Springer Handbook of Condensed Matter and Materials Data

Martienssen
Warlimont
Editors

CD-ROM

Springer

Springer Handbook of Condensed Matter and Materials Data

W. Martienssen and H. Warlimont (Eds.)

With 1025 Figures and 914 Tables

Springer

Professor Werner Martienssen
Universität Frankfurt
Fachbereich 13, Physik
Robert-Mayer-Str. 2 – 4
60325 Frankfurt
Germany

Professor Hans Warlimont
IWF Dresden
Helmholzstr. 20
01069 Dresden
Germany

Library of Congress Control Number: 2004116537

ISBN 3-540-44376-2
Spinger Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media

springeronline.com

Printed in Germany

Production and typesetting: LE-TeX GbR, Leipzig
Handbook coordinator: Dr. W. Skolaut, Heidelberg
Typography, layout and illustrations: schreiberVIS, Seeheim
Cover design: eStudio Calamar Steinen, Barcelona
Cover production: *design&production* GmbH, Heidelberg
Printing and binding: Stürtz GmbH, Würzburg

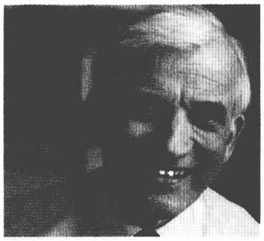
Printed on acid-free paper
SPIN 10678245 62/3141/ 5 4 3 2 1 0

Preface

The Springer Handbook of Condensed Matter and Materials Data is the realization of a new concept in reference literature, which combines introductory and explanatory texts with a compilation of selected data and functional relationships from the fields of solid-state physics and materials in a single volume. The data have been extracted from various specialized and more comprehensive data sources, in particular the Landolt–Börnstein data collection, as well as more recent publications. This Handbook is designed to be used as a desktop reference book for fast and easy finding of essential information and reliable key data. References to more extensive data sources are provided in each section. The main users of this new Handbook are envisaged to be students, scientists, engineers, and other knowledge-seeking persons interested and engaged in the fields of solid-state sciences and materials technologies.

The editors have striven to find authors for the individual sections who were experienced in the full breadth of their subject field and ready to provide succinct accounts in the form of both descriptive text and representative data. It goes without saying that the sections represent the individual approaches of the authors to their subject and their understanding of this task. Accordingly, the sections vary somewhat in character. While some editorial influence was exercised, the flexibility that we have shown is deliberate. The editors are grateful to all of the authors for their readiness to provide a contribution, and to cooperate in delivering their manuscripts and by accepting essentially all alterations which the editors requested to achieve a reasonably coherent presentation.

An onerous task such as this could not have been completed without encouragement and support from the publisher. Springer has entrusted us with this novel project, and Dr. Hubertus von Riedesel has been a persistent but patient reminder and promoter of our work throughout. Dr. Rainer Poerschke has accompanied and helped the editors constantly with his professional attitude and very personable style during the process of developing the concept, soliciting authors, and dealing with technical matters. In the later stages, Dr. Werner Skolaut became a relentless and hard-working member of our team with his painstaking contribution to technically editing the authors' manuscripts and linking the editors' work with the copy editing and production of the book.



Prof. Werner Martienssen

Prof. Hans Warlimont

We should also like to thank our families for having graciously tolerated the many hours we have spent in working on this publication.

We hope that the users of this Handbook, whose needs we have tried to anticipate, will find it helpful and informative. In view of the novelty of the approach and any possible inadvertent deficiencies which this first edition may contain, we shall be grateful for any criticisms and suggestions which could help to improve subsequent editions so that they will serve the expectations of the users even better and more completely.

