

The General Physical Constants.

(Reprinted by permission from the paper by R. T. Birge in *Reports on Progress in Physics*, 1941, 8, 90.)

TABLE a.

Principal Constants and Ratios.*

Velocity of light	$c = (2.99776 \pm 0.00004) \times 10^{10}$ cm. sec. ⁻¹ .
Gravitation constant	$G = (6.670 \pm 0.005) \times 10^{-8}$ dyne cm. ² g. ⁻² .
Litre (= 1000 ml.)	$l = 1000.028 \pm 0.002$ cm. ³ .
Volume of ideal gas (0° C., A_0)	$V_0 = (22.4146 \pm 0.0006) \times 10^3$ cm. ³ atmos. mol. ⁻¹ .
	$V'_0 = 22.4140 \pm 0.0006$ litre atmos. mol. ⁻¹ .
Volume of ideal gas (0° C., A_{45})	$V_{45} = (22.4157 \pm 0.0006) \times 10^3$ cm. ³ atmos. mol. ⁻¹ .
	$V'_{45} = 22.4151 \pm 0.0006$ litre atmos. mol. ⁻¹ .
International ohm (= p abs. ohm)	$p = 1.00048 \pm 0.00002$.
International ampere (= q abs. amp.)	$q = 0.99986 \pm 0.00002$.
Atomic weights (see table a')	
Standard atmosphere	$A_0 = (1.013246 \pm 0.000004) \times 10^6$ dyne cm. ⁻² atmos. ⁻¹ .
45° atmosphere	$A_{45} = (1.013195 \pm 0.000004) \times 10^6$ dyne cm. ⁻² atmos. ⁻¹ .
Ice-point (absolute scale)	$T_0 = 273.16 \pm 0.01^\circ$ K.
Joule equivalent	$J_{15} = 4.1855 \pm 0.0004$ abs.-joule cal. ₁₅ ⁻¹ .
Joule equivalent (electrical)	$J'_{15} = 4.1847 \pm 0.0003$ int.-joule cal. ₁₅ ⁻¹ .
Faraday constant	
(1) Chemical scale :	
	$F = 96501.2 \pm 10$ int.-coul. g.-equiv. ⁻¹ .
	$= 96487.7 \pm 10$ abs.-coul. g.-equiv. ⁻¹ .
	$= 9648.77 \pm 1.0$ abs.-e.m.u. g.-equiv. ⁻¹ .
	$F' = Fc = (2.89247 \pm 0.00030) \times 10^{14}$ abs.-e.s.u. g.-equiv. ⁻¹ .
(2) Physical scale :	
	$F = 96514.0 \pm 10$ abs.-coul. g.-equiv. ⁻¹ .
	$= 9651.4_0 \pm 1.0$ abs.-e.m.u. g.-equiv. ⁻¹ .
	$F' = Fc = (2.89326 \pm 0.00030) \times 10^{14}$ abs.-e.s.u. g.-equiv. ⁻¹ .
Avogadro number (chemical scale)	$N_0 = (6.0223_8 \pm 0.0011) \times 10^{23}$ mol. ⁻¹ .
Electronic charge	$e = F/N_0 = (1.60203_3 \pm 0.00034) \times 10^{-20}$ abs. e.m.u.
	$e' = ec = (4.8025_1 \pm 0.0010) \times 10^{-10}$ abs. e.s.u.
Specific electronic charge	$e/m = (1.7592 \pm 0.0005) \times 10^7$ abs.-e.m.u. g. ⁻¹ .
Planck constant	$e'/m = ec/m = (5.2736_6 \pm 0.0015) \times 10^{17}$ abs.-e.s.u. g. ⁻¹ .
	h (see table c).

TABLE a'.

Atomic Weights.

(1) Physical scale (¹⁶O = 16.0000).

