1. PHYSICAL CONSTANTS

Table 1.1. Reviewed 2004 by P.J. Mohr and B.N. Taylor (NIST). Based mainly on the "CODATA Recommended Values of the Fundamental Physical Constants: 2002" by P.J. Mohr and B.N. Taylor, to be published in 2004. 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 fractional uncertainties in parts per 10^9 (ppb) 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). The full 2002 CODATA set of constants may be found at `http://physics.nist.gov/constants`

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	299 792 458 m s^{-1}	exact*
Planck constant	h	6.626 0693(11)$\times 10^{-34}$ J s	170
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 571 68(18)$\times 10^{-34}$ J s	170
		= 6.582 119 15(56)$\times 10^{-22}$ MeV s	85
electron charge magnitude	e	1.602 176 53(14)$\times 10^{-19}$ C = 4.803 204 41(41)$\times 10^{-10}$ esu	85, 85
conversion constant	$\hbar c$	197.326 968(17) MeV fm	85
conversion constant	$(\hbar c)^2$	0.389 379 323(67) GeV^2 mbarn	170
electron mass	m_e	0.510 998 918(44) MeV/c^2 = 9.109 3826(16)$\times 10^{-31}$ kg	86, 170
proton mass	m_p	938.272 029(80) MeV/c^2 = 1.672 621 71(29)$\times 10^{-27}$ kg	86, 170
		= 1.007 276 466 88(13) u = 1836.152 672 61(85) m_e	0.13, 0.46
deuteron mass	m_d	1875.612 82(16) MeV/c^2	86
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	931.494 043(80) MeV/c^2 = 1.660 538 86(28)$\times 10^{-27}$ kg	86, 170
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	8.854 187 817 ... $\times 10^{-12}$ F m^{-1}	exact
permeability of free space	μ_0	$4\pi \times 10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times 10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297 352 568(24)$\times 10^{-3}$ = 1/137.035 999 11(46)†	3.3, 3.3
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 325(28)$\times 10^{-15}$ m	10
(e^- Compton wavelength)/2π	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e \alpha^{-1}$	3.861 592 678(26)$\times 10^{-13}$ m	6.7
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 2108(18)$\times 10^{-10}$ m	3.3
wavelength of 1 eV/c particle	$hc/(1\text{ eV})$	1.239 841 91(11)$\times 10^{-6}$ m	85
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 6923(12) eV	85
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 245 873(13) barn	20
Bohr magneton	$\mu_B = e\hbar/2m_e$	5.788 381 804(39)$\times 10^{-11}$ MeV T^{-1}	6.7
nuclear magneton	$\mu_N = e\hbar/2m_p$	3.152 451 259(21)$\times 10^{-14}$ MeV T^{-1}	6.7
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	1.758 820 12(15)$\times 10^{11}$ rad s^{-1} T^{-1}	86
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	9.578 833 76(82)$\times 10^{7}$ rad s^{-1} T^{-1}	86
gravitational constant‡	G_N	6.6742(10)$\times 10^{-11}$ m^3 kg^{-1} s^{-2}	1.5×10^5
		= 6.7087(10)$\times 10^{-39}$ $\hbar c$ (GeV/c^2)$^{-2}$	1.5×10^5
standard gravitational accel.	g_n	9.806 65 m s^{-2}	exact
Avogadro constant	N_A	6.022 1415(10)$\times 10^{23}$ mol^{-1}	170
Boltzmann constant	k	1.380 6505(24)$\times 10^{-23}$ J K^{-1}	1800
		= 8.617 343(15)$\times 10^{-5}$ eV K^{-1}	1800
molar volume, ideal gas at STP	$N_A k$(273.15 K)/(101 325 Pa)	22.413 996(39)$\times 10^{-3}$ m^3 mol^{-1}	1700
Wien displacement law constant	$b = \lambda_{\max} T$	2.897 7685(51)$\times 10^{-3}$ m K	1700
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	5.670 400(40)$\times 10^{-8}$ W m^{-2} K^{-4}	7000
Fermi coupling constant**	$G_F/(\hbar c)^3$	1.166 37(1)$\times 10^{-5}$ GeV^{-2}	9000
weak-mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\text{MS}}$)	0.23120(15)††	6.5×10^5
$W^\pm$ boson mass	m_W	80.425(38) GeV/c^2	4.8×10^5
Z^0 boson mass	m_Z	91.1876(21) GeV/c^2	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	0.1187(20)	1.7×10^7

π = 3.141 592 653 589 793 238		e = 2.718 281 828 459 045 235	γ = 0.577 215 664 901 532 861
1 in ≡ 0.0254 m	1 G ≡ 10^{-4} T	1 eV = 1.602 176 53(14) × 10^{-19} J	kT at 300 K = [38.681 684(68)]$^{-1}$ eV
1 Å ≡ 0.1 nm	1 dyne ≡ 10^{-5} N	1 eV/c^2 = 1.782 661 81(15) × 10^{-36} kg	0 °C ≡ 273.15 K
1 barn ≡ 10^{-28} m^2	1 erg ≡ 10^{-7} J	2.997 924 58 × 10^9 esu = 1 C	1 atmosphere ≡ 760 Torr ≡ 101 325 Pa

* The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.
† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is ~ 1/128.
‡ Absolute lab 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 0.23149(15).

2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised 2001 by D.E. Groom (LBNL), February 2004 by M.A. Dobbs (LBNL). The figures in parentheses after some values give the one-standard deviation uncertainties in the last digit(s). Physical constants are from Ref. 1. While every effort has been made to obtain the most accurate current values of the listed quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference. The values and uncertainties for the cosmological parameters depend on the exact datasets, priors, and basis parameters used in the fit. Many of the parameters reported in this table are derived parameters or have non-Gaussian likelihoods. Their error bars may be highly correlated with other parameters and care must be taken when extrapolating to higher significance levels. In most cases we report the best fit running spectral index model parameters from the WMAPext plus 2dFGRS and Lyman α forest dataset, as reported in Ref. 2. Refer to Ref. 3 and the original papers for more information.