September 2004
Frankfurt am Main, Dresden

Werner Martienssen,
Hans Warlimont

List of Authors

Wolf Assmus
Johann Wolfgang Goethe-University
Physics Department
Robert-Mayer-Str. 2 – 4
60054 Frankfurt am Main, Germany
e-mail: *assmus@physik.uni-frankfurt.de*

Stefan Brühne
Johann Wolfgang Goethe-University
Physics Department
Robert-Mayer-Str. 2 – 4
60054 Frankfurt am Main, Germany
e-mail: *bruehne@physik.uni-frankfurt.de*

Fabrice Charra
Commissariat à l'Énergie Atomique, Saclay
Département de Recherche sur l'État Condensé, les Atomes et les Molécules
DRECAM-SPCSI, Centre d'Études de Saclay
91191 Gif-sur-Yvette, France
e-mail: *fabrice.charra@cea.fr*

Gianfranco Chiarotti
University of Rome "Tor Vergata"
Department of Physics
Via della Ricerca Scientifica 1
00133 Roma, Italy
e-mail: *chiarotti@roma2.infn.it*

Claus Fischer
Formerly Institute of Solid State and Materials Research (IFW)
Georg-Schumann-Str. 20
01187 Dresden, Germany
e-mail: *A_C.FischerDD@t-online.de*

Günter Fuchs
Leibniz Institute for Solid State and Materials Research (IFW) Dresden
Magnetism and Superconductivity in the Institute of Metallic Materials
Helmholtzstraße 20
01171 Dresden, Germany
e-mail: *fuchs@ifw-dresden.de*

Frank Goodwin
International Lead Zinc Research Organization, Inc.
PO BOX 12036
Research Triangle Parc, NC 27709, USA
e-mail: *fgoodwin@ilzro.org*

Susana Gota-Goldmann
Commissariat à l'Energie Atomique (CEA)
Direction de la Recherche Technologique (DRT)
Centre de Fontenay aux Roses BP 6
92265 Fontenay aux Roses Cédex, France
e-mail: *susana.gota-goldmann@cea.fr*

Sivaraman Guruswamy
University of Utah
Metallurgical Engineering
135 South 1460 East RM 412
Salt Lake City, UT 84112-0114, USA
e-mail: *sguruswa@mines.utah.edu*

Gagik G. Gurzadyan
Technical University of Munich
Institute for Physical and Theoretical Chemistry
Lichtenbergstrasse 4
85748 Garching, Germany
e-mail: *gurzadyan@ch.tum.de*

Hideki Harada
High Tech Association Ltd.
3730-30 Higashikaya, Fukaya,Saitama, Japan
e-mail: *khb16457@nifty.com*

Bernhard Holzapfel
Leibniz Institute for Solid State and Materials Research Dresden – Institute of Metallic Materials
Superconducting Materials
Helmholtzstr. 20
01069 Dresden, Germany
e-mail: *B.Holzapfel@ifw-dresden.de*

Karl U. Kainer
GKSS Research Center Geesthacht
Institute for Materials Research
Max-Planck-Str. 1
21502 Geesthacht, Germany
e-mail: *karl.kainer@gkss.de*

Catrin Kammer
METALL – Intl. Journal for Metallurgy
Kielsche Straße 43B
38642 Goslar, Germany
e-mail: *Kammer@metall-news.com*

Wolfram Knabl
Plansee AG
Technology Center
6600 Reutte, Austria
e-mail: *wolfram.knabl@plansee.com*

Alfred Koethe
Leibniz-Institut für Festkörper- und Werkstoffforschung
Institut für Metallische Werkstoffe (retired)
Lessingstrasse 11
01099 Dresden, Germany
e-mail: *alfred.koethe@web.de*

Dieter Krause
Schott AG
Research and Technology-Development
PO BOX 2480
55014 Mainz, Germany
e-mail: *dieter.krause@schott.com*

Manfred D. Lechner
Universität Osnabrück
Institut für Chemie – Physikalische Chemie
Barbarastraße 7
46069 Osnabrück, Germany
e-mail: *lechner@uni-osnabrueck.de*

Gerhard Leichtfried
Plansee AG
Technology Center
6600 Reutte, Austria
e-mail: *gerhard.leichtfried@plansee.com*

Werner Martienssen
Universität Frankfurt/Main
Physikalisches Institut
Robert-Mayer-Strasse 2 – 4
60054 Frankfurt/Main, Germany
e-mail: *Martienssen@Physik.uni-frankfurt.de*

