

## 1. Physical Constants (a major revision)

**Table 1.1.** Revised 2019 by C.G. Wohl (LBNL). Reviewed by P.J. Mohr and D.B. Newell (NIST). Mainly from “CODATA Recommended Values of the Fundamental Physical Constants: 2018,” E. Tiesinga, D.B. Newell, P.J. Mohr, and B.N. Taylor, NIST SP961 (May 2019). The electron charge magnitude  $e$ , and the Planck, Boltzmann, and Avogadro constants  $h$ ,  $k$ , and  $N_A$ , now join  $c$  as having defined values; the free-space permittivity and permeability constants  $\epsilon_0$  and  $\mu_0$  are no longer exact. These changes affect practically everything else in the Table. Figures in parentheses after the values are the 1-standard-deviation uncertainties in the last digits; the fractional uncertainties in parts per  $10^9$  (ppb) are in the last column. The full 2018 CODATA Committee on Data for Science and Technology set of constants are found at <https://physics.nist.gov/constants>. The last set of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. See also “The International System of Units (SI),” 9th ed. (2019) of the International Bureau of Weights and Measures (BIPM), <https://www.bipm.org/utis/common/pdf/si-brochure/SI-Brochure-9-EN.pdf>.

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	$c$	299 792 458 m s <sup>-1</sup>	exact
Planck constant	$h$	6.626 070 15 × 10 <sup>-34</sup> J s (or J/Hz) <sup>‡</sup>	exact
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 571 817... × 10 <sup>-34</sup> J s = 6.582 119 569... × 10 <sup>-22</sup> MeV s	exact* exact*
electron charge magnitude	$e$	1.602 176 634 × 10 <sup>-19</sup> C	exact
conversion constant	$hc$	197.326 980 4... MeV fm	exact*
conversion constant	$(hc)^2$	0.389 379 372 1... GeV <sup>2</sup> mbarn	exact*
electron mass	$m_e$	0.510 998 950 00(15) MeV/c <sup>2</sup> = 9.109 383 7015(28) × 10 <sup>-31</sup> kg	0.30
proton mass	$m_p$	938.272 088 16(29) MeV/c <sup>2</sup> = 1.672 621 923 69(51) × 10 <sup>-27</sup> kg = 1.007 276 466 621(53) u = 1836.152 673 43(11) $m_e$	0.053, 0.060
neutron mass	$m_n$	939.565 420 52(54) MeV/c <sup>2</sup> = 1.008 664 915 95(49) u	0.57, 0.48
deuteron mass	$m_d$	1875.612 942 57(57) MeV/c <sup>2</sup>	0.30
unified atomic mass unit**	$u = (\text{mass } ^{12}\text{C atom})/12$	931.494 102 42(28) MeV/c <sup>2</sup> = 1.660 539 066 60(50) × 10 <sup>-27</sup> kg	0.30
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	8.854 187 8128(13) × 10 <sup>-12</sup> F m <sup>-1</sup>	0.15
permeability of free space	$\mu_0/(4\pi \times 10^{-7})$	1.000 000 000 55(15) N A <sup>-2</sup>	0.15
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297 352 5693(11) × 10 <sup>-3</sup> = 1/137.035 999 084(21) <sup>†</sup>	0.15
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 3262(13) × 10 <sup>-15</sup> m	0.45
( $e^-$ Compton wavelength)/ $2\pi$	$\lambda_e = \hbar/m_e c = r_e \alpha^{-1}$	3.861 592 6796(12) × 10 <sup>-13</sup> m	0.30
Bohr radius ( $m_{\text{nucleus}} = \infty$ )	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e \alpha^{-2}$	0.529 177 210 903(80) × 10 <sup>-10</sup> m	0.15
wavelength of 1 eV/ $c$ particle	$hc/(1 \text{ eV})$	1.239 841 984... × 10 <sup>-6</sup> m	exact*
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2 \hbar^2 = m_e c^2 \alpha^2/2$	13.605 693 122 994(26) eV	1.9 × 10 <sup>-3</sup>
