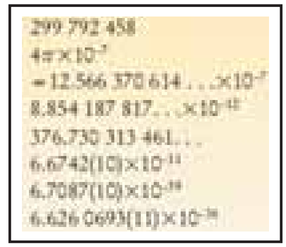
The fundamental physical constants

Peter J. Mohr, Barry N. Taylor
mohr@nist.gov
barry.taylor@nist.gov



The Committee on Data for Science and Technology was established in 1966 as an interdisciplinary committee of the International Council of Scientific Unions (now the International Council of Science). Three years later, CODATA created the task group on fundamental constants to periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values for the basic constants and conversion factors of physics and chemistry. Under the auspices of the task group, we have completed a new least-squares adjustment of those values--termed the 2002 adjustment--that takes into account all relevant data available through 31 December 2002.[1] The accompanying tables give the 2002 CODATA recommended values resulting from that adjustment, except for some specialized x-ray-related quantities and various natural and atomic units.

The complete 2002 CODATA set of more than 300 recommended values, together with a detailed description of the data and their analysis, is given in reference 1. All of the values, as well as the correlation coefficients between any two constants, are available online in a searchable database provided by NIST's fundamental constants data center. The internet address is http://physics.nist.gov/constants.

The 2002 CODATA set replaces its immediate predecessor, which resulted from the 1998 adjustment,[2] also carried out under the auspices of the task group. Only four years have elapsed between the 31 December 1998 and 31 December 2002 closing dates of the two adjustments (12 years separated the 1998 adjustment and its predecessor), but a number of advances in experiment and theory have led to improvements in our knowledge of the values of the constants.

The new information includes measurements of the Newtonian constant of gravitation G; improved experimental values of the relative atomic masses of helium-4, oxygen-16, and cesium-133 (carbon-12 has a relative atomic mass of exactly 12, by definition); a more accurate value of the $1S_{1/2}2S_{1/2}$ transition frequency in hydrogen; a new result for the bound-state root-mean-square (rms) charge radius of the proton R_p; and highly accurate measurements related to the bound-state g-factor of the electron in the hydrogenic ions $^{12}C^{5+}$ and $^{16}O^{7+}$. Additional experimental refinements include a new, quite accurate measurement of the muon magnetic moment anomaly a_μ; an accurate value, obtained from the atomic recoil frequency shift of photons absorbed and emitted by Cs atoms, for the quotient $h/m(^{133}Cs)$, where h is the Planck constant and $m(^{133}Cs)$ is the mass of the ^{133}Cs atom; a result for the molar volume of silicon $V_m(Si)$; and new experimental findings concerning previous measurements of the {220} lattice spacing of particular Si crystals.

Theorists have developed improved expressions for the hydrogen and deuterium energy levels, the electron and muon magnetic moment anomalies a_e and a_μ, the ground-state hyperfine splitting of muonium (that is, the μ^+e^- "atom"), and the electron bound-state g-factor in hydrogenic ions.

CONSEQUENCES OF NEW RESULTS

The new information available to the task group led to significant changes in both the values and the uncertainties of many of the fundamental constants. A few highlights follow.

- The new results for G agreed sufficiently well among themselves to convince the task group that an earlier, highly discrepant but credible result need no longer be considered in determining the recommended value. That decision led to a new recommended value of G with a relative standard uncertainty (that is, relative estimated standard deviation) $u_r = 1.5 \times 10^{-4}$. The new u_r is a factor of 10 smaller than that of the 1998 recommended value.
- Accurate measurements of the frequency ratios $f_s(^{12}C^{5+})/f_c(^{12}C^{5+})$ and $f_s(^{16}O^{7+})/f_c(^{16}O^{7+})$, together with the theoretical expression for the bound-state g-factor of the electron in each ion, have yielded values for the relative atomic mass of the electron $A_r(e)$ and the electron-to-proton mass ratio m_e/m_p with relative uncertainties of about 5×10^{-10}. (In the expressions for the frequency ratios, f_s is the precession, or "spin-flip," frequency of the electron in the ground state of the indicated hydrogenic ion in an applied magnetic flux density, and f_c is the cyclotron frequency of the ion in the same flux density.) Compared to the 1998 uncertainties, the new uncertainties represent a reduction by more than a factor of four.
- The new result for $V_m(Si)$ is credible, but inconsistent with four credible measurements of other quantities. Thus, one or more of the five results has a problem. We present some details below about the discrepancy and how we dealt with it.
- The 1998 adjustment included input from three combined x-ray and optical-interferometer determinations of the {220} lattice spacing of particular Si crystals. Subsequently, it was discovered that two of those three experiments appeared to have problems, so the data from those experiments were not included in the 2002 adjustment. Removing these data eliminates the scatter in the fine-structure-constant (α) values implied by the accurate x-ray measurement of h/m_n, where m_n is the neutron mass. Moreover, the value of α inferred from h/m_n now agrees well with values of α from other sources.
- An error was discovered in the eighth-order coefficient $A_1^{(8)}$ in the theoretical expression for the electron magnetic moment anomaly a_e(th). That discovery has led to a fractional increase of 5.7×10^{-9} in the value for α implied by the experimental result for a_e, about 1.5 times the relative uncertainty of the 1998 a_e value of α. Other experiments also yield values for α. In particular, the new result for $h/m(^{133}Cs)$ has yielded a reduction of the uncertainty of the recommended value of α from u_r 3.7×10^{-9} in 1998 to u_r 3.3×10^{-9}.
- The significant advances in the theory of hydrogen and deuterium energy levels and the improved value of R_p have eliminated a systematic deviation between theory and experiment observed in the 1998 adjustment. As a result, the CODATA set now includes recommended values for R_p and the bound-state rms charge radius of the deuteron R_d.