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	299 792 458 m s^{-1}	defined[4]
Newtonian gravitational constant	G_N	$6.6742(10) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[1, 5]
astronomical unit (mean $\oplus$–$\odot$ distance)	au	149 597 870 660(20) m	[6, 7]
tropical year (equinox to equinox) (2005.0)	yr	31 556 925.2 s	[6]
sidereal year (fixed star to fixed star) (2005.0)		31 558 149.8 s	[6]
mean sidereal day (2005.0)		$23^{\rm h}\,56^{\rm m}\,04\overset{\rm s}{.}090\,53$	[6]
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}	
Planck mass	$\sqrt{\hbar c/G_N}$	$1.22090(9) \times 10^{19}$ GeV/c^2	[1]
		$= 2.17645(16) \times 10^{-8}$ kg	
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.61624(12) \times 10^{-35}$ m	[1]
Hubble length	c/H_0	$\sim 1.2 \times 10^{26}$ m	[8]
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly	[9]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,1\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	2.953 250 08 km	[10]
solar mass	$M_\odot$	$1.988\,44(30) \times 10^{30}$ kg	[11]
solar equatorial radius	$R_\odot$	6.961×10^8 m	[6]
solar luminosity	$L_\odot$	$(3.846 \pm 0.008) \times 10^{26}$ W	[12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	8.870 056 22 mm	[13]
Earth mass	$M_\oplus$	$5.972\,3(9) \times 10^{24}$ kg	[14]
Earth mean equatorial radius	$R_\oplus$	$6.378\,140 \times 10^6$ m	[6]
luminosity conversion	L	$3.02 \times 10^{28} \times 10^{-0.4\ M_{\rm bol}}$ W	[15]
		($M_{\rm bol}$ = absolute bolometric magnitude	
		= bolometric magnitude at 10 pc	
flux conversion	$\mathscr{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\ m_{\rm bol}}$ W m^{-2}	from above
		($m_{\rm bol}$ = apparent bolometric magnitude)	
$v_\odot$ around center of Galaxy	$\Theta_\circ$	220(20) km s^{-1}	[16]
solar distance from galactic center	$R_\circ$	8.0(5) kpc	[17]
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3}	[18]
local halo density	$\rho_{\rm halo}$	2–13 $\times 10^{-25}$ g cm^{-3} $\approx$ 0.1–0.7 GeV/c^2cm^{-3}	[19]
present day Hubble expansion rate	H_0	100 h km s^{-1} Mpc^{-1}	
		$= h \times (9.778\,13$ Gyr$)^{-1}$	[20]
present day normalized Hubble expansion rate	h	$0.71^{+0.04}_{-0.03}$	[2]
critical density of the universe	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\ h^2\ M_\odot$Mpc^{-3}	
		$= 1.878\,37(28) \times 10^{-29}\ h^2$ g cm^{-3}	
		$= 1.053\,69(16) \times 10^{-5}\ h^2$ GeV cm^{-3}	derived
pressureless matter density of the universe	$\Omega_m \equiv \rho_m/\rho_c$	$0.135^{+0.008}_{0.009}/h^2 = 0.27 \pm 0.04$	[2]
baryon density of the universe	$\Omega_b \equiv \rho_b/\rho_c$	$0.0224 \pm 0.0009/h^2 = 0.044 \pm 0.004$	[2]
dark matter density of the universe	$\Omega_{dm} \equiv \Omega_m - \Omega_b$	$0.113^{+0.008}_{-0.009}/h^2 = 0.22 \pm 0.04$	[21]
radiation density of the universe	$\Omega_\gamma = \rho_\gamma/\rho_c$	$(2.471 \pm 0.004) \times 10^{-5}/h^2 = (4.9 \pm 0.5) \times 10^{-5}$	[22]
neutrino density of the universe	Ω_ν	$< (0.0076/h^2 = 0.015)$, 95% C.L.	[2]
dark energy density	Ω_Λ	0.73 ± 0.04	[2]
total energy density	$\Omega_{\rm tot} = \Omega_m + \ldots + \Omega_\Lambda$	1.02 ± 0.02	[2]
number density of baryons	n_b	$(2.5 \pm 0.1) \times 10^{-7}$/cm^3	[2]
number density of CMB photons	n_γ	(410.4 ± 0.5)/cm^{-3}	[23]
baryon-to-photon ratio	$\eta = n_b/n_\gamma$	$(6.1 \pm 0.2) \times 10^{-10}$	derived
scale factor for cosmological constant	$c^2/3H_0^2$	$2.853 \times 10^{51}\ h^{-2}$ m^2	
dark energy equation of state	w	< -0.78 at 95% C.L.	[2, 24]
fluctuation amplitude at $8h^{-1}$ Mpc scale	σ_8	0.84 ± 0.04	[2]
scalar spectral index at $k_0 = 0.05$ Mpc^{-1}	n_s	0.93 ± 0.03	[2]

Quantity	Symbol, equation	Value	Reference, footnote
running spectral index slope at $k_0 = 0.05$ Mpc^{-1}	$dn_s/d\ln k$	$-0.031^{+0.016}_{-0.018}$	[2]
tensor to scalar field perturbations ratio at $k_0 = 0.002$ Mpc^{-1}	$r = T/S$	< 0.71 at 95% C.L.	[2, 25]
reionization optical depth	τ	0.17 ± 0.04	[2]
age of the universe	t_0	13.7 ± 0.2 Gyr	[2]
present day CBR temperature	T_0	2.725 ± 0.001 K	[26]
solar velocity with respect to CBR		368 ± 2 km/s towards $(\ell, b) = (263.85° \pm 0.10°, 48.25° \pm 0.04°)$	[27, 28]
Local group velocity with respect to CBR	$v_{\rm LG}$	$627 \pm 22\,{\rm km\,s^{-1}}$ towards $(\ell, b) = (276° \pm 3°, 30° \pm 3°)$	[27]
entropy density/Boltzmann constant	s/k	$2\,889.2\ (T/2.725)^3$ cm^{-3}	[15]

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7. JPL Planetary Ephemerides, E. Myles Standish, Jr., private communication (1989).
8. Derived from H_0 [2].
9. 1 AU divided by $\pi/648\,000$; quoted error is from the JPL Planetary Ephemerides value of the AU [7].
10. Product of $2/c^2$ and the heliocentric gravitational constant [6]. The given 9-place accuracy seems consistent with uncertainties in defining the earth's orbital parameters.
11. Obtained from the heliocentric gravitational constant [6] and G_N [1]. The error is the 150 ppm standard deviation of G_N.
12. 1996 mean total solar irradiance (TSI) = 1367.5 ± 2.7 [29]; the solar luminosity is $4\pi \times (1\ {\rm AU})^2$ times this quantity. This value increased by 0.036% between the minima of solar cycles 21 and 22. It was modulated with an amplitude of 0.039% during solar cycle 21 [30].

    Sackmann *et al.* [31] use TSI = 1370 ± 2 W m^{-2}, but conclude that the solar luminosity ($L_\odot = 3.853 \times 10^{26}$ J s^{-1}) has an uncertainty of 1.5%. Their value comes from three 1977–83 papers, and they comment that the error is based on scatter among the reported values, which is substantially in excess of that expected from the individual quoted errors.

    The conclusion of the 1971 review by Thekaekara and Drummond [32] ($1353 \pm 1\%$ W m^{-2}) is often quoted [33]. The conversion to luminosity is not given in the Thekaekara and Drummond paper, and we cannot exactly reproduce the solar luminosity given in Ref. 33.

