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The Atmospheric Chemist's Companion

Numerical Data for Use in the Atmospheric Sciences

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Preface

A survey conducted several years ago within the local atmospheric science community had indicated the need for a comprehensive reference book of atmospheric chemistry and physics. The present compilation of data has been prepared in an attempt to fill this need.

While the subject, as a whole or in parts, has received an adequate treatment in textbooks, encyclopedias, and in other overviews, these publications do not generally present numerical data but discuss important observations by way of illustrations. Even the current scientific literature tends to display observations and results graphically and often relegates numerical data, on which the results are based, to unpublished supplements made available only upon request. Because of this practice the data are prone to sink into oblivion sooner or later. Yet, numerical data are required whenever a quantitative assessment is to be made of the processes at work in the atmosphere.

The aim of the present data collection is to assemble, in one handy volume, frequently needed fundamental data as well as observational data on the structure and the chemical composition of Earth and its atmosphere. Thereby, we hope to assist atmospheric scientists in their daily work and to provide detailed information as a reference to other persons interested in the subject. The data are mostly arranged in the form of annotated tables; any explanatory text is kept to a minimum. The sources of the material presented are indicated at the bottom of each table (or figure) with literature citations being given at the end of each section. Because of the range of the subject we have added a Glossary to provide explanations and definitions of technical terms.

In a compilation of this type the occurrence of unwanted errors will be inevitable. We shall be grateful to all users that notify us of such errors so that corrections can be made in a future edition. We also recognize that some of the data might have to be replaced by more recent or more accurate material not yet known to us, and that additional data, currently not included, would be of interest. We encourage all users to alert us of the existence of such material so that we may consider it for inclusion in a future edition. Any suggestions should be directed to the e-mail address atmoschemcompanion@lists.mpic.de.

We are pleased to acknowledge the unswerving support by our editors at Springer: Gert-Jan Geraeds, who initiated this project, and Robert Doe, whose help was essential in bringing the project to completion. We are particularly grateful to Andreas Zimmer at the Max-Planck-Institute's library for supplying us with much of the material from which data were selected.

We thank the AGU, Elsevier Ltd and IUPAC for permissions to reproduce material from other sources. We are also grateful for the help and advice from our colleagues, in particular Janeen Auld, Steven S. Brown, Stephanie Brückner, Tim Butler, John Crowley, Frank Drewnick, Günter Helas, Peter Hoor, Marloes Penning de Vries, Rolf Sander, Lothar Schütz, Claudia Stubenrauch, Thomas Wagner.

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Contents

IUPAC Periodic Table of the Elements

Key: atomic number / **Symbol** / name / standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen [1.007; 1.009]																	2 **He** helium 4.003
3 **Li** lithium [6.938; 6.997]	4 **Be** beryllium 9.012											5 **B** boron [10.80; 10.83]	6 **C** carbon [12.00; 12.02]	7 **N** nitrogen [14.00; 14.01]	8 **O** oxygen [15.99; 16.00]	9 **F** fluorine 19.00	10 **Ne** neon 20.18
11 **Na** sodium 22.99	12 **Mg** magnesium 24.31											13 **Al** aluminium 26.98	14 **Si** silicon [28.08; 28.09]	15 **P** phosphorus 30.97	16 **S** sulfur [32.05; 32.08]	17 **Cl** chlorine [35.44; 35.46]	18 **Ar** argon 39.95
19 **K** potassium 39.10	20 **Ca** calcium 40.08	21 **Sc** scandium 44.96	22 **Ti** titanium 47.87	23 **V** vanadium 50.94	24 **Cr** chromium 52.00	25 **Mn** manganese 54.94	26 **Fe** iron 55.85	27 **Co** cobalt 58.93	28 **Ni** nickel 58.69	29 **Cu** copper 63.55	30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.72	32 **Ge** germanium 72.63	33 **As** arsenic 74.92	34 **Se** selenium 78.96(3)	35 **Br** bromine 79.90	36 **Kr** krypton 83.80
37 **Rb** rubidium 85.47	38 **Sr** strontium 87.62	39 **Y** yttrium 88.91	40 **Zr** zirconium 91.22	41 **Nb** niobium 92.91	42 **Mo** molybdenum 95.96(2)	43 **Tc** technetium	44 **Ru** ruthenium 101.1	45 **Rh** rhodium 102.9	46 **Pd** palladium 106.4	47 **Ag** silver 107.9	48 **Cd** cadmium 112.4	49 **In** indium 114.8	50 **Sn** tin 118.7	51 **Sb** antimony 121.8	52 **Te** tellurium 127.6	53 **I** iodine 126.9	54 **Xe** xenon 131.3
55 **Cs** caesium 132.9	56 **Ba** barium 137.3	57-71 lanthanoids	72 **Hf** hafnium 178.5	73 **Ta** tantalum 180.9	74 **W** tungsten 183.8	75 **Re** rhenium 186.2	76 **Os** osmium 190.2	77 **Ir** iridium 192.2	78 **Pt** platinum 195.1	79 **Au** gold 197.0	80 **Hg** mercury 200.6	81 **Tl** thallium [204.3; 204.4]	82 **Pb** lead 207.2	83 **Bi** bismuth 209.0	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium	89-103 actinoids	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium						
		57 **La** lanthanum 138.9	58 **Ce** cerium 140.1	59 **Pr** praseodymium 140.9	60 **Nd** neodymium 144.2	61 **Pm** promethium	62 **Sm** samarium 150.4	63 **Eu** europium 152.0	64 **Gd** gadolinium 157.3	65 **Tb** terbium 158.9	66 **Dy** dysprosium 162.5	67 **Ho** holmium 164.9	68 **Er** erbium 167.3	69 **Tm** thulium 168.9	70 **Yb** ytterbium 173.1	71 **Lu** lutetium 175.0	
		89 **Ac** actinium	90 **Th** thorium 232.0	91 **Pa** protactinium 231.0	92 **U** uranium 238.0	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium	

Notes

- IUPAC 2009 Standard atomic weights abridged to four significant digits (Table 4 published in *Pure Appl. Chem.* 83, 359-396 (2011); doi:10.1351/PAC-REP-10-09-14). The uncertainty in the last digit of the standard atomic weight value is listed in parentheses following the value. In the absence of parentheses, the uncertainty is one in that last digit. An interval in square brackets provides the lower and upper bounds of the standard atomic weight for that element. No values are listed for elements with no stable isotopes. See PAC for more details.
- "Aluminum" and "cesium" are commonly used alternative spellings for "aluminium" and "caesium."

For updates to this table, see iupac.org/reports/periodic_table/. This version is dated 21 January 2011.

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Chapter 1
Fundamental Quantities and Units

1.1 Fundamental Constants

Table 1.1 Fundamental and frequently used constants

Quantity	Symbol	Value[a]
Universal constants		
Gravitational constant	G	$6.6742(10) \times 10^{-11}$ m^3 kg^{-1} s^{-2}
Speed of light in vacuum	c_0	299 792 458 m s^{-1} (defined)
Permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ N A^{-2} (defined)
Permittivity of vacuum	$\varepsilon_0 = 1/(\mu_0\, c_0^2)$	$8.854\ 187\ 816\ldots \times 10^{-12}$ F m^{-1}
Planck constant	h	$6.626\ 069\ 3(11) \times 10^{-34}$ J s
Atomic constants		
Elementary charge	e	$1.602\ 176\ 53(14) \times 10^{-19}$ C
Electron rest mass	m_e	$9.109\ 3826(16) \times 10^{-31}$ kg
Electron specific charge	$-e/m_e$	$1.758\ 820\ 12(15) \times 10^{11}$ C kg^{-1}
Proton rest mass	m_p	$1.672\ 621\ 71(29) \times 10^{-27}$ kg
Neutron rest mass	m_n	$1.674\ 927\ 28(29) \times 10^{-27}$ kg
Unified atomic mass unit	$(m^{12}\mathrm{C}/12) = 1$ u	$1.660\ 538\ 86(28) \times 10^{-27}$ kg
Bohr radius	$a_0 = \varepsilon_0 h^2/\pi m_e e^2$	$5.291\ 772\ 108(18) \times 10^{-11}$ m
Hartree energy	$E_h = h^2/4\pi^2 m_e a_0^{\ 2}$	$4.359\ 744\ 17(75) \times 10^{-18}$ J
Rydberg constant	$R_\infty = E_h/2hc_0$	10 973 731.568 525(73) m^{-1}
Fine structure constant	$\alpha = \mu_0 e^2 c_0/2hc_0$	$7.297\ 352\ 568(24) \times 10^{-3}$
	α^{-1}	137.035 999 11(46)
Bohr magneton	$\mu_B = eh/4\pi m_e$	$9.274\ 000\ 949(80) \times 10^{-24}$ J T^{-1}
Electron magnetic moment	μ_e	$9.284\ 764\ 12(80) \times 10^{-24}$ J T^{-1}
Nuclear magneton	$\mu_N = (m_e/m_p)\ \mu_B$	$5.050\ 783\ 43(43) \times 10^{-27}$ J T^{-1}
Proton magnetic moment	μ_p	$1.410\ 606\ 71(12) \times 10^{-26}$ J T^{-1}
Physicochemical constants		
Avogadro constant	N_A	$6.022\ 14179(30) \times 10^{23}$ mol^{-1}
Molar gas constant	R	8.314 472(15) J mol^{-1} K^{-1}
Boltzmann constant	$k = R/N_A$	$1.380\ 6504(24) \times 10^{-23}$ J K^{-1}
Zero of Celsius scale		273.15 K (defined)