DATA ANALYSIS

The 2002 adjustment is similar to the 1998 adjustment in many key respects. First, we treat all of the input data on an essentially equal footing, regardless of their uncertainties. Doing so allows us to properly consider all components of uncertainty and all significant correlations among the data. It also eliminates any arbitrary division of the data into different categories--such divisions generally occurred in adjustments before that of 1998.

Second, we used the standard least-squares algorithm to analyze the data rather than an extended algorithm that tries to take into account the "uncertainty of the uncertainty" assigned to an input datum. An extended algorithm was applied as part of the 1986 adjustment,[3] but the complexity of the measurements and calculations in the field of fundamental constants makes it difficult enough to evaluate uncertainties in a meaningful way, let alone the uncertainties of those uncertainties.

Third, we reprised an innovation from the 1998 adjustment to properly take into account the uncertainty of various theoretical expressions--for example, the energy levels of H and D required to obtain the Rydberg constant R_i from measurements of transition frequencies. We used an additive correction δ_i for each such expression, included those corrections among the variables of the least-squares adjustment, and took their estimated values as input data. The best a priori estimate of each δ_i was zero but with a standard uncertainty equal to the standard uncertainty of the theoretical expression.

Fourth, we analyzed the data using the method of least squares for correlated input data. Although the need to consider correlations among the input data in the evaluation of the fundamental constants was first emphasized well over half a century ago, the 1998 adjustment was the first time it was actually done.

As in the 1998 adjustment, the analysis of the input data proceeded in several stages. First, we compared the various measured values of each quantity. Next, by comparing values of a common inferred constant, principally α or h, we examined whether measured values of different quantities were consistent. Finally, we used the least-squares method as described above to carry out a multivariate analysis of the data. The focus of all those investigations was the compatibility of the data and the extent to which a particular datum would contribute to the 2002 recommended values of the constants.

The final least-squares adjustment used 105 of the 112 input data that were initially considered and 61 variables or adjusted constants whose values were determined by the least-squares algorithm. The input data included, for example, 27 H and D transition frequencies and frequency differences. Among the adjusted constants were R_i, α, h, and $A_r(e)$. Most of the recommended values in the 2002 CODATA set were calculated from the adjusted constants. For example, the elementary charge follows from the expression e $(2\alpha h/\mu_0 c)^{1/2}$, where μ_0 $4\pi \times 10^{-7}$ N/A^2 is the magnetic constant and the speed of light c is defined to be 299 792 458 m/s. The uncertainties of derived quantities are obtained from the uncertainties and covariances of the adjusted constants on which they depend.

A DISCREPANT MEASUREMENT

The primary difficulty with the input data uncovered in the course of the 2002 adjustment was a significant incompatibility of the value of V_m(Si) with four measurements involving the Josephson constant K_J 2e/h and the von Klitzing constant R_K h/e^2: two moving-coil watt-balance results for the product $K_J^2 R_K$, a mercury-electrometer result for K_J, and a capacitor volt-balance result for K_J. The inconsistencies led us to consider whether relaxing either one or both of the assumptions that K_J 2e/h and R_K h/e^2 would reduce or possibly even eliminate the inconsistencies. Although both theory and experiment support the exactness of the assumed relations, we would have deemed our analysis incomplete had we not investigated possible modifications.

To that end, we assumed K_J (2e/h)(1 + ε_J) and R_K (h/e^2)(1 + ε_K), where ε_J and ε_K are unknown correction factors taken as additional adjusted constants. We set the initial input values of the correction factors to be zero, but gave them a sufficiently large uncertainty that their output values resulting from a least-squares adjustment were determined by other input data, not by those initial values. If we found that the adjusted values of the correction factors were statistically compatible with zero, then we could conclude that the experimental evidence suggested the relations K_J 2e/h and R_K h/e^2 were valid. On the other hand, an adjusted value of either of the correction factors that differed from zero in a statistically significant way would engender doubt about the exactness of the associated relation. We found no statistically significant deviations from zero for either ε_J or ε_K.

The task group ultimately decided that, in the final least-squares adjustment, the a priori assigned uncertainties of the five incompatible input data would be weighted by a multiplicative factor 2.325. That weighting reduced the discrepancy between the value of V_m(Si) and the four other measurements to 1.5 standard deviations. As a consequence of the new V_m(Si) datum and the increased uncertainties, the 2002 recommended value of h is larger than the 1998 recommended value by a fractional amount of about

8×10^{-8}, and its uncertainty is increased by about a factor of two, from $u_r = 7.8 \times 10^{-8}$ to $u_r = 1.7 \times 10^{-7}$. The 2002 CODATA set includes comparable changes in the recommended values and uncertainties of other constants, such as e, that depend strongly on h. Usually, new information leads to a reduction in uncertainties, but in this case new information has led to an increase.

REDUNDANCY IS SOLIDITY

Because there is little redundancy among some of the key input data, the 2002 CODATA set does not rest on as solid a foundation as one might wish. The constants α and h and the molar gas constant R play a critical role in determining many other constants, yet the recommended value of each is largely determined by a severely limited number of input data. Moreover, some of those data have rather different uncertainties u and hence rather different weights $1/u^2$.

The key input data used to determine α are the electron magnetic moment anomaly a_e and the quotient $h/m(^{133}Cs)$. (The relative uncertainty of the quotient exceeds that of the anomaly by more than a factor of two.) Furthermore, only a single competitive experimental value of a_e exists, along with a single calculated value of the eighth-order coefficient $A_1^{(8)}$ in the theoretical expression for a_e based on quantum electrodynamics.

