INTERNATIONAL UNION OF PURE AND APPLIED PHYSICS
Commission C2 - SUNAMCO

# SYMBOLS, UNITS, NOMENCLATURE AND FUNDAMENTAL CONSTANTS IN PHYSICS

## 1987 REVISION (2010 REPRINT)

Prepared by

E. Richard Cohen

and

Pierre Giacomo

(SUNAMCO 87-1)

# PREFACE TO THE 2010 REPRINT

The 1987 revision of the SUNAMCO 'Red Book' has for nearly a quarter of a century provided physicists with authoritative guidance on the use of symbols, units and nomenclature. As such, it is cited as a primary reference by the IUPAC 'Green Book' (*Quantities, Units and Symbols in Physical Chemistry*, 3rd edition, E. R. Cohen et al., RSC Publishing, Cambridge, 2007) and the SI Brochure (*The International System of Units (SI)*, 8th edition, BIPM, Sèvres, 2006).

This electronic version has been prepared from the original TeX files and reproduces the content of the printed version, although there are some minor differences in formatting and layout. In issuing this version, we recognise that there are areas of physics which have come to prominence over the last two decades which are not covered and also that some material has been superseded. In particular, the values of the fundamental constants presented in section 6 have been superseded by more recent recommended values from the CODATA Task Group on Fundamental Constants. The currently recommended values can be obtained at http://physics.nist.gov/constants. SUNAMCO has established a Committee for Revision of the Red Book. Suggestions for material to be included in a revised version can be directed to the SUNAMCO Secretary at stephen.lea@npl.co.uk.

Copies of the 1987 printed version are available on application to the IUPAP Secretariat, c/o Insitute of Physics, 76 Portland Place, London W1B 1NT, United Kingdom, e-mail: admin.iupap@iop.org.

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UNION INTERNATIONALE DE
PHYSIQUE PURE ET APPLIQUÉE
Commission SUNAMCO

INTERNATIONAL UNION OF
PURE AND APPLIED PHYSICS
SUNAMCO Commission

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## 1987 REVISION

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## INTRODUCTION

The recommendations in this document, compiled by the Commission for Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants (SUN/AMCO Commission) of the International Union of Pure and Applied Physics (IUPAP), have been approved by the successive General Assemblies of the IUPAP held from 1948 to 1984.

These recommendations are in general agreement with recommendations of the following international organizations:

(1) International Organization for Standardization, Technical Committee ISO /TC12
(2) General Conference on Weights and Measures (1948–1983)
(3) International Union of Pure and Applied Chemistry (IUPAC)
(4) International Electrotechnical Commission, Technical Committee IEC/TC25
(5) International Commission on Illumination.

This document replaces the previous recommendations of the SUN Commission published under the title *Symbols, Units and Nomenclature in Physics* in 1961 (UIP-9, [SUN 61-44]), 1965 (UIP-11, [SUN 65-3]) and 1978 (UIP-20, [SUN 78-5], Physica **93A** (1978) 1–63).

Robert C. Barber, Chairman IUPAP Commission 2

**International Union of Pure and Applied Physics**
Commission on Symbols, Units, Nomenclature,
Atomic Masses and Fundamental Constants

Chairman, R. C. Barber (Canada); Secretary, P. Giacomo (France)

Members (1981–1987): K. Birkeland (Norway), W. R. Blevin (Australia), E. R. Cohen (USA), V. I. Goldansky (USSR, Chairman, 1981–1984), E. Ingelstam (Sweden), H. H. Jensen (Denmark), M. Morimura (Japan), B. W. Petley (UK), E. Roeckl (Fed. Rep. Germany), A. Sacconi (Italy), A. H. Wapstra (The Netherlands), N. Zeldes (Israel).

## CONTENTS

## PREFACE

There are two broad classes of dictionaries: those that are proscriptive and attempt to establish the norms of a language and those that are descriptive and report the language as it is used. For dictionaries of a living language, both types have their place. A manual of usage in science however must be primarily descriptive and should reflect the standards of practice that are current in the field and should attempt to impose a standard only in those cases where no accepted standards exist. This revision of the handbook has taken these precepts into account while expanding the discussion of some topics and correcting typographical errors of the 1978 edition. There has been some reordering of the material with the hope that the new arrangement will improve the logical flow, but, since physics is not one-dimensional, that goal may be unachievable.

The recommended symbols in section **4**, particularly those related to physical chemistry, have been actively coordinated with the corresponding recommendations of Commission I.1 on Symbols, Units and Terminology of IUPAC in order to avoid any conflict between the two. The values of the physical constants given in section **6** are drawn from the 1986 adjustment by the CODATA Task Group on Fundamental Constants.

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July, 1987

# 1 GENERAL RECOMMENDATIONS*

## 1.1 Physical quantities

There are two somewhat different meanings of the term 'physical quantity'. One refers to the abstract metrological concept (*e.g.*, length, mass, temperature), the other to a specific example of that concept (an attribute of a specific object or system: diameter of a steel cylinder, mass of the proton, critical temperature of water). Sometimes it is important to distinguish between the two and, ideally, it might be useful to be able to do so in all instances. However little is to be gained by attempting to make that distinction in this report. The primary concern here is with symbols and terminology in general; section **6**, however, gives the symbols and numerical values of specific physical constants.

### 1.1.1 Definitions

A physical quantity** is expressed as the product of a numerical value (*i.e.*, a pure number) and a unit:

$$\text{physical quantity} = \text{numerical value} \times \text{unit}.$$

For a physical quantity symbolized by $a$, this relationship is represented in the form

$$a = \{a\} \cdot [a],$$

where $\{a\}$ stands for the numerical value of $a$ and $[a]$ stands for the unit of $a$. Neither the name nor the symbol for a physical quantity should imply any particular choice of unit.

When physical quantities combine by multiplication or division the usual rules of arithmetic apply to both the numerical values and to the units. A quantity which arises (or may be considered to arise) from dividing one physical quantity by another with the same dimension has a unit which may be symbolized by the number 1; such a unit often has no special name or symbol and the quantity is expressed as a pure number.

*Examples*:

$$E = 200\ \mathrm{J}$$
$$F = 27\ \mathrm{N/m^2} \qquad n = 1.55 \quad \text{(refractive index)}$$
$$f = 3 \times 10^8\ \mathrm{Hz}$$

---

* For further details see International Standard ISO 31/0-1981: *General Principles Concerning Quantities, Units and Symbols*.

** French: *grandeur physique*; German: *physikalische Grösse*; Italian: *grandezza fisica*; Russian: *fizicheskaya velichina*; Spanish: *magnitud física*.

### 1.1.2 Symbols

Symbols for physical quantities should be single letters of the Latin or Greek alphabet with or without modifying signs (subscripts, superscripts, primes, etc.). The two-letter symbols used to represent dimensionless combinations of physical quantities are an exception to this rule (see section **4.14** "Dimensionless parameters"). When such a two-letter symbol appears as a factor in a product it should be separated from the other symbols by a dot, by a space, or by parentheses. It is treated as a single symbol and can be raised to a positive or negative power without using parentheses.

Abbreviations (*i.e.*, shortened forms of names or expressions, such as p.f. for partition function) may be used in text, but should not be used in physical equations. Abbreviations in text should be written in ordinary roman type.

Symbols for physical quantities and symbols for numerical variables should be printed in italic (*sloping*) type, while descriptive subscripts and numerical subscripts are to be printed in roman (upright) type.

*Examples*:

| | | |
|---|---|---|
| $C_\mathrm{g}$ | (g = gas) | $C_p$ |
| $g_\mathrm{n}$ | (n = normal) | $\sum_n a_n \psi_n$ |
| $\mu_\mathrm{r}$ | (r = relative) | $\sum_r b_r x^r$ |
| $E_\mathrm{k}$ | (k = kinetic) | $g_{i,k}$ but $g_{1,2}$ |
| $\chi_\mathrm{e}$ | (e = electric) | $p_\chi$ |

It is convenient to use symbols with distinctive typefaces in order to distinguish between the components of a vector (or a tensor) and the vector (or tensor) as an entity in itself, or to avoid the use of subscripts. The following standard conventions should be adhered to whenever the appropriate typefaces are available:

(a) Vectors should be printed in bold italic type, *e.g.*, $\boldsymbol{a}$, $\boldsymbol{A}$.
(b) Tensors should be printed in slanted bold sans serif type, *e.g.*, $\boldsymbol{\mathsf{S}}$, $\boldsymbol{\mathsf{T}}$.