(continued)

P. Warneck and J. Williams, *The Atmospheric Chemist's Companion: Numerical Data for Use in the Atmospheric Sciences*, DOI 10.1007/978-94-007-2275-0_1,

Table 1.1 (continued)

Quantity	Symbol	Value[a]
Molar volume (ideal gas)	V_m	$2.241\,3996(39) \times 10^{-2}$ m^3 mol^{-1}
Loschmidt constant	$n_0 = N_A/V_m$	$2.686\,7774(47) \times 10^{25}$ m^{-3}
Standard atmosphere	atm	101 325 Pa (defined)
Faraday constant	F	$9.648\,533\,83(83) \times 10^4$ C mol^{-1}
Radiation constants		
Stefan-Boltzmann constant	$\sigma = 2\pi^5 k^4/15h^3 c_0^2$	$5.670\,400(40) \times 10^{-8}$ W m^{-2} K^{-4}
Radiation density constant	$a = 4\sigma/c_0$	$7.565\,767(53) \times 10^{-16}$ J m^{-3} K^{-4}
First radiation constant	$c_1 = 2\pi h c_0^2$	$3.741\,771\,38(64) \times 10^{-16}$ W m^2
Second radiation constant	$c_2 = hc_0/k$	$1.438\,7752(25) \times 10^{-2}$ m K
Wien displacement law constant	$b = \lambda_{max} T$	$2.897\,7685(51) \times 10^{-3}$ m K
Astronomical constants		
Standard acceleration of free fall	g_a	9.806 65 m s^{-1} (defined)
Sidereal second	s	0.9972696 s
Mean sidereal year	yr	365.256 36 d = 315 581 49.5 s
Tropical year (equinox to equinox)	yr	365.242 189 7 d
Anomalistic year (perihelion to perihelion)	yr	365.259 64 d
Gregorian calendar year	a, yr	365.242 5 d
Astronomical unit	AU	$1.495\,978\,061 \times 10^{11}$ m
Light travel time for 1 AU		499.004 783 5 s
Solar constant (at 1 AU)		1.3676 kW m^{-2}
Earth mass	M_e	5.9736×10^{24} kg
Mean Earth radius	R_e	6371.01 km
Solar mass	M_s	1.98910×10^{30} kg
Solar radius	R_s	695950 km
Solar effective surface temperature	T_{eff}	5778 K
Solar absolute luminosity	L	3.8268×10^{26} W
Mathematical constants		
Ratio circumference/diameter of a circle	π	3.141 592 653 59
Base of natural logarithm	e	2.718 281 828 46
Natural logarithm of 10	ln 10	2.302 585 092 99

For a continual updating of values compare with www.physics.nist.gov/constants

[a]The standard deviation uncertainty in the least significant digits is shown in parentheses

1.2 Units for Use in Atmospheric Chemistry

Introductory Comments:

The international system of units (système international d'unités, SI) has now largely replaced all earlier systems of units used to describe physical quantities. SI is built upon seven base quantities each having its own dimension: length, mass, time, thermodynamic temperature, amount of substance (chemical amount), electric current, and luminous intensity (Bureau International des Poids et Mesures 1991). All other quantities are derived quantities that acquire dimensions derived algebraically from the seven base quantities by multiplication and division. The possibility of combining SI units with prefixes designating decimal multiples or submultiples of units provides additional flexibility when dealing with quantities that range over many orders of magnitude, a feature which makes SI especially suitable for use in the atmospheric sciences. Accordingly, SI units are strongly recommended for use in atmospheric chemistry. However, some non-SI units are still required, and they will remain in use along with SI. Examples are time periods such as minute, hour, day and year, which can be expressed in terms of the second, but which defy decimalization. The tables that follow provide an overview on SI, on units that are not part of SI but are used along with it, and on a variety of non-SI units still in use together with the conversion factors to the corresponding SI units. For the correct treatment of symbols and units the reader should consult the manual *Quantities, Units and Symbols in Physical Chemistry* by Mills et al. (1993).

The suitability of SI for use in atmospheric chemistry has been examined by Schwartz and Warneck (1995). In the atmospheric sciences, some non-SI units have remained in favor mainly for historic reasons. In most cases, these units can be replaced by SI units without difficulty. Where non-SI units are preferred, the appropriate conversion rule to SI units should be indicated (example: 1 atm = 101325 Pa). There are a number of other aspects regarding units used in atmospheric chemistry that require attention. The most important aspects will be briefly summarized below.

Time: The length of minute, hour and day are defined exactly in terms of the second (see Table 1.4). For the length of the year, which is somewhat variable because of the occurrence of leap years, the mean Gregorian year (365.2425 d) is recommended, or the actual number of days (365 or 366) multiplied by 86 400 s d^{-1} for any specific year. Because of variability in the length of the calendar month, its use as a unit of time should be avoided. Seasonal variations of atmospheric quantities should be reported on the basis of actual calendar days.

Concentration is the amount of a substance of concern in a given volume divided by that volume. It may be expressed in terms of amount of substance per volume (mol m^{-3}), number of molecules (atoms, particles, or other entities) per volume (m^{-3}), mass per volume (kg m^{-3}), or volume per volume (m^3 m^{-3}). Chemical amount concentration is appropriate for a substance of known chemical formula; number concentration is appropriate for aerosol particles, and it is frequently used also for gaseous substances (see further below); mass concentration is required for a substance whose composition or chemical formula is unknown or indeterminate, such as particulate matter suspended in air; volume concentration is appropriate for the volume of condensed phase matter per volume of air, for example, cloud water.

Units of concentration also are involved when dealing with rates of chemical reactions. The most appropriate SI unit in this application would be mol m^{-3}. This unit is, in fact, used for concentrations of solutes in the aqueous phase of clouds and rain water in the form mol dm^{-3}. Regarding gas phase reactions, however, atmospheric chemists have for some time favored number concentration as a unit for concentration, with a widespread use of the unit molecule cm^{-3} (atom cm^{-3}, etc.). This unit violates the rule that a qualifying name should not be part of a unit. On the other hand, it designates the entity involved but not the name of the molecule, atom, etc., which must be specified separately. Thus, it distinguishes between several possibilities and helps to remove potential ambiguities. For this reason, the use of molecule cm^{-3} (atom cm^{-3}, etc.) as a unit for number concentration is currently tolerated.

Mixing ratio in atmospheric chemistry is defined as the ratio of the amount (mass, volume) of the substance of concern in a given volume to the amount (mass, volume) of all constituents of air in that volume. Here, air denoted gaseous substances, including water vapor, but not condensed phase water or particulate matter. Mixing ratio is frequently employed to quantify the abundance of a trace gas in air. The specific advantage of mixing ratio over concentration in this context is that mixing ratio is unchanged by differences in pressure or temperature associated with altitude or with meteorological variability, whereas concentration depends on pressure and temperature in accordance with the equation of state. Since mixing ratio refers to the total gas mixture, the presence of water causes the mixing ratio to vary somewhat with humidity. For this reason it is preferable to refer to dry air when reporting mixing ratios of trace gases in the atmosphere whenever possible.