The two watt-balance values of $K_J^2 R_K$ are the key input data that determine h. The uncertainties in the two measurements differ by a factor of 2.3 and, as we have already discussed, the two measurements are incompatible with a measurement for the molar volume of Si.

For the molar gas constant, the key input data are based on two speed-of-sound measurements in argon: One of them used a spherical acoustic resonator; the other, an acoustic interferometer. The uncertainties of the two measurements differ by a factor of 4.7.

If our knowledge of the values of α, h, and R is to advance, we need additional input data that can provide for those constants uncertainties that are no larger than the current uncertainties. Ideally, the uncertainties would be considerably smaller than those of the current values.

New experimental and theoretical data that influence our knowledge of the values of the constants appear nearly continuously. And, thanks to the World Wide Web, it's easy to distribute new recommended values of the fundamental constants. Indeed, the 2002 CODATA set first appeared on the Web on 9 December 2003. The Web has also engendered new modes of work and thought--users expect that the information they find is up-to-date. For these reasons, the CODATA task group on fundamental constants decided at the time of the 1998 adjustment to take advantage of the high degree of computerization that had been incorporated in the 1998 compilation and to provide a new CODATA set of recommended values every 4 years: The 1213 years separating the first CODATA set[4] of 1973, the second set[3] of 1986, and the 1998 set[2] was no longer acceptable. The 2002 set is the first from the new schedule.

Based on the experience gained in preparing that set, we expect to maintain the new schedule in the future. The reader may therefore anticipate an updated fundamental constants article in the Physics Today Buyer's Guide in four years.

NIST

National Institute of Standards and Technology

http://www.nist.gov/

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CODATA Recommended Values of the Fundamental Physical Constants – 2002

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	$6.6742(10)\times10^{-11}$	m^3 kg^{-1} s^{-2}	1.5×10^{-4}
	$G/\hbar c$	$6.7087(10)\times10^{-39}$	(GeV/c^2)$^{-2}$	1.5×10^{-4}
Planck constant	h	$6.626\ 0693(11)\times10^{-34}$	J s	1.7×10^{-7}
in eV s		$4.135\ 667\ 43(35)\times10^{-15}$	eV s	8.5×10^{-8}
$h/2\pi$	$\hbar$	$1.054\ 571\ 68(18)\times10^{-34}$	J s	1.7×10^{-7}
in eV s		$6.582\ 119\ 15(56)\times10^{-16}$	eV s	8.5×10^{-8}
$\hbar c$ in MeV fm		197.326 968(17)	MeV fm	8.5×10^{-8}
Planck mass $(\hbar c/G)^{1/2}$	m_P	$2.176\ 45(16)\times10^{-8}$	kg	7.5×10^{-5}
Planck temperature $(\hbar c^5/G)^{1/2}/k$	T_P	$1.416\ 79(11)\times10^{32}$	K	7.5×10^{-5}
Planck length $\hbar/m_P c=(\hbar G/c^3)^{1/2}$	l_P	$1.616\ 24(12)\times10^{-35}$	m	7.5×10^{-5}
Planck time $l_P/c=(\hbar G/c^5)^{1/2}$	t_P	$5.391\ 21(40)\times10^{-44}$	s	7.5×10^{-5}
ELECTROMAGNETIC				
elementary charge	e	$1.602\ 176\ 53(14)\times10^{-19}$	C	8.5×10^{-8}
	e/h	$2.417\ 989\ 40(21)\times10^{14}$	A J^{-1}	8.5×10^{-8}