    Finally, a value based on the 1954 spectral curve due to Johnson [34] ($1395 \pm 1\%$ W m^{-2}, or $L_\odot = 3.92 \times 10^{26}$ J s^{-1}) has been used widely, and may be the basis for the higher value of the solar luminosity and the corresponding lower value of the solar absolute bolometric magnitude (4.72) still common in the literature [15].
13. Product of $2/c^2$, the heliocentric gravitational constant from Ref. 6, and the earth/sun mass ratio, also from Ref. 6. The given 9-place accuracy appears to be consistent with uncertainties in actually defining the earth's orbital parameters.
14. Obtained from the geocentric gravitational constant [6] and G_N [1]. The error is the 150 ppm standard deviation of G_N.
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19. E.I. Gates, G. Gyuk, and M.S. Turner (Astrophys. J. **449**, L133 (1995)) find the local halo density to be $9.2^{+3.8}_{-3.1} \times 10^{-25}$ g cm^{-3}, but also comment that previously published estimates are in the range $1–10 \times 10^{-25}$ g cm^{-3}.

    The value 0.3 GeV/c^2 has been taken as "standard" in several papers setting limits on WIMP mass limits, *e.g.* in M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992).
20. Conversion using length of tropical year.
21. Derived from [2].
22. $\rho_\gamma = \dfrac{\pi^2}{15}\dfrac{(k_BT)^4}{(\hbar c)^3}$, using T_0 from Ref. 26.
23. $n_\gamma = \dfrac{2\zeta(3)}{\pi^2}(\dfrac{k_BT}{\hbar c})^3$, using T_0 from Ref. 26.
24. Note that one of the priors assumed when deriving this parameter is $w \geq -1$.
25. There are several definitions of r used in the literature, here r corresponds to the definition used by Ref. 2.
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3. INTERNATIONAL SYSTEM OF UNITS (SI)

See "The International System of Units (SI)," NIST Special Publication **330**, B.N. Taylor, ed. (USGPO, Washington, DC, 1991); and "Guide for the Use of the International System of Units (SI)," NIST Special Publication **811**, 1995 edition, B.N. Taylor (USGPO, Washington, DC, 1995).

Physical quantity	**Name of unit**	**Symbol**
Base units		
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
Derived units with special names		
plane angle	radian	rad
solid angle	steradian	sr
frequency	hertz	Hz
energy	joule	J
force	newton	N
pressure	pascal	Pa
power	watt	W
electric charge	coulomb	C
electric potential	volt	V
electric resistance	ohm	Ω
electric conductance	siemens	S
electric capacitance	farad	F
magnetic flux	weber	Wb
inductance	henry	H
magnetic flux density	tesla	T
luminous flux	lumen	lm
illuminance	lux	lx
celsius temperature	degree celsius	°C
activity (of a radioactive source)*	becquerel	Bq
absorbed dose (of ionizing radiation)*	gray	Gy
dose equivalent*	sievert	Sv

*See our section 29, on "Radioactivity and radiation protection," p. 272.

SI prefixes

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

4. PERIODIC TABLE OF THE ELEMENTS

Table 4.1. Revised 2004 by C.G. Wohl (LBNL). Adapted from the Commission of Atomic Weights and Isotopic Abundances, "Atomic Weights of the Elements 1995," Pure and Applied Chemistry **68**, 2339 (1996), and G. Audi and A.H. Wapstra, "The 1993 Mass Evaluation," Nucl. Phys. **A565**, 1 (1993). The atomic number (top left) is the number of protons in the nucleus. The atomic mass (bottom) is weighted by isotopic abundances in the Earth's surface. For a new determination of atomic masses, not weighted by abundances, see G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003). Atomic masses are relative to the mass of the carbon-12 isotope, defined to be exactly 12 unified atomic mass units (u). Errors range from 1 to 9 in the last digit quoted. Relative isotopic abundances often vary considerably, both in natural and commercial samples. A number in parentheses is the mass of the longest-lived isotope of that element—no stable isotope exists. However, although Th, Pa, and U have no stable isotopes, they do have characteristic terrestrial compositions, and meaningful weighted masses can be given. For elements 110 and 111, the atomic numbers of confirmed isotopes are given.

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 Ds Darmstadt. [269,271]	111 [272]							

Series															
Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)

5. ELECTRONIC STRUCTURE OF THE ELEMENTS

Table 5.1. Reviewed 2002 by W.C. Martin (NIST). The electronic configurations and the ionization energies are from the NIST database *Ground Levels and Ionization Energies for the Neutral Atoms*, W.C. Martin and A. Musgrove (2002), `http://physics.nist.gov` (select "Physical Reference Data"). The electron configuration for, say, iron indicates an argon electronic core (see argon) plus six $3d$ electrons and two $4s$ electrons. The ionization energy is the least energy necessary to remove to infinity one electron from an atom of the element.

	Element		Electron configuration ($3d^5$ = five $3d$ electrons, *etc.*)		Ground state $^{2S+1}L_J$	Ionization energy (eV)
1	H	Hydrogen	$1s$		$^2S_{1/2}$	13.5984
2	He	Helium	$1s^2$		$^1S_0$	24.5874
3	Li	Lithium	(He) $2s$		$^2S_{1/2}$	5.3917
4	Be	Beryllium	(He) $2s^2$		$^1S_0$	9.3227
5	B	Boron	(He) $2s^2\ 2p$		$^2P_{1/2}$	8.2980
6	C	Carbon	(He) $2s^2\ 2p^2$		$^3P_0$	11.2603
7	N	Nitrogen	(He) $2s^2\ 2p^3$		$^4S_{3/2}$	14.5341
8	O	Oxygen	(He) $2s^2\ 2p^4$		$^3P_2$	13.6181
9	F	Fluorine	(He) $2s^2\ 2p^5$		$^2P_{3/2}$	17.4228
10	Ne	Neon	(He) $2s^2\ 2p^6$		$^1S_0$	21.5646
11	Na	Sodium	(Ne) $3s$		$^2S_{1/2}$	5.1391
12	Mg	Magnesium	(Ne) $3s^2$		$^1S_0$	7.6462
13	Al	Aluminum	(Ne) $3s^2\ 3p$		$^2P_{1/2}$	5.9858
14	Si	Silicon	(Ne) $3s^2\ 3p^2$		$^3P_0$	8.1517
15	P	Phosphorus	(Ne) $3s^2\ 3p^3$		$^4S_{3/2}$	10.4867
16	S	Sulfur	(Ne) $3s^2\ 3p^4$		$^3P_2$	10.3600
17	Cl	Chlorine	(Ne) $3s^2\ 3p^5$		$^2P_{3/2}$	12.9676
18	Ar	Argon	(Ne) $3s^2\ 3p^6$		$^1S_0$	15.7596
19	K	Potassium	(Ar) $4s$		$^2S_{1/2}$	4.3407
20	Ca	Calcium	(Ar) $4s^2$		$^1S_0$	6.1132
21	Sc	Scandium	(Ar) $3d\ 4s^2$	Transition elements	$^2D_{3/2}$	6.5615
22	Ti	Titanium	(Ar) $3d^2\ 4s^2$		$^3F_2$	6.8281
23	V	Vanadium	(Ar) $3d^3\ 4s^2$		$^4F_{3/2}$	6.7463
24	Cr	Chromium	(Ar) $3d^5\ 4s$		$^7S_3$	6.7665
25	Mn	Manganese	(Ar) $3d^5\ 4s^2$		$^6S_{5/2}$	7.4340
26	Fe	Iron	(Ar) $3d^6\ 4s^2$		$^5D_4$	7.9024
27	Co	Cobalt	(Ar) $3d^7\ 4s^2$		$^4F_{9/2}$	7.8810
28	Ni	Nickel	(Ar) $3d^8\ 4s^2$		$^3F_4$	7.6398
29	Cu	Copper	(Ar) $3d^{10}\ 4s$		$^2S_{1/2}$	7.7264
30	Zn	Zinc	(Ar) $3d^{10}\ 4s^2$		$^1S_0$	9.3942
31	Ga	Gallium	(Ar) $3d^{10}\ 4s^2\ 4p$		$^2P_{1/2}$	5.9993
32	Ge	Germanium	(Ar) $3d^{10}\ 4s^2\ 4p^2$		$^3P_0$	7.8994
33	As	Arsenic	(Ar) $3d^{10}\ 4s^2\ 4p^3$		$^4S_{3/2}$	9.7886
34	Se	Selenium	(Ar) $3d^{10}\ 4s^2\ 4p^4$		$^3P_2$	9.7524
35	Br	Bromine	(Ar) $3d^{10}\ 4s^2\ 4p^5$		$^2P_{3/2}$	11.8138
36	Kr	Krypton	(Ar) $3d^{10}\ 4s^2\ 4p^6$		$^1S_0$	13.9996
37	Rb	Rubidium	(Kr) $5s$		$^2S_{1/2}$	4.1771
38	Sr	Strontium	(Kr) $5s^2$		$^1S_0$	5.6949
39	Y	Yttrium	(Kr) $4d\ 5s^2$	Transition elements	$^2D_{3/2}$	6.2173
40	Zr	Zirconium	(Kr) $4d^2\ 5s^2$		$^3F_2$	6.6339
41	Nb	Niobium	(Kr) $4d^4\ 5s$		$^6D_{1/2}$	6.7589
42	Mo	Molybdenum	(Kr) $4d^5\ 5s$		$^7S_3$	7.0924
43	Tc	Technetium	(Kr) $4d^5\ 5s^2$		$^6S_{5/2}$	7.28
44	Ru	Ruthenium	(Kr) $4d^7\ 5s$		$^5F_5$	7.3605
45	Rh	Rhodium	(Kr) $4d^8\ 5s$		$^4F_{9/2}$	7.4589
46	Pd	Palladium	(Kr) $4d^{10}$		$^1S_0$	8.3369
47	Ag	Silver	(Kr) $4d^{10}\ 5s$		$^2S_{1/2}$	7.5762
48	Cd	Cadmium	(Kr) $4d^{10}\ 5s^2$		$^1S_0$	8.9938

49	In	Indium	(Kr) $4d^{10}\,5s^2\;5p$		$^2P_{1/2}$	5.7864
50	Sn	Tin	(Kr) $4d^{10}\,5s^2\;5p^2$		$^3P_0$	7.3439
51	Sb	Antimony	(Kr) $4d^{10}\,5s^2\;5p^3$		$^4S_{3/2}$	8.6084
52	Te	Tellurium	(Kr) $4d^{10}\,5s^2\;5p^4$		$^3P_2$	9.0096
53	I	Iodine	(Kr) $4d^{10}\,5s^2\;5p^5$		$^2P_{3/2}$	10.4513
54	Xe	Xenon	(Kr) $4d^{10}\,5s^2\;5p^6$		$^1S_0$	12.1298
55	Cs	Cesium	(Xe) $6s$		$^2S_{1/2}$	3.8939
56	Ba	Barium	(Xe) $6s^2$		$^1S_0$	5.2117
57	La	Lanthanum	(Xe) $5d\;6s^2$		$^2D_{3/2}$	5.5770
58	Ce	Cerium	(Xe) $4f\;5d\;6s^2$		$^1G_4$	5.5387
59	Pr	Praseodymium	(Xe) $4f^3\;6s^2$	Lanthanides	$^4I_{9/2}$	5.464
60	Nd	Neodymium	(Xe) $4f^4\;6s^2$		$^5I_4$	5.5250
61	Pm	Promethium	(Xe) $4f^5\;6s^2$		$^6H_{5/2}$	5.58
62	Sm	Samarium	(Xe) $4f^6\;6s^2$		$^7F_0$	5.6437
63	Eu	Europium	(Xe) $4f^7\;6s^2$		$^8S_{7/2}$	5.6704
64	Gd	Gadolinium	(Xe) $4f^7\;5d\;6s^2$		$^9D_2$	6.1498
65	Tb	Terbium	(Xe) $4f^9\;6s^2$		$^6H_{15/2}$	5.8638
66	Dy	Dysprosium	(Xe) $4f^{10}\;6s^2$		$^5I_8$	5.9389
67	Ho	Holmium	(Xe) $4f^{11}\;6s^2$		$^4I_{15/2}$	6.0215
68	Er	Erbium	(Xe) $4f^{12}\;6s^2$		$^3H_6$	6.1077
69	Tm	Thulium	(Xe) $4f^{13}\;6s^2$		$^2F_{7/2}$	6.1843
70	Yb	Ytterbium	(Xe) $4f^{14}\;6s^2$		$^1S_0$	6.2542
71	Lu	Lutetium	(Xe) $4f^{14}5d\;6s^2$		$^2D_{3/2}$	5.4259
72	Hf	Hafnium	(Xe) $4f^{14}5d^2\;6s^2$	Transition elements	$^3F_2$	6.8251
73	Ta	Tantalum	(Xe) $4f^{14}5d^3\;6s^2$		$^4F_{3/2}$	7.5496
74	W	Tungsten	(Xe) $4f^{14}5d^4\;6s^2$		$^5D_0$	7.8640
75	Re	Rhenium	(Xe) $4f^{14}5d^5\;6s^2$		$^6S_{5/2}$	7.8335
76	Os	Osmium	(Xe) $4f^{14}5d^6\;6s^2$		$^5D_4$	8.4382
77	Ir	Iridium	(Xe) $4f^{14}5d^7\;6s^2$		$^4F_{9/2}$	8.9670
78	Pt	Platinum	(Xe) $4f^{14}5d^9\;6s$		$^3D_3$	8.9588
79	Au	Gold	(Xe) $4f^{14}5d^{10}6s$		$2S_{1/2}$	9.2255
80	Hg	Mercury	(Xe) $4f^{14}5d^{10}6s^2$		$^1S_0$	10.4375
81	Tl	Thallium	(Xe) $4f^{14}5d^{10}6s^2\;6p$		$^2P_{1/2}$	6.1082
82	Pb	Lead	(Xe) $4f^{14}5d^{10}6s^2\;6p^2$		$^3P_0$	7.4167
83	Bi	Bismuth	(Xe) $4f^{14}5d^{10}6s^2\;6p^3$		$^4S_{3/2}$	7.2855
84	Po	Polonium	(Xe) $4f^{14}5d^{10}6s^2\;6p^4$		$^3P_2$	8.4167
85	At	Astatine	(Xe) $4f^{14}5d^{10}6s^2\;6p^5$		$^2P_{3/2}$	
86	Rn	Radon	(Xe) $4f^{14}5d^{10}6s^2\;6p^6$		$^1S_0$	10.7485
87	Fr	Francium	(Rn) $7s$		$^2S_{1/2}$	4.0727
88	Ra	Radium	(Rn) $7s^2$		$^1S_0$	5.2784
89	Ac	Actinium	(Rn) $6d\;7s^2$		$^2D_{3/2}$	5.17
90	Th	Thorium	(Rn) $6d^2\;7s^2$		$^3F_2$	6.3067
91	Pa	Protactinium	(Rn) $5f^2\;6d\;7s^2$	Actinides	$^4K_{11/2}$	5.89
92	U	Uranium	(Rn) $5f^3\;6d\;7s^2$		$^5L_6$	6.1941
93	Np	Neptunium	(Rn) $5f^4\;6d\;7s^2$		$^6L_{11/2}$	6.2657
94	Pu	Plutonium	(Rn) $5f^6\;7s^2$		$^7F_0$	6.0262
95	Am	Americium	(Rn) $5f^7\;7s^2$		$^8S_{7/2}$	5.9738
96	Cm	Curium	(Rn) $5f^7\;6d\;7s^2$		$^9D_2$	5.9915
97	Bk	Berkelium	(Rn) $5f^9\;7s^2$		$^6H_{15/2}$	6.1979
98	Cf	Californium	(Rn) $5f^{10}\;7s^2$		$^5I_8$	6.2817
99	Es	Einsteinium	(Rn) $5f^{11}\;7s^2$		$^4I_{15/2}$	6.42
100	Fm	Fermium	(Rn) $5f^{12}\;7s^2$		$^3H_6$	6.50
101	Md	Mendelevium	(Rn) $5f^{13}\;7s^2$		$^2F_{7/2}$	6.58
102	No	Nobelium	(Rn) $5f^{14}\;7s^2$		$^1S_0$	6.65
103	Lr	Lawrencium	(Rn) $5f^{14}\;7s^2\;7p$?		$^2P_{1/2}$?	
104	Rf	Rutherfordium	(Rn) $5f^{14}6d^2\;7s^2$?		$^3F_2$?	6.0?

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\rm min}$ [b] $\left\{\frac{\rm MeV}{\rm g/cm^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times 10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	$\approx$0.32	$\approx$18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO_2 solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete [f]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 [g]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH_4			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C_2H_6			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) [h]	184.5	(1.038) [h]
Propane, C_3H_8			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, $(CH_3)_2CHCH_3$			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, $CH_3(CH_2)_6CH_3$			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, $CH_3(CH_2)_{n\approx 23}CH_3$			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 [i]			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) [j]			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthlate (Mylar) [k]			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene [l]			0.57034	57.0	78.4	2.076	44.64	$\approx$47.9	0.92–0.95		—
Polyimide film (Kapton) [m]			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas [n]			0.53937	59.3	83.0	1.929	40.49	$\approx$34.4	1.16–1.20		$\approx$1.49
Polystyrene, scintillator [o]			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) [p]			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltolulene, scintillator [q]			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Aluminum oxide (Al_2O_3)			0.49038	67.0	98.9	1.647	27.94	7.04	3.97		1.761
Barium fluoride (BaF_2)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) [r]			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel [s]			0.50093	66.3	96.9	1.740	27.25	136@ρ=0.2	0.04–0.6		1.0+0.21ρ
NEMA G10 plate [t]				62.6	90.2	1.87	33.0	19.4	1.7		—

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is ($\kappa$–1)×$10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(253.9)	—	—	—	—	—
He	(64)	—	—	—	—	—
Li	—	—	56	0.86	8.55(0°)	0.17
Be	—	37	12.4	0.436	5.885(0°)	0.38
C	—	0.7	0.6–4.3	0.165	1375(0°)	0.057
N_2	(548.5)	—	—	—	—	—
O_2	(495)	—	—	—	—	—
Ne	(127)	—	—	—	—	—
Al	—	10	23.9	0.215	2.65(20°)	0.53
Si	11.9	16	2.8–7.3	0.162	—	0.20
Ar	(517)	—	—	—	—	—
Ti	—	16.8	8.5	0.126	50(0°)	—
Fe	—	28.5	11.7	0.11	9.71(20°)	0.18
Cu	—	16	16.5	0.092	1.67(20°)	0.94
Ge	16.0	—	5.75	0.073	—	0.14
Sn	—	6	20	0.052	11.5(20°)	0.16
Xe	—	—	—	—	—	—
W	—	50	4.4	0.032	5.5(20°)	0.48
Pt	—	21	8.9	0.032	9.83(0°)	0.17
Pb	—	2.6	29.3	0.038	20.65(20°)	0.083
U	—	—	36.1	0.028	29(20°)	0.064

1. R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables **30**, 261–271 (1984).
2. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **33**, 1189–1218 (1982).
3. D.E. Groom, N.V. Mokhov, and S.I. Striganov, "Muon stopping-power and range tables," Atomic Data and Nuclear Data Tables **78**, 183–356 (2001).
4. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **35**, 665 (1984) & `http://physics.nist.gov/PhysRefData/Star/Text/contents.html`.

a. σ_T, λ_T and λ_I are energy dependent. Values quoted apply to high energy range, where energy dependence is weak. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda^{-1} = N_A \sum w_j \, \sigma_j \, /A_j$, where N is Avogadro's number and w_j is the weight fraction of the jth element in the element, compound, or mixture. $\sigma_{\rm total}$ at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$. $\sigma_{\rm inelastic} = \sigma_{\rm total} - \sigma_{\rm elastic} - \sigma_{\rm quasielastic}$; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

b. For minimum-ionizing muons (results are very slightly different for other particles). Minimum dE/dx from Ref. 3, using density effect correction coefficients from Ref. 1. For electrons and positrons see Ref. 4. Ionization energy loss is discussed in Sec. 27.

c. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium are given. Corrections for molecular binding applied for H_2 and D_2. For atomic H, X_0 = 63.05 g/cm^2.

d. For molecular hydrogen (deuterium). For atomic H, X_0 = 63.047 g cm^{-2}.

e. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm^3.

f. Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN–LRL–RHEL Shielding exp., UCRL–17841 (1968).

g. For typical fused quartz. The specific gravity of crystalline quartz is 2.64.

h. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

i. Nylon, Type 6, $(NH(CH_2)_5CO)_n$

j. Polycarbonate (Lexan), $(C_{16}H_{14}O_3)_n$

k. Polyethylene terephthlate, monomer, $C_5H_4O_2$

l. Polyethylene, monomer CH_2 =CH_2

m. Polymide film (Kapton), $(C_{22}H_{10}N_2O_5)_n$

n. Polymethylmethacralate, monomer CH_2 =$C(CH_3)CO_2CH_3$

o. Polystyrene, monomer C_6H_5CH=CH_2

p. Teflon, monomer CF_2 =CF_2

q. Polyvinyltolulene, monomer 2-$CH_3C_6H_4CH$=CH_2

r. Bismuth germanate (BGO), $(Bi_2O_3)_2(GeO_2)_3$

s. 97% SiO_2 + 3% H_2O by weight; see A. R. Buzykaev *et al.*, Nucl. Instrum. Methods **A433**, 396 (1999). Aerogel in the density range 0.04–0.06 g/cm^3 has been used in Čerenkov counters, but aerogel with higher and lower densities has been produced. ρ = density in g/cm^3.

t. G10-plate, typically 60% SiO_2 and 40% epoxy.

7. ELECTROMAGNETIC RELATIONS

Quantity	Gaussian CGS	SI
Conversion factors:		
Charge:	$2.997\,924\,58 \times 10^9$ esu	$= 1$ C $= 1$ A s
Potential:	$(1/299.792\,458)$ statvolt (ergs/esu)	$= 1$ V $= 1$ J C^{-1}
Magnetic field:	10^4 gauss $= 10^4$ dyne/esu	$= 1$ T $= 1$ N $A^{-1}m^{-1}$
Lorentz force:	$\mathbf{F} = q\,(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B})$	$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
Maxwell equations:	$\boldsymbol{\nabla} \cdot \mathbf{D} = 4\pi\rho$ $\boldsymbol{\nabla} \times \mathbf{H} - \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} = \frac{4\pi}{c}\mathbf{J}$ $\boldsymbol{\nabla} \cdot \mathbf{B} = 0$ $\boldsymbol{\nabla} \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$	$\boldsymbol{\nabla} \cdot \mathbf{D} = \rho$ $\boldsymbol{\nabla} \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$ $\boldsymbol{\nabla} \cdot \mathbf{B} = 0$ $\boldsymbol{\nabla} \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$
Constitutive relations:	$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}, \quad \mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$	$\mathbf{D} = \epsilon_0\mathbf{E} + \mathbf{P}, \quad \mathbf{H} = \mathbf{B}/\mu_0 - \mathbf{M}$
Linear media:	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$	$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{H} = \mathbf{B}/\mu$
Permitivity of free space:	1	$\epsilon_0 = 8.854\,187\ldots \times 10^{-12}$ F m^{-1}
Permeability of free space:	1	$\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}
Fields from potentials:	$\mathbf{E} = -\boldsymbol{\nabla}V - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \boldsymbol{\nabla} \times \mathbf{A}$	$\mathbf{E} = -\boldsymbol{\nabla}V - \frac{\partial \mathbf{A}}{\partial t}$ $\mathbf{B} = \boldsymbol{\nabla} \times \mathbf{A}$
Static potentials: (coulomb gauge)	$V = \sum_{\text{charges}} \frac{q_i}{r_i} = \int \frac{\rho\,(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\,d^3x'$ $\mathbf{A} = \frac{1}{c}\oint \frac{I\,d\boldsymbol{\ell}}{\lvert\mathbf{r} - \mathbf{r}'\rvert} = \frac{1}{c}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\,d^3x'$	$V = \frac{1}{4\pi\epsilon_0}\sum_{\text{charges}} \frac{q_i}{r_i} = \frac{1}{4\pi\epsilon_0}\int \frac{\rho\,(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\,d^3x'$ $\mathbf{A} = \frac{\mu_0}{4\pi}\oint \frac{I\,d\boldsymbol{\ell}}{\lvert\mathbf{r} - \mathbf{r}'\rvert} = \frac{\mu_0}{4\pi}\int \frac{\mathbf{J}(\mathbf{r}')}{\lvert\mathbf{r} - \mathbf{r}'\rvert}\,d^3x'$
Relativistic transformations: ($\mathbf{v}$ is the velocity of the primed frame as seen in the unprimed frame)	$\mathbf{E}'_{\parallel} = \mathbf{E}_{\parallel}$ $\mathbf{E}'_{\perp} = \gamma(\mathbf{E}_{\perp} + \frac{1}{c}\mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_{\parallel} = \mathbf{B}_{\parallel}$ $\mathbf{B}'_{\perp} = \gamma(\mathbf{B}_{\perp} - \frac{1}{c}\mathbf{v} \times \mathbf{E})$	$\mathbf{E}'_{\parallel} = \mathbf{E}_{\parallel}$ $\mathbf{E}'_{\perp} = \gamma(\mathbf{E}_{\perp} + \mathbf{v} \times \mathbf{B})$ $\mathbf{B}'_{\parallel} = \mathbf{B}_{\parallel}$ $\mathbf{B}'_{\perp} = \gamma(\mathbf{B}_{\perp} - \frac{1}{c^2}\mathbf{v} \times \mathbf{E})$

$\frac{1}{4\pi\epsilon_0} = c^2 \times 10^{-7}$ N $A^{-2} = 8.987\,55\ldots \times 10^9$ m F^{-1} ; $\quad \frac{\mu_0}{4\pi} = 10^{-7}$ N A^{-2} ; $\quad c = \frac{1}{\sqrt{\mu_0\epsilon_0}} = 2.997\,924\,\,58 \times 10^8$ m s^{-1}

7.1. Impedances (SI units)

ρ = resistivity at room temperature in $10^{-8}\ \Omega$ m:
~ 1.7 for Cu ~ 5.5 for W
~ 2.4 for Au ~ 73 for SS 304
~ 2.8 for Al ~ 100 for Nichrome
(Al alloys may have double the Al value.)

For alternating currents, instantaneous current I, voltage V, angular frequency ω:

$$V = V_0\, e^{j\omega t} = ZI\ . \quad (7.1)$$

Impedance of self-inductance L: $Z = j\omega L$.

Impedance of capacitance C: $Z = 1/j\omega C$.

Impedance of free space: $Z = \sqrt{\mu_0/\epsilon_0} = 376.7\ \Omega$.

High-frequency surface impedance of a good conductor:

$$Z = \frac{(1+j)\,\rho}{\delta}\ , \quad \text{where } \delta = \text{skin depth}\ ; \quad (7.2)$$

$$\delta = \sqrt{\frac{\rho}{\pi\nu\mu}} \approx \frac{6.6\text{ cm}}{\sqrt{\nu\,(\text{Hz})}} \quad \text{for Cu}\ . \quad (7.3)$$

7.2. Capacitance $\widehat{C}$ and inductance $\widehat{L}$ per unit length (SI units) [negligible skin depth]

Flat rectangular plates of width w, separated by $d \ll w$ with linear medium (ϵ, μ) between:

$$\widehat{C} = \epsilon\,\frac{w}{d}\ ; \qquad \widehat{L} = \mu\,\frac{d}{w}\ ; \quad (7.4)$$

$$\epsilon/\epsilon_0 = 2 \text{ to } 6 \text{ for plastics; } 4 \text{ to } 8 \text{ for porcelain, glasses;} \quad (7.5)$$

$$\mu/\mu_0 \simeq 1\ . \quad (7.6)$$

Coaxial cable of inner radius r_1, outer radius r_2:

$$\widehat{C} = \frac{2\pi\,\epsilon}{\ln\,(r_2/r_1)}\ ; \quad \widehat{L} = \frac{\mu}{2\pi}\,\ln\,(r_2/r_1)\ . \quad (7.7)$$

Transmission lines (no loss):

$$\text{Impedance: } Z = \sqrt{\widehat{L}/\widehat{C}}\ . \quad (7.8)$$

$$\text{Velocity: } v = 1/\sqrt{\widehat{L}\,\widehat{C}} = 1/\sqrt{\mu\epsilon}\ . \quad (7.9)$$

7.3. Synchrotron radiation (CGS units)

For a particle of charge e, velocity $v = \beta c$, and energy $E = \gamma mc^2$, traveling in a circular orbit of radius R, the classical energy loss per revolution δE is

$$\delta E = \frac{4\pi}{3}\,\frac{e^2}{R}\,\beta^3\,\gamma^4\ . \quad (7.10)$$

For high-energy electrons or positrons ($\beta \approx 1$), this becomes

$$\delta E\ (\text{in MeV}) \approx 0.0885\ [E(\text{in GeV})]^4/R(\text{in m})\ . \quad (7.11)$$

For $\gamma \gg 1$, the energy radiated per revolution into the photon energy interval $d(\hbar\omega)$ is

$$dI = \frac{8\pi}{9}\alpha\,\gamma\,F(\omega/\omega_c)\,d(\hbar\omega)\ , \quad (7.12)$$

where $\alpha = e^2/\hbar c$ is the fine-structure constant and

$$\omega_c = \frac{3\gamma^3 c}{2R} \quad (7.13)$$

is the critical frequency. The normalized function $F(y)$ is

$$F(y) = \frac{9}{8\pi}\sqrt{3}\,y\int_y^\infty K_{5/3}(x)\ dx\ , \quad (7.14)$$

where $K_{5/3}(x)$ is a modified Bessel function of the third kind. For electrons or positrons,

$$\hbar\omega_c\,(\text{in keV}) \approx 2.22\ [E(\text{in GeV})]^3/R(\text{in m})\ . \quad (7.15)$$

Fig. 7.1 shows $F(y)$ over the important range of y.

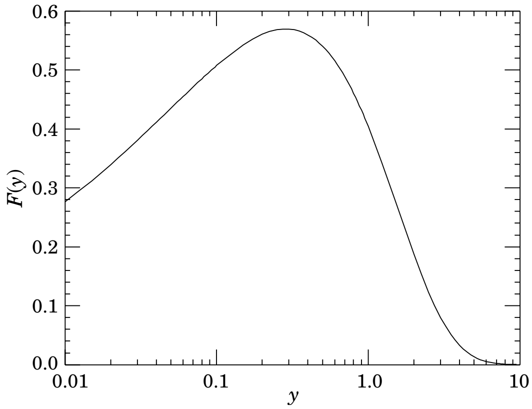

Figure 7.1: The normalized synchrotron radiation spectrum $F(y)$.

For $\gamma \gg 1$ and $\omega \ll \omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx 3.3\alpha\,(\omega R/c)^{1/3}\ , \quad (7.16)$$

whereas for

$\gamma \gg 1$ and $\omega \gtrsim 3\omega_c$,

$$\frac{dI}{d(\hbar\omega)} \approx \sqrt{\frac{3\pi}{2}}\,\alpha\,\gamma\left(\frac{\omega}{\omega_c}\right)^{1/2} e^{-\omega/\omega_c}\left[1 + \frac{55}{72}\frac{\omega_c}{\omega} + \ldots\right]\ . \quad (7.17)$$

The radiation is confined to angles $\lesssim 1/\gamma$ relative to the instantaneous direction of motion. For $\gamma \gg 1$, where Eq. (7.12) applies, the mean number of photons emitted per revolution is

$$N_\gamma = \frac{5\pi}{\sqrt{3}}\alpha\gamma\ , \quad (7.18)$$

and the mean energy per photon is

$$\langle\hbar\omega\rangle = \frac{8}{15\sqrt{3}}\hbar\omega_c\ . \quad (7.19)$$

When $\langle\hbar\omega\rangle \gtrsim \text{O}(E)$, quantum corrections are important.

See J.D. Jackson, *Classical Electrodynamics*, 3rd edition (John Wiley & Sons, New York, 1998) for more formulae and details. (Note that ealier editions had ω_c twice as large as Eq. (7.13).

8. NAMING SCHEME FOR HADRONS

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8.1. Introduction

We introduced in the 1986 edition [1] a new naming scheme for the hadrons. Changes from older terminology affected mainly the heavier mesons made of the light (u, d, and s) quarks. Old and new names were listed alongside until 1994. Names also change from edition to edition because some characteristic like mass or spin changes. The Summary Tables give both the new and old names whenever a change occurred.

8.2. "Neutral-flavor" mesons ($S = C = B = T = 0$)

Table 8.1 shows the names for mesons having the strangeness and all heavy-flavor quantum numbers equal to zero. The scheme is designed for all ordinary non-exotic mesons, but it will work for many exotic types too, if needed.