Toshio Mitsui
Osaka University
Nakasuji-Yamate, 3-6-24
665-0875 Takarazuka, Japan
e-mail: *t-mitsui@jttk.zaq.ne.jp*

Manfred Müller
Dresden University of Technology
Institute of Materials Science
Leubnitzer Straße 26
01069 Dresden, Germany
e-mail: *m.mueller33@t-online.de*

Sergei Pestov
Moscow State Academy of Fine Chemical Technology
Department of Inorganic Chemistry
Vernadsky pr., 86
119571 Moscow, Russia
e-mail: *pestovsm@yandex.ru*

Günther Schlamp
Metallgesellschaft Ffm and Degussa Demetron (retired)
Stettinerstr. 25
61449 Steinbach/Ts, Germany
e-mail:

Barbara Schüpp-Niewa
Leibniz-Institute for Solid State and Materials Research Dresden
Institute for Metallic Materials
Helmholtzstraße 20
01069 Dresden, Germany
e-mail: *b.schuepp@ifw-dresden.de*

Roland Stickler
University of Vienna
Department of Chemistry
Währingerstr. 42
1090 Vienna, Austria
e-mail: *roland.stickler@univie.ac.at*

Pancho Tzankov
Max Born Institute for Nonlinear Optics
and Short Pulse Spectroscopy
Max-Born-Str. 2A
12489 Berlin, Germany
e-mail: *tzankov@mbi-berlin.de*

Volkmar Vill
University of Hamburg
Department of Chemistry,
Institute of Organic Chemistry
Martin-Luther-King-Platz 6
20146 Hamburg, Germany
e-mail: *vill@chemie.uni-hamburg.de*

Hans Warlimont
DSL Dresden Material-Innovation GmbH
Helmholtzstrasse 20
01069 Dresden, Germany
e-mail: *warlimont@ifw-dresden.de*

Contents

List of Abbreviations XV

Part 1 General Tables

1 **The Fundamental Constants**
Werner Martienssen 3
1.1 What are the Fundamental Constants and Who Takes Care of Them? 3
1.2 The CODATA Recommended Values of the Fundamental Constants 4
References 9

2 **The International System of Units (SI), Physical Quantities, and Their Dimensions**
Werner Martienssen 11
2.1 The International System of Units (SI) 11
2.2 Physical Quantities 12
2.3 The SI Base Units 13
2.4 The SI Derived Units 16
2.5 Decimal Multiples and Submultiples of SI Units 19
2.6 Units Outside the SI 20
2.7 Some Energy Equivalents 24
References 25

3 **Rudiments of Crystallography**
Wolf Assmus, Stefan Brühne 27
3.1 Crystalline Materials 28
3.2 Disorder 38
3.3 Amorphous Materials 39
3.4 Methods for Investigating Crystallographic Structure 39
References 41

Part 2 The Elements

1 **The Elements**
Werner Martienssen 45
1.1 Introduction 45
1.2 Description of Properties Tabulated 46
1.3 Sources 49
1.4 Tables of the Elements in Different Orders 49
1.5 Data 54
References 158

Part 3 Classes of Materials

1 **Metals**
Frank Goodwin, Sivaraman Guruswamy, Karl U. Kainer, Catrin Kammer, Wolfram Knabl, Alfred Koethe, Gerhard Leichtfried, Günther Schlamp, Roland Stickler, Hans Warlimont ... 161
1.1 Magnesium and Magnesium Alloys ... 162
1.2 Aluminium and Aluminium Alloys ... 171
1.3 Titanium and Titanium Alloys ... 206
1.4 Zirconium and Zirconium Alloys ... 217
1.5 Iron and Steels ... 221
1.6 Cobalt and Cobalt Alloys ... 272
1.7 Nickel and Nickel Alloys ... 279
1.8 Copper and Copper Alloys ... 296
1.9 Refractory Metals and Alloys ... 303
1.10 Noble Metals and Noble Metal Alloys ... 329
1.11 Lead and Lead Alloys ... 407
References ... 422