magnetic flux quantum $h/2e$	Φ_0	$2.067\ 833\ 72(18)\times10^{-15}$	Wb	8.5×10^{-8}
conductance quantum $2e^2/h$	G_0	$7.748\ 091\ 733(26)\times10^{-5}$	S	3.3×10^{-9}
inverse of conductance quantum	G_0^{-1}	12 906.403 725(43)	Ω	3.3×10^{-9}
Josephson constant[a] $2e/h$	K_J	$483\ 597.879(41)\times10^{9}$	Hz V^{-1}	8.5×10^{-8}
von Klitzing constant[b] $h/e^2=\mu_0 c/2\alpha$	R_K	25 812.807 449(86)	Ω	3.3×10^{-9}
Bohr magneton $e\hbar/2m_e$	μ_B	$927.400\ 949(80)\times10^{-26}$	J T^{-1}	8.6×10^{-8}
in eV T^{-1}		$5.788\ 381\ 804(39)\times10^{-5}$	eV T^{-1}	6.7×10^{-9}
	μ_B/h	$13.996\ 2458(12)\times10^{9}$	Hz T^{-1}	8.6×10^{-8}
	μ_B/hc	46.686 4507(40)	m^{-1} T^{-1}	8.6×10^{-8}
	μ_B/k	0.671 7131(12)	K T^{-1}	1.8×10^{-6}
nuclear magneton $e\hbar/2m_p$	μ_N	$5.050\ 783\ 43(43)\times10^{-27}$	J T^{-1}	8.6×10^{-8}
in eV T^{-1}		$3.152\ 451\ 259(21)\times10^{-8}$	eV T^{-1}	6.7×10^{-9}
	μ_N/h	7.622 593 71(65)	MHz T^{-1}	8.6×10^{-8}
	μ_N/hc	$2.542\ 623\ 58(22)\times10^{-2}$	m^{-1} T^{-1}	8.6×10^{-8}
	μ_N/k	$3.658\ 2637(64)\times10^{-4}$	K T^{-1}	1.8×10^{-6}
ATOMIC AND NUCLEAR				
General				
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\ 352\ 568(24)\times10^{-3}$		3.3×10^{-9}
inverse fine-structure constant	α^{-1}	137.035 999 11(46)		3.3×10^{-9}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	10 973 731.568 525(73)	m^{-1}	6.6×10^{-12}
	$R_\infty c$	$3.289\ 841\ 960\ 360(22)\times10^{15}$	Hz	6.6×10^{-12}
	$R_\infty hc$	$2.179\ 872\ 09(37)\times10^{-18}$	J	1.7×10^{-7}
$R_\infty hc$ in eV		13.605 6923(12)	eV	8.5×10^{-8}
Bohr radius $\alpha/4\pi R_\infty=4\pi\epsilon_0\hbar^2/m_e e^2$	a_0	$0.529\ 177\ 2108(18)\times10^{-10}$	m	3.3×10^{-9}
Hartree energy $e^2/4\pi\epsilon_0 a_0=2R_\infty hc=\alpha^2 m_e c^2$	E_h	$4.359\ 744\ 17(75)\times10^{-18}$	J	1.7×10^{-7}
in eV		27.211 3845(23)	eV	8.5×10^{-8}
quantum of circulation	$h/2m_e$	$3.636\ 947\ 550(24)\times10^{-4}$	m^2 s^{-1}	6.7×10^{-9}
	h/m_e	$7.273\ 895\ 101(48)\times10^{-4}$	m^2 s^{-1}	6.7×10^{-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)				
$\sin^2\theta_W=s_W^2\equiv1-(m_W/m_Z)^2$	$\sin^2\theta_W$	0.222 15(76)		3.4×10^{-3}
Electron, e$^-$				
electron mass	m_e	$9.109\ 3826(16)\times10^{-31}$	kg	1.7×10^{-7}
in u, $m_e=A_r(e)$ u (electron rel. atomic mass times u)		$5.485\ 799\ 0945(24)\times10^{-4}$	u	4.4×10^{-10}
energy equivalent	$m_e c^2$	$8.187\ 1047(14)\times10^{-14}$	J	1.7×10^{-7}
in MeV		0.510 998 918(44)	MeV	8.6×10^{-8}
electron-muon mass ratio	m_e/m_μ	$4.836\ 331\ 67(13)\times10^{-3}$		2.6×10^{-8}
electron-tau mass ratio	m_e/m_τ	$2.875\ 64(47)\times10^{-4}$		1.6×10^{-4}
electron-proton mass ratio	m_e/m_p	$5.446\ 170\ 2173(25)\times10^{-4}$		4.6×10^{-10}
electron-neutron mass ratio	m_e/m_n	$5.438\ 673\ 4481(38)\times10^{-4}$		7.0×10^{-10}
electron-deuteron mass ratio	m_e/m_d	$2.724\ 437\ 1095(13)\times10^{-4}$		4.8×10^{-10}
electron to alpha particle mass ratio	m_e/m_α	$1.370\ 933\ 555\ 75(61)\times10^{-4}$		4.4×10^{-10}
electron charge to mass quotient	$-e/m_e$	$-1.758\ 820\ 12(15)\times10^{11}$	C kg^{-1}	8.6×10^{-8}
electron molar mass $N_A m_e$	$M(e), M_e$	$5.485\ 799\ 0945(24)\times10^{-7}$	kg mol^{-1}	4.4×10^{-10}