The above definition of mixing ratio is identical to the fraction that the amount (mass, volume) contributes to the total amount (mass, volume) of the whole mixture. For gaseous species chemical amount fraction and volume fraction are practically identical because air at atmospheric pressure is essentially an ideal gas. Chemical amount fraction is preferable, however, because it is applicable also to condensed phase species present in the same volume. Thus, one can express abundances of gaseous SO_2, NH_3, and HNO_3 as well as aerosol sulfate, ammonium, and nitrate all as chemical amount fraction and thereby immediately infer chemically meaningful relationships among these quantities.

Chemical amount fraction, like any other fraction, is a quantity of dimension one and does not require the application of units. A notation widely used in atmospheric chemistry to quantify mixing ratios includes ppm (parts per million $= 10^{-6}$), ppb (parts per billion $= 10^{-9}$), and ppt (parts per trillion $= 10^{-12}$). Because of inherent ambiguities (for example, whether one is dealing with the mass fraction or the chemical amount fraction), there is an increasing tendency to apply appropriate SI units to specify gas phase mixing ratios. Thus, it is strongly recommended that the above notations be replaced by, respectively, μmol mol^{-1}, nmol mol^{-1}, and pmol mol^{-1}. If the mixing ratio is expressed as a mass fraction, the corresponding units would be mg kg^{-1}, μg kg^{-1}, and ng kg^{-1}, respectively.

Light intensity: The SI base unit candela is not used in atmospheric chemistry. The intensity of solar radiation is expressed in terms of other base units of SI, depending on the application. With regard to the energy flux, the appropriate unit for irradiance is W m^{-2}. In photochemical considerations, it is generally desirable to express the radiation flux as a flux of photons, because in the act of optical absorption a single photon is taken up by the absorbing molecule. The process resembles that of a chemical reaction between molecules and photons. In the photochemically important ultraviolet region of the solar spectrum, the spectral irradiance of the sun is presented in terms of photon m^{-2} s^{-1} for specific wavelength intervals. Although this usage violates the convention that qualifying names should not be included in the unit, the practice is tolerated for the same reasons as in the case of units for concentration.

References

Bureau International des Poids et Mesures, *Le Système International d'Unités (SI)*, 6th French and English edition (BIPM, Sèvres, 1991)

Mills, I., T. Cvitaš, K. Homann, N. Kallay, K. Kuchitsu, *Quantities, Units and Symbols in Physical Chemistry*, 2nd edn. (International Union of Pure and Applied Chemistry, Blackwell Scientific Publications, Oxford, 1993)

Schwartz, S.E., P. Warneck, Pure and Appl. Chem. **67**, 1377–1406 (1995)

Table 1.2 SI base units

Quantity	Frequently used formula symbol	Name of SI unit	Symbol for SI unit
Length	l	metre	m
Mass	m	kilogram	kg
Time	t	second	s
Amount of substance	n	mole	mol
Thermodynamic temperature	T	kelvin	K
Electric current	I	ampere	A
Luminous intensity	I_v	candela	cd

Definitions of SI Base Units (Bureau International des Poids et Mesures 1991):

metre: The metre is the length of path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.

kilogram: The kilogram (unit of mass) is equal to the mass of the international prototype of the kilogram.

second: The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

mole: The mole is the amount of substance of a system, which contains as many elementary entities as there are atoms in 0.012 kg of carbon-12. When the mole is used, the elementary entities must be specified (atoms, molecules, ions, particles, etc.).

ampere: The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross section, and placed 1 m apart in vacuum, would produce between them force equal to 2×10^{-7} N/m of length.

candela: The candela is the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and has a radiant intensity in that direction of 1/683 W/per steradian.

Table 1.3 SI prefixes[a] to indicate decimal multiples and sub-multiples of SI units

Prefix	Submultiple	Symbol	Prefix	Multiple	Symbol
deci	10^{-1}	d	deca	10	da
centi	10^{-2}	c	hecto	10^{2}	h
milli	10^{-3}	m	kilo	10^{3}	k
micro	10^{-6}	μ	mega	10^{6}	M
nano	10^{-9}	n	giga	10^{9}	G
pico	10^{-12}	p	tera	10^{12}	T
femto	10^{-15}	f	peta	10^{15}	P
atto	10^{-18}	a	exa	10^{18}	E
zepto	10^{-21}	z	zetta	10^{21}	Z
yocto	10^{-24}	y	yotta	10^{24}	Y

[a]Prefix symbols should be printed in roman (upright) type without space between prefix and unit symbol (example: kilometre, km). The combination of prefix and SI symbol is taken to represent a new symbol that can be raised to any power without the use of parentheses (example: $cm^3 = 10^{-6}\ m^3$)

Table 1.4 Time periods used in atmospheric chemistry

Name of unit	Symbol	Relation to SI
second	s	SI unit
minute	min	60 s
hour	h	3600 s
day	d	86400 s
year (mean Gregorian)[a]	a	31 556 952 s (exactly)

[a]Mean Gregorian year = 365.2425 d. The symbol a (abbreviation for annum) is a recommendation taken from the ISO Standards Handbook 2 (1993) *Quantities and Units*, International Organization for Standardization, Central Secretariat, Geneva, Switzerland

Table 1.5 Definitions of SI derived units with special names and symbols

Physical quantity	Name of SI unit	Symbol for SI unit	Expression in terms of SI base units
Frequency[a]	hertz	Hz	s^{-1}
Force	newton	N	$m\ kg\ s^{-2}$
Pressure, stress	pascal	Pa	$N\ m^{-2} = m^{-1}\ kg\ s^{-2}$
Energy, work, heat	joule	J	$N\ m = m^2\ kg\ s^{-2}$
Power, radiant flux	watt	W	$J\ s^{-1} = m^2\ kg\ s^{-3}$
Electric charge	coulomb	C	A s
Electric potential	volt	V	$J\ C^{-1} = m^2\ kg\ s^{-3}\ A^{-1}$
Electric resistance	ohm	Ω	$V\ A^{-1} = m^2\ kg\ s^{-3}\ A^{-2}$
Electric conductance	siemens	S	$\Omega^{-1} = m^{-2}\ kg^{1}\ s^3\ A^2$
Electric capacitance	farad	F	$C\ V^{-1} = m^{-2}\ kg^{-1}\ s^4\ A^2$
Magnetic flux density	tesla	T	$V\ s\ m^{-2} = kg\ s^{-2}\ A^{-1}$
Magnetic flux	weber	Wb	$V\ s = m^2\ kg\ s^{-2}\ A^{-1}$
Inductance	henry	H	$V\ A^{-1}\ s = m^2\ kg\ s^{-2}\ A^{-2}$
Luminous Flux	lumen	lm	cd sr
Illuminance	lux	lx	$cd\ sr\ m^{-2}$
Radioactive decay rate[b]	becquerel	Bq	s^{-1}

(continued)

Table 1.5 (continued)

Physical quantity	Name of SI unit	Symbol for SI unit	Expression in terms of SI base units
Absorbed radiation dose[b]	gray	Gy	$J\ kg^{-1} = m^2\ s^{-2}$
Dose equivalent[b]	sievert	Sv	$J\ kg^{-1} = m^2\ s^{-2}$
Plane angle[c]	radian	rad	$1 = m\ m^{-1}$
Solid angle[c]	steradian	sr	$1 = m^2\ m^{-2}$

[a]The unit Hz should be used only for frequency in the sense of cycles per second
[b]The units becquerel, gray and sievert are admitted for reasons of safeguarding human health
[c]The units radian (defined as the angle subtended by an arc equal to the radius) and steradian (the solid angle which encloses a surface on the sphere equivalent to the square of the radius) are treated as SI supplementary units. Since they are of dimension 1 they may as well be omitted from the list of SI derived units. In practice, rad and sr may be used when appropriate and may be omitted if this does not lead to loss of clarity