*Remark*: When such type is not available, a vector may be indicated by an arrow above the symbol: *e.g.*, $\vec{a}$, $\vec{B}$. Second-rank tensors may be indicated by a double arrow or by a double-headed arrow: *e.g.*, $\vec{\vec{S}}$, $\overleftrightarrow{S}$. The extension of this to higher order tensors becomes awkward; in such cases the index notation should be used uniformly for tensors and vectors:

*Examples*:

$$A_i, \quad S_{ij}, \quad R_{ijkl}, \quad R^{ij}{}_{kl}, \quad R^{i}{}_{\cdot jk\cdot}{}^{l}$$

### 1.1.3 Simple mathematical operations

Addition and subtraction of two physical quantities are indicated by:

$$a + b \qquad \text{and} \qquad a - b.$$

Multiplication of two physical quantities may be indicated in one of the following ways:

$$ab \qquad a \cdot b \qquad a \times b.$$

Division of one quantity by another quantity may be indicated in one of the following ways:

$$\frac{a}{b} \qquad a/b \qquad ab^{-1}$$

or in any other way of writing the product of $a$ and $b^{-1}$.

These procedures can be extended to cases where one of the quantities or both are themselves products, quotients, sums or differences of other quantities. If brackets are necessary, they should be used in accordance with the rules of mathematics. When a solidus is used to separate the numerator from the denominator, brackets should be inserted if there is any doubt where the numerator starts or where the denominator ends.

*Examples*:

| Expressions with a horizontal bar | Same expressions with a solidus |
|---|---|
| $\dfrac{a}{bcd}$ | $a/bcd$ or $a/(bcd)$ |
| $\dfrac{2}{9}\sin kx$ | $(2/9)\sin kx$ |
| $\dfrac{a}{b}+c$ | $a/b+c$ |
| $\dfrac{a}{b-c}$ | $a/(b-c)$ |
| $\dfrac{a+b}{c-d}$ | $(a+b)/(c-d)$ |
| $\dfrac{a}{b}+\dfrac{c}{d}$ | $a/b+c/d$ or $(a/b)+(c/d)$ |

The argument of a mathematical function is placed in parentheses, brackets or braces, if necessary, in order to define its extent unambiguously.

*Examples*:

$$\sin\{2\pi(x-x_0)/\lambda\} \qquad \exp\{(r-r_0)/\sigma\}$$
$$\exp[-V(r)/kT\,] \qquad \surd(G/\rho)$$

Parentheses may be omitted when the argument is a single quantity or a simple product: *e.g.*, $\sin\theta$, $\tan kx$. A horizontal overbar may be used with the square root sign to define the outermost level of aggregation, *e.g.*, $\sqrt{G(t)/H(t)}$, and this may be preferable to $\surd\{G(t)/H(t)\}$.

Table 1. Prefixes for use with SI units.

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

## 1.2 Units

### 1.2.1 Symbols for units

The full name of a unit is always printed in lower case roman (upright) type. If that name is derived from a proper name then its abbreviation is a one or two letter symbol whose first letter is capitalized. The symbol for a unit whose name is not derived from a proper name is printed in lower case roman type.

*Examples*:

metre, m    ampere, A    watt, W    weber, Wb

*Remark*: Although by the above rule the symbol for litre is l, in order to avoid confusion between the letter l and the number 1, the symbol may also be written L.

Symbols for units do not contain a full stop (period) and remain unaltered in the plural.

*Example*:

7 cm   and not   7 cm.   or   7 cms

### 1.2.2 Prefixes

The prefixes that should be used to indicate decimal multiples or submultiples of a unit are given in table 1. Compound prefixes formed by the juxtaposition of two or more prefixes should not be used.

| | | | | |
|---|---|---|---|---|
| *Not* : | m$\mu$s , | *but* : | ns | (nanosecond) |
| *Not* : | kMW , | *but* : | GW | (gigawatt) |
| *Not* : | $\mu\mu$F , | *but* : | pF | (picofarad) |

When a prefix symbol is used with a unit symbol the combination should be considered as a single new symbol that can be raised to a positive or negative power without using brackets.

*Examples*:

$$\text{cm}^3 \qquad \text{mA}^2 \qquad \mu\text{s}^{-1}$$

*Remark*:

| | | | | | |
|---|---|---|---|---|---|
| $\text{cm}^3$ | means | $(0.01\ \text{m})^3$ | $= 10^{-6}\ \text{m}^3$ | and never | $0.01\ \text{m}^3$ |
| $\mu\text{s}^{-1}$ | means | $(10^{-6}\ \text{s})^{-1}$ | $= 10^{6}\ \text{s}^{-1}$ | and never | $10^{-6}\ \text{s}^{-1}$ |

### 1.2.3 Mathematical operations

Multiplication of two units should be indicated in one of the following ways :

$$\text{N m} \qquad \text{N} \cdot \text{m}$$

Division of one unit by another unit should be indicated in one of the following ways:

$$\frac{\text{m}}{\text{s}} \qquad \text{m/s} \qquad \text{m s}^{-1}$$

or by any other way of writing the product of m and $\text{s}^{-1}$. Not more than one solidus should be used in an expression.

*Examples*:

| | | | | | |
|---|---|---|---|---|---|
| *Not* : | cm/s/s , | *but* : | $\text{cm/s}^2$ | or | $\text{cm s}^{-2}$ |
| *Not* : | J/K/mol , | *but* : | J/(K mol) | or | $\text{J K}^{-1}\ \text{mol}^{-1}$ |

Since the rules of algebra may be applied to units and to physical quantities as well as to pure numbers, it is possible to divide a physical quantity by its unit. The result is the numerical value of the physical quantity in the specified unit system: $\{a\} = a/[a]$. This number is the quantity that is listed in tables or used to mark the axes of graphs. The form “quantity/unit” should therefore be used in the headings of tables and as the labels on graphs for an unambiguous indication of the meaning of the numbers to which it pertains.

*Examples*:

| | | | |
|---|---|---|---|
| Given | $p = 0.1013$ MPa, | then | $p/\text{MPa} = 0.1013$ |
| Given | $v = 2200$ m/s, | then | $v/(\text{m/s}) = 2200$ |
| Given | $T = 295$ K, | then | $T/\text{K} = 295, \quad 1000\,\text{K}/T = 3.3898$ |

## 1.3 Numbers

### 1.3.1 Decimal sign

In most European languages (including Russian and other languages using the Cyrillic alphabet) the decimal sign is a comma on the line (,); this sign is preferred by ISO (ISO 31/0-1981, p. 7) and is used in ISO publications even in English. However, in both American and British English the decimal sign is a dot on the line (.). The centered dot, (·), which has sometimes been used in British English, should never be used as a decimal sign in scientific writing.

### 1.3.2 Writing numbers

Numbers should normally be printed in roman (upright) type. There should always be at least one numerical digit both before and after the decimal sign. An integer should never be terminated by a decimal sign, and if the magnitude of the number is less than unity the decimal sign should be preceded by a zero.

*Examples*:

35 or 35.0 *but not* 35.        0.0035 *but not* .0035

To facilitate the reading of long numbers (greater than four digits either to the right or to the left of the decimal sign) the digits may be grouped in groups of three separated by a thin space, but no comma or point should be used except for the decimal sign. Instead of a single final digit, the last four digits may be grouped.

*Examples*:

1987    299 792 458    1.234 567 8  or  1.234 5678

### 1.3.3 Arithmetical operations

The sign for multiplication of numbers is a cross (×) or a centered dot (·); however, when a dot is used as a decimal sign the centered dot should not be used as the multiplication sign.

*Examples*:

$$2.3 \times 3.4 \quad \text{or} \quad 2,3 \times 3,4 \quad \text{or} \quad 2,3 \cdot 3,4 \quad \text{or} \quad (137.036)(273.16)$$

*but not* $2.3 \cdot 3.4$

Division of one number by another number may be indicated either by a horizontal bar or by a solidus (/), or by writing it as the product of numerator and the inverse first power of the denominator. In such cases the number under the inverse power should always be placed in brackets, parentheses or other sign of aggregation.

*Examples*:

$$\frac{136}{273.16} \qquad 136/273.16 \qquad 136\,(273.16)^{-1}$$

As in the case of quantities (see section **1.1.3**), when the solidus is used and there is any doubt where the numerator starts or where the denominator ends, brackets or parentheses should be used.

## 1.4 Nomenclature for intensive properties

**1.4.1** The adjective ‘specific’ in the English name for an intensive physical quantity should be avoided if possible and should in all cases be restricted to the meaning ‘divided by mass’ (mass of the system, if this consists of more than one component or more than one phase). In French, the adjective ‘*massique*’ is used with the sense of ‘divided by mass’ to express this concept.

*Examples*:

| | | |
|---|---|---|
| specific volume, | *volume massique,* | volume/mass |
| specific energy, | *énergie massique,* | energy/mass |
| specific heat capacity, | *capacité thermique massique,* | heat capacity/mass |

**1.4.2** The adjective 'molar' in the English name for an intensive physical quantity should be restricted to the meaning 'divided by amount of substance' (the amount of substance of the system if it consists of more than one component or more than one phase).