CODATA Recommended Values of the Fundamental Physical Constants – 2002

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
Compton wavelength $h/m_e c$	λ_C	$2.426\,310\,238(16)\times10^{-12}$	m	6.7×10^{-9}
$\lambda_C/2\pi = \alpha a_0 = \alpha^2/4\pi R_\infty$	$\bar{\lambda}_C$	$386.159\,2678(26)\times10^{-15}$	m	6.7×10^{-9}
classical electron radius $\alpha^2 a_0$	r_e	$2.817\,940\,325(28)\times10^{-15}$	m	1.0×10^{-8}
Thomson cross section $(8\pi/3)r_e^2$	σ_e	$0.665\,245\,873(13)\times10^{-28}$	m^2	2.0×10^{-8}
electron magnetic moment	μ_e	$-928.476\,412(80)\times10^{-26}$	$J\ T^{-1}$	8.6×10^{-8}
to Bohr magneton ratio	μ_e/μ_B	$-1.001\,159\,652\,1859(38)$		3.8×10^{-12}
to nuclear magneton ratio	μ_e/μ_N	$-1838.281\,971\,07(85)$		4.6×10^{-10}
electron magnetic moment anomaly $\lvert\mu_e\rvert/\mu_B - 1$	a_e	$1.159\,652\,1859(38)\times10^{-3}$		3.2×10^{-9}
electron g-factor $-2(1+a_e)$	g_e	$-2.002\,319\,304\,3718(75)$		3.8×10^{-12}
electron–muon magnetic moment ratio	μ_e/μ_μ	$206.766\,9894(54)$		2.6×10^{-8}
electron–proton magnetic moment ratio	μ_e/μ_p	$-658.210\,6862(66)$		1.0×10^{-8}
electron to shielded proton magnetic moment ratio (H_2O, sphere, 25 °C)	μ_e/μ'_p	$-658.227\,5956(71)$		1.1×10^{-8}
electron–neutron magnetic moment ratio	μ_e/μ_n	$960.920\,50(23)$		2.4×10^{-7}
electron–deuteron magnetic moment ratio	μ_e/μ_d	$-2143.923\,493(23)$		1.1×10^{-8}
electron to shielded helion[e] magnetic moment ratio (gas, sphere, 25 °C)	μ_e/μ'_h	$864.058\,255(10)$		1.2×10^{-8}
electron gyromagnetic ratio $2\lvert\mu_e\rvert/\hbar$	γ_e	$1.760\,859\,74(15)\times10^{11}$	$s^{-1}\ T^{-1}$	8.6×10^{-8}
	$\gamma_e/2\pi$	$28\,024.9532(24)$	MHz T^{-1}	8.6×10^{-8}
Muon, μ^-				
muon mass	m_μ	$1.883\,531\,40(33)\times10^{-28}$	kg	1.7×10^{-7}
in u, $m_\mu = A_r(\mu)$ u (muon rel. atomic mass times u)		$0.113\,428\,9264(30)$	u	2.6×10^{-8}
energy equivalent	$m_\mu c^2$	$1.692\,833\,60(29)\times10^{-11}$	J	1.7×10^{-7}
in MeV		$105.658\,3692(94)$	MeV	8.9×10^{-8}
muon–electron mass ratio	m_μ/m_e	$206.768\,2838(54)$		2.6×10^{-8}
muon–tau mass ratio	m_μ/m_τ	$5.945\,92(97)\times10^{-2}$		1.6×10^{-4}
muon–proton mass ratio	m_μ/m_p	$0.112\,609\,5269(29)$		2.6×10^{-8}
muon–neutron mass ratio	m_μ/m_n	$0.112\,454\,5175(29)$		2.6×10^{-8}
muon molar mass $N_A m_\mu$	$M(\mu)$, M_μ	$0.113\,428\,9264(30)\times10^{-3}$	kg mol^{-1}	2.6×10^{-8}
muon Compton wavelength $h/m_\mu c$	$\lambda_{C,\mu}$	$11.734\,441\,05(30)\times10^{-15}$	m	2.5×10^{-8}
$\lambda_{C,\mu}/2\pi$	$\bar{\lambda}_{C,\mu}$	$1.867\,594\,298(47)\times10^{-15}$	m	2.5×10^{-8}
muon magnetic moment	μ_μ	$-4.490\,447\,99(40)\times10^{-26}$	$J\ T^{-1}$	8.9×10^{-8}
to Bohr magneton ratio	μ_μ/μ_B	$-4.841\,970\,45(13)\times10^{-3}$		2.6×10^{-8}
to nuclear magneton ratio	μ_μ/μ_N	$-8.890\,596\,98(23)$		2.6×10^{-8}
muon magnetic moment anomaly $\lvert\mu_\mu\rvert/(e\hbar/2m_\mu)-1$	a_μ	$1.165\,919\,81(62)\times10^{-3}$		5.3×10^{-7}
muon g-factor $-2(1+a_\mu)$	g_μ	$-2.002\,331\,8396(12)$		6.2×10^{-10}
muon–proton magnetic moment ratio	μ_μ/μ_p	$-3.183\,345\,118(89)$		2.8×10^{-8}
Tau, τ^-				
tau mass[f]	m_τ	$3.167\,77(52)\times10^{-27}$	kg	1.6×10^{-4}
in u, $m_\tau = A_r(\tau)$ u (tau rel. atomic mass times u)		$1.907\,68(31)$	u	1.6×10^{-4}
energy equivalent	$m_\tau c^2$	$2.847\,05(46)\times10^{-10}$	J	1.6×10^{-4}
in MeV		$1776.99(29)$	MeV	1.6×10^{-4}
tau–electron mass ratio	m_τ/m_e	$3477.48(57)$		1.6×10^{-4}
tau–muon mass ratio	m_τ/m_μ	$16.8183(27)$		1.6×10^{-4}
tau–proton mass ratio	m_τ/m_p	$1.893\,90(31)$		1.6×10^{-4}
tau–neutron mass ratio	m_τ/m_n	$1.891\,29(31)$		1.6×10^{-4}
tau molar mass $N_A m_\tau$	$M(\tau)$, M_τ	$1.907\,68(31)\times10^{-3}$	kg mol^{-1}	1.6×10^{-4}
tau Compton wavelength $h/m_\tau c$	$\lambda_{C,\tau}$	$0.697\,72(11)\times10^{-15}$	m	1.6×10^{-4}
$\lambda_{C,\tau}/2\pi$	$\bar{\lambda}_{C,\tau}$	$0.111\,046(18)\times10^{-15}$	m	1.6×10^{-4}
Proton, p				
proton mass	m_p	$1.672\,621\,71(29)\times10^{-27}$	kg	1.7×10^{-7}
in u, $m_p = A_r(p)$ u (proton rel. atomic mass times u)		$1.007\,276\,466\,88(13)$	u	1.3×10^{-10}
energy equivalent	$m_p c^2$	$1.503\,277\,43(26)\times10^{-10}$	J	1.7×10^{-7}
in MeV		$938.272\,029(80)$	MeV	8.6×10^{-8}
proton–electron mass ratio	m_p/m_e	$1836.152\,672\,61(85)$		4.6×10^{-10}
proton–muon mass ratio	m_p/m_μ	$8.880\,243\,33(23)$		2.6×10^{-8}
proton–tau mass ratio	m_p/m_τ	$0.528\,012(86)$		1.6×10^{-4}
proton–neutron mass ratio	m_p/m_n	$0.998\,623\,478\,72(58)$		5.8×10^{-10}
proton charge to mass quotient	e/m_p	$9.578\,833\,76(82)\times10^{7}$	C kg^{-1}	8.6×10^{-8}
proton molar mass $N_A m_p$	$M(p)$, M_p	$1.007\,276\,466\,88(13)\times10^{-3}$	kg mol^{-1}	1.3×10^{-10}
proton Compton wavelength $h/m_p c$	$\lambda_{C,p}$	$1.321\,409\,8555(88)\times10^{-15}$	m	6.7×10^{-9}
$\lambda_{C,p}/2\pi$	$\bar{\lambda}_{C,p}$	$0.210\,308\,9104(14)\times10^{-15}$	m	6.7×10^{-9}