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 245 873 21(60) barn	0.91
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 381 8060(17) × 10 <sup>-11</sup> MeV T <sup>-1</sup>	0.3
nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 258 44(96) × 10 <sup>-14</sup> MeV T <sup>-1</sup>	0.31
electron cyclotron freq./field	$\omega_{\text{cycl}}^e/B = e/m_e$	1.758 820 010 76(53) × 10 <sup>11</sup> rad s <sup>-1</sup> T <sup>-1</sup>	0.30
proton cyclotron freq./field	$\omega_{\text{cycl}}^p/B = e/m_p$	9.578 833 1560(29) × 10 <sup>7</sup> rad s <sup>-1</sup> T <sup>-1</sup>	0.31
gravitational constant <sup>‡</sup>	$G_N$	6.674 30(15) × 10 <sup>-11</sup> m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup> = 6.708 83(15) × 10 <sup>-39</sup> $\hbar c$ (GeV/c <sup>2</sup> ) <sup>-2</sup>	2.2 × 10 <sup>4</sup> 2.2 × 10 <sup>4</sup>
standard gravitational accel.	$g_N$	9.806 65 m s <sup>-2</sup>	exact
Avogadro constant	$N_A$	6.022 140 76 × 10 <sup>23</sup> mol <sup>-1</sup>	exact
Boltzmann constant	$k$	1.380 649 × 10 <sup>-23</sup> J K <sup>-1</sup> = 8.617 333 262... × 10 <sup>-5</sup> eV K <sup>-1</sup>	exact* exact*
molar volume, ideal gas at STP	$N_A k$ (273.15 K)/(101 325 Pa)	22.413 969 54... × 10 <sup>-3</sup> m <sup>3</sup> mol <sup>-1</sup>	exact*
Wien displacement law constant	$b = \lambda_{\text{max}} T$	2.897 771 955... × 10 <sup>-3</sup> m K	exact*
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	5.670 374 419... × 10 <sup>-8</sup> W m <sup>-2</sup> K <sup>-4</sup>	exact*
Fermi coupling constant <sup>‡‡</sup>	$G_F/(\hbar c)^3$	1.166 378 7(6) × 10 <sup>-5</sup> GeV <sup>-2</sup>	510
weak-mixing angle	$\sin^2 \hat{\theta}(M_Z)$ ( $\overline{\text{MS}}$ )	0.231 22(4) <sup>††</sup>	1.7 × 10 <sup>5</sup>
$W^\pm$ boson mass	$m_W$	80.379(12) GeV/c <sup>2</sup>	1.5 × 10 <sup>5</sup>
$Z^0$ boson mass	$m_Z$	91.1876(21) GeV/c <sup>2</sup>	2.3 × 10 <sup>4</sup>
strong coupling constant	$\alpha_s(m_Z)$	0.1179(10)	8.5 × 10 <sup>6</sup>
$\pi = 3.141 592 653 589 793 238...$		$e = 2.718 281 828 459 045 235...$	$\gamma = 0.577 215 664 901 532 860...$
1 in $\equiv$ 0.0254 m	1 G $\equiv$ 10 <sup>-4</sup> T	1 eV = 1.602 176 634 × 10 <sup>-19</sup> J (exact)	$kT$ at 300 K = [38.681 740(22)] <sup>-1</sup> eV
1 Å $\equiv$ 0.1 nm	1 dyne $\equiv$ 10 <sup>-5</sup> N	(1 kg)c <sup>2</sup> = 5.609 588 603... × 10 <sup>35</sup> eV (exact*)	0 °C $\equiv$ 273.15 K
1 barn $\equiv$ 10 <sup>-28</sup> m <sup>2</sup>	1 erg $\equiv$ 10 <sup>-7</sup> J	1 C = 2.997 924 58 × 10 <sup>9</sup> esu	1 atmosphere $\equiv$ 760 Torr $\equiv$ 101 325 Pa

<sup>‡</sup> CODATA recommends that the unit be J/Hz to stress that in  $h = E/\nu$  the frequency  $\nu$  is in cycles/sec (Hz), not radians/sec.

\* These are calculated from exact values and are exact to the number of places given (*i.e.* no rounding).

\*\* The molar mass of <sup>12</sup>C is 11.999 999 9958(36) g.

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

‡ Absolute laboratory measurements of  $G_N$  have been made only on scales of about 1 cm to 1 m.

‡‡ See the discussion in Sec. 10, “Electroweak model and constraints on new physics.”

†† The corresponding  $\sin^2 \theta$  for the effective angle is 0.23155(4).