*Examples*:

| | |
|---|---|
| molar mass, | mass/amount of substance |
| molar volume, | volume/amount of substance |
| molar energy, | energy/amount of substance |
| molar heat capacity, | heat capacity/amount of substance |

An intensive molar quantity is usually denoted by attaching the subscript m to the symbol for the corresponding extensive quantity, (*e.g.*, volume, $V$; molar volume, $V_\mathrm{m} = V/n$). In a mixture the symbol $X_\mathrm{B}$, where $X$ denotes an extensive quantity and B is the chemical symbol for a substance, denotes the partial molar quantity of the substance B defined by the relation:

$$X_\mathrm{B} = (\partial X/\partial n_\mathrm{B})_{T,p,n_\mathrm{C},\ldots}.$$

For a pure substance B the partial molar quantity $X_\mathrm{B}$ and the molar quantity $X_\mathrm{m}$ are identical. The molar quantity $X_\mathrm{m}(\mathrm{B})$ of pure substance B may be denoted by $X^*_\mathrm{B}$, where the superscript $^*$ denotes 'pure', so as to distinguish it from the partial molar quantity $X_\mathrm{B}$ of substance B in a mixture, which may alternatively be designated $X'_\mathrm{B}$.

**1.4.3** The noun 'density' in the English name for an intensive physical quantity (when it is not modified by the adjectives 'linear' or 'surface') usually implies 'divided by volume' for scalar quantities but 'divided by area' for vector quantities denoting flow or flux. In French, the adjectives *volumique*, *surfacique*, or *linéique* as appropriate are used with the name of a scalar quantity to express division by volume, area or length, respectively.

*Examples*:

| | | |
|---|---|---|
| mass density, | *masse volumique,* | mass/volume |
| energy density, | *énergie volumique,* | energy/volume |

*but*

| | | |
|---|---|---|
| current density, | *densité de courant,* | flow/area |
| surface charge density, | *charge surfacique,* | charge/area |

## 1.5 Dimensional and dimensionless ratios

### 1.5.1 Coefficients and factors

When a quantity $A$ is proportional to another quantity $B$, the relationship is expressed by an equation of the form $A = k \cdot B$. The quantity $k$ is usually given the name 'coefficient' or 'modulus' if $A$ and $B$ have different dimensions and 'factor' or 'index' if $A$ and $B$ have the same dimension.

*Examples*:

| | | |
|---|---|---|
| $\boldsymbol{E} = A_{\mathrm{H}}(\boldsymbol{B} \times \boldsymbol{J})$ | $A_{\mathrm{H}}$, | Hall coefficient |
| $\sigma = E\epsilon$ | $E$, | Young's modulus |
| $\boldsymbol{J} = -D\,\boldsymbol{\nabla} n$ | $D$, | diffusion coefficient |
| $L_{12} = k\sqrt{L_1 L_2}$ | $k$, | coupling factor |
| $F = \mu F_{\mathrm{n}}$ | $\mu$, | friction factor |

### 1.5.2 Parameters, numbers and ratios

Certain combinations of physical quantities often are useful in characterizing the behavior or properties of a physical system; it is then convenient to consider such a combination as a new quantity. In general this new quantity is called a 'parameter'; if, however, the quantity is dimensionless it is referred to as a 'number' or a 'ratio'. If such a ratio is inherently positive and less than 1 it is often denoted as a 'fraction'.

*Examples*:

| | |
|---|---|
| Grüneisen parameter : $\gamma$ | $\gamma = \alpha/\kappa\rho c_V$ |
| Reynold's number : $Re$ | $Re = \rho v l/\eta$ |
| mobility ratio : $b$ | $b = \mu_-/\mu_+$ |
| mole fraction : $x_{\mathrm{B}}$ | $x_{\mathrm{B}} = n_{\mathrm{B}}/\Sigma_j n_{\mathrm{B}_j}$ |

# 2 SYMBOLS FOR ELEMENTS, PARTICLES, STATES AND TRANSITIONS

## 2.1 Chemical elements

Names and symbols for the chemical elements are given in table 2. Symbols for chemical elements should be written in roman (upright) type. The symbol is not followed by a full stop.

*Examples*:

Ca   C   H   He

The nucleon number (mass number, baryon number) of a nuclide is shown as a left superscript (*e.g.*, $^{14}N$).

In nuclear physics, when there will be no confusion with molecular compounds a left subscript may be used to indicate the number of protons and a right subscript to indicate the number of neutrons in the nucleus (*e.g.*, $^{235}_{92}U_{143}$). Although these subscripts are redundant they are often useful. The right subscript is usually omitted and should never be included unless the left subscript is also present.

The right subscript position is also used to indicate the number of atoms of a nuclide in a molecule (*e.g.*, $^{14}N_2{}^{16}O$). The right superscript position should be used, if required, to indicate a state of ionization (*e.g.*, $Ca_2^+$, $PO_4^{3-}$) or an excited *atomic* state (*e.g.*, $He^*$). A metastable *nuclear* state, however, often is treated as a distinct nuclide: *e.g.*, either $^{118}Ag^{m}$ or $^{118m}Ag$.

Roman numerals are used in two different ways:

i. The spectrum of a $z$-fold ionized atom is specified by the small capital roman numeral corresponding to $z + 1$, written on the line with a thin space following the chemical symbol.

*Examples*:

H I (spectrum of neutral hydrogen)   Ca II   Al III

ii. Roman numerals in right superscript position are used to indicate the oxidation number.

*Examples*:

$Pb_2^{II}Pb^{IV}O_4$   $K_6Mn^{IV}Mo_9O_{32}$

Table 2. Names and symbols for the chemical elements.*

| Atomic number | Name | Symbol | Atomic number | Name | Symbol |
|---|---|---|---|---|---|
| 1 | hydrogen | H | 39 | yttrium | Y |
| 2 | helium | He | 40 | zirconium | Zr |
| 3 | lithium | Li | 41 | niobium | Nb |
| 4 | beryllium | Be | 42 | molybdenum | Mo |
| 5 | boron | B | 43 | technetium | Tc |
| 6 | carbon | C | 44 | ruthenium | Ru |
| 7 | nitrogen | N | 45 | rhodium | Rh |
| 8 | oxygen | O | 46 | palladium | Pd |
| 9 | fluorine | F | 47 | silver | Ag |
| 10 | neon | Ne | 48 | cadmium | Cd |
| 11 | sodium | Na | 49 | indium | In |
| 12 | magnesium | Mg | 50 | tin | Sn |
| 13 | aluminum | Al | 51 | antimony | Sb |
| 14 | silicon | Si | 52 | tellurium | Te |
| 15 | phosphorus | P | 53 | iodine | I |
| 16 | sulfur | S | 54 | xenon | Xe |
| 17 | chlorine | Cl | 55 | cesium | Cs |
| 18 | argon | Ar | 56 | barium | Ba |
| 19 | potassium | K | 57 | lanthanum | La |
| 20 | calcium | Ca | 58 | cerium | Ce |
| 21 | scandium | Sc | 59 | praseodymium | Pr |
| 22 | titanium | Ti | 60 | neodymium | Nd |
| 23 | vanadium | V | 61 | promethium | Pm |
| 24 | chromium | Cr | 62 | samarium | Sm |
| 25 | manganese | Mn | 63 | europium | Eu |
| 26 | iron | Fe | 64 | gadolinium | Gd |
| 27 | cobalt | Co | 65 | terbium | Tb |
| 28 | nickel | Ni | 66 | dysprosium | Dy |
| 29 | copper | Cu | 67 | holmium | Ho |
| 30 | zinc | Zn | 68 | erbium | Er |
| 31 | gallium | Ga | 69 | thulium | Tm |
| 32 | germanium | Ge | 70 | ytterbium | Yb |
| 33 | arsenic | As | 71 | lutetium | Lu |
| 34 | selenium | Se | 72 | hafnium | Hf |
| 35 | bromine | Br | 73 | tantalum | Ta |
| 36 | krypton | Kr | 74 | tungsten | W |
| 37 | rubidium | Rb | 75 | rhenium | Re |
| 38 | strontium | Sr | 76 | osmium | Os |

Table 2. Names and symbols for the chemical elements (continued).

| Atomic number | Name | Symbol | Atomic number | Name | Symbol |
|---|---|---|---|---|---|
| 77 | iridium | Ir | 91 | protactinium | Pa |
| 78 | platinum | Pt | 92 | uranium | U |
| 79 | gold | Au | 93 | neptunium | Np |
| 80 | mercury | Hg | 94 | plutonium | Pu |
| 81 | thallium | Tl | 95 | americium | Am |
| 82 | lead | Pb | 96 | curium | Cm |
| 83 | bismuth | Bi | 97 | berkelium | Bk |
| 84 | polonium | Po | 198 | californium | Cf |
| 85 | astatine | At | 199 | einsteinium | Es |
| 86 | radon | Rn | 100 | fermium | Fm |
| 87 | francium | Fr | 101 | mendelevium | Md |
| 88 | radium | Ra | 102 | nobelium | No |
| 89 | actinium | Ac | 103 | lawrencium | Lr |
| 90 | thorium | Th | | | |

* For values of the relative atomic masses of the elements, see *Pure and Applied Chemistry* **58** (1986) 1677.

## 2.2 Nuclear particles

The common designations for particles used as projectiles or products in nuclear reactions are listed in table 3. In addition to the symbols given in the table, an accepted designation for a general heavy ion (where there is no chance of ambiguity) is HI.