¹ H = 1.00813 ± 0.00001 ₇ .	² H = 2.01473 ± 0.00001 ₉ .
H = 1.00827 ₆ ± 0.00001 ₇ (from ¹ H/ ² H abundance = 6900 ± 100).	
⁴ He = 4.00389 ± 0.00007.	
¹² C = 12.00386 ± 0.00004.	¹³ C = 13.00761 ± 0.00015.
C = 12.01465 ± 0.00023 (from ¹² C/ ¹³ C abundance = 92 ± 2).	
¹⁴ N = 14.00753 ± 0.00005.	¹⁵ N = 15.0049 ± 0.0002.
N = 14.01121 ± 0.00009 ₅ (from ¹⁴ N/ ¹⁵ N abundance = 270 ± 6).	
¹⁶ O = 16.0000.	¹⁷ O = 17.0045.
O = 16.00435 ₇ ± 0.00008 ₆ .	¹⁸ O = 18.0049.

(from abundance ¹⁶O : ¹⁸O : ¹⁷O = (506 ± 10) : 1 : (0.204 ± 0.008).

(2) Chemical scale (O = 16.0000).

Ratio physical to chemical scale :

$r = (16.004357 \pm 0.000086)/16 = 1.000272 \pm 0.000005$.
¹ H = 1.00785 ₆ ± 0.00001 ₈ (from physical scale).
² H = 2.01418 ₃ ± 0.00002 ₁ (from physical scale).
H = 1.00800 ₃ ± 0.00001 ₈ (from physical scale).
⁴ He = 4.00280 ± 0.00007 (from physical scale).
C = 12.01139 ± 0.00024 (from physical scale).
N = 14.00740 ± 0.00012 (from physical scale).
N = 14.0086 ± 0.0007 (direct observation).
Na = 22.994 ± 0.003.
Cl = 35.457 ± 0.001.
Ca = 40.080 ± 0.005.
Ag = 107.880 ± 0.002.
I = 126.915 ± 0.004.

* Unless otherwise specified, all quantities in these tables that involve the mol. or the gram equivalent are on the chemical scale of atomic weights.

TABLE b.

Additional Quantities Evaluated or Used in Connection with Table a.