Table 1.6 Conversion factors for selected units

length, l	metre (SI unit), m	
	Ångström: 1 Å = 10^{-10} m	foot: 1 ft = 12 in = 0.3048 m
	x unit: 1 X = 1.00206×10^{-13} m	yard: 1 yd = 3 ft = 0.9144 m
	fermi: 1 fm = 10^{-15} m	mile: 1 mi = 1760 yd = 1609.344 m
	inch: 1 in = 2.54×10^{-2} m	nautical mile: = 1852 m
plane angle, α	radian (SI unit), rad	
	degree: 1° = 17.4532925 mrad	minute: 1′ = 1°/60 = 0.290888209 mrad
	second: 1″ = 1°/3600 = 4.8481368 μrad	
area, A	square metre (SI unit), m^2	
	barn: 1 b = 10^{-28} m^2	are: 1 a = 100 m^2
	acre: 1 acre ≈ 4046.856 m^2	hectare: 1 ha = 10^4 m^2
	square mile: 1 mi^2 = 2.589988 km^2	
volume, V	cubic metre (SI unit), m^3	
	litre: 1 L = 1 dm^3	bushel (US, dry): 1 bu = 35.238 dm^3
	gallon (US): 1 gal = 3.78541 dm^3	bushel (UK, dry): 1 bu = 36.3687 dm^3
	gallon (UK): 1 gal = 4.54609 dm^3	barrel (US, oil): 1 bbl ≈ 158.987 dm^3
mass, m	kilogram (SI unit), kg	
	gram (cgs unit): 1 g = 10^{-3} kg	pound (avoirdupois): 1 lb = 453.59237 g
	tonne: 1 t = 10^3 kg = 1 Mg	ounce (avoirdupois): 1 oz ≈ 28.34952 g
	long ton: = 1016.047 kg	ounce (troy): 1 oz (troy) ≈ 31.1035 g
	short ton (US): = 907.185 kg	grain: 1 gr = 64.79891 mg
force, F	newton (SI unit), N	
	dyne (cgs unit): 1 dyn = 10^{-5} N	kilogram force: 1 kgf = 9.80665 N
pressure, p	pascal (SI unit), Pa	
	bar: 1 bar = 10^5 Pa, 1 mbar = 1 hPa	
	atmosphere: 1 atm = 101325 Pa	torr: 1 torr = 1/760 atm ≈ 133.3224 Pa
	millimetre of mercury: 1 mmHg = 13.5951 × 9.80665 Pa ≈ 133.3224 Pa	
	pounds per square inch: 1 psi = $6.894\ 757 \times 10^3$ Pa	

(continued)

Table 1.6 (continued)

energy, E, U	joule (SI unit), J	
	erg (cgs unit): = 10^{-7} J;	electronvolt: 1 eV = $1.602\,1765 \times 10^{-19}$ J;
	calorie, thermochemical: 1 $cal_{th} = 4.184$ J;	
	calorie, international: 1 $cal_{IT} = 4.1868$ J;	15 °C calorie: 1 $cal_{15} = 4.1855$ J;
	British thermal unit: 1 Btu = 1055.06 J.	
power, P	watt (SI unit), W	
	horse power: 1 hp = 745.7 W;	kilocalorie per hour: 1 kcal/h = 1.1628 W
dynamic viscosity, η	SI unit: Pa s = kg m^{-1} s^{-1}	
	poise: 1 P = 10^{-1} Pa s; centipoise: 1 cP = 1 mPa s	
kinematic viscosity, ν	SI unit: m^2 s^{-1}	
	stokes: 1 St = 10^{-4} m^2 s^{-1}	
temperature, T	kelvin (SI unit), K	
	Celsius: θ/°C = T/K – 273.15;	Fahrenheit: θ_F/°F = (9/5)(θ/°C) + 32
molar volume, Vm	SI unit: m^3 mol^{-1}	
	amagat[a]: 1 amagat = 2.24141×10^{-2} m^3 mol^{-1}(ideal gas);	
	1 amagat ≈ 2.24×10^{-2} m^3 mol^{-1}(real gas)	
Molar column density	SI unit: mol m^{-2}	
	Dobson unit: 1 DU ≈ 446.149 µmol m^{-2} (for atmospheric ozone)	
Radioactivity, A	becquerel (SI unit), Bq	
	curie: 1 Ci = 3.7×10^{10} Bq	
Absorbed radiation dose	gray (SI unit), Gy	
	roentgen[b]: 1 R = 2.58×10^{-4} C kg^{-1}; rad: 1 rd = 10^{-2} Gy	
magnetic flux density, B	tesla (SI unit), T	
	gauss: 1 G = 10^{-4} T	
magnetic flux, ϕ	weber (SI unit), Wb	
	maxwell: 1 Mx = 1 Gcm^{-2} = 10^{-8} Wb	
magnetic field, H	SI unit: A m^{-1}	
	oersted[c]: 1 Oe = $10^3/4\pi$ A m^{-1}	

[a]The amagat is defined as the mole volume of a real gas at 1 atm and 273.15 K
[b]The amount of radiation that will produce one electrostatic unit of ions per cm^3
[c]In practice, the oersted is only used as a unit for $4\pi H$

Table 1.7 Conversion factors for pressure units

Unit	Pa	bar	atm	torr	psi
1 Pa	1	10^{-5}	9.869233×10^{-6}	7.50062×10^{-3}	1.45038×10^{-4}
1 bar	10^5	1	0.986923	750.0615	14.50377
1 atm	101325	1.01325	1	760	14.69595
1 torr	133.3224	1.33322×10^{-3}	1.31579×10^{-3}	1	1.933678×10^{-2}
1 psi	6894.757	6.89476×10^{-2}	6.804596×10^{-2}	51.71491	1

Table 1.8 Conversion factors for concentrations and rate coefficients of chemical reactions

Quantity[a]	Unit	mol m^{-3}, s	mol dm^{-3}, s	molecule cm^{-3}, s
c	1 mol m^{-3}	1	10^{-3}	6.022014×10^{17}
	1 mol dm^{-3}	10^{3}	1	6.022014×10^{20}
	1 molecule cm^{-3}	1.66054×10^{-18}	1.66054×10^{-21}	1
k_{bim}	1 m^3 mol^{-1} s^{-1}	1	10^{3}	1.66054×10^{-18}
	1 dm^3 mol^{-1} s^{-1}	10^{-3}	1	1.66054×10^{-21}
	1 cm^3 molecule^{-1} s^{-1}	6.022014×10^{17}	6.022014×10^{20}	1
k_{term}	1 m^3 mol^{-1} s^{-1}	1	10^{6}	2.757389×10^{-36}
	1 dm^6 mol^{-2} s^{-1}	10^{-6}	1	2.757389×10^{-42}
	1 cm^6 molecule^{-2} s^{-1}	3.62662×10^{35}	3.62662×10^{41}	1

[a]Symbols: c concentration, k_{bim} rate coefficient for bimolecular reactions, k_{term} rate coefficient for termolecular reactions. To convert chemical amount concentration to mass concentration multiply mol m^{-3} by molar mass

Comments: To convert gas phase concentration to (partial) pressure requires the knowledge of ambient temperature. The quantities are related by the (ideal) gas law $p = nkT = cRT$, where p (Pa) is pressure, n (molecule m^{-3}) is number concentration, $k \approx 1.38 \times 10^{-23}$ (J K^{-1}) is the Boltzmann constant, c (mol m^{-3}) is molar concentration, $R \approx 8.31$ J mol^{-1} K^{-1} is the gas constant, and T (K) is temperature. For the conversion of pressure units use Table 1.7

Table 1.9 Conversion factors[a] for optical absorption cross section σ, absorption coefficient k, and molar absorption coefficient ε

To convert from	Base	To	Base	Multiply by
σ (cm^2 molecule^{-1})	e	ε (dm^3 mol^{-1} cm^{-1})	10	2.615325×10^{20}
σ (cm^2 molecule^{-1})	e	ε (m^2 mol^{-1})	10	2.615325×10^{19}
σ (cm^2 molecule^{-1})	e	ε (m^2 mol^{-1})	e	6.022141×10^{19}
ε (dm^3 mol^{-1} cm^{-1})	10	σ (cm^2 molecule^{-1})	e	3.823600×10^{-21}
ε (m^2 mol^{-1})	10	σ (cm^2 molecule^{-1})	e	3.823600×10^{-20}
k (cm^{-1})	e	σ (cm^2 molecule^{-1})	e	3.721931×10^{-20}
σ (cm^2 molecule^{-1})	e	k (cm^{-1})	e	2.686777×10^{19}

[a]The relations are $\ln(I_0/I) = \sigma nl$, $\ln(I_0/I) = kl = \sigma n_0 l$, and $\log_{10}(I_0/I) = \varepsilon cl$ where I_0/I is the ratio of incident to transmitted radiation along the path length l, n is the number concentration (molecule cm^{-3}), $n_0 = 2.686777 \times 10^{19}$ (molecule cm^{-3}) is Loschmidt's constant, both used with l (cm), c is molar concentration, (mol dm^{-3}) used with l (cm) or (mol m^{-3}) with l (m)