The charge of a particle may be indicated by adding a superscript $^+, ^0, ^-$ to the symbol for the particle.

*Examples*:

$$\pi^+, \pi^0, \pi^- \qquad \mathrm{e}^+, \mathrm{e}^- \qquad \beta^+, \beta^-$$

If no charge is indicated in connection with the symbols p and e, these symbols refer to the positive proton and the negative electron respectively. The bar ¯ or the tilde ˜ above the symbol for a particle is used to indicate the corresponding anti-particle; the notation $\bar{\mathrm{p}}$ is preferable to $\mathrm{p}^-$ for the anti-proton, but both $\bar{\mathrm{e}}$ and $\mathrm{e}^+$ (or $\bar{\beta}$ and $\beta^+$) are commonly used for the positron.

The symbol e (roman) for the electron should not be confused with the symbol *e* (italic) for the elementary charge.

## 2.3 'Fundamental' particles

There is little information to be imparted by listing simply that the symbol for the P-particle is 'P'. Furthermore, a complete set of nomenclature rules

Table 3. Symbols for nuclear particles.

| | | | |
|---|---|---|---|
| photon | $\gamma$ | nucleon | N |
| neutrino | $\nu, \nu_e, \nu_\mu, \nu_\tau$ | neutron | n |
| electron | e, $\beta$ | proton ($^1H^+$) | p |
| muon | $\mu$ | deuteron ($^2H^+$) | d |
| tauon | $\tau$ | triton ($^3H^+$) | t |
| pion | $\pi$ | helion ($^3He^{2+}$) | h |
| | | alpha particle ($^4He^{2+}$) | $\alpha$ |

*Note*: The symbol $\tau$ has previously been used for the helion, but $\tau$ should be reserved for the tauon (heavy lepton).

in high energy physics is still being formulated. The biennial "Review of Particle Properties" issued by the Particle Data Group (Lawrence Berkeley Laboratory and CERN) is the best reference for this and for related topics. Since it is beyond the scope of this guide to present detailed information on the relationships among these particles, the list below gives only the broadest family groupings of those particles that are stable under the strong nuclear force and can truly be called 'particles' rather than 'resonances'. Each fermion listed has an associated anti-particle; bosons are their own anti-particles.

| | |
|---|---|
| Gauge bosons | $\gamma$, W, Z |
| Leptons | e, $\nu_e$, $\mu$, $\nu_\mu$, $\tau$, $\nu_\tau$ |
| Quarks (q) | u, d, c, s, t, b |
| Mesons ($q\bar{q}$) | |
| nonstrange ($S = 0$) | $\pi^+$, $\pi^0$, $\pi^-$, $\eta$, $D^+$, $D^0$ |
| strange ($S = 1$) | $K^+$, $K^0$, ($K_L, K_S$), $F^+$ |
| Baryons (qqq) | |
| ($S = 0$) | p, n, $\Lambda_c^+$ |
| ($S = -1$) | $\Lambda, \Sigma^+, \Sigma^0, \Sigma^-$ |
| ($S = -2$) | $\Xi^0, \Xi^-$ |
| ($S = -3$) | $\Omega^-$ |

The names for quarks are the symbols themselves; the names 'up', 'down', 'charm', 'strange', 'top (truth)' and 'bottom (beauty)' are to be considered only as mnemonics for these symbols.

The mesons $D^+$, $D^0$ and $F^+$ and the charm baryon $\Lambda_c^+$ have charm quantum number $C = +1$. The B-mesons have 'bottomness' (beauty) quantum number $B = +1$.

## 2.4 Spectroscopic notation

A letter symbol indicating a quantum number of a *single particle* should be printed in lower case upright type. A letter symbol indicating a quantum number of a *system* should be printed in capital upright type.

### 2.4.1 Atomic spectroscopy

The letter symbols indicating the orbital angular momentum quantum number are

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $l =$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | ... |
| symbol | s | p | d | f | g | h | i | k | l | m | n | o | ... |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $L =$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | ... |
| symbol | S | P | D | F | G | H | I | K | L | M | N | O | ... |

A right subscript attached to the angular momentum symbol indicates the total angular momentum quantum number $j$ or $J$. A left superscript indicates the spin multiplicity, $2s + 1$ or $2S + 1$.

*Examples*:

| | |
|---|---|
| $\mathrm{d}_{\frac{3}{2}}$ - electron | $(j = \frac{3}{2})$ |
| $^3\mathrm{D}$ - term | (spin multiplicity = 3) |
| $^3\mathrm{D}_2$ - level | $J = 2$ |

An atomic electron configuration is indicated symbolically by:

$$(nl)^k(n'l')^{k'} \ \ldots$$

in which $k, k', \ldots$ are the numbers of electrons with principal quantum numbers $n, n', \ldots$ and orbital angular momentum quantum numbers $l, l', \ldots$, respectively. Instead of $l = 0, 1, 2, 3, \ldots$ one uses the quantum number symbols s, p, d, f, ..., and the parentheses are usually omitted.

*Example*:

the atomic electron configuration: $1\mathrm{s}^2 2\mathrm{s}^2 2\mathrm{p}^3$

An atomic state is specified by giving all of its quantum numbers. In Russell–Saunders ($LS$) coupling an atomic *term* is specified by $L$ and $S$ and an atomic *level* by $L$, $S$ and $J$. An atomic *state* is specified by $L$, $S$, $J$ and $M_J$ or by $L$, $S$, $M_S$ and $M_L$.

### 2.4.2 Molecular spectroscopy

For *linear molecules* the letter symbols indicating the quantum number of the component of electronic orbital angular momentum along the molecular axis are

| | | | | |
|---|---|---|---|---|
| $\lambda =$ | 0 | 1 | 2 | ... |
| symbol | $\sigma$ | $\pi$ | $\delta$ | ... |

| | | | | |
|---|---|---|---|---|
| $\Lambda =$ | 0 | 1 | 2 | ... |
| symbol | $\Sigma$ | $\Pi$ | $\Delta$ | ... |

A left superscript indicates the spin multiplicity. For molecules having a symmetry center, the parity symbol g (*gerade*) or u (*ungerade*) indicating respectively symmetric or antisymmetric behavior on inversion is attached as a right subscript. A $^+$ or $^-$ sign attached as a right superscript indicates the symmetry with regard to reflection in any plane through the symmetry axis of the molecule.

*Examples*:

$$\Sigma_\mathrm{g}^+,\ \Pi_\mathrm{u},\ {}^2\Sigma,\ {}^3\Pi,\ \text{etc.}$$

The letter symbols indicating the quantum number of vibrational angular momentum are

$$\begin{array}{rcccc} l = & 0 & 1 & 2 & 3\ \ldots \\ \text{symbol} & \Sigma & \Pi & \Delta & \Phi\ \ldots \end{array}$$

### 2.4.3 Nuclear spectroscopy

The spin and parity assignment of a nuclear state is

$$J^\pi$$

where the parity symbol $\pi$ is + for even parity and − for odd parity.

*Examples*:

$$3^+, \quad 2^-$$

A shell model configuration is indicated symbolically by:

$$\nu(nl_j)^\kappa(n'l'_{j'})^{\kappa'}\ldots\pi(n''l''_{j''})^{\kappa''}(n'''l'''_{j'''})^{\kappa'''}\ldots$$

where the letter $\pi$ refers to the proton shell and the letter $\nu$ to the neutron shell. Negative values of the superscript indicate holes in a completed shell. Instead of $l = 0, 1, 2, 3, \ldots$ one uses the symbols s, p, d, f, ... as in atoms (except for $l = 7$ which is denoted by k in atoms and by j in nuclei).

*Example*:

$$\text{the nuclear configuration:}\quad \nu(2\mathrm{d}_{\frac{5}{2}})^6\,\pi(2\mathrm{p}_{\frac{1}{2}})^2(1\mathrm{g}_{\frac{9}{2}})^3$$

When the neutrons and protons are in the same shell with well-defined isospin $T$, the notation $(nl_j)^\alpha$ is used where $\alpha$ denotes the total number of nucleons.

*Example*:

$$(1\mathrm{f}_{\frac{7}{2}})^5$$

### 2.4.4 Spectroscopic transitions

The upper (higher energy) level and the lower (lower energy) level of a transition are indicated respectively by $'$ and $''$.

*Examples*:

$$h\nu = E' - E'' \qquad\qquad \sigma = T' - T''$$

The designation of spectroscopic transitions is not uniform. In *atomic* spectroscopy* the convention is to write the *lower* state first and the *upper* state second; however, in *molecular* and *polyatomic* spectroscopy** the convention is reversed and one writes the *upper* state first and the *lower* state second.

In either case the two state designations are connected by a dash — or, if it is necessary to indicate whether the transition is an absorption or an emission process, by arrows ← and →. If there is any chance of ambiguity, the convention being used with regard to the ordering of the states should be clearly stated.