Ratio of e.s.u. to e.m.u. (direct).	
$c' = (2.9971_2 \pm 0.0001) \times 10^{10} \text{ cm.}^{1/2} \text{ sec.}^{-1/2} \text{ int.-ohm}^{1/2}.$	
$= (2.9978_4 \pm 0.0001_0) \times 10^{10} \text{ cm. sec.}^{-1}.$	
Ratio of e.s.u. to e.m.u. (indirect).	
$c' = c = (2.99776 \pm 0.00004) \times 10^{10} \text{ cm. sec.}^{-1}.$	
Average density of earth	$\delta = 5.517 \pm 0.004 \text{ g. cm.}^{-3}.$
Maximum density of water	$\delta_m(\text{H}_2\text{O}) = 0.999972 \pm 0.000002 \text{ g. cm.}^{-3}$
Acceleration of gravity (standard)	$g_0 = 980.665 \text{ cm. sec.}^{-2}.$
Acceleration of gravity (45°)	$g_{45} = 980.616 \text{ cm. sec.}^{-2}.$
Density of oxygen gas ($0^\circ \text{ C.}, A_{45}$)	$L_1 = 1.42897 \pm 0.00003 \text{ g. litre}^{-1}.$
Limiting density of oxygen gas ($0^\circ \text{ C.}, A_{45}$)	$L_{\text{lim}} = 1.427609 \pm 0.000037 \text{ g. litre}^{-1}.$
Factor converting oxygen ($0^\circ \text{ C.}, A_{45}$) to ideal gas	$1-a = 1.000953_5 \pm 0.000009_4.$
International coulomb (= q abs. coul.)	$q = 0.99986 \pm 0.00002.$
International gauss (= q abs. gauss).	
International henry (= p abs. henry)	$p = 1.00048 \pm 0.00002.$
International volt (= pq abs. volt)	$pq = 1.00034 \pm 0.00003.$
International joule (= pq^2 abs. joule)	$pq^2 = 1.00020 \pm 0.00004_5.$
Specific gravity of Hg ($0^\circ \text{ C.}, A_0$) referred to air-free water at maximum density	$\rho_0 = 13.59542 \pm 0.00005.$
Density of Hg ($0^\circ \text{ C.}, A_0$)	$D_0 = 13.59504_0 \pm 0.00005, \text{ g. cm.}^{-3}.$
Electrochemical equivalents (chemical scale) :	
Silver (apparent)	$E_{\text{Ag}}^* = 1.11800 \times 10^{-3} \text{ g. int.-coul.}^{-1}.$
(corrected)	$E_{\text{Ag}} = (1.11807 \pm 0.00012) \times 10^{-3} \text{ g. abs.-coul.}^{-1}.$
Iodine (apparent)	$E_{\text{I}}^* = (1.315026 \pm 0.000025) \times 10^{-3} \text{ g. int.-coul.}^{-1}.$
(corrected)	$E_{\text{I}} = (1.31535 \pm 0.00014) \times 10^{-3} \text{ g. abs.-coul.}^{-1}.$
Effective calcite grating space (18° C.), Siegbahn system	$d'_{18} = 3.02904 \times 10^{-8} \text{ cm.}$
True calcite grating space (20° C.), Siegbahn system	$d'_{20} = 3.02951_2 \times 10^{-8} \text{ cm.}$
True calcite grating space (20° C.), c.g.s. system	$d_{20} = (3.03567_4 \pm 0.00018) \times 10^{-8} \text{ cm.}$
Ratio of grating and Siegbahn scales of wavelengths	$\lambda_g/\lambda_s = 1.002034 \pm 0.000060.$
Density of calcite (20° C.)	$\rho = 2.71029 \pm 0.00003 \text{ g. cm.}^{-3}.$
Structural constant of calcite (20° C.)	$\phi = 1.09594 \pm 0.00001.$
Molecular weight of calcite (chemical scale)	$M = 100.091_4 \pm 0.005.$
Rydberg constant for hydrogen (^1H)	$R_{\text{H}} = 109677.581_2 \pm 0.007_5 \text{ cm.}^{-1} \text{ (I.A. scale).}$
Rydberg constant for deuterium (^2H)	$R_{\text{D}} = 109707.419_3 \pm 0.007_5 \text{ cm.}^{-1} \text{ (I.A. scale).}$
Rydberg constant for helium	$R_{\text{He}} = 109722.263 \pm 0.012 \text{ cm.}^{-1} \text{ (I.A. scale).}$
Rydberg constant for infinite mass	$R_\infty = 109737.303 \pm 0.017 \text{ cm.}^{-1} \text{ (I.A. scale),}$ $\text{or } \pm 0.05 \text{ cm.}^{-1} \text{ (c.g.s. system).}$

TABLE c.

Partial List of Derived Quantities.†

Planck constant :	
$h = \left\{ \frac{2\pi^2 c^3 F^5}{R_\infty N_0^3 (e/m)} \right\}^{1/3} = (6.624_2 \pm 0.002_4) \times 10^{-27} \text{ erg. sec.}$	
$h/e = \left\{ \frac{2\pi^2 c^3 F^2}{R_\infty N_0^2 (e/m)} \right\}^{1/3} = (4.1349_0 \pm 0.0007_1) \times 10^{-7} \text{ erg. sec. abs.-e.m.u.}^{-1}.$	
$h/e' = h/ec = \left\{ \frac{2\pi^2 F^2}{R_\infty N_0^2 (e/m)} \right\}^{1/3} = (1.3793_3 \pm 0.0002_3) \times 10^{-17} \text{ erg. sec. abs.-e.s.u.}^{-1}$	
Atomic weight of electron :	$E = F/(e/m).$
(physical scale)	$= (5.4862_4 \pm 0.0017) \times 10^{-4}.$
(chemical scale)	$= (5.4847_5 \pm 0.0017) \times 10^{-4}.$
Band spectra constant connecting wave number and moment of inertia :	
$h/8\pi^2 c = \left\{ \frac{F^5}{256\pi^4 R_\infty N_0^3 (e/m)} \right\}^{1/3} = (27.98_{65} \pm 0.01_0) \times 10^{-40} \text{ g. cm.}$	
Boltzmann constant :	
$k = R_0/N_0 = V_0 A_0/T_0 N_0 = (1.38047_4 \pm 0.00026) \times 10^{-16} \text{ erg. deg.}^{-1}.$	
Charge in electrolysis of one gram of H :	
$F/H = 9572.1_{73} \pm 1.0 \text{ abs.-e.m.u. g.}^{-1}.$	
Charge in electrolysis of one gram of ^1H :	
$e/M_{\text{H}} = F/{}^1\text{H} = 9573.5_{60} \pm 1.0 \text{ abs.-e.m.u. g.}^{-1}.$	