Table 1.10 Conversion factors for energy units[a]

Unit	Wave number cm^{-1} [b]	Molar energy J mol^{-1}	Molar energy cal mol^{-1}	Energy eV[c]	Temperature K
1 cm^{-1}	1	11.96266	2.859144	1.239842×10^{-4}	1.438769
1 J mol^{-1}	0.08359347	1	0.239006	1.036427×10^{-5}	0.120272
1 cal mol^{-1}	0.3499891	4.184	1	4.339312×10^{-5}	0.503217
1 eV	8065.544	96485.34	23060.54	1	1160.448
1 K	0.695039	8.314472	1.987207	8.61738×10^{-5}	1

[a]Conversion formulae are: $E = h\nu = hc\nu' = kT$; $E_{molar} = N_A E$, where $h = 6.62607 \times 10^{-34}$ is the Planck constant, $c = 2.9979 \times 10^{8}$ m s^{-1} is the speed of light, $k = 1.3807 \times 10^{-23}$ is the Boltzmann constant, T is temperature, and $N_A = 6.02214 \times 10^{23}$ is the Avogadro constant

[b]Wave number $\nu' = 1/\lambda$ is a measure of energy used in spectroscopy

[c]One electron volt is equivalent to the kinetic energy of a singly charged particle (electron or ion) after acceleration by a potential difference of 1 V

1.3 Properties of the Elements

Table 1.11 Standard atomic weights of naturally occurring elements, listed alphabetically[a]

Name, *Z*	Symbol	Atomic weight	Name, Z	Symbol	Atomic weight
Actinium, 89	Ac	227.0278[b]	Magnesium, 12	Mg	24.3050
Aluminum, 13	Al	26.9815386	Manganese, 25	Mn	54.938045
Antimony, 51	Sb	121.760	Mercury, 80	Hg	200.59
Argon, 18	Ar	39.948	Molybdenum, 42	Mo	95.96
Arsenic, 33	As	74.92160	Neodymium, 60	Nd	144.242
Astatine, 85	At	209.9871[b]	Neon, 10	Ne	20.1797
Barium, 56	Ba	137.327	Nickel, 28	Ni	58.6934
Beryllium, 4	Be	9.012182	Niobium, 41	Nb	92.90638
Bismuth, 83	Bi	208.98040	Nitrogen, 7	N	14.0067
Boron, 5	B	10.811	Osmium, 76	Os	190.23
Bromine, 35	Br	79.904	Oxygen, 8	O	15.9994
Cadmium, 48	Cd	112.411	Palladium, 46	Pd	106.42
Calcium, 20	Ca	40.078	Phosphorus, 15	P	30.973762
Carbon, 6	C	12.0107	Platinum, 78	Pt	195.084
Cerium, 58	Ce	140.116	Polonium, 84	Po	208.9824[b]
Cesium, 58	Cs	132.9054519	Potassium, 19	K	39.0983
Chlorine, 17	Cl	35.453	Praseodymium, 59	Pr	140.90765
Chromium, 24	Cr	51.9961	Promethium, 61	Pm	144.9127[b]
Cobalt, 27	Co	58.933195	Protactinium, 91	Pa	231.0359
Copper, 29	Cu	63.546	Radium, 88	Ra	226.0254[b]
Dysprosium, 66	Dy	162.500	Radon, 86	Rn	222.0176[b]
Erbium, 68	Er	167.259	Rhenium,75	Re	186.207
Europium, 63	Eu	151.964	Rhodium, 45	Rh	102.90550
Fluorine, 9	F	18.9984032	Rubidium, 37	Rb	85.4678
Francium, 87	Fr	223.0197[b]	Ruthenium, 44	Ru	101.07
Gadolinium, 64	Gd	157.25	Samarium, 62	Sm	150.36
Gallium, 31	Ga	69.723	Scandium, 21	Sc	44.955912
Germanium, 32	Ge	72.64	Selenium, 34	Se	78.96
Gold, 79	Au	196.966569	Silicon, 14	Si	28.0855
Hafnium, 72	Hf	178.49	Silver, 47	Ag	107.8682
Helium, 2	He	4.002602	Sodium, 11	Na	22.98976928
Holmium, 67	Ho	164.93032	Strontium, 38	Sr	87.62
Hydrogen, 1	H	1.00794	Sulfur, 16	S	32.065
Indium, 49	In	114.818	Tantalum, 73	Ta	180.94788
Iodine, 53	I	126.90447	Technetium, 43	Tc	97.9072[b]
Iridium, 77	Ir	192.217	Tellurium, 52	Te	127.60
Iron, 26	Fe	55.845	Terbium, 65	Tb	158.92535
Krypton, 36	Kr	83.798	Thallium, 81	Tl	204.3833
Lanthanum, 57	La	138.90547	Thorium, 90	Th	232.03806
Lead, 82	Pb	207.2	Thulium, 69	Tm	168.93421
Lithium, 3	Li	6.941	Tin, 50	Sn	118.710
Lutetium, 71	Lu	174.9668	Titanium, 22	Ti	47.867

(continued)

Table 1.11 (continued)

Name, Z	Symbol	Atomic weight	Name, Z	Symbol	Atomic weight
Tungsten, 74	W	183.84	Ytterbium, 70	Yb	173.054
Uranium, 92	U	238.02891	Yttrium, 39	Y	88.90585
Vanadium, 23	V	50.9415	Zinc, 30	Zn	65.38
Xenon, 54	Xe	131.293	Zirconium, 40	Zr	91.224

[a]Based on the unified atomic mass unit $(1/12)m(^{12}C) = 10^{-3}$ kg mol^{-1}/N_A. Data Source: Wieser, M.E., Berglund, M. (2009) Pure Appl. Chem. **81**, 2131–2156

[b]The element has no stable isotope. The value given refers to the isotope with the longest half-life. Thorium, protactinium, and uranium have no stable isotopes but the terrestrial composition is sufficiently uniform for a standard atomic weight to be specified

Table 1.12 Isotopic composition (natural abundance) of the elements[a]

Element Isotope	Abundance %	Atomic Mass	Element Isotope	Abundance %	Atomic Mass
Hydrogen		1.00794	**Magnesium**		24.3050
^{1}H	99.9885	1.007825032	^{24}Mg	78.99	23.98504187
^{2}H	0.0115	2.014101778	^{25}Mg	10.00	24.98583700
Helium		4.002602	^{26}Mg	11.01	25.98259300
^{3}He	0.000134	3.0160293094	**Aluminum**		26.981538
^{4}He	99.999866	4.0026032497	^{27}Al	100	26.98153841
Lithium		6.941	**Silicon**		28.0855
^{6}Li	7.59	6.0151223	^{28}Si	92.223	27.97692649
^{7}Li	92.41	7.0160041	^{29}Si	4.685	28.97649468
Beryllium		9.0121822	^{30}Si	3.092	29.97377018
^{9}Be	100	9.0121822	**Phosphorus**		30.973761
Boron		10.811	^{31}P	100	30.97376149
^{10}B	19.9	10.0129371	**Sulfur**		32.065
^{11}B	80.1	11.0093055	^{32}S	94.99	31.97207073
Carbon		12.0107	^{33}S	0.75	32.97145854
^{12}C	98.93	12 (defined)	^{34}S	4.25	33.96786687
^{13}C	1.07	13.003354838	^{36}S	0.01	35.96708088
Nitrogen		14.0067	**Chlorine**		35.453
^{14}N	99.636	14.003074007	^{35}Cl	75.76	34.96885271
^{15}N	0.364	15.000108973	^{37}Cl	24.24	36.96590260
Oxygen		15.9994	**Argon**		39.948
^{16}O	99.757	15.994914622	^{36}Ar	0.3365	35.96754626
^{17}O	0.038	16.99913150	^{38}Ar	0.0632	37.9627322
^{18}O	0.205	17.9991604	^{40}Ar	99.6003	39.962383124
Fluorine		18.9984032	**Potassium**		39.0983
^{18}F	100	18.9984032	^{39}K	93.2581	38.9637069
Neon		20.1797	^{40}K*	0.0117	39.96399867
^{20}Ne	90.48	19.992440176	^{41}K	6.7302	39.96182597
^{21}Ne	0.27	20.99384674	**Calcium**		40.078
^{22}Ne	9.25	21.99138550	^{40}Ca	96.941	39.9625912
Sodium		22.989770	^{42}Ca	0.647	41.9586183
^{23}Na	100	22.98976966	^{43}Ca	0.135	42.9587668