*Examples*:

| | |
|---|---|
| $2\,^2\mathrm{S}_{\frac{1}{2}} — 4\,^2\mathrm{P}_{\frac{3}{2}}$ | atomic transition |
| $(J', K') \leftarrow (J'', K'')$ | molecular rotational absorption |

The difference between two quantum numbers is that of the upper state minus that of the lower state.

*Example*:

$$\Delta J = J' - J''$$

The branches of the rotation–vibration band are designated as:

| | $\Delta J = J' - J''$ |
|---|---|
| O branch: | $-2$ |
| P branch: | $-1$ |
| Q branch: | $0$ |
| R branch: | $+1$ |
| S branch: | $+2$ |

## 2.5 Nomenclature conventions in nuclear physics

### 2.5.1 Nuclides

A species of atoms identical as regards atomic number (proton number) and mass number (nucleon number) should be indicated by the word 'nuclide', not by the word 'isotope'. Different nuclides having the same mass number are called *isobaric nuclides* or *isobars*.

Different nuclides having the same atomic number are called *isotopic nuclides* or *isotopes*. (Since nuclides with the same number of protons are 'isotopes', nuclides with the same number of neutrons have sometimes been designated as 'isotones'.)

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* See R. D. Cowan, *The Theory of Atomic Structure and Spectra* (Univ. of California Press, 1981).

** See *Report on Notation for the Spectra of Polyatomic Molecules*, J. Chem. Phys. **23** (1955) 1997.

The symbolic expression representing a nuclear reaction should follow the pattern:

$$\begin{matrix}\text{initial} \\ \text{nuclide}\end{matrix}\left(\begin{matrix}\text{incoming particle} \\ \text{or photon}\end{matrix}\quad , \quad \begin{matrix}\text{outgoing particle(s)} \\ \text{or photon(s)}\end{matrix}\right)\begin{matrix}\text{final} \\ \text{nuclide}\end{matrix}$$

*Examples*:

$$^{14}\mathrm{N}\,(\alpha,\mathrm{p})\,^{17}\mathrm{O} \qquad ^{59}\mathrm{Co}\,(\mathrm{n},\gamma)\,^{60}\mathrm{Co}$$
$$^{23}\mathrm{Na}\,(\gamma,3\mathrm{n})\,^{20}\mathrm{Na} \qquad ^{31}\mathrm{P}\,(\gamma,\mathrm{pn})\,^{29}\mathrm{Si}$$

### 2.5.2 Characterization of interactions

Multipolarity of a transition:

| | |
|---|---|
| electric or magnetic monopole | E0 or M0 |
| electric or magnetic dipole | E1 or M1 |
| electric or magnetic quadrupole | E2 or M2 |
| electric or magnetic octopole | E3 or M3 |
| electric or magnetic $2^n$-pole | E$n$ or M$n$ |

Designation of parity change in a transition:

| | |
|---|---|
| transition *with* parity change : | (yes) |
| transition *without* parity change : | (no) |

Notation for covariant character of coupling:

| | | | |
|---|---|---|---|
| S | Scalar coupling | A | Axial vector coupling |
| V | Vector coupling | P | Pseudoscalar coupling |
| T | Tensor coupling | | |

### 2.5.3 Polarization conventions

*Sign of polarization vector* (Basel convention): In a nuclear interaction the positive polarization direction for particles with spin $\frac{1}{2}$ is taken in the direction of the vector product

$$\boldsymbol{k}_\mathrm{i} \times \boldsymbol{k}_\mathrm{o}$$

where $\boldsymbol{k}_\mathrm{i}$ and $\boldsymbol{k}_\mathrm{o}$ are the wave vectors of the incoming and outgoing particles respectively.

*Description of polarization effects* (Madison convention): In the symbolic expression for a nuclear reaction A(b,c)D, an arrow placed over a symbol denotes a particle which is initially in a polarized state or whose state of polarization is measured.

*Examples*:

| | |
|---|---|
| $A(\vec{b}, c)D$ | polarized incident beam |
| $A(\vec{b}, \vec{c})D$ | polarized incident beam; polarization of the outgoing particle c is measured (polarization transfer) |
| $A(b, \vec{c})D$ | unpolarized incident beam; polarization of the outgoing particle c is measured |
| $\vec{A}(b, c)D$ | unpolarized beam incident on a polarized target |
| $\vec{A}(b, \vec{c})D$ | unpolarized beam incident on a polarized target; polarization of the outgoing particle c is measured |
| $A(\vec{b}, c)\vec{D}$ | polarized incident beam; measurement of the polarization of the residual nucleus |

# 3 DEFINITION OF UNITS AND SYSTEMS OF UNITS

## 3.1 Systems of units

In a system consisting of a set of physical quantities and the relational equations connecting them, a certain number of quantities are regarded by convention as dimensionally independent and form the set of *base quantities* for the whole system. All other physical quantities are *derived quantities*, defined in terms of the base quantities and expressed algebraically as products of powers of the base quantities.

In a similar way, a *system of units* is based on a set of units chosen by convention to be the units of the base quantities, and all units for derived quantities are expressed as products of powers of the base units, analogous to the corresponding expressions in the system of quantities. When the derived units are expressed in terms of the base units by relations with numerical factors equal to unity, the system and its units are said to be coherent.

The number of base units of the unit system is equal to that of the corresponding set of base quantities. The base units themselves are defined samples of the base quantities.

The expression of a quantity as a product of powers of the base quantities (neglecting their vectorial or tensorial character and all numerical factors including their sign) is called the dimensional product (or the dimension) of the quantity with respect to the chosen set of base quantities or base dimensions. The powers to which the various base quantities or base dimensions are raised are called the dimensional exponents; the quantities and the corresponding units are of the same dimension.

Derived units and their symbols are expressed algebraically in terms of base units by means of the mathematical signs for multiplication and division. Some derived units have received special names and symbols, which can themselves be used to form names and symbols of other derived units (see sections **3.2** and **3.3**).

Physical quantities that have as their dimension a product of powers of the base dimensions with all exponents equal to zero are called dimensionless quantities. The values of dimensionless quantities (*e.g.*, relative density, refractive index) are expressed by pure numbers. The corresponding unit, which is the ratio of a unit to itself, is usually not written; if necessary it may be expressed by the number 1. Since the primary purpose of a system of units is to provide a basis for the transformation of the numerical values of physical quantities under a transformation of units, and since dimensionless quantities are invariant to such a transformation, there is no need to include quantities like plane angle and solid angle in the category of base quantities. Plane angle is usually considered to be a derived quantity, defined in terms of the ratio of two lengths, and solid angle, a derived quantity defined in terms of the ratio of an area to the square of a lenghth. Nevertheless, in some situations (notably in statistical physics, in particle transport and radiative transfer and particularly in photometry and illumination) the steradian must be treated as a base *unit* in order to avoid ambiguity and to distinguish between units corresponding to different quantities.

### 3.2 The International System of Units (SI)

The name Système International d'Unités (International System of Units) with the international abbreviation SI was adopted by the Conférence Générale des Poids et Mesures (CGPM) in 1960. It is a coherent system based on the seven base units (CGPM 1960 and 1971) listed in table 4. These units are presently defined in the following way:

1: metre; *mètre*

*Le mètre est la longueur du trajet parcouru dans le vide par la lumière pendant une durée de* 1/299 792 458 *de seconde.* (17th CGPM (1983), Resolution 1).

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

2: kilogram; *kilogramme*

*Le kilogramme est l'unité de masse; il est égal à la masse du prototype international du kilogramme.* (1st CGPM (1889) and 3rd CGPM (1901)).

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

3: second; *seconde*

*La seconde est la durée de* 9 192 631 770 *périodes de la radiation correspondant à la transition entre les deux niveaux hyperfins de l'état fondamental de l'atome de cesium 133.* (13th CGPM (1967), Resolution 1).

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.

4: ampere; *ampère*

*L'ampère est l'intensité d'un courant constant qui, maintenu dans deux conducteurs parallèles, rectilignes, de longueur infinie, de section circulaire négligeable, et placés à une distance de 1 mètre l'un de l'autre dans le vide, produirait entre ces conducteurs une force égale à* $2 \times 10^{-7}$ *newton par mètre de longueur.* (9th CGPM (1948), Resolutions 2 and 7).

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ newton per metre of length.

Table 4. SI base units.

| Base quantity | Name | Symbol |
|---|---|---|
| length<br>*longueur* | metre<br>*mètre* | m |
| mass<br>*masse* | kilogram<br>*kilogramme* | kg |
| time<br>*temps* | second<br>*seconde* | s |
| electric current<br>*courant électrique* | ampere<br>*ampère* | A |
| thermodynamic temperature<br>*température thermodynamique* | kelvin<br>*kelvin* | K |
| amount of substance<br>*quantité de matière* | mole<br>*mole* | mol |
| luminous intensity<br>*intensité lumineuse* | candela<br>*candela* | cd |

5: kelvin; *kelvin*

*Le kelvin, unité de température thermodynamique, est la fraction 1/273,16 de la température thermodynamique du point triple de l'eau.* (13th CGPM (1967), Resolution 4).