CODATA Recommended Values of the Fundamental Physical Constants – 2002

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
proton rms charge radius	R_p	$0.8750(68)\times10^{-15}$	m	7.8×10^{-3}
proton magnetic moment	μ_p	$1.410\,606\,71(12)\times10^{-26}$	J T^{-1}	8.7×10^{-8}
to Bohr magneton ratio	μ_p/μ_B	$1.521\,032\,206(15)\times10^{-3}$		1.0×10^{-8}
to nuclear magneton ratio	μ_p/μ_N	2.792 847 351(28)		1.0×10^{-8}
proton g-factor $2\mu_p/\mu_N$	g_p	5.585 694 701(56)		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	$1.410\,570\,47(12)\times10^{-26}$	J T^{-1}	8.7×10^{-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	2.792 775 604(30)		1.1×10^{-8}
proton magnetic shielding correction $1-\mu'_p/\mu_p$				
(H_2O, sphere, 25 °C)	σ'_p	$25.689(15)\times10^{-6}$		5.7×10^{-4}
proton gyromagnetic ratio $2\mu_p/\hbar$	γ_p	$2.675\,222\,05(23)\times10^{8}$	s^{-1} T^{-1}	8.6×10^{-8}
	$\gamma_p/2\pi$	42.577 4813(37)	MHz T^{-1}	8.6×10^{-8}
shielded proton gyromagnetic ratio $2\mu'_p/\hbar$				
(H_2O, sphere, 25 °C)	γ'_p	$2.675\,153\,33(23)\times10^{8}$	s^{-1} T^{-1}	8.6×10^{-8}
	$\gamma'_p/2\pi$	42.576 3875(37)	MHz T^{-1}	8.6×10^{-8}
Neutron, n				
neutron mass	m_n	$1.674\,927\,28(29)\times10^{-27}$	kg	1.7×10^{-7}
in u, $m_n=A_r$(n) u (neutron rel. atomic mass times u)		1.008 664 915 60(55)	u	5.5×10^{-10}
energy equivalent	m_nc^2	$1.505\,349\,57(26)\times10^{-10}$	J	1.7×10^{-7}
in MeV		939.565 360(81)	MeV	8.6×10^{-8}
neutron–electron mass ratio	m_n/m_e	1838.683 6598(13)		7.0×10^{-10}
neutron–muon mass ratio	m_n/m_μ	8.892 484 02(23)		2.6×10^{-8}
neutron–tau mass ratio	m_n/m_τ	0.528 740(86)		1.6×10^{-4}
neutron–proton mass ratio	m_n/m_p	1.001 378 418 70(58)		5.8×10^{-10}
neutron molar mass N_Am_n	M(n), M_n	$1.008\,664\,915\,60(55)\times10^{-3}$	kg mol^{-1}	5.5×10^{-10}
neutron Compton wavelength h/m_nc	$\lambda_{C,n}$	$1.319\,590\,9067(88)\times10^{-15}$	m	6.7×10^{-9}
$\lambda_{C,n}/2\pi$	$\bar{\lambda}_{C,n}$	$0.210\,019\,4157(14)\times10^{-15}$	m	6.7×10^{-9}
neutron magnetic moment	μ_n	$-0.966\,236\,45(24)\times10^{-26}$	J T^{-1}	2.5×10^{-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 73(45)		2.4×10^{-7}
neutron g-factor $2\mu_n/\mu_N$	g_n	−3.826 085 46(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 $2\|\mu_n\|/\hbar$	γ_n	$1.832\,471\,83(46)\times10^{8}$	s^{-1} T^{-1}	2.5×10^{-7}
	$\gamma_n/2\pi$	29.164 6950(73)	MHz T^{-1}	2.5×10^{-7}
Deuteron, d				
deuteron mass	m_d	$3.343\,583\,35(57)\times10^{-27}$	kg	1.7×10^{-7}
in u, $m_d=A_r$(d) u (deuteron rel. atomic mass times u)		2.013 553 212 70(35)	u	1.7×10^{-10}
energy equivalent	m_dc^2	$3.005\,062\,85(51)\times10^{-10}$	J	1.7×10^{-7}
in MeV		1875.612 82(16)	MeV	8.6×10^{-8}
deuteron–electron mass ratio	m_d/m_e	3670.482 9652(18)		4.8×10^{-10}
deuteron–proton mass ratio	m_d/m_p	1.999 007 500 82(41)		2.0×10^{-10}
deuteron molar mass N_Am_d	M(d), M_d	$2.013\,553\,212\,70(35)\times10^{-3}$	kg mol^{-1}	1.7×10^{-10}
deuteron rms charge radius	R_d	$2.1394(28)\times10^{-15}$	m	1.3×10^{-3}
deuteron magnetic moment	μ_d	$0.433\,073\,482(38)\times10^{-26}$	J T^{-1}	8.7×10^{-8}
to Bohr magneton ratio	μ_d/μ_B	$0.466\,975\,4567(50)\times10^{-3}$		1.1×10^{-8}
to nuclear magneton ratio	μ_d/μ_N	0.857 438 2329(92)		1.1×10^{-8}
deuteron–electron magnetic moment ratio	μ_d/μ_e	$-4.664\,345\,548(50)\times10^{-4}$		1.1×10^{-8}
deuteron–proton magnetic moment ratio	μ_d/μ_p	0.307 012 2084(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	$5.006\,412\,14(86)\times10^{-27}$	kg	1.7×10^{-7}
in u, $m_h=A_r$(h) u (helion rel. atomic mass times u)		3.014 932 2434(58)	u	1.9×10^{-9}
energy equivalent	m_hc^2	$4.499\,538\,84(77)\times10^{-10}$	J	1.7×10^{-7}
in MeV		2808.391 42(24)	MeV	8.6×10^{-8}
helion–electron mass ratio	m_h/m_e	5495.885 269(11)		2.0×10^{-9}
helion–proton mass ratio	m_h/m_p	2.993 152 6671(58)		1.9×10^{-9}
helion molar mass N_Am_h	M(h), M_h	$3.014\,932\,2434(58)\times10^{-3}$	kg mol^{-1}	1.9×10^{-9}
shielded helion magnetic moment (gas, sphere, 25 °C)	μ'_h	$-1.074\,553\,024(93)\times10^{-26}$	J T^{-1}	8.7×10^{-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 – 2002

