750(35)\times10^{-8}\ E_h$
1 Hz	$(1\ \mathrm{Hz})h/k =$ $4.799\ 2374(84)\times10^{-11}$ K	$(1\ \mathrm{Hz})h =$ $4.135\ 667\ 27(16)\times10^{-15}$ eV	$(1\ \mathrm{Hz})h/c^2 =$ $4.439\ 821\ 637(34)\times10^{-24}$ u	$(1\ \mathrm{Hz})h =$ $1.519\ 829\ 846\ 003(12)\times10^{-16}\ E_h$
1 K	$(1\ \mathrm{K}) =$ 1 K	$(1\ \mathrm{K})k =$ $8.617\ 342(15)\times10^{-5}$ eV	$(1\ \mathrm{K})k/c^2 =$ $9.251\ 098(16)\times10^{-14}$ u	$(1\ \mathrm{K})k =$ $3.166\ 8153(55)\times10^{-6}\ E_h$
1 eV	$(1\ \mathrm{eV})/k =$ $1.160\ 4506(20)\times10^{4}$ K	$(1\ \mathrm{eV}) =$ 1 eV	$(1\ \mathrm{eV})/c^2 =$ $1.073\ 544\ 206(43)\times10^{-9}$ u	$(1\ \mathrm{eV}) =$ $3.674\ 932\ 60(14)\times10^{-2}\ E_h$
1 u	$(1\ \mathrm{u})c^2/k =$ $1.080\ 9528(19)\times10^{13}$ K	$(1\ \mathrm{u})c^2 =$ $931.494\ 013(37)\times10^{6}$ eV	$(1\ \mathrm{u}) =$ 1 u	$(1\ \mathrm{u})c^2 =$ $3.423\ 177\ 709(26)\times10^{7}\ E_h$
1 E_h	$(1\ E_h)/k =$ $3.157\ 7465(55)\times10^{5}$ K	$(1\ E_h) =$ $27.211\ 3834(11)$ eV	$(1\ E_h)/c^2 =$ $2.921\ 262\ 304(22)\times10^{-8}$ u	$(1\ E_h) =$ 1 E_h

(continued from page 7)

follows from the expression $e = (2\alpha h/\mu_0 c)^{1/2}$, the mass of the electron from $m_e = 2R_\infty h/c\alpha^2$, and the Avogadro constant from $N_A = c\alpha^2 A_r(e)M_u/2R_\infty h$, where $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}, $c = 299\ 792\ 458$ m s^{-1}, and $M_u = 10^{-3}$ kg/mol, are the exactly known magnetic constant, speed of light in vacuum, and molar mass constant, respectively. The uncertainties of such derived values are obtained from the uncertainties and covariances of the adjusted constants.

The improvement in our knowledge of the values of the constants represented by the 1998 CODATA set of recommended values is truly impressive. Still, it is not as well founded as one might like. Specifically, there is little redundancy among some of the key input data of the 1998 adjustment. As indicated above, α, h, and R play an especially critical role in the determination of many constants, yet the recommended value of each is to a large extent determined by a single input datum or, at best, two input data with rather different standard uncertainties u and hence rather different weights $1/u^2$. In the case of α, the input data are merely the single experimental value of a_e and the single calculated value of the mass-independent eighth-order coefficient $A_1^{(8)}$ in the QED-based theoretical expression for a_e. In the case of h, the input data are the two watt-balance values of $K_J^2 R_K$, with uncertainties that differ by a factor of about 2.3. And in the case of the molar gas constant, the input data are the two values of R based on speed-of-sound measurements in argon using a resonator and an interferometer with uncertainties that differ by about a factor of 4.7. The experimental and theoretical work required to solidify and continue the progress of the last 13 years is thus clear: We must obtain new input data related to α, h, and R with uncertainties no larger than their current uncertainties, and eventually with significantly smaller uncertainties.

The existence of the Web has dramatically changed the availability of information—we can expect to have the latest data available electronically only a mouse-click away. In fact, the new 1998 CODATA set of recommended values was available at the NIST Web site mentioned above seven months before the appearance of the first printed version. Because of the Web and the new modes of work and thought it has engendered, and because experimental and theoretical data that influence our knowledge of the values of the constants appear nearly continuously, the CODATA task group has concluded that 13 years between adjustments is no longer acceptable. (The first set of CODATA recommended values of the constants was issued in 1973,[3] 13 years before the second set in 1986 and 26 years before the 1998 set.) Thus, in the future, by taking advantage of the high degree of automation we have incorporated in the 1998 adjustment, CODATA plans to issue a new set of recommended values every four years, or more frequently if new data become available that have a significant impact on the values of the constants. You can thus expect a much shorter wait to see the next revision of this article in the PHYSICS TODAY *Buyers' Guide*.

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References

1. P. J. Mohr and B. N. Taylor, J. Phys. Chem. Ref. Data **28**, 1713 (1999); Rev. Mod. Phys. **72**, 351 (2000).
2. E. R. Cohen and B. N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987).
3. E. R. Cohen and B. N. Taylor, J. Phys. Chem. Ref. Data **2**, 663 (1973). ■