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

The 13th CGPM (1967, Resolution 3) also decided that the unit kelvin and its symbol K should be used to express both the thermodynamic temperature and an interval or a difference of temperature.

In addition to the thermodynamic temperature (symbol $T$) there is also the Celsius temperature (symbol $t$) defined by the equation

$$t = T - T_0$$

where $T_0 = 273.15\,\mathrm{K}$. Celsius temperature is expressed in degree Celsius; *degré Celsius* (symbol, °C). The unit 'degree Celsius' is equal to the unit 'kelvin', and a temperature interval or a difference of temperature may also be expressed in degrees Celsius.

6: mole; *mole*

1°. *La mole est la quantité de matière d'un système contenant autant d'entités élémentaires qu'il y a d'atomes dans 0,012 kilogramme de carbone 12.*

2°. *Lorsqu'on emploie la mole, les entités élémentaires doivent être spécifiées et peuvent être des atomes, des molécules, des ions,* *des électrons, d'autres particules ou des groupements spécifiés de telles particules.* (14th CGPM (1971), Resolution 3).

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

*Note*: In this definition, it is understood that the carbon 12 atoms are unbound, at rest and in their ground state.

7: candela; *candela*

*La candela est l'intensité lumineuse, dans une direction donnée, d'une source qui émet une radiation monochromatique de fréquence* $540 \times 10^{12}$ *hertz et dont l'intensité énergétique dans cette direction est 1/683 watt par stéradian.* (16th CGPM (1979), Resolution 3).

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

Specific names and symbols have been given to several coherent derived SI units; these derived units are listed in table 5.

### 3.3 Non-SI units of special interest in physics

Because consistency and uniformity of usage tend to enhance clarity, it is a general rule of SI that the use of non-SI units should be discontinued. However there are some important instances where this is either impractical or inadvisable. The SI recognizes three categories of non-SI units to be used with the SI.

#### 3.3.1 Units accepted for use whose value in SI units is exactly defined

The CIPM (1969) recognized that users of the SI will wish to employ certain units which are important and widely used, but which do not properly fall within the SI. The special names and symbols of those units that have been accepted for continuing use and the corresponding units of the SI are listed in table 6. Although the use of these units is acceptable, their combination with SI units to form incoherent compound units should be authorized only in limited cases.

Decimal multiples or sub-multiples of the time units listed in table 6 should not be formed by using the prefixes given in table 1. Forming symbols for decimal multiples or sub-multiples of units by using the symbols of the prefixes given in table 1 is not possible with superscript symbols, such as $^\circ$, $'$, and $''$ for angle units.

Table 5. Derived SI units with special names.

| Quantity<br>*Grandeur* | Derived SI unit; *Unité SI dérivée*<br>Name<br>*Nom* | Symbol<br>*Symbole* | Expression in terms of base units<br>*Expression en unités de base* | Expression in terms of other SI units<br>*Expression en d'autres unités SI* |
|---|---|---|---|---|
| plane angle<br>*angle plan* | radian | rad | m/m | |
| solid angle<br>*angle solide* | steradian<br>*stéradian* | sr | $m^2/m^2$ | |
| frequency<br>*fréquence* | hertz | Hz | $s^{-1}$ | |
| force<br>*force* | newton | N | $m\ kg\ s^{-2}$ | J/m |
| pressure<br>*pression* | pascal | Pa | $m^{-1}\ kg\ s^{-2}$ | $N/m^2$, $J/m^3$ |
| energy, work, quantity of heat<br>*énergie, travail, quantité de chaleur* | joule | J | $m^2\ kg\ s^{-2}$ | N m |
| power, radiant flux<br>*puissance, flux énergétique* | watt | W | $m^2\ kg\ s^{-3}$ | J/s |
| quantity of electricity, electric charge<br>*quantité d'électricité, charge électrique* | coulomb | C | A s | |
| electric potential, potential difference, electromotive force<br>*tension électrique, différence de potentiel, force électromotrice* | volt | V | $m^2\ kg\ s^{-3}\ A^{-1}$ | W/A, J/C |
| capacitance<br>*capacité électrique* | farad | F | $m^{-2}\ kg^{-1}\ s^4\ A^2$ | C/V |
| electric resistance<br>*résistance électrique* | ohm | Ω | $m^2\ kg\ s^{-3}\ A^{-2}$ | V/A |

Table 5. Derived SI units with special names (continued).

| Quantity<br>*Grandeur* | Derived SI unit; *Unité SI dérivée*<br>Name<br>*Nom* | Symbol<br>*Symbole* | Expression in terms of base units<br>*Expression en unités de base* | Expression in terms of other SI units<br>*Expression en d'autres unités SI* |
|---|---|---|---|---|
| conductance<br>*conductance* | siemens | S | $m^{-2}$ $kg^{-1}$ $s^3$ $A^2$ | A/V, $\Omega^{-1}$ |
| magnetic flux<br>*flux d'induction magnétique* | weber | Wb | $m^2$ kg $s^{-2}$ $A^{-1}$ | V s |
| magnetic flux density<br>*induction magnétique* | tesla | T | kg $s^{-2}$ $A^{-1}$ | Wb/$m^2$ |
| inductance<br>*inductance* | henry | H | $m^2$ kg $s^{-2}$ $A^{-2}$ | Wb/A |
| Celsius temperature<br>*température Celsius* | degree Celsius<br>*degré Celsius* | °C | K | |
| luminous flux<br>*flux lumineux* | lumen | lm | cd sr * | |
| illuminance<br>*éclairement lumineux* | lux | lx | $m^{-2}$ cd sr * | lm/$m^2$ |
| activity<br>*activité* | becquerel | Bq | $s^{-1}$ | |
| absorbed dose**<br>*dose absorbée* | gray | Gy | $m^2$ $s^{-2}$ | J/kg |
| dose equivalent**<br>*équivalent de dose* | sievert | Sv | $m^2$ $s^{-2}$ | J/kg |

* The symbol sr must be included here to distinguish luminous flux (lumen) from luminous intensity (candela).

** The dose equivalent is equal to the absorbed dose multiplied by dimensionless factors defining the relative biological effectiveness of the radiation. Although the gray and the sievert have the same expression in terms of base units, they measure conceptually distinct quantities.

Table 6. Commonly used non-SI units.

| Quantity *Grandeur* | Unit; *Unité* Name *Nom* | Symbol *Symbole* | Definition *Définition* |
|---|---|---|---|
| plane angle *angle plan* | degree *degré* | $^\circ$ | $1^\circ = \frac{\pi}{180}$ rad |
| | minute (of angle) *minute (d'angle)* | $'$ | $1' = \left(\frac{1}{60}\right)^\circ = \frac{\pi}{10\,800}$ rad |
| | second (of angle) *seconde (d'angle)* | $''$ | $1'' = \left(\frac{1}{60}\right)' = \frac{\pi}{648\,000}$ rad |
| time* *temps* | minute *minute* | min | 1 min = 60 s |
| | hour *heure* | h | 1 h = 60 min = 3600 s |
| | day *jour* | d | 1 d = 24 h = 86 400 s |
| volume *volume* | litre *litre* | l, L | $1\ \text{L} = 1\ \text{dm}^3 = 10^{-3}\ \text{m}^3$ |
| mass *masse* | tonne *tonne* | t | 1 t = 1 Mg = 1000 kg |

* The general symbol for the time unit year (*année*) is a.

Table 7. Units whose values are defined by experiment.
For the values of these units see section **6**, table 10.

| Quantity *Grandeur* | Unit; *Unité* Name *Nom* | Symbol *Symbole* | Definition *Définition* |
|---|---|---|---|
| mass *masse* | (unified) atomic mass unit *unité de masse atomique (unifiée)* | u | $1\ \text{u} = \text{m}(^{12}\text{C})/12$ |
| energy *énergie* | electronvolt *électronvolt* | eV | $1\ \text{eV} = (e/\text{C})\ \text{J}$ |

### 3.3.2 Units accepted for use whose value expressed in SI units must be obtained by experiment

The units listed in table 7, which are important and widely used for special problems, are also accepted by the CIPM (1969) for continuing use with those of the SI.

### 3.3.3 Units whose use may be discontinued

In view of existing practice, the CIPM (1978) considered it acceptable to retain for the time being the units listed in table 8 for use with those of the SI, with the exception of the units fermi, torr and calorie. These three units should be avoided in favor of an appropriate SI unit or decimal multiple formed by using the prefixes of table 1. All of the units listed in table 8 may be abandoned in the future; they should not be introduced where they are not already in use at present.

The appearance of the bar in table 8 does not imply a preference for the use of $p_\circ = 10^5$ Pa as the thermodynamic standard state pressure. The choice between $10^5$ Pa and 101 325 Pa (or any other value) is a matter of convenience, and is not a direct consequence of the choice of units. However, the use of a standard pressure as a *unit* under the name "standard atmosphere" should be avoided.