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
to nuclear magneton ratio	μ'_h/μ_N	−2.127 497 723(25)		1.2×10^{-8}
shielded helion to proton magnetic moment ratio				
(gas, sphere, 25 °C)	μ'_h/μ_p	−0.761 766 562(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	$2.037\ 894\ 70(18)\times10^{8}$	$s^{-1}\ T^{-1}$	8.7×10^{-8}
	$\gamma'_h/2\pi$	32.434 1015(28)	MHz T^{-1}	8.7×10^{-8}
Alpha particle, α				
alpha particle mass	m_α	$6.644\ 6565(11)\times10^{-27}$	kg	1.7×10^{-7}
in u, $m_\alpha = A_r(\alpha)$ u (alpha particle rel. atomic mass times u)		4.001 506 179 149(56)	u	1.4×10^{-11}
energy equivalent	$m_\alpha c^2$	$5.971\ 9194(10)\times10^{-10}$	J	1.7×10^{-7}
in MeV		3727.379 17(32)	MeV	8.6×10^{-8}
alpha particle to electron mass ratio	m_α/m_e	7294.299 5363(32)		4.4×10^{-10}
alpha particle to proton mass ratio	m_α/m_p	3.972 599 689 07(52)		1.3×10^{-10}
alpha particle molar mass $N_A m_\alpha$	$M(\alpha)$, M_α	$4.001\ 506\ 179\ 149(56)\times10^{-3}$	kg mol^{-1}	1.4×10^{-11}
PHYSICOCHEMICAL				
Avogadro constant	N_A, L	$6.022\ 1415(10)\times10^{23}$	mol^{-1}	1.7×10^{-7}
atomic mass constant				
$m_u = \frac{1}{12}m(^{12}C) = 1\ u = 10^{-3}$ kg mol^{-1}/N_A	m_u	$1.660\ 538\ 86(28)\times10^{-27}$	kg	1.7×10^{-7}
energy equivalent	$m_u c^2$	$1.492\ 417\ 90(26)\times10^{-10}$	J	1.7×10^{-7}
in MeV		931.494 043(80)	MeV	8.6×10^{-8}
Faraday constant[g] $N_A e$	F	96 485.3383(83)	C mol^{-1}	8.6×10^{-8}
molar Planck constant	$N_A h$	$3.990\ 312\ 716(27)\times10^{-10}$	J s mol^{-1}	6.7×10^{-9}
	$N_A hc$	0.119 626 565 72(80)	J m mol^{-1}	6.7×10^{-9}
molar gas constant	R	8.314 472(15)	J mol^{-1} K^{-1}	1.7×10^{-6}
Boltzmann constant R/N_A	k	$1.380\ 6505(24)\times10^{-23}$	J K^{-1}	1.8×10^{-6}
in eV K^{-1}		$8.617\ 343(15)\times10^{-5}$	eV K^{-1}	1.8×10^{-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	$2.686\ 7773(47)\times10^{25}$	m^{-3}	1.8×10^{-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]				
$\frac{5}{2} + \ln[(2\pi m_u k T_1/h^2)^{3/2} k T_1/p_0]$				
$T_1 = 1$ K, $p_0 = 100$ kPa	S_0/R	−1.151 7047(44)		3.8×10^{-6}
$T_1 = 1$ K, $p_0 = 101.325$ kPa		−1.164 8677(44)		3.8×10^{-6}
Stefan–Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	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	$3.741\ 771\ 38(64)\times10^{-16}$	W m^2	1.7×10^{-7}
first radiation constant for spectral radiance $2hc^2$	c_{1L}	$1.191\ 042\ 82(20)\times10^{-16}$	W m^2 sr^{-1}	1.7×10^{-7}
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	$2.897\ 7685(51)\times10^{-3}$	m K	1.7×10^{-6}

[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 [Hagiwara et al., *Phys. Rev. D* **66**, 010001 (2002)].
[d] Based on the ratio of the masses of the W and Z bosons m_W/m_Z recommended by the Particle Data Group [Hagiwara et al., *Phys. Rev. D* **66**, 010001 (2002)]. 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 [Hagiwara et al., *Phys. Rev. D* **66**, 010001 (2002)], 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 96 485.336(16) [1.7×10^{-7}] 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 internationally adopted 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
relative atomic mass of[a] ^{12}C	$A_r(^{12}\mathrm{C})$	12		(exact)
molar mass constant	M_u	1×10^{-3}	kg mol^{-1}	(exact)
molar mass of ^{12}C	$M(^{12}\mathrm{C})$	12×10^{-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[d]	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, M_u is the molar 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.