(continued)

Table 1.12 (continued)

Element Isotope	Abundance %	Atomic Mass
^{44}Ca	2.086	43.9554811
^{46}Ca	0.004	45.9536927
^{48}Ca	0.187	47.952533
Scandium		44.955910
^{45}Sc	100	44.9559102
Titanium		47.867
^{46}Ti	8.25	45.9526295
^{47}Ti	7.44	46.9517637
^{48}Ti	73.72	47.9479470
^{49}Ti	5.41	48.9478707
^{50}Ti	5.18	49.9447920
Vanadium		50.9415
^{50}V	0.25	49.9471627
^{51}V	99.75	50.9439635
Chromium		51.9961
^{50}Cr	4.345	49.9460495
^{52}Cr	83.789	51.9405115
^{53}Cr	9.501	52.9406534
^{54}Cr	2.365	53.9388846
Manganese		54.938049
^{55}Mn	100	54.9380493
Iron		55.845
^{54}Fe	4.345	53.9396147
^{56}Fe	91.754	55.9349418
^{57}Fe	2.119	56.9353983
^{58}Fe	0.282	57.9332801
Cobalt		58.933200
^{58}Co	100	58.9331999
Nickel		58.6934
^{58}Ni	68.0769	57.9353477
^{60}Ni	26.2231	59.9307903
^{61}Ni	1.1399	60.9310601
^{62}Ni	3.6345	61.9283484
^{64}Ni	0.9256	63.9279692
Copper		63.546
^{63}Cu	69.15	62.9296007
^{65}Cu	30.85	64.9277938
Zinc		65.409
^{64}Zn	48.268	63.9291461
^{66}Zn	27.975	65.9260364
^{67}Zn	4.102	66.9271305
^{68}Zn	19.024	67.9248473
^{70}Zn	0.631	69.925325
Gallium		69.723
^{69}Ga	60.108	68.925581
^{71}Ga	39.892	70.9247073
Germanium		72.64
^{70}Ge	20.38	69.9242500
^{72}Ge	27.31	71.9220763
^{73}Ge	7.76	72.9234595
^{74}Ge	36.72	73.9211784
^{76}Ge	7.83	75.9214029
Arsenic		74.92160
^{75}As	100	74.9215966
Selenium		78.96
^{74}Se	0.89	73.9224767
^{76}Se	9.37	75.9192143
^{77}Se	7.63	76.9199148
^{78}Se	23.77	77.9173097
^{80}Se	49.61	79.9165221
^{82}Se	8.73	81.9167003
Bromine		79.904
^{79}Br	50.69	78.9183379
^{81}Br	49.31	80.916291
Krypton		83.798
^{78}Kr	0.355	77.920388
^{80}Kr	2.286	79.916379
^{82}Kr	11.593	81.9134850
^{83}Kr	11.500	82.914137
^{84}Kr	56.987	83.911508
^{86}Kr	17.279	85.910615
Rubidium		85.4678
^{85}Rb	72.17	84.9117924
^{87}Rb	27.83	86.9091858
Strontium		87.62
^{84}Sr	0.56	83.913426
^{86}Sr	9.86	84.9092647
^{87}Sr	7	86.9088816
^{88}Sr	82.58	87.9056167
Ytterbium		88.90585
^{89}Y	100	88.9058485
Zirconium		91.224
^{90}Zr	51.45	89.9047022
^{91}Zr	11.22	90.9056434
^{92}Zr	17.15	91.9050386
^{94}Zr	17.38	93.9063144
^{96}Zr	2.80	95.908275
Niobium		92.90638
^{93}Nb	100	92.9063762
Molybdenum		95.94
^{92}Mo	14.77	91.906810
^{94}Mo	9.23	93.9050867

(continued)

Table 1.12 (continued)

Element Isotope	Abundance %	Atomic Mass
^{95}Mo	15.9	94.9058406
^{96}Mo	16.68	95.9046780
^{97}Mo	9.56	96.9060201
^{98}Mo	24.19	97.9054069
^{100}Mo	9.67	99.907476
Ruthenium		101.07
^{96}Ru	5.54	95.907604
^{98}Ru	1.87	97.905287
^{99}Ru	12.76	98.9059385
^{100}Ru	12.60	99.9042189
^{101}Ru	17.06	100.9055815
^{102}Ru	31.55	101.9043488
^{104}Ru	18.62	103.905430
Rhodium		102.90550
^{103}Rh	100	102.905504
Palladium		106.42
^{102}Pd	1.02	101.905607
^{104}Pd	11.14	103.904034
^{105}Pd	22.33	104.905083
^{106}Pd	27.33	105.903484
^{108}Pd	26.46	107.903895
^{110}Pd	11.72	109.905153
Silver		107.8682
^{107}Ag	51.839	106.905093
^{109}Ag	48.161	108.904756
Cadmium		112.411
^{106}Cd	1.25	105.906458
^{108}Cd	0.89	107.904183
^{110}Cd	12.49	109.903006
^{111}Cd	12.8	110.904182
^{112}Cd	24.13	111.9027577
^{113}Cd	12.22	112.9044014
^{114}Cd	28.73	113.9033586
^{116}Cd	7.49	115.904756
Indium		114.818
^{113}In	4.29	112.904062
^{115}In	95.71	114.903879
Tin		118.71
^{112}Sn	0.97	111.904822
^{114}Sn	0.66	113.902783
^{115}Sn	0.34	114.903347
^{116}Sn	14.54	115.901745
^{117}Sn	7.68	116.902955
^{118}Sn	24.22	117.901608
^{119}Sn	8.59	118.903311
^{120}Sn	32.58	119.9021985
^{122}Sn	4.63	121.9034411
^{124}Sn	5.79	123.9052745
Antimony		121.76
^{121}Sb	57.21	120.9038222
^{123}Sb	42.79	122.9042160
Tellurium		127.60
^{120}Te	0.09	119.904026
^{122}Te	2.55	121.9030558
^{123}Te	0.89	122.9042711
^{124}Te	4.74	123.9028188
^{125}Te	7.07	124.9044241
^{126}Te	18.84	125.903049
^{128}Te	31.74	127.9044615
^{130}Te	34.08	129.9062229
Iodine		126.90447
^{127}I	100	126.904468
Xenon		131.293
^{124}Xe	0.0952	123.9058954
^{126}Xe	0.0890	125.904268
^{128}Xe	1.9102	127.9035305
^{129}Xe	26.4006	128.9047799
^{130}Xe	4.071	129.9035089
^{131}Xe	21.2324	130.9050828
^{132}Xe	26.9086	131.9041546
^{134}Xe	10.4357	133.9053945
^{136}Xe	8.8573	135.907220
Cesium		132.90545
^{133}Cs	100	132.905447
Barium		137.327
^{130}Ba	0.106	129.906311
^{132}Ba	0.101	131.90506
^{134}Ba	2.417	133.904504
^{135}Ba	6.592	134.905684
^{136}Ba	7.854	135.904571
^{137}Ba	11.232	136.905822
^{138}Ba	71.698	137.905242
Lanthanum		138.9055
^{138}La	0.090	137.907108
^{139}La	99.910	138.906349
Cerium		140.116
^{136}Ce	0.185	135.907140
^{138}Ce	0.251	137.905986
^{140}Ce	88.450	139.905435
^{142}Ce	11.114	141.909241
Praseodymium	140.90765	160Gd
^{141}Pr	100	140.907648

(continued)

Table 1.12 (continued)