2 **Ceramics**
Hans Warlimont ... 431
2.1 Traditional Ceramics and Cements ... 432
2.2 Silicate Ceramics ... 433
2.3 Refractory Ceramics ... 437
2.4 Oxide Ceramics ... 437
2.5 Non-Oxide Ceramics ... 451
References ... 476

3 **Polymers**
Manfred D. Lechner ... 477
3.1 Structural Units of Polymers ... 480
3.2 Abbreviations ... 482
3.3 Tables and Figures ... 483
References ... 522

4 **Glasses**
Dieter Krause ... 523
4.1 Properties of Glasses – General Comments ... 526
4.2 Composition and Properties of Glasses ... 527
4.3 Flat Glass and Hollowware ... 528
4.4 Technical Specialty Glasses ... 530
4.5 Optical Glasses ... 543
4.6 Vitreous Silica ... 556
4.7 Glass-Ceramics ... 558
4.8 Glasses for Miscellaneous Applications ... 559
References ... 572

Part 4 Functional Materials

1 **Semiconductors**
Werner Martienssen 575
1.1 Group IV Semiconductors and IV–IV Compounds 578
1.2 III–V Compounds 604
1.3 II–VI Compounds 652
References 691

2 **Superconductors**
Claus Fischer, Günter Fuchs, Bernhard Holzapfel, Barbara Schüpp-Niewa, Hans Warlimont 695
2.1 Metallic Superconductors 696
2.2 Non-Metallic Superconductors 711
References 749

3 **Magnetic Materials**
Hideki Harada, Manfred Müller, Hans Warlimont 755
3.1 Basic Magnetic Properties 755
3.2 Soft Magnetic Alloys 758
3.3 Hard Magnetic Alloys 794
3.4 Magnetic Oxides 811
References 814

4 **Dielectrics and Electrooptics**
Gagik G. Gurzadyan, Pancho Tzankov 817
4.1 Dielectric Materials: Low-Frequency Properties 822
4.2 Optical Materials: High-Frequency Properties 824
4.3 Guidelines for Use of Tables 826
4.4 Tables of Numerical Data for Dielectrics and Electrooptics 828
References 890

5 **Ferroelectrics and Antiferroelectrics**
Toshio Mitsui 903
5.1 Definition of Ferroelectrics and Antiferroelectrics 903
5.2 Survey of Research on Ferroelectrics 904
5.3 Classification of Ferroelectrics 906
5.4 Physical Properties of 43 Representative Ferroelectrics 912
References 936

Part 5 Special Structures

1 **Liquid Crystals**
Sergei Pestov, Volkmar Vill 941
1.1 Liquid Crystalline State 941
1.2 Physical Properties of the Most Common Liquid Crystalline Substances 946

1.3 Physical Properties of Some Liquid Crystalline Mixtures 975
References 977

2 **The Physics of Solid Surfaces**
Gianfranco Chiarotti 979
2.1 The Structure of Ideal Surfaces 979
2.2 Surface Reconstruction and Relaxation 986
2.3 Electronic Structure of Surfaces 996
2.4 Surface Phonons 1012
2.5 The Space Charge Layer at the Surface of a Semiconductor 1020
2.6 Most Frequently Used Acronyms 1026
References 1029

3 **Mesoscopic and Nanostructured Materials**
Fabrice Charra, Susana Gota-Goldmann 1031
3.1 Introduction and Survey 1031
3.2 Electronic Structure and Spectroscopy 1035
3.3 Electromagnetic Confinement 1044
3.4 Magnetic Nanostructures 1048
3.5 Preparation Techniques 1063
References 1066

Acknowledgements 1073
About the Authors 1075
Detailed Contents 1081
Subject Index 1091

Part 1

General Ta

Part 1 General Tables

1 **The Fundamental Constants**
Werner Martienssen, Frankfurt/Main, Germany

2 **The International System of Units (SI), Physical Quantities, and Their Dimensions**
Werner Martienssen, Frankfurt/Main, Germany