[d]The value given was adopted by the 3rd General Conference on Weights and Measures (CGPM), 1903, and is the conventional value used to calculate the now obsolete unit kilogram force.

CODATA Recommended Values of Energy Equivalents – 2002

	Relevant unit			
	J	**kg**	**m^{-1}**	**Hz**
1 J	(1 J) = 1 J	(1 J)/c^2 = 1.112 650 056 . . . ×10^{-17} kg	(1 J)/hc = 5.034 117 20(86)×10^{24} m^{-1}	(1 J)/h = 1.509 190 37(26)×10^{33} Hz
1 kg	(1 kg)c^2 = 8.987 551 787 . . . ×10^{16} J	(1 kg) = 1 kg	(1 kg)c/h = 4.524 438 91(77)×10^{41} m^{-1}	(1 kg)c^2/h = 1.356 392 66(23)×10^{50} Hz
1 m^{-1}	(1 m^{-1})hc = 1.986 445 61(34)×10^{-25} J	(1 m^{-1})h/c = 2.210 218 81(38)×10^{-42} kg	(1 m^{-1}) = 1 m^{-1}	(1 m^{-1})c = 299 792 458 Hz
1 Hz	(1 Hz)h = 6.626 0693(11)×10^{-34} J	(1 Hz)h/c^2 = 7.372 4964(13)×10^{-51} kg	(1 Hz)/c = 3.335 640 951 . . . ×10^{-9} m^{-1}	(1 Hz) = 1 Hz
1 K	(1 K)k = 1.380 6505(24)×10^{-23} J	(1 K)k/c^2 = 1.536 1808(27)×10^{-40} kg	(1 K)k/hc = 69.503 56(12) m^{-1}	(1 K)k/h = 2.083 6644(36)×10^{10} Hz
1 eV	(1 eV) = 1.602 176 53(14)×10^{-19} J	(1 eV)/c^2 = 1.782 661 81(15)×10^{-36} kg	(1 eV)/hc = 8.065 544 45(69)×10^{5} m^{-1}	(1 eV)/h = 2.417 989 40(21)×10^{14} Hz
1 u	(1 u)c^2 = 1.492 417 90(26)×10^{-10} J	(1 u) = 1.660 538 86(28)×10^{-27} kg	(1 u)c/h = 7.513 006 608(50)×10^{14} m^{-1}	(1 u)c^2/h = 2.252 342 718(15)×10^{23} Hz
1 E_h	(1 E_h) = 4.359 744 17(75)×10^{-18} J	(1 E_h)/c^2 = 4.850 869 60(83)×10^{-35} kg	(1 E_h)/hc = 2.194 746 313 705(15)×10^{7} m^{-1}	(1 E_h)/h = 6.579 683 920 721(44)×10^{15} Hz

CODATA Recommended Values of Energy Equivalents – 2002

	Relevant unit			
	K	**eV**	**u**	**E_h**
1 J	(1 J)/k = 7.242 963(13)×10^{22} K	(1 J) = 6.241 509 47(53)×10^{18} eV	(1 J)/c^2 = 6.700 5361(11)×10^{9} u	(1 J) = 2.293 712 57(39)×10^{17} E_h
1 kg	(1 kg)c^2/k = 6.509 650(11)×10^{39} K	(1 kg)c^2 = 5.609 588 96(48)×10^{35} eV	(1 kg) = 6.022 1415(10)×10^{26} u	(1 kg)c^2 = 2.061 486 05(35)×10^{34} E_h
1 m^{-1}	(1 m^{-1})hc/k = 1.438 7752(25)×10^{-2} K	(1 m^{-1})hc = 1.239 841 91(11)×10^{-6} eV	(1 m^{-1})h/c = 1.331 025 0506(89)×10^{-15} u	(1 m^{-1})hc = 4.556 335 252 760(30)×10^{-8} E_h
1 Hz	(1 Hz)h/k = 4.799 2374(84)×10^{-11} K	(1 Hz)h = 4.135 667 43(35)×10^{-15} eV	(1 Hz)h/c^2 = 4.439 821 667(30)×10^{-24} u	(1 Hz)h = 1.519 829 846 006(10)×10^{-16} E_h
1 K	(1 K) = 1 K	(1 K)k = 8.617 343(15)×10^{-5} eV	(1 K)k/c^2 = 9.251 098(16)×10^{-14} u	(1 K)k = 3.166 8153(55)×10^{-6} E_h
1 eV	(1 eV)/k = 1.160 4505(20)×10^{4} K	(1 eV) = 1 eV	(1 eV)/c^2 = 1.073 544 171(92)×10^{-9} u	(1 eV) = 3.674 932 45(31)×10^{-2} E_h
1 u	(1 u)c^2/k = 1.080 9527(19)×10^{13} K	(1 u)c^2 = 931.494 043(80)×10^{6} eV	(1 u) = 1 u	(1 u)c^2 = 3.423 177 686(23)×10^{7} E_h
1 E_h	(1 E_h)/k = 3.157 7465(55)×10^{5} K	(1 E_h) = 27.211 3845(23) eV	(1 E_h)/c^2 = 2.921 262 323(19)×10^{-8} u	(1 E_h) = 1 E_h