Element Isotope	Abundance %	Atomic Mass
Neodymium		144.24
^{142}Nd	27.2	141.907719
^{143}Nd	12.2	142.909810
^{144}Nd	23.8	143.910083
^{145}Nd	8.3	144.912569
^{146}Nd	17.2	145.913113
^{148}Nd	5.7	147.916889
^{150}Nd	5.6	149.920887
Samarium		150.36
^{144}Sm	3.07	143.911996
^{147}Sm	14.99	146.914894
^{148}Sm	11.24	147.914818
^{149}Sm	13.82	148.917180
^{150}Sm	7.38	149.919272
^{152}Sm	26.75	151.919729
^{154}Sm	22.75	151.922206
Europium		151.964
^{151}Eu	47.81	150.919846
^{153}Eu	52.19	152.921227
Gadolinium		157.25
^{152}Gd	0.20	151.919789
^{154}Gd	2.18	153.920862
^{155}Gd	14.80	154.922619
^{156}Gd	20.47	155.922120
^{157}Gd	15.65	156.923957
^{158}Gd	24.84	157.924101
^{160}Gd	21.86	159.927051
Terbium		158.92534
^{159}Tb	100	158.925343
Dysprosium		162.50
^{156}Dy	0.056	155.92478
^{158}Dy	0.095	157.924405
^{160}Dy	2.329	159.925194
^{161}Dy	18.889	160.926930
^{162}Dy	25.475	161.926795
^{163}Dy	24.896	162.928728
^{164}Dy	28.26	163.929171
Holmium		164.93032
^{165}Ho	100	164.930319
Erbium		167.259
^{162}Er	0.139	161.928778
^{164}Er	1.601	163.92920
^{166}Er	33.503	165.930293
^{167}Er	22.869	166.932048
^{168}Er	26.978	167.932368
^{170}Er	14.91	169.935461
Thulium		168.93421
^{169}Tm	100	168.934211
Ytterbium		173.04
^{168}Yb	0.13	167.933895
^{170}Yb	3.04	169.934759
^{171}Yb	14.28	170.936323
^{172}Yb	21.83	171.936378
^{173}Yb	16.13	172.938207
^{174}Yb	31.83	173.938858
^{176}Yb	12.76	175.942569
Lutetium		174.967
^{175}Lu	97.41	174.9407682
^{176}Lu	2.59	175.9426827
Hafnium		178.49
^{174}Hf	0.16	173.940042
^{176}Hf	5.26	175.941403
^{177}Hf	18.6	176.9432204
^{178}Hf	27.28	177.9436981
^{179}Hf	13.62	178.9458154
^{180}Hf	35.08	179.9465488
Tantalum		180.9479
^{180}Ta	0.012	179.947466
^{181}Ta	99.988	180.947996
Tungsten		183.84
^{180}W	0.12	179.946706
^{182}W	26.50	181.948205
^{183}W	14.31	182.9502242
^{184}W	30.64	183.9509323
^{186}W	28.43	185.954362
Rhenium		186.207
^{185}Re	37.40	184.952955
^{187}Re	62.60	186.9557505
Osmium		190.23
^{184}Os	0.02	183.952491
^{186}Os	1.59	185.953838
^{187}Os	1.96	186.9557476
^{188}Os	13.24	187.9558357
^{189}Os	16.15	188.958145
^{190}Os	26.26	189.958445
^{192}Os	40.78	191.961479
Iridium		192.217
^{191}Ir	37.3	190.960591
^{193}Ir	62.7	192.962923
Platinum		195.078
^{190}Pt	0.014	189.959930
^{192}Pt	0.782	191.961035

(continued)

Table 1.12 (continued)

Element Isotope	Abundance %	Atomic Mass
^{194}Pt	32.967	193.962663
^{195}Pt	33.832	194.964774
^{196}Pt	25.242	195.964934
^{198}Pt	7.163	197.967875
Gold		196.966
^{197}Au	100	196.966551
Mercury		200.59
^{196}Hg	0.15	195.965814
^{198}Hg	9.97	197.966752
^{199}Hg	16.87	198.968262
^{200}Hg	23.10	199.968309
^{201}Hg	13.18	200.970285
^{202}Hg	29.86	201.970625
^{204}Hg	6.87	203.973475
Thallium		204.3833
^{203}Tl	29.52	202.972329
^{205}Tl	70.48	204.974412
Lead[b]		207.2
^{204}Pb	1.4	203.973028
^{206}Pb	24.1	205.974449
^{207}Pb	22.1	206.975880
^{208}Pb	52.4	207.976636
Bismuth		208.98038
^{209}Bi	100	208.980384
Thorium		232.0381
^{232}Th*	100	232.0380495
Protactinium		231.03588
^{231}Pa*	100	231.03588
Uranium		238.02891
^{234}U*	0.0054	234.0409447
^{235}U*	0.72	235.0439222
^{238}U*	99.2	238.0507835

Source of data: De Laeter, J.R., Böhlke, J.K., De Bièvre, P., Hidaka, H., Peiser, H.S., Rosman, K.J.R., Taylor, P.D.P. (2003) Pure Appl. Chem. **75**, 683–800

[a]Radioactive isotopes are indicated by an asterisk. For radioactive species that occur only in trace amounts see Table 1.13

[b]The isotope composition varies somewhat with location

Table 1.13 Radioactive isotopes in the environment, origins and half-lifetimes[a]

Element	Isotope	Atomic mass	Half-lifetime	Decay process[b]	Origin[c]
Tritium	^{3}H	3.016049278	12.33 a	β^-	cosmic radiat. (N, O), artificial
Beryllium	^{7}Be	7.0169298	53.28 d	ec	cosmic radiation (N, O)
	^{10}Be	10.0135338	1.52×10^{6} a	β^-	cosmic radiation (N, O)
Carbon	^{14}C	14.003242	5715 a	β^-	cosmic radiat. (N, O), artificial
Sodium	^{22}Na	21.9944364	2.605 a	β^+	cosmic radiation (Ar)
Aluminum	^{26}Al	25.9868917	7.1×10^{5} a	β^+	cosmic radiation (Ar)
Silicon	^{32}Si	31.9741481	160 a	β^-	cosmic radiation (Ar)
Phosphorus	^{32}P	31.9739073	14.28 d	β^-	cosmic radiation (Ar)
	^{33}P	32.971726	25.3 d	β^-	cosmic radiation (Ar)
Chlorine	^{36}Cl	35.968307	3.01×10^{5} a	β^-	cosmic radiation (Ar)
Argon	^{37}Ar	36.9667763	35.0 d	ec	cosmic radiation (Ar)
	^{39}Ar	38.964313	268 a	β^-	cosmic radiation (Ar)
Potassium[d]	^{40}K	39.9639985	1.248×10^{9} a	β^+/ec, β^-	primordial
Krypton	^{81}Kr	80.916592	2.1×10^{5} a	ec	cosmic radiation (Kr)
Krypton	^{85}Kr	84.912527	10.73 a	β^-	artificial
Rubidium	^{87}Rb	86.9091805	4.88×10^{10} a	β^-	primordial
Strontium	^{90}Sr	89.907738	29.1 a	β^-	artificial
Iodine	^{129}I	128.904988	1.7×10^{7} a	β^-	cosmic radiat. (Xe), artificial

(continued)

Table 1.13 (continued)

Element	Isotope	Atomic mass	Half-lifetime	Decay process[b]	Origin[c]
Cesium	^{137}Cs	136.907089	30.2 a	β^-	artificial
Polonium	^{210}Po	209.982874	138.4 d	α	Radon decay
Lead	^{210}Pb	209.984189	22.6 a	β^-	Radon decay
Radon	^{222}Rn	222.017578	3.823 d	α	Uranium decay
Radium	^{223}Ra	223.018502	11.43 d	α	Uranium decay
	^{224}Ra	224.020212	3.66 d	α	Uranium decay
	^{226}Ra	226.025410	1599 a	α	Uranium decay
Actinium	^{227}Ac	227.027752	21.77 a	β^-	Uranium decay
Thorium	^{227}Th	227.027704	18.72 d	α	Uranium decay
	^{228}Th	228.028741	1.913 a	α	Uranium decay
	^{230}Th	230.033134	7.54×10^4 a	α	Uranium decay
	^{232}Th	232.038055	1.4×10^{10} a	α	primordial
	^{234}Th	234.043601	24.1 d	β^-	Uranium decay
Protactinium	^{231}Pa	231.035884	3.25×10^4 a	α	Uranium decay
Uranium	^{234}U	234.040952	2.455×10^5 a	α	primordial
Uranium	^{235}U	235.043930	7.04×10^8 a	α	primordial
	^{238}U	238.050788	4.47×10^9 a	α	primordial

[a]Half-lifetimes (>1 d) are taken from Holden, N.E. (2006), in Lide, D.R. (Editor in Chief) *CRC Handbook of Chemistry and Physics*, Taylor & Francis, Boca Raton, pp. 11-51–11-203
[b]Decay modes: α emission of alpha-particles, β^- emission of electrons, β^+ emission of positrons, ec orbital electron capture
[c]Cosmic radiation: the element undergoing disintegration to form the isotope is indicated. Artificial sources include nuclear weapons tests and nuclear industry
[d]The disintegration proceeds to about 90% to form ^{40}Ar and 10% to form ^{40}Ca