† In order to be able to calculate, by propagation of errors, the probable error in a derived quantity, it is necessary to express the quantity explicitly in terms of the various fundamental quantities of Table a or of Table b, and that has been done in each case. Since in this paper e and h are treated as derived quantities, they do not therefore appear in such explicit expressions. But in calculating the numerical value of a derived quantity, the work can often be greatly simplified by using the values of other previously calculated derived quantities—in particular e and h . In order to show how certain derived quantities depend on quantities like e and h , such alternative expressions are given in many cases.

Compton shift at 90°:

$$h/mc = \left\{ \frac{2\pi^2 F^2 (e/m)^2}{R_\infty N_0^2} \right\}^{1/3} = (0.024265_{14} \pm 0.000005_7) \times 10^{-8} \text{ cm.}$$

Energy in ergs of one abs.-volt-electron:

$$E_0 = 10^8 e = 10^8 F/N_0 = (1.60203_3 \pm 0.00034) \times 10^{-12} \text{ erg}$$

Energy in calories per mol. for one abs.-volt-electron per molecule:

$$\frac{F \text{ (abs. coul. per gram-equiv.)}}{J_{15} \text{ (abs. joules per cal.)}} = 23052.8_5 \pm 3.2 \text{ cal.}_{15} \text{ mol.}^{-1}.$$

Fine structure constant:

$$\alpha = 2\pi(e')^2/hc = \left\{ \frac{4\pi R_\infty F(e/m)}{N_0} \right\}^{1/3} = (7.2976_6 \pm 0.0008_6) \times 10^{-3}.$$

$$1/\alpha = 137.030_2 \pm 0.016.$$

$$\alpha^2 = (5.3256 \pm 0.0013) \times 10^{-5}.$$

Gas constant per mol.:

$$R_0 = V_0 A_0 / T_0 = (8.31436 \pm 0.00038) \times 10^7 \text{ erg. deg.}^{-1} \text{ mol.}^{-1}.$$

$$R_0' = R_0 \cdot 10^{-7} / J_{15} = 1.98646_7 \pm 0.00021 \text{ cal.}_{15} \text{ deg.}^{-1} \text{ mol.}^{-1}.$$

$$R_0'' = V_0' / T_0 = (8.20544_7 \pm 0.00037) \times 10^{-2} \text{ litre atmos. deg.}^{-1} \text{ mol.}^{-1}.$$

$$R_0''' = R_0 / A_0 = V_0 / T_0 = 82.0566_7 \pm 0.0037 \text{ cm.}^3 \text{ atmos. deg.}^{-1} \text{ mol.}^{-1};$$

also

$$R_0 T_0 = V_0 A_0 = (2.27115_0 \pm 0.00006) \times 10^{19} \text{ erg. mol.}^{-1}.$$

Loschmidt number (0° C., A_0):

$$n_0 = N_0 / V_0 = (2.6870_{12} \pm 0.0005_0) \times 10^{19} \text{ atmos.}^{-1} \text{ cm.}^{-3}.$$

Magnetic moment of one Bohr magneton:

$$\mu_1 = (h/4\pi)(e/m) = \frac{1}{4\pi} \left\{ \frac{2\pi^2 c^3 F^5 (e/m)^2}{R_\infty N_0^5} \right\}^{1/3}.$$

$$= (0.9273_{45} \pm 0.0003_7) \times 10^{-20} \text{ erg. gauss}^{-1}.$$

Magnetic moment per mol. for one Bohr magneton per molecule:

$$\mu_1 N_0 = \frac{1}{4\pi} \left\{ \frac{2\pi^2 c^3 F^5 (e/m)^2}{R_\infty N_0^2} \right\}^{1/3} = 5585.2_4 \pm 1.6 \text{ erg. gauss.}^{-1} \text{ mol.}^{-1}.$$