Table 8. Non-SI units, the use of which may be discontinued.

| Quantity<br>*Grandeur* | Unit; *Unité*<br>Name<br>*Nom* | Symbol<br>*Symbole* | Definition<br>*Définition* |
|---|---|---|---|
| length<br>*longueur* | angstrom<br>fermi | Å<br>fm * | 1 Å = $10^{-10}$ m<br>1 fermi = $10^{-15}$ m |
| area<br>*aire* | barn | b | 1 b = 100 $\mathrm{fm}^2$<br>= $10^{-28}$ $\mathrm{m}^2$ |
| pressure<br>*pression* | bar<br>torr | bar<br>Torr | 1 bar = $10^5$ Pa<br>$1\ \mathrm{Torr} = \frac{101325}{760}\ \mathrm{Pa}$ |
| quantity of heat<br>*quantité de chaleur* | calorie | cal | $1\ \mathrm{cal_{IT}} = 4.1868$ J ** <br>$1\ \mathrm{cal_{15}} = 4.1855$ J ** <br>$1\ \mathrm{cal_{th}} = 4.184$ J ** |
| activity of a radio-active source<br>*activité d'une source radioactive* | curie | Ci | 1 Ci = $3.7\times10^{10}$ $\mathrm{s}^{-1}$ |
| exposure of X or $\gamma$ radiations<br>*exposition des rayonnements* X *ou* $\gamma$ | roentgen | R | 1 R = $2.58\times10^{-4}$ C/kg |
| absorbed dose<br>*dose absorbée* | rad | rad***, rd | 1 rad = 0.01 Gy |
| dose equivalent<br>*équivalent de dose* | rem | rem | 1 rem = 0.01 Sv |

* fm is the correct symbol for femtometre (*femtomètre*): 1 fm = $10^{-15}$ m (see section **1.2.2**, table 1).

** These units are, respectively, the so-called “International Table” calorie, the 15 °C calorie and the thermochemical calorie.

*** The symbol rad should be avoided whenever there is a risk of confusion with the symbol for radian.

# 4 RECOMMENDED SYMBOLS FOR PHYSICAL QUANTITIES

This section presents a listing of the most commonly used symbols for physical quantities. The list is not intended to contain all of the symbols used in physics; its purpose is to provide a guide for teachers and students, and to facilitate the flow of information across disciplinary boundaries.

Each symbol is listed under that category deemed most appropriate and will generally be repeated in a second category only when such repetition is useful for a logical grouping of related symbols. The emphasis here is on symbols and nomenclature; therefore, an expression given with the name of a symbol should be considered as a description rather than as a definition.

Many of the symbols listed are general; they may be made more specific by adding superscripts or subscripts or by using both lower and upper case forms if there is no ambiguity or conflict with other symbols. Where more than one symbol is given there is no implied preference in the ordering. Symbols in parentheses generally are secondary choices that are available to reduce repeated use of one symbol with different meanings. When there are alternate forms of a Greek letter (*e.g.*, $\theta, \vartheta$; $\phi, \varphi$) either or both may be used. The form $\varpi$ of the letter $\pi$ may be used as if it were a distinct letter.

## 4.1 Space and time

| | |
|---|---|
| space coordinates; *coordonnées d'espace* | $(x, y, z)$, $(r, \theta, \phi)$ |
| | $(x_1, x_2, x_3)$ |
| relativistic coordinates; *coordonnées relativistes* : | $(x_0, x_1, x_2, x_3)$ |
| $x_0 = ct,\ x_1 = x,\ x_2 = y,\ x_3 = z,\ x_4 = \mathrm{i}ct$ | $(x_1, x_2, x_3, x_4)$ |
| position vector; *vecteur de position* | $\boldsymbol{r}$ |
| length; *longueur* | $l,\ L,\ a$ |
| breadth; *largeur* | $b$ |
| height; *hauteur* | $h$ |
| radius; *rayon* | $r$ |
| thickness; *épaisseur* | $d,\ \delta$ |
| diameter; *diamètre* : $2r$ | $d$ |
| element of path; *élément de parcours* | $\mathrm{d}s,\ \mathrm{d}l$ |
| area; *aire, superficie* | $A,\ S$ |
| volume; *volume* | $V,\ v$ |
| plane angle; *angle plan* | $\alpha,\ \beta,\ \gamma,\ \theta,\ \phi$ |
| solid angle; *angle solide* | $\Omega,\ \omega$ |
| wavelength; *longueur d'onde* | $\lambda$ |
| wave number; *nombre d'onde* : $1/\lambda$ | $\sigma$ [1] |

[1] In molecular spectroscopy the wave number in vacuum $\nu/c$ is denoted by $\bar{\nu}$.

| | |
|---|---|
| wave vector; *vecteur d'onde* | $\boldsymbol{\sigma}$ |
| angular wave number; *nombre d'onde angulaire* : $2\pi/\lambda$ | $k$ |
| angular wave vector, propagation vector; *vecteur d'onde angulaire* | $\boldsymbol{k}$ |
| time; *temps* | $t$ |
| period, periodic time; *période, durée d'une période* | $T$ |
| frequency; *fréquence* : $1/T$ | $f,\ \nu$ |
| angular frequency; *pulsation*: $2\pi f$ | $\omega$ |
| relaxation time; *constante de temps* : $F(t) = \exp(-t/\tau)$ | $\tau$ |
| damping coefficient; *coefficient d'amortissement* : $F(t) = \exp(-\delta t)\sin\omega t$ | $\delta,\ \lambda$ |
| growth rate; *taux d'agrandissement linéique* : $F(t) = \exp(\gamma t)\sin\omega t$ | $\gamma$ |
| logarithmic decrement; *décrément logarithmique* : $T\delta = T/\tau$ | $\Lambda$ |
| speed; *vitesse* : $\mathrm{d}s/\mathrm{d}t$ | $v,\ u$ |
| velocity and its components; *vecteur vitesse et ses coordonnées* : $\mathrm{d}\boldsymbol{s}/\mathrm{d}t$ | $\boldsymbol{u},\ \boldsymbol{v},\ \boldsymbol{w},\ \boldsymbol{c},\ (u,v,w)$ |
| angular velocity; *vitesse angulaire* : $\mathrm{d}\phi/\mathrm{d}t$ | $\omega$ |
| acceleration; *accélération* : $\mathrm{d}\boldsymbol{v}/\mathrm{d}t$ | $\boldsymbol{a}$ |
| angular acceleration; *accélération angulaire* : $\mathrm{d}\omega/\mathrm{d}t$ | $\alpha$ |
| acceleration of free fall; *accélération due à la pesanteur* | $g$ |

## 4.2 Mechanics

| | |
|---|---|
| mass;*masse* | $m$ |
| (mass) density; *masse volumique* : m/V | $\rho$ |
| relative density; *densité* : $\rho/\rho_\circ$ | $d$ |
| specific volume; *volume massique* : $V/m = 1/\rho$ | $v$ |
| reduced mass; *masse réduite* : $m_1 m_2/(m_1+m_2)$ | $\mu,\ m_\mathrm{r}$ |
| momentum; *quantité de mouvement* : $m\boldsymbol{v}$ | $\boldsymbol{p}$ |
| angular momentum; *moment cinétique* : $\boldsymbol{r}\times\boldsymbol{p}$ | $\boldsymbol{L},\ \boldsymbol{J}$ |
| moment of inertia; *moment d'inertie* : $\int(x^2+y^2)\,\mathrm{d}m$ | $I,\ J$ [2] |
| force; *force* | $\boldsymbol{F}$ |
| impulse; *impulsion* : $\int \boldsymbol{F}\,\mathrm{d}t$ | $\boldsymbol{I}$ |
| weight; *poids* | $G,\ W,\ P$ |
| moment of force; *moment d'une force* | $\boldsymbol{M}$ |
| angular impulse; *impulsion angulaire* : $\int \boldsymbol{M}\,\mathrm{d}t$ | $\boldsymbol{H}$ |
| torque, moment of a couple; *torque, moment d'un couple* | $\boldsymbol{T}$ |
| pressure; *pression* | $p,\ P$ |
| normal stress; *contrainte normale* | $\sigma$ |
| shear stress; *contrainte tangentielle, cission* | $\tau$ |

[2] The moment of inertia tensor is defined by $I_{ij} = \int(\boldsymbol{r}\cdot\boldsymbol{r}\,\delta_{ij} - x_i x_j)\,\mathrm{d}m$. With respect to principal axes, this is often written as a vector, $I_\alpha = \int(x_\beta^2 + x_\gamma^2)\,\mathrm{d}m$, where $(\alpha,\beta,\gamma)$ is a permutation of $(x,y,z)$.

