# 1. PHYSICAL CONSTANTS

**Table 1.1.** Reviewed 1993 by B.N. Taylor, NIST. Based mainly on the "1986 Adjustment of the Fundamental Physical Constants" by E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The last group of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. The figures in parentheses after the values give the 1-standard-deviation uncertainties in the last digits; the corresponding uncertainties in parts per million (ppm) are given in the last column. This set of constants (aside from the last group) is recommended for international use by CODATA (the Committee on Data for Science and Technology).

Since the 1986 adjustment, new experiments have yielded improved values for a number of constants, including the Rydberg constant $R_\infty$, the Planck constant $h$, the fine-structure constant $\alpha$, and the molar gas constant $R$, and hence also for constants directly derived from these, such as the Boltzmann constant $k$ and Stefan-Boltzmann constant $\sigma$. The new results and their impact on the 1986 recommended values are discussed extensively in "Recommended Values of the Fundamental Physical Constants: A Status Report," B.N. Taylor and E.R. Cohen, J. Res. Natl. Inst. Stand. Technol. **95**, 497 (1990); see also E.R. Cohen and B.N. Taylor, "The Fundamental Physical Constants," Phys. Today, August 1993 Part 2, BG9. In general, the new results give uncertainties for the affected constants that are 5 to 7 times smaller than the 1986 uncertainties, but the changes in the values themselves are smaller than twice the 1986 uncertainties. Because the output values of a least-squares adjustment are correlated, the new results cannot readily be incorporated with the 1986 values. Until the next complete adjustment of the constants, the 1986 CODATA set, given (in part) below, remains the set of choice.