3 **Rudiments of Crystallography**
Wolf Assmus, Frankfurt am Main, Germany
Stefan Brühne, Frankfurt am Main, Germany

1.1. The Fundamental Constants

In the quantitative description of physical phenomena and physical relationships, we find constant parameters which appear to be independent of the scale of the phenomena, independent of the place where the phenomena happen, and independent of the time when the phenomena is observed. These parameters are called fundamental constants. In Sect. 1.1.1, we give a qualitative description of these basic parameters and explain how "recommended values" for the numerical values of the fundamental constants are found. In Sect. 1.1.2, we present tables of the most recently determined recommended numerical values for a large number of those fundamental constants which play a role in solid-state physics and chemistry and in materials science.

1.1.1 **What are the Fundamental Constants and Who Takes Care of Them?** 3

1.1.2 **The CODATA Recommended Values of the Fundamental Constants** 4

1.1.2.1 The Most Frequently Used Fundamental Constants 4

1.1.2.2 Detailed Lists of the Fundamental Constants in Different Fields of Application 5

1.1.2.3 Constants from Atomic Physics and Particle Physics 7

References 9

1.1.1 What are the Fundamental Constants and Who Takes Care of Them?

The fundamental constants are constant parameters in the laws of nature. They determine the size and strength of the phenomena in the natural and technological worlds. We conclude from observation that the numerical values of the fundamental constants are independent of space and time; at least, we can say that if there is any dependence of the fundamental constants on space and time, then this dependence must be an extremely weak one. Also, we observe that the numerical values are independent of the scale of the phenomena observed; for example, they seem to be the same in astrophysics and in atomic physics. In addition, the numerical values are quite independent of the environmental conditions. So we have confidence in the idea that the numerical values of the fundamental constants form a set of numbers which are the same everywhere in the world, and which have been the same in the past and will be the same in the future. Whereas the properties of all material objects in nature are more or less subject to continuous change, the fundamental constants seem to represent a constituent of the world which is absolutely permanent.

On the basis of this expected invariance of the fundamental constants in space and time, it appears reasonable to relate the units of measurement for physical quantities to fundamental constants as far as possible. This would guarantee that also the units of measurement become independent of space and time and of environmental conditions. Within the frame work of the International System of Units (Système International d'Unités, abbreviated to SI), the International Committee for Weights and Measures (Comité International des Poids et Mesures, CIPM) has succeeded in relating a large number of units of measurement for physical quantities to the numerical values of selected fundamental constants; however, several units for physical quantities are still represented by prototypes. For example, the unit of length 1 meter, is defined as the distance light travels in vacuum during a fixed time; so the unit of length is related to the fundamental constant c, i. e. the speed of light, and the unit of time, 1 second. The unit of mass, 1 kilogram, however, is still represented by a prototype, the mass of a metal cylinder made of a platinum–iridium alloy, which is carefully stored at the International Office for Weights and Measures (Bureau International des Poids et Mesures, BIPM), at Sèvres near Paris. In a few years, however, it might become possible also to relate the unit of mass to one or more fundamental constants.

The fundamental constants play an important role in basic physics as well as in applied physics and technology; in fact, they have a key function in the development of a system of reproducible and unchanging units for physical quantities. Nevertheless, there is, at present, no theory which would allow us to calculate the numerical values of the fundamental constants. Therefore, national institutes for metrology (NIMs), together with research institutes and university laboratories, are making efforts worldwide to determine the fundamental constants experimentally with the greatest possible accuracy and reliability. This, of course, is a continuous process, with hundreds of new publications every year.

The Committee on Data for Science and Technology (CODATA), established in 1966 as an interdisciplinary, international committee of the International Council of the Scientific Unions (ICSU), has taken the responsibility for improving the quality, reliability, processing, management, and accessibility of data of importance to science and technology. The CODATA task group on fundamental constants, established in 1969, has taken on the job of periodically providing the scientific and technological community with a self-consistent set of internationally recommended values of the fundamental constants based on all relevant data available at given points in time.

What is the meaning of "recommended values" of the fundamental constants?