linear strain, relative elongation;
*dilatation linéique relative*: $\Delta l/l_\circ$ — $\epsilon,\ e$
modulus of elasticity, Young's modulus;
*module d'élasticité longitudinale, module d'Young*: $\sigma/\epsilon$ — $E,\ (Y)$
shear strain; *glissement unitaire* — $\gamma$
shear modulus; *module d'élasticité de glissement*: $\tau/\gamma$ — $G, \mu$
stress tensor; *tenseur de contrainte* — $\tau_{ij}$
strain tensor; *tenseur de déformation* — $\epsilon_{ij}$
elasticity tensor; *tenseur d'élasticité*: $\tau_{ij} = c_{ijkl}\epsilon_{lk}$ — $c_{ijkl}$
compliance tensor; *tenseur de complaisance*: $\epsilon_{kl} = s_{klji}\tau_{ij}$ — $s_{klji}$
Lamé coefficients for an isotropic medium;
*coefficients de Lamé d'un milieu isotrope*:
$c_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$ — $\lambda, \mu$
volume strain, bulk strain;
*dilatation volumique relative*: $\Delta V/V_0$ — $\theta$
bulk modulus; *module de compressibilité*: $p = -K\theta$ — $K,\ \kappa$
Poisson ratio; *nombre de Poisson* — $\mu,\ \nu$
viscosity; *viscosité* — $\eta,\ (\mu)$
kinematic viscosity; *viscosité cinématique*: $\eta/\rho$ — $\nu$
friction coefficient; *facteur de frottement* — $\mu,\ (f)$
surface tension; *tension superficielle* — $\gamma,\ \sigma$
energy; *énergie* — $E,\ W$
potential energy; *énergie potentielle* — $E_\mathrm{p},\ V,\ \Phi,\ U$
kinetic energy; *énergie cinétique* — $E_\mathrm{k},\ T,\ K$
work; *travail*: $\int \boldsymbol{F} \cdot \mathrm{d}\boldsymbol{s}$ — $W,\ A$
power; *puissance*: $\mathrm{d}E/\mathrm{d}t$ — $P$
generalized coordinate; *coordonnée généralisée* — $\boldsymbol{q},\ q_i$
generalized momentum; *moment généralisé*: $p_i = \partial L/\partial q_i$ — $\boldsymbol{p},\ p_i$
action integral; *intégrale d'action*: $\oint p\,\mathrm{d}q$ — $J,\ S$
Lagrangian function, Lagrangian;
*fonction de Lagrange*: $T(q_i, \dot{q}_i) - V(q_i, \dot{q}_i)$ — $L,\ (\mathcal{L})$
Hamiltonian function, Hamiltonian;
*fonction de Hamilton*: $\Sigma_i p_i \dot{q}_i - L$ — $H,\ (\mathcal{H})$
principal function of Hamilton;
*fonction principale de Hamilton*: $\int L\,\mathrm{d}t$ — $W,\ S_\mathrm{p}$
characteristic function of Hamilton;
*fonction caractéristique de Hamilton*: $2\int T\,\mathrm{d}t$ — $S$

## 4.3 Statistical physics

number of particles; *nombre de particules* — $N$
number density of particles;
*nombre volumique de particules*: $N/V$ — $n$
particle position vector and its components;
*vecteur position particulaire et ses coordonées* — $\boldsymbol{r},\ (x, y, z);\ (r, \theta, \phi)$

particle velocity vector and its components;
*vecteur vitesse particulaire et ses coordonées* $\boldsymbol{c},\ (c_x, c_y, c_z)$
$\boldsymbol{v},\ (v_x, v_y, v_z);\ \boldsymbol{u},\ (u_x, u_y, u_z)$
particle momentum vector and its components;
*vecteur quantité de mouvement particulaire et ses coordonnées* $\boldsymbol{p},\ (p_x, p_y, p_z)$
average velocity; *vitesse moyenne (vecteur)* $\boldsymbol{c}_0,\ \boldsymbol{v}_0,\ \langle \boldsymbol{c} \rangle,\ \langle \boldsymbol{v} \rangle$
average speed; *vitesse moyenne* $\bar{c},\ \bar{v},\ \langle c \rangle,\ \langle v \rangle,\ u$
most probable speed; *vitesse la plus probable* $\hat{c},\ \hat{v}$
mean free path; *libre parcours moyen* $l,\ \lambda$
interaction energy between particles $i$ and $j$;
*énergie d'interaction entre les particules $i$ et $j$* $\phi_{ij},\ V_{ij}$
velocity distribution function; *fonction de distribution des vitesses* : $n = \int f\,\mathrm{d}c_x\,\mathrm{d}c_y\,\mathrm{d}c_z$ $f(\boldsymbol{c})$
Boltzmann function; *fonction de Boltzmann* $H$
volume in $\gamma$ phase space; *volume dans l'espace $\gamma$* $\mathit{\Omega}$
canonical partition function;
*fonction de partition canonique* $Z$
microcanonical partition function;
*fonction de partition microcanonique* $\mathit{\Omega}$
grand canonical partition function;
*fonction de partition grand canonique* $\mathit{\Xi}$
symmetry number; *facteur de symétrie* $s$
diffusion coefficient; *coefficient de diffusion* $D$
thermal diffusion coefficient;
*coefficient de thermodiffusion* $D_{\mathrm{td}}$
thermal diffusion ratio; *rapport de thermodiffusion* $k_{\mathrm{T}}$
thermal diffusion factor; *facteur de thermodiffusion* $\alpha_{\mathrm{T}}$
characteristic temperature; *température caractéristique* $\mathit{\Theta}$
rotational characteristic temperature ;
*température caractéristique de rotation* : $h^2/8\pi^2 kI$ $\mathit{\Theta}_{\mathrm{rot}}$
vibrational characteristic temperature;
*température caractéristique de vibration* : $h\nu/k$ $\mathit{\Theta}_{\mathrm{vib}}$
Debye temperature; *température de Debye* : $h\nu_{\mathrm{D}}/k$ $\mathit{\Theta}_{\mathrm{D}}$
Einstein temperature; *température d'Einstein* : $h\nu_{\mathrm{E}}/k$ $\mathit{\Theta}_{\mathrm{E}}$

## 4.4 Thermodynamics

The index m is added to a symbol to denote a molar quantity if needed to distinguish it from a quantity referring to the whole system. The convention is often used that uppercase letters refer to extensive quantities and lower case letters to specific quantities (see section **1.4**).

quantity of heat; *quantité de chaleur* $Q$
work; *travail* $W$

| | |
|---|---|
| thermodynamic temperature; *température thermodynamique* | $T$ |
| Celsius temperature; *température Celsius* | $t,\ \theta$ [3] |
| entropy; *entropie* | $S$ |
| internal energy; *énergie interne* | $U$ |
| Helmholtz function; *fonction de Helmholtz, énergie libre*: $U - TS$ | $A,\ F$ |
| enthalpy; *enthalpie*: $U + pV$ | $H$ |
| Gibbs function; *fonction de Gibbs, enthalpie libre*: $H - TS$ | $G$ |
| Massieu function; *fonction de Massieu*: $-A/T$ | $J$ |
| Planck function; *fonction de Planck*: $-G/T$ | $Y$ |
| pressure coefficient; *coefficient de pression*: $(\partial p/\partial T)_V$ | $\beta$ |
| relative pressure coefficient; *coefficient relatif de pression*: $(1/p)(\partial p/\partial T)_V$ | $\alpha_p,\ \alpha$ |
| compressibility; *compressibilité*: $-(1/V)(\partial V/\partial p)_T$ | $\kappa_T,\ \kappa$ |
| linear expansion coefficient; *dilatabilité linéique* | $\alpha_l$ |
| cubic expansion coefficient; *dilatabilité volumique*: $(1/V)(\partial V/\partial T)_p$ | $\alpha_V,\ \gamma$ |
| heat capacity; *capacité thermique* | $C_p,\ C_V$ |
| specific heat capacity; *capacité thermique massique*: $C/m$ | $c_p,\ c_V$ |
| Joule–Thomson coefficient; *coefficient de Joule–Thomson* | $\mu$ |
| isentropic exponent; *exposant isentropique*: $-(V/p)(\partial p/\partial V)_S$ | $\kappa$ |
| ratio of specific heat capacities; *rapport des capacités thermiques massiques*: $c_p/c_V = (\partial V/\partial p)_T(\partial p/\partial V)_S$ | $\gamma,\ (\kappa)$ |
| heat flow rate; *flux thermique* | $\Phi,\ (q)$ |
| density of heat flow rate; *densité de flux thermique* | $\boldsymbol{q}, (\boldsymbol{\phi})$ |
| thermal conductivity: *conductivité thermique* | $\kappa,\ k,\ K,\ (\lambda)$ |
| thermal diffusivity; *diffusivité thermique*: $\lambda/\rho c_p$ | $a,\ (D)$ |

## 4.5 Electricity and magnetism

The relationships given here are in accord with the rationalized 4-dimensional Système International. See Appendix, section **A.2**.

| | |
|---|---|
| quantity of electricity, electric charge; *quantité d'électricité, charge électrique* | $Q,\ q$ |
| charge density; *charge volumique* | $\rho$ |
| surface charge density; *charge surfacique* | $\sigma$ |
| electric current; *courant électrique* | $I,\ (i)$ |
| electric current density; *densité de courant électrