

Contents

3 Fundamental constants	3– 1
3.1 The role of fundamental constants in physics and chemistry (B. KRAMER, W. WÖGER)	3– 1
3.1.1 Introduction	3– 1
3.1.2 Atomic properties of matter	3– 1
3.1.3 Fundamental interactions	3– 2
3.1.4 Fundamental physical relations	3– 6
3.1.5 Fundamental constants in the theories of physics	3– 7
3.1.6 Experimental determinations	3– 9
3.1.6.1 Relation between constants and units	3– 9
3.1.6.2 Early measurements	3– 11
3.1.6.3 Modern precision measurements	3– 12
3.1.7 The CODATA classification scheme	3– 14
3.1.8 Least squares adjustments	3– 14
3.1.9 Symbols and abbreviations	3– 17
3.1.10 References for 3.1	3– 25
3.2 Experimental determination of the fundamental constants	3– 28
3.2.1 The gravitational constant (W. MICHAELIS)	3– 28
3.2.1.1 Basic relations	3– 28
3.2.1.2 Relation to other constants	3– 30
3.2.1.3 Experimental methods	3– 30
3.2.1.3.1 Torsion balances	3– 30
3.2.1.3.2 Large-scale experiments	3– 33
3.2.1.4 Sources of uncertainties	3– 33
3.2.1.4.1 Torsion filaments	3– 33
3.2.1.4.2 Dimensions and densities	3– 33
3.2.1.4.3 Vibrations of the ground, microseism, Brownian motion	3– 34
3.2.1.4.4 Electric and magnetic fields	3– 35
3.2.1.4.5 Surrounding masses	3– 35
3.2.1.4.6 Variations of temperature	3– 35
3.2.1.5 References for 3.2.1	3– 35
3.2.2 The speed of light (C.O. WEISS, Y.C. NI)	3– 37
3.2.2.1 Historical review of measurements	3– 37
3.2.2.2 Speed of light determinations based on frequency and wavelength measurement of optical radiation	3– 39
3.2.2.2.1 Experimental methods	3– 39
3.2.2.2.2 Laser frequency stabilization	3– 39
3.2.2.2.3 Optical frequency measurement system	3– 40
3.2.2.2.4 Frequency measurement of visible light	3– 45
3.2.2.2.5 Wavelength measurements	3– 46
3.2.2.2.6 Incoherent sources	3– 46
3.2.2.2.7 Coherent sources	3– 46
3.2.2.2.8 Upconversion	3– 47
3.2.2.3 Definition of the metre and values of frequencies and wavelengths recommended by CCDM	3– 49
3.2.2.4 References for 3.2.2	3– 50
3.2.3 The Planck constant	3– 52
3.2.3.1 Basic relations (B.W. PETLEY)	3– 52
3.2.3.2 Relations to other constants and units (B.W. PETLEY)	3– 55
3.2.3.3 Experimental determination (B. KRAMER)	3– 56
3.2.3.3.1 Historical experiments	3– 56

3.2.3.3.2	Direct determination via the realization of the watt	3– 62
3.2.3.3.2.1	The NIST moving coil experiment	3– 62
3.2.3.3.2.2	The NPL moving coil experiment	3– 67
3.2.3.4	Uncertainties (B. KRAMER)	3– 73
3.2.3.4.1	Historical determinations	3– 73
3.2.3.4.2	The moving coil experiment at NIST	3– 74
3.2.3.4.3	The realization of the watt at NPL	3– 74
3.2.3.5	References for 3.2.3	3– 77
3.2.4	The elementary charge (H. BACHMAIR)	3– 79
3.2.4.1	Basic relations	3– 79
3.2.4.2	Experimental methods	3– 79
3.2.4.3	Relations to other constants and units	3– 81
3.2.4.4	References for 3.2.4	3– 82
3.2.5	The magnetic flux quantum (B. KRAMER, J. NIEMEYER)	3– 83
3.2.5.1	Basic relations	3– 83
3.2.5.2	Relations to other constants and units	3– 85
3.2.5.3	Experimental determination	3– 86
3.2.5.3.1	Voltage balance	3– 90
3.2.5.3.2	Moving coil balance	3– 92
3.2.5.3.3	Superconducting magnetic levitation	3– 92
3.2.5.4	Sources of uncertainties	3– 93
3.2.5.5	References for 3.2.5	3– 93
3.2.6	The gyromagnetic coefficient of the proton (K. WEYAND)	3– 95
3.2.6.1	Basic relations	3– 95
3.2.6.2	Relations to other constants and units	3– 96
3.2.6.3	Experimental determination	3– 96
3.2.6.3.1	Determination of flux density	3– 96
3.2.6.3.2	High-field experiments	3– 97
3.2.6.3.3	Low-field experiments	3– 100
3.2.6.3.4	Results	3– 103
3.2.6.4	Uncertainties	3– 104
3.2.6.5	References for 3.2.6	3– 105
3.2.7	The quantized Hall resistance (E. BRAUN, L. BLIEK)	3– 107
3.2.7.1	Basic relations	3– 107
3.2.7.2	Relations to other constants and units	3– 110
3.2.7.3	Experimental methods	3– 110
3.2.7.4	Sources of uncertainties	3– 115
3.2.7.5	References for 3.2.7	3– 115
3.2.8	The Bohr magneton and the nuclear magneton (G.-D. WILLENBERG)	3– 117
3.2.8.1	Definition and basic relations	3– 117
3.2.8.2	Relation to other constants and units	3– 117
3.2.8.3	Experimental determination	3– 118
3.2.8.4	Sources of uncertainties	3– 123
3.2.8.5	References for 3.2.8	3– 124
3.2.9	The fine-structure constant (B.N. TAYLOR)	3– 125
3.2.9.1	Basic relations	3– 125
3.2.9.2	Relations to other constants and units	3– 125
3.2.9.3	Experimental methods	3– 127
3.2.9.4	Sources of uncertainty	3– 130
3.2.9.5	References for 3.2.9	3– 131
3.2.10	The Rydberg constant (T.W. HÄNSCH, D.H. MCINTYRE)	3– 132
3.2.10.1	Basic relations	3– 132
3.2.10.2	Relations to other constants and units	3– 133

3.2.10.3 Experimental methods	3-134
3.2.10.4 Sources of uncertainties	3-138
3.2.10.5 References for 3.2.10	3-139
3.2.11 The atomic masses of pure nuclides (A.H. WAPSTRA)	3-140
3.2.11.1 Definitions and units	3-140
3.2.11.2 Binding energy	3-141
3.2.11.3 Effects providing information on atomic masses	3-142
3.2.11.3.1 Gamma decay	3-142
3.2.11.3.2 Beta decay	3-142
3.2.11.3.3 Alpha decay	3-142
3.2.11.3.4 Nuclear reactions	3-143
3.2.11.3.5 Mass spectrometry	3-144
3.2.11.3.6 Relation with fundamental constants	3-144
3.2.11.4 Experimental methods	3-145
3.2.11.4.1 Conventional mass spectrometry	3-145
3.2.11.4.2 Radiofrequency mass spectrometers	3-147
3.2.11.4.3 Mass spectrometry on unstable nuclides	3-147
3.2.11.4.4 Charged particle spectroscopy	3-148
3.2.11.4.5 Beta ray spectrometers	3-148
3.2.11.4.6 Gamma ray spectroscopy	3-149
3.2.11.4.7 Neutrons; time of flight spectrometry	3-149
3.2.11.5 Collections of atomic mass values, their precision and dependability	3-149
3.2.11.6 References for 3.2.11	3-181
3.2.12 The Avogadro constant (B. KRAMER)	3-183
3.2.12.1 Basic relations	3-183
3.2.12.2 Relations to other constants and units	3-184
3.2.12.3 Experimental determination	3-185
3.2.12.3.1 Historical development	3-185
3.2.12.3.2 Early X-ray experiments	3-185
3.2.12.3.3 X-ray interferometry	3-186
3.2.12.3.3.1 NIST (NBS)-approach	3-187
3.2.12.3.3.2 PTB-approach	3-193
3.2.12.4 Sources of uncertainties	3-209
3.2.12.5 References for 3.2.12	3-211
3.2.13 The Faraday constant (W.F. KOCH)	3-213
3.2.13.1 Introduction	3-213
3.2.13.2 Early development	3-213
3.2.13.3 Electrochemical determinations of the Faraday	3-214
3.2.13.4 Physical methods	3-217
3.2.13.5 Conclusions	3-218
3.2.13.6 References for 3.2.13	3-218
3.2.14 The molar gas constant (B. KRAMER)	3-219
3.2.14.1 Definitions and basic relations	3-219
3.2.14.2 Relations to other constants and units	3-220
3.2.14.3 Experimental determinations	3-220
3.2.14.3.1 Limiting density method	3-220
3.2.14.3.2 Acoustic interferometer method	3-223
3.2.14.3.3 Spherical resonator method	3-237
3.2.14.4 Sources of uncertainties	3-250
3.2.14.4.1 Limiting density method	3-250
3.2.14.4.2 Acoustic interferometer method	3-252
3.2.14.4.3 Spherical resonator method	3-256
3.2.14.5 References for 3.2.14	3-257

3.2.15 The Boltzmann constant (B. KRAMER)	3-259
3.2.15.1 Definitions and basic relations	3-259
3.2.15.2 Relations to other constants and units	3-260
3.2.15.3 Experimental methods	3-261
3.2.15.3.1 Garrison-Lawson method	3-261
3.2.15.3.2 Noise power method	3-262
3.2.15.3.3 Direct method	3-264
3.2.15.3.4 Correlation method	3-268
3.2.15.4 Sources of uncertainties	3-272
3.2.15.5 References for 3.2.15	3-273
3.2.16 The Stefan-Boltzmann constant (W.R. BLEVIN)	3-274
3.2.16.1 Definitions and historical remarks	3-274
3.2.16.2 Theoretical determination from other constants	3-275
3.2.16.3 Results of experimental determinations	3-275
3.2.16.4 Experimental methods and principal sources of uncertainty	3-276
3.2.16.4.1 The exitance method	3-276
3.2.16.4.2 The radiance method	3-277
3.2.16.4.3 Measurements by Blevin and Brown and by Quinn and Martin	3-279
3.2.16.5 Conclusion	3-281
3.2.16.6 References for 3.2.16	3-282
3.3 The adjustment of the fundamental constants (E.R. COHEN)	3-285
3.3.1 Methods	3-285
3.3.1.1 Introduction	3-285
3.3.1.2 Least squares	3-285
3.3.1.3 Extensions of least squares	3-287
3.3.2 The 1986 adjustment	3-288
3.3.2.1 Summary	3-288
3.3.2.2 1986 recommended values of the fundamental physical constants	3-288
3.3.2.3 Variance of the output	3-289
3.3.3 Tables of constants	3-290
3.3.4 References for 3.3	3-300
3.4 Recommended values of the fundamental constants in physics and chemistry; the status in 1992 (E.R. COHEN, B.N. TAYLOR)	3-303
3.4.1 Introduction	3-303
3.4.2 Review of the data	3-304
3.4.2.1 Auxiliary constants	3-304
3.4.2.1.1 The speed of light and the definition of the meter	3-304
3.4.2.1.2 Proton-electron mass ratio	3-304
3.4.2.1.3 Relative atomic masses and mass ratios	3-304
3.4.2.1.4 Rydberg constant	3-305
3.4.2.1.5 <i>g</i> -factor of the free electron and muon	3-306
3.4.2.1.6 Electron and nuclear magnetic moment ratios	3-307
3.4.2.1.7 "As-maintained" volt and ohm standard	3-307
3.4.2.1.8 Acceleration due to gravity	3-309
3.4.2.2 Primary stochastic input data	3-309
3.4.2.2.1 Direct ohm determinations	3-309
3.4.2.2.2 Direct ampere determinations (now watt determinations)	3-311
3.4.2.2.3 Direct volt determinations	3-311
3.4.2.2.4 Faraday constant	3-312
3.4.2.2.5 Gyromagnetic ratio (low field)	3-312
3.4.2.2.6 Gyromagnetic ratio (high field)	3-313
3.4.2.2.7 Silicon lattice spacing and 3.4.2.2.8 Molar volume of silicon	3-313

3.4.2.2.9	Quantized Hall resistance	3-314
3.4.2.2.10	Fine-structure constant	3-314
3.4.2.2.11	Muon-proton magnetic moment ratio	3-315
3.4.2.2.12	Muonium hyperfine splitting	3-315
3.4.2.3	Secondary stochastic data	3-316
3.4.2.3.1	Molar gas constant	3-316
3.4.2.3.2	Stefan-Boltzmann constant	3-316
3.4.2.3.3	Newtonian constant of gravitation	3-316
3.4.3	Data analysis and results	3-316
3.4.3.1	Relationships among data of different types	3-317
3.4.3.2	Multivariate analysis of the data	3-320
3.4.3.3	Changes in the 1986 recommended values and their uncertainties	3-322
3.4.3.4	Effect of the three dominant new results alone	3-325
3.4.4	Conclusion	3-326
3.4.5	References for 3.4	3-327
3.5	Tables	3-329
3.5.1	Fundamental constants and maintained units in alphabetical order	3-329
3.5.2	Energy conversion factors, covariance and correlation coefficients	3-334
3.5.3	Naturally occurring nuclides	3-336
3.5.4	Periodic table of the elements	3-343
4	Subject index for subvolumes a and b	4- 1