Many fundamental constants are not independent of one another; they are related to one another by equations which allow one to calculate a numerical value for one particular constant from the numerical values of other constants. In consequence, the numerical value of a constant can be determined either by measuring it directly or by calculating it from the measured values of other constants related to it. In addition, there are usually several different experimental methods for measuring the value of any particular fundamental constant. This allows one to compute an adjustment on the basis of a least-squares fit to the whole set of experimental data in order to determine a set of best-fitting fundamental constants from the large set of all experimental data. Such an adjustment is done today about every four years by the CODATA task group mentioned above. The resulting set of best-fit values is then called the "CODATA recommended values of the fundamental constants" based on the adjustment of the appropriate year.

The tables in Sect. 1.1.2 show the CODATA recommended values of the fundamental constants of science and technology based on the 2002 adjustment. This adjustment takes into account all data that became available before 31 December 2002. A detailed description of the adjustment has been published by *Mohr* and *Taylor* of the National Institute of Standards and Technology, Gaithersburg, in [1.1].

The editors of this Handbook, H. Warlimont and W. Martienssen, would like to express their sincere thanks to Mohr and Taylor for kindly putting their data at our disposal prior to publication in Reviews of Modern Physics. These data first became available in December 2003 on the web site of the NIST fundamental constants data center [1.2].

1.1.2 The CODATA Recommended Values of the Fundamental Constants

1.1.2.1 The Most Frequently Used Fundamental Constants

Tables 1.1-1 – 1.1-9 list the CODATA recommended values of the fundamental constants based on the 2002 adjustment.

Table 1.1-1 Brief list of the most frequently used fundamental constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Speed of light in vacuum	c	299 792 458	m/s	Fixed by definition
Magnetic constant	$\mu_0 = 4\pi \times 10^{-7}$	$12.566370614\ldots \times 10^{-7}$	N/A^2	Fixed by definition
Electric constant	$\varepsilon_0 = 1/(\mu_0 c^2)$	$8.854187817\ldots \times 10^{-12}$	F/m	Fixed by definition
Newtonian constant of gravitation	G	$6.6742(10) \times 10^{-11}$	$m^3/(kg\,s^2)$	1.5×10^{-4}
Planck constant	h	$4.13566743(35) \times 10^{-15}$	eV s	8.5×10^{-8}
Reduced Planck constant	$\hbar = h/2\pi$	$6.58211915(56) \times 10^{-16}$	eV s	8.5×10^{-8}
Elementary charge	e	$1.60217653(14) \times 10^{-19}$	C	8.5×10^{-8}

Table 1.1-1 Brief list of the most frequently used fundamental constants, cont.

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Fine-structure constant	$\alpha = (1/4\pi\varepsilon_0)(e^2/\hbar c)$	$7.297352568(24) \times 10^{-3}$		3.3×10^{-9}
Magnetic flux quantum	$\Phi_0 = h/2e$	$2.06783372(18) \times 10^{-15}$	Wb	8.5×10^{-8}
Conductance quantum	$G_0 = 2e^2/h$	$7.748091733(26) \times 10^{-5}$	S	3.3×10^{-9}
Rydberg constant	$R_\infty = \alpha^2 m_e c/2h$	10 973 731.568525(73)	1/m	6.6×10^{-12}
Electron mass	m_e	$9.1093826(16) \times 10^{-31}$	kg	1.7×10^{-7}
Proton mass	m_p	$1.67262171(29) \times 10^{-27}$	kg	1.7×10^{-7}
Proton–electron mass ratio	m_p/m_e	1836.15267261(85)		4.6×10^{-10}
Avogadro number	N_A, L	$6.0221415(10) \times 10^{23}$		1.7×10^{-7}
Faraday constant	$F = N_A e$	96 485.3383(83)	C	8.6×10^{-8}
Molar gas constant	R	8.314472(15)	J/K	1.7×10^{-6}
Boltzmann constant	$k = R/N_A$	$1.3806505(24) \times 10^{-23}$ $8.617343(15) \times 10^{-5}$	J/K eV/K	1.8×10^{-6} 1.8×10^{-6}
Stefan–Boltzmann constant	$\sigma = (\pi^2/60)(k^4/(\hbar^3 c^2))$	$5.670400(40) \times 10^{-8}$	W/(m² K⁴)	7.0×10^{-6}

1.1.2.2 Detailed Lists of the Fundamental Constants in Different Fields of Application

Table 1.1-2 Universal constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Speed of light in vacuum	c	299 792 458	m/s	Fixed by definition
Magnetic constant	$\mu_0 = 4\pi \times 10^{-7}$	$12.566370614\ldots \times 10^{-7}$	N/A²	Fixed by definition
Electric constant	$\varepsilon_0 = 1/(\mu_0 c^2)$	$8.854187817\ldots \times 10^{-12}$	F/m	Fixed by definition
Characteristic impedance of vacuum	$Z_0 = (\mu_0/\varepsilon_0)^{1/2} = \mu_0 c$	376.730313461 ...	Ω	Fixed by definition
Newtonian constant of gravitation	G	$6.6742(10) \times 10^{-11}$	m³/(kg s²)	1.5×10^{-4}
Reduced Planck constant	$G/\hbar c$	$6.7087(10) \times 10^{-39}$	$(\mathrm{GeV}/c^2)^{-2}$	1.5×10^{-4}
Planck constant	h	$6.6260693(11) \times 10^{-34}$ $4.13566743(35) \times 10^{-15}$	J s eV s	1.7×10^{-7} 8.5×10^{-8}
(Ratio)	$\hbar = h/2\pi$	$1.05457168(18) \times 10^{-34}$ $6.58211915(56) \times 10^{-16}$	J s eV s	1.7×10^{-7} 8.5×10^{-8}
(Product)	$\hbar c$	197.326968(17)	MeV fm	8.5×10^{-8}
(Product)	$c_1 = 2\pi h c^2$	$3.74177138(64) \times 10^{-16}$	W m²	1.7×10^{-7}
(Product)	$(1/\pi)c_1 = 2hc^2$	$1.19104282(20) \times 10^{-16}$	W m²/sr	1.7×10^{-7}
(Product)	$c_2 = h(c/k)$	$1.4387752(25) \times 10^{-2}$	m K	1.7×10^{-6}
Stefan–Boltzmann constant	$\sigma = (\pi^2/60)(k^4/(\hbar^3 c^2))$	$5.670400(40) \times 10^{-8}$	W/(m² K⁴)	7.0×10^{-6}
Wien displacement law constant	$b = \lambda_{max} T = c_2/4.965114231$	$2.8977685(51) \times 10^{-3}$	m K	1.7×10^{-6}
Planck mass	$m_P = (\hbar c/G)^{1/2}$	$2.17645(16) \times 10^{-8}$	kg	7.5×10^{-5}
Planck temperature	$T_P = (1/k)(\hbar c^5/G)^{1/2}$	$1.41679(11) \times 10^{32}$	K	7.5×10^{-5}
Planck length	$l_P = \hbar/m_P c = (\hbar G/c^3)^{1/2}$	$1.61624(12) \times 10^{-35}$	m	7.5×10^{-5}
Planck time	$t_P = l_P/c = (\hbar G/c^5)^{1/2}$	$5.39121(40) \times 10^{-44}$	s	7.5×10^{-5}