Mass of α -particle:

$$M_\alpha = (\text{He} - 2E)/N_0 = (6.6442_2 \pm 0.0012) \times 10^{-24} \text{ g.}$$

Mass of atom of unit atomic weight:

$$M_0 = 1/N_0 = (1.66035 \pm 0.00031) \times 10^{-24} \text{ g.}$$

Mass of electron:

$$m = e/(e/m) = (F/N_0)/(e/m) = (9.1066_0 \pm 0.0032) \times 10^{-28} \text{ g.}$$

Mass of ^1H atom:

$$M_{1\text{H}} = {}^1\text{H}/N_0 = (1.67339_3 \pm 0.00031) \times 10^{-24} \text{ g.}$$

Mass of proton:

$$M_P = ({}^1\text{H} - E)/N_0 = (1.67248_2 \pm 0.00031) \times 10^{-24} \text{ g.}$$

Radiation density constant:

$$\alpha = 8\pi^5 k^4 / 15c^3 h^3 = \left(\frac{V_0 A_0}{T_0} \right) \frac{4\pi N_0^3 R_\infty (e/m)}{15c^6 F^5} = (7.569_{42} \pm 0.004_9) \times 10^{-15} \text{ erg. cm.}^{-3} \text{ deg.}^{-4}.$$

Ratio mass ^1H atom to mass electron:

$$M_{1\text{H}}/m = (e/m)({}^1\text{H}/F) = 1837.5_{61} \pm 0.5_6.$$

Ratio mass proton to mass electron:

$$M_P/m = (e/m) \left(\frac{{}^1\text{H} - E}{F} \right) = 1836.5_{61} \pm 0.5_6.$$

Second radiation constant:

$$c_2 = hc/k = \frac{T_0 c^2}{V_0 A_0} \left\{ \frac{2\pi^2 F^5}{R_\infty N_0^2 (e/m)} \right\}^{1/3} = 1.4384_8 \pm 0.0003_4 \text{ cm. deg.}$$

Specific charge of α -particle:

$$2e/M_\alpha = \frac{2F}{\text{He} - 2E} = 4822.3_3 \pm 0.5_1 \text{ abs.-e.m.u. g.}^{-1}.$$

Specific charge of proton:

$$e/M_P = \frac{F}{{}^1\text{H} - E} = 9578.7_7 \pm 1.0 \text{ abs.-e.m.u. g.}^{-1}.$$

Stefan-Boltzmann constant:

$$\sigma = ac/4 = 2\pi^5 k^4 / 15c^2 h^3 = \left(\frac{V_0 A_0}{T_0} \right) \frac{4\pi^3 N_0 R_\infty (e/m)}{15(Fc)^5}$$

$$= (5.672_{83} \pm 0.003_7) \times 10^{-5} \text{ erg. cm.}^{-2} \text{ deg.}^{-4} \text{ sec.}^{-1}.$$

Wave-length associated with one abs. volt :

$$\lambda_0 = 10^{-8} c^2 (h/e^2) = \frac{c^2}{10^8} \left\{ \frac{2\pi^2 F^2}{R_\infty N_0^2 (e/m)} \right\}^{1/3} = (12395.4 \pm 2.1) \times 10^{-8} \text{ cm. abs.-volt.}$$

Wave number associated with one abs. volt :

$$s_0 = 1/\lambda_0 = \frac{10^8}{c^2} \left\{ \frac{R_\infty N_0^2 (e/m)}{2\pi^2 F^2} \right\}^{1/3} = 8067.4_8 \pm 1.4 \text{ cm.}^{-1} \text{ abs.-volt}^{-1}.$$

Wien's displacement-law constant : *

$$A = c_2/4.965114 = 0.28971_8 \pm 0.00007 \text{ cm. deg.}$$

Zeeman displacement per gauss :

$$(e/m)/4\pi c = (4.6699_1 \pm 0.0013) \times 10^{-5} \text{ cm.}^{-1} \text{ gauss.}^{-1}.$$

* The factor 4.965114 is the root of $e^{-\beta} + (\beta/5) - 1 = 0$.