Table 1.14 Natural radioactive decay series: Isotopes, decay processes and half-lifetimes[a]

$^{92}\mathbf{U}_{238}$	**Uranium**-238	$^{92}\mathbf{U}_{235}$	**Uranium**-235		
↓ α	4.47×10^9 a	↓ α	7.04×10^8 a		
$^{90}\mathbf{Th}_{234}$	Thorium-234	$^{90}\mathbf{Th}_{231}$	Thorium-231	$^{90}\mathbf{Th}_{232}$	**Thorium**-232
↓ β	24.1 d	↓ β	1.063 d	↓ α	1.4×10^{10} a
$^{91}\mathbf{Pa}_{234}$	Protactinium-234	$^{91}\mathbf{Pa}_{231}$	Protactinium-231	$^{88}\mathbf{Ra}_{228}$	Radium-228
↓ β	1.17 min	↓ α	3.25×10^4 a	↓ β	5.76 a
$^{92}\mathbf{U}_{234}$	Uranium-234	$^{89}\mathbf{Ac}_{227}$	Actinium-227	$^{89}\mathbf{Ac}_{228}$	Actinium-228
↓ α	2.46×10^5 a	↓ β	21.77 a	↓ β	6.15 h
$^{90}\mathbf{Th}_{230}$	Thorium-230	$^{90}\mathbf{Th}_{227}$	Thorium-227	$^{90}\mathbf{Th}_{228}$	Thorium-228
↓ α	7.54×10^4 a	↓ α	18.72 d	↓ α	1.913 a
$^{88}\mathbf{Ra}_{226}$	Radium-226	$^{88}\mathbf{Ra}_{223}$	Radium-223	$^{88}\mathbf{Ra}_{224}$	Radium-224
↓ α	1600 a	↓ α	11.43 d	↓ α	3.66 d

(continued)

Table 1.14 (continued)

$^{86}\mathbf{Rn}_{222}$	Radon-222	$^{86}\mathbf{Rn}_{219}$	Radon-219	$^{86}\mathbf{Rn}_{220}$	Radon-220
↓ α	3.82 d	↓ α	3.96 s	↓ α	55.6 s
$^{84}\mathbf{Po}_{218}$	Polonium-218	$^{84}\mathbf{Po}_{215}$	Polonium-215	$^{84}\mathbf{Po}_{216}$	Polonium-216
↓ α	182 s	↓ α	1.78 ms	↓ α	0.145 s
$^{82}\mathbf{Pb}_{214}$	Lead-214	$^{82}\mathbf{Pb}_{211}$	Lead-211	$^{82}\mathbf{Pb}_{212}$	Lead-212
↓ β	26.9 min	↓ β	36.1 min	↓ β	16.6 h
$^{83}\mathbf{Bi}_{214}$	Bismuth-214	$^{83}\mathbf{Bi}_{211}$	Bismuth-211	$^{83}\mathbf{Bi}_{212}$	Bismuth-212
↓ β	19.7 min	↓ α	2.14 min	α 36% (→ $^{81}\mathbf{Tl}_{208}$) ↓ β 64%	1.009 h
$^{84}\mathbf{Po}_{214}$	Polonium-214	$^{81}\mathbf{Tl}_{207}$	Thallium-207	$^{84}\mathbf{Po}_{212}$	Polonium-212
↓ α	163.7 µs	↓ β	4.77 min	↓ α	0.3 µs
$^{82}\mathbf{Pb}_{210}$	Lead-210	$^{82}\mathbf{Pb}_{207}$	**Lead**-210	$^{82}\mathbf{Pb}_{208}$	**Lead**-208
↓ β	22.6 a		(stable)	↑ α	(stable)
$^{83}\mathbf{Bi}_{210}$	Bismuth-210			$^{81}\mathbf{Tl}_{208}$	Thallium-208
↓ β	5.01 d				3.05 min
$^{84}\mathbf{Po}_{210}$	Polonium-210				
↓ α	138.4 d				
$^{82}\mathbf{Pb}_{206}$	**Lead**-206 (stable)				

[a] Half-life times from Holden, N.E. (2006) in Lide, D.R. (Editor in Chief) *CRC Handbook of Chemistry and Physics*, Taylor & Francis, Boca Raton, pp. 11-51–11-203

Chapter 2
Data Regarding the Earth

2.1 Physical Properties and Interior Structure of the Earth

Table 2.1 Physical properties of the Earth[a]

Mean distance to sun (10^6 km)	149.598	Surface area (10^{12} m^2), total	510
Eccentricity of orbit	0.0167	Ocean surface area	361
Inclination of equator to orbit (°)	23.45	Continental surface area	149
Period of sideral revolution (d)	365.256	Mean height of continents (m)	875
Sideral rotation period (h)	23.9345	Mean depth of oceans (m)	3,794
Radius (km), mean	6,371.0	Acceleration due to gravity (m s^{-2})	
Equatorial	6,378.14	Mean for entire surface[b]	9.7978
Polar	6,356.75	Equatorial	9.78036
Mass (10^{21} kg), total	5,973.6	Polar	9.83208
Metallic core	1,941.	Escape velocity (km s^{-1})	11.18
Silicate mantle	4,007.	Mean surface temperature[c] (K)	288
Crust, total	27.1	Heat flow (mW m^{-2})	
Continental crust[d]	22.5	Global mean	87 ± 2.0
Oceanic crust[d]	4.6	Oceanic mean	101 ± 2.2
Sedimentary rocks	2.24	Continental mean	65 ± 1.6
Hydrosphere[e]	1.664	Total global heat loss (TW)	44 ± 1
Mean density (g cm^{-3})	5.515	Solar constant (kW m^{-2})	1.3676

[a]Sources of data: Garrels and MacKenzie (1971), Lang (1992), Lodders and Fegley (1998), Ronov and Yaroshevsky (1969), Taylor and McLennan (1985), Wedepohl (1995)
[b]The internationally adopted standard value is $g = 9.80665$ m s^{-2}
[c]At sea level
[d]Continental crust: 40 km average thickness including continental shelf regions and margins; Oceanic crust: 5 km average thickness and 3.0×10^3 kg m^{-3} average density
[e]Includes pore waters in sediments and water in rocks

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Structure: The solid earth consists of the core, the mantel and the crust. Seismic data show that the (iron-rich) core is divided into a solid inner core, which is denser than iron and is probably an Fe-Ni alloy, and a molten outer core, which is slightly less dense than iron. The silicate mantle is also subdivided into a lower and an upper mantle by seismic discontinuities occurring at depths between 400 and 670 km. The crust is the uppermost layer of the earth. The continental crust (granitic) is enriched in incompatible elements and contains most of the earth alkaline elements as well as a large fraction of uranium and other radioactive elements. Most of the continental crust is 20–50 km thick, with an average thickness of 35–40 km. The oldest known rocks are nearly 4×10^9 years old. The (basaltic) oceanic crust is about 5–10 km thick. It is fairly young with an average age of 60 million years. The oceanic crust is less enriched with incompatible elements than the continental crust. The upper 100–200 km of the earth is made up of about 12 plates that float on the upper mantle. The thickness of oceanic plates is about 60 km, and that of continental plates 100–200 km. The mutual interaction of plates gives rise to divergence zones, such as the mid-ocean ridges where they spread apart, and convergence zones, where the higher density oceanic plates are subducted under the lower density continental plates and mountain ranges are formed. These zones are active regions of volcanism.

Table 2.2 The interior structure of the Earth[a]

Region or boundary	Outer radius (km)	Depth (km)	Density (g cm^{-3})	Pressure (10^8 Pa)	Temperature (K)
Inner core (metallic solid)	1,220	5,150–6,370	12.8–13.1	3,290–3,570	5,000–5,500
Outer core (metallic liquid)	3,485	2,890–5,150	9.9–12.2	1,390–3,290	3,930–5,000
Lower mantle	5,700	670–2,890	4.3–5.7	240–1,390	2,000–3,930
Transition zone	5,970	400–670	3.8–4.0	140–240	1,770–2,000
Upper mantle	6,333	35–400	3.3–3.5	2–140	200–1,770
Continental crust	–	0–35	2.7–2.8	0–13	290–770
Oceanic crust	–	0–10	3.0	0–3.3	290–500

[a]Source of data: Lodders and Fegley (1998)

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