Table 1.1–3 Electromagnetic constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Elementary charge	e	$1.60217653(14)\times10^{-19}$	C	8.5×10^{-8}
(Ratio)	e/h	$2.41798940(21)\times10^{14}$	A/J	8.5×10^{-8}
Fine-structure constant	$\alpha=(1/4\pi\varepsilon_0)(e^2/\hbar c)$	$7.297352568(24)\times10^{-3}$		3.3×10^{-9}
Inverse fine-structure constant	$1/\alpha$	137.03599911(46)		3.3×10^{-9}
Magnetic flux quantum	$\Phi_0=h/2e$	$2.06783372(18)\times10^{-15}$	Wb	8.5×10^{-8}
Conductance quantum	$G_0=2e^2/h$	$7.748091733(26)\times10^{-5}$	S	3.3×10^{-9}
Inverse of conductance quantum	$1/G_0$	12 906.403725(43)	Ω	3.3×10^{-9}
Josephson constant[a]	$K_J=2e/h$	$483\,597.879(41)\times10^{9}$	Hz/V	8.5×10^{-8}
von Klitzing constant[b]	$R_K=h/e^2=\mu_0c/2\alpha$	25 812.807449(86)	Ω	3.3×10^{-9}
Bohr magneton	$\mu_B=e\hbar/2m_e$	$927.400949(80)\times10^{-26}$ $5.788381804(39)\times10^{-5}$	J/T eV/T	8.6×10^{-8} 6.7×10^{-9}
(Ratio)	μ_B/h	$13.9962458(12)\times10^{9}$	Hz/T	8.6×10^{-8}
(Ratio)	μ_B/hc	46.6864507(40)	1/(m T)	8.6×10^{-8}
(Ratio)	μ_B/k	0.6717131(12)	K/T	1.8×10^{-6}
Nuclear magneton	$\mu_N=e\hbar/2m_p$	$5.05078343(43)\times10^{-27}$ $3.152451259(21)\times10^{-8}$	J/T eV/T	8.6×10^{-8} 6.7×10^{-9}
(Ratio)	μ_N/h	7.62259371(65)	MHz/T	8.6×10^{-8}
(Ratio)	μ_N/hc	$2.54262358(22)\times10^{-2}$	1/(m T)	8.6×10^{-8}
(Ratio)	μ_N/k	$3.6582637(64)\times10^{-4}$	K/T	1.8×10^{-6}

[a] See Table 1.2-16 for the conventional value adopted internationally for realizing representations of the volt using the Josephson effect.

[b] See Table 1.2-16 for the conventional value adopted internationally for realizing representations of the ohm using the quantum Hall effect.

Table 1.1–4 Thermodynamic constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Avogadro number	N_A, L	$6.0221415(10)\times10^{23}$		1.7×10^{-7}
Atomic mass constant	$u=(1/12)m(^{12}C)$ $=(1/N_A)\times10^{-3}$ kg	$1.66053886(28)\times10^{-27}$	kg	1.7×10^{-7}
Energy equivalent of atomic mass constant	m_uc^2	$1.49241790(26)\times10^{-10}$ 931.494043(80)	J MeV	1.7×10^{-7} 8.6×10^{-8}
Faraday constant	$F=N_Ae$	96 485.3383(83)	C	8.6×10^{-8}
Molar Planck constant	N_Ah	$3.990312716(27)\times10^{-10}$	J s	6.7×10^{-9}
(Product)	N_Ahc	0.11962656572(80)	J m	6.7×10^{-9}
Molar gas constant	R	8.314472(15)	J/K	1.7×10^{-6}
Boltzmann constant	$k=R/N_A$	$1.3806505(24)\times10^{-23}$ $8.617343(15)\times10^{-5}$	J/K eV/K	1.8×10^{-6} 1.8×10^{-6}
(Ratio)	k/h	$2.0836644(36)\times10^{10}$	Hz/K	1.7×10^{-6}
(Ratio)	k/hc	69.50356(12)	1/(m K)	1.7×10^{-6}
Molar volume of ideal gas at STP	$V_m=RT/p$ at $T=273.15$ K and $p=101.325$ kPa	$22.413996(39)\times10^{-3}$	m^3	1.7×10^{-6}
Loschmidt constant	$n_0=N_A/V_m$	$2.6867773(47)\times10^{25}$	$1/m^3$	1.8×10^{-6}
Stefan–Boltzmann constant	$\sigma=(\pi^2/60)(k^4/(\hbar^3c^2))$	$5.670400(40)\times10^{-8}$	$W/(m^2 K^4)$	7.0×10^{-6}
Wien displacement law constant	$b=\lambda_{max}T=c_2/4.965114231$	$2.8977685(51)\times10^{-3}$	m K	1.7×10^{-6}