| Quantity | Symbol, equation | Value | Uncert. (ppm) |
|---|---|---|---|
| speed of light in vacuum | $c$ | 299 792 458 m s$^{-1}$ | exact* |
| Planck constant | $h$ | 6.626 075 5(40)$\times 10^{-34}$ J s | 0.60 |
| Planck constant, reduced | $\hbar \equiv h/2\pi$ | 1.054 572 66(63)$\times 10^{-34}$ J s | 0.60 |
| | | = 6.582 122 0(20)$\times 10^{-22}$ MeV s | 0.30 |
| electron charge magnitude | $e$ | 1.602 177 33(49)$\times 10^{-19}$ C = 4.803 206 8(15)$\times 10^{-10}$ esu | 0.30, 0.30 |
| conversion constant | $\hbar c$ | 197.327 053(59) MeV fm | 0.30 |
| conversion constant | $(\hbar c)^2$ | 0.389 379 66(23) GeV$^2$ mbarn | 0.59 |
| electron mass | $m_e$ | 0.510 999 06(15) MeV/$c^2$ = 9.109 389 7(54)$\times 10^{-31}$ kg | 0.30, 0.59 |
| proton mass | $m_p$ | 938.272 31(28) MeV/$c^2$ = 1.672 623 1(10)$\times 10^{-27}$ kg | 0.30, 0.59 |
| | | = 1.007 276 470(12) u = 1836.152 701(37) $m_e$ | 0.012, 0.020 |
| deuteron mass | $m_d$ | 1875.613 39(57) MeV/$c^2$ | 0.30 |
| unified atomic mass unit (u) | (mass $^{12}$C atom)/12 = (1 g)/($N_A$ mol) | 931.494 32(28) MeV/$c^2$ = 1.660 540 2(10)$\times 10^{-27}$ kg | 0.30, 0.59 |
| permittivity of free space | $\epsilon_0$ $\}$ $\epsilon_0\mu_0 = 1/c^2$ | 8.854 187 817 ... $\times 10^{-12}$ F m$^{-1}$ | exact |
| permeability of free space | $\mu_0$ | $4\pi \times 10^{-7}$ N A$^{-2}$ = 12.566 370 614 ... $\times 10^{-7}$ N A$^{-2}$ | exact |
| fine-structure constant | $\alpha = e^2/4\pi\epsilon_0\hbar c$ | 1/137.035 989 5(61)$^\dagger$ | 0.045 |
| classical electron radius | $r_e = e^2/4\pi\epsilon_0 m_e c^2$ | 2.817 940 92(38)$\times 10^{-15}$ m | 0.13 |
| electron Compton wavelength | $\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$ | 3.861 593 23(35)$\times 10^{-13}$ m | 0.089 |
| Bohr radius ($m_{\text{nucleus}} = \infty$) | $a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$ | 0.529 177 249(24)$\times 10^{-10}$ m | 0.045 |
| wavelength of 1 eV/$c$ particle | $hc/e$ | 1.239 842 44(37)$\times 10^{-6}$ m | 0.30 |
| Rydberg energy | $hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$ | 13.605 698 1(40) eV | 0.30 |
| Thomson cross section | $\sigma_T = 8\pi r_e^2/3$ | 0.665 246 16(18) barn | 0.27 |
| Bohr magneton | $\mu_B = e\hbar/2m_e$ | 5.788 382 63(52)$\times 10^{-11}$ MeV T$^{-1}$ | 0.089 |
| nuclear magneton | $\mu_N = e\hbar/2m_p$ | 3.152 451 66(28)$\times 10^{-14}$ MeV T$^{-1}$ | 0.089 |
| electron cyclotron freq./field | $\omega^e_{\text{cycl}}/B = e/m_e$ | 1.758 819 62(53)$\times 10^{11}$ rad s$^{-1}$ T$^{-1}$ | 0.30 |
| proton cyclotron freq./field | $\omega^p_{\text{cycl}}/B = e/m_p$ | 9.578 830 9(29)$\times 10^{7}$ rad s$^{-1}$ T$^{-1}$ | 0.30 |
| gravitational constant | $G_N$ | 6.672 59(85)$\times 10^{-11}$ m$^3$ kg$^{-1}$ s$^{-2}$ | 128 |
| | | = 6.707 11(86)$\times 10^{-39}$ $\hbar c$ (GeV/$c^2$)$^{-2}$ | 128 |
| standard grav. accel., sea level | g | 9.806 65 m s$^{-2}$ | exact |
| Avogadro constant | $N_A$ | 6.022 136 7(36)$\times 10^{23}$ mol$^{-1}$ | 0.59 |
| Boltzmann constant | $k$ | 1.380 658(12)$\times 10^{-23}$ J K$^{-1}$ | 8.5 |
| | | = 8.617 385(73)$\times 10^{-5}$ eV K$^{-1}$ | 8.4 |
| molar volume, ideal gas at STP | $N_A k$(273.15 K)/(101 325 Pa) | 22.414 10(19)$\times 10^{-3}$ m$^3$ mol$^{-1}$ | 8.4 |
| Wien displacement law constant | $b = \lambda_{\max} T$ | 2.897 756(24)$\times 10^{-3}$ m K | 8.4 |
| Stefan-Boltzmann constant | $\sigma = \pi^2 k^4/60\hbar^3 c^2$ | 5.670 51(19)$\times 10^{-8}$ W m$^{-2}$ K$^{-4}$ | 34 |
| Fermi coupling constant$^\ddagger$ | $G_F/(\hbar c)^3$ | 1.166 39(2)$\times 10^{-5}$ GeV$^{-2}$ | 20 |
| weak mixing angle | $\sin^2\hat{\theta}(M_Z)$ ($\overline{\text{MS}}$) | 0.2319(5) | 2200 |
| $W^\pm$ boson mass | $m_W$ | 80.22(26) GeV/$c^2$ | 3200 |
| $Z^0$ boson mass | $m_Z$ | 91.187(7) GeV/$c^2$ | 77 |
| strong coupling constant | $\alpha_s(m_Z)$ | 0.117(5) | 43000 |

| | | |
|---|---|---|
| $\pi$ = 3.141 592 653 589 793 238 | $e$ = 2.718 281 828 459 045 235 | $\gamma$ = 0.577 215 664 901 532 861 |

| | | | |
|---|---|---|---|
| 1 in $\equiv$ 0.0254 m | 1 G $\equiv 10^{-4}$ T | 1 eV = 1.602 177 33(49) $\times 10^{-19}$ J | $kT$ at 300 K = [38.681 49(33)]$^{-1}$ eV |
| 1 Å $\equiv$ 0.1 nm | 1 dyne $\equiv 10^{-5}$ N | 1 eV/$c^2$ = 1.782 662 70(54) $\times 10^{-36}$ kg | 0° C $\equiv$ 273.15 K |
| 1 barn $\equiv 10^{-28}$ m$^2$ | 1 erg $\equiv 10^{-7}$ J | 2.997 924 58 $\times 10^9$ esu = 1 C | 1 atmosphere $\equiv$ 760 torr $\equiv$ 101 325 Pa |

* The meter is defined to be the length of path traveled by light in vacuum in 1/299 792 458 s. See B.W. Petley, Nature **303**, 373 (1983).

† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is approximately 1/128.

‡ See discussion in Sec. 26 "Standard Model of electroweak interactions."