Table 8.1: Symbols for mesons with the strangeness and all heavy-flavor quantum numbers equal to zero.

	$J^{PC} =$	0^{-+}, 2^{-+}, ⋮	1^{+-}, 3^{+-}, ⋮	1^{--}, 2^{--}, ⋮	0^{++}, 1^{++}, ⋮
$q\overline{q}$ content	$^{2S+1}L_J =$	$^1(L\,\text{even})_J$	$^1(L\,\text{odd})_J$	$^3(L\,\text{even})_J$	$^3(L\,\text{odd})_J$
$u\overline{d}, u\overline{u} - d\overline{d}, d\overline{u}$	$(I = 1)$	π	b	ρ	a
$d\overline{d} + u\overline{u}$ and/or $s\overline{s}$	$(I = 0)$	η, η'	h, h'	ω, ϕ	f, f'
$c\overline{c}$		η_c	h_c	$\psi^\dagger$	χ_c
$b\overline{b}$		η_b	h_b	Υ	χ_b
$t\overline{t}$		η_t	h_t	θ	χ_t

†The J/ψ remains the J/ψ.

First, we assign names to those states with quantum numbers compatible with being $q\overline{q}$ states. The rows of the Table give the possible $q\overline{q}$ content. The columns give the possible parity/charge-conjugation states,

$$PC = -+,\ +-,\ --,\ \text{and}\ ++\ ;$$

these combinations correspond one-to-one with the angular-momentum state $^{2S+1}L_J$ of the $q\overline{q}$ system being

$$^1(L\ \text{even})_J,\ ^1(L\ \text{odd})_J,\ ^3(L\ \text{even})_J,\ \text{or}\ ^3(L\ \text{odd})_J\ .$$

Here S, L, and J are the spin, orbital, and total angular momenta of the $q\overline{q}$ system. The quantum numbers are related by

$$P = (-1)^{L+1},\ C = (-1)^{L+S},\ \text{and}\ G\ \text{parity}\ = (-1)^{L+S+I},$$

where of course the C quantum number is only relevant to neutral mesons.

The entries in the Table give the meson names. The spin J is added as a subscript except for pseudoscalar and vector mesons, and the mass is added in parentheses for mesons that decay strongly. However, for the lightest meson resonances, we omit the mass.

Measurements of the mass, quark content (where relevant), and quantum numbers I, J, P, and C (or G) of a meson thus fix its symbol. Conversely, these properties may be inferred unambiguously from the symbol.

If the main symbol cannot be assigned because the quantum numbers are unknown, X is used. Sometimes it is not known whether a meson is mainly the isospin-0 mix of $u\overline{u}$ and $d\overline{d}$ or is mainly $s\overline{s}$. A prime (or pair ω, ϕ) may be used to distinguish two such mixing states.

We follow custom and use spectroscopic names such as $\Upsilon(1S)$ as the primary name for most of those ψ, Υ, and χ states whose spectroscopic identity is known. We use the form $\Upsilon(9460)$ as an alternative, and as the primary name when the spectroscopic identity is not known.

Names are assigned for $t\overline{t}$ mesons, although the top quark is evidently so heavy that it is expected to decay too rapidly for bound states to form.

Gluonium states or other mesons that are not $q\overline{q}$ states are, if the quantum numbers are *not* exotic, to be named just as are the $q\overline{q}$ mesons. Such states will probably be difficult to distinguish from $q\overline{q}$ states and will likely mix with them, and we make no attempt to distinguish those "mostly gluonium" from those "mostly $q\overline{q}$."

An "exotic" meson with J^{PC} quantum numbers that a $q\overline{q}$ system cannot have, namely $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \cdots$, would use the same symbol as does an ordinary meson with all the same quantum numbers as the exotic meson except for the C parity. But then the J subscript may still distinguish it; for example, an isospin-0 1^{-+} meson could be denoted ω_1.

8.3. Mesons with nonzero S, C, B, and/or T

Since the strangeness or a heavy flavor of these mesons is nonzero, none of them are eigenstates of charge conjugation, and in each of them one of the quarks is heavier than the other. The rules are:

1. The main symbol is an upper-case italic letter indicating the heavier quark as follows:

   $$s \to \overline{K} \qquad c \to D \qquad b \to \overline{B} \qquad t \to T\ .$$

   We use the convention that *the flavor and the charge of a quark have the same sign*. Thus the strangeness of the s quark is negative, the charm of the c quark is positive, and the bottom of the b quark is negative. In addition, I_3 of the u and d quarks are positive and negative, respectively. The effect of this convention is as follows: *Any flavor carried by a charged meson has the same sign as its charge.* Thus the K^+, D^+, and B^+ have positive strangeness, charm, and bottom, respectively, and all have positive I_3. The D_s^+ has positive charm *and* strangeness. Furthermore, the $\Delta(\text{flavor}) = \Delta Q$ rule, best known for the kaons, applies to every flavor.
2. If the lighter quark is not a u or a d quark, its identity is given by a subscript. The D_s^+ is an example.
3. If the spin-parity is in the "normal" series, $J^P = 0^+, 1^-, 2^+, \cdots$, a superscript "*" is added.
4. The spin is added as a subscript except for pseudoscalar or vector mesons.

8.4. Ordinary (3-quark) baryons

The symbols N, Δ, Λ, Σ, Ξ, and Ω used for more than 30 years for the baryons made of light quarks (u, d, and s quarks) tell the isospin and quark content, and the same information is conveyed by the symbols used for the baryons containing one or more heavy quarks (c and b quarks). The rules are:

1. Baryons with *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).
2. Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a c, b, or t quark, its identity is given by a subscript.
3. Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, *etc.**
4. Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.
5. A baryon that decays strongly has its mass as part of its name. Thus p, Σ^-, Ω^-, Λ_c^+, *etc.*, but $\Delta(1232)^0$, $\Sigma(1385)^-$, $\Xi_c(2645)^+$, *etc.*

In short, the number of u plus d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, *etc.*

8.5. Exotic baryons

In 2003, several experiments reported finding a strangeness $S = +1$, charge $Q = +1$ baryon, and one experiment reported finding an $S = -2$, $Q = -2$ baryon; see the "Exotic Baryons" section of the Data Listings. Baryons with such quantum numbers cannot be made from three quarks, and thus they are exotic. The $S = +1$ baryon, which once would have been called a Z, was quickly dubbed the $\Theta(1540)^+$, and we propose to name the $S = -2$ baryon the $\Phi(1860)$.

Footnote and Reference:

* Sometimes a prime is necessary to distinguish two Ξ_c's in the same SU(n) multiplet. See the "Note on Charmed Baryons" in the Charmed Baryon Listings.

1. Particle Data Group: M. Aguilar-Benitez *et al.,* Phys. Lett. **170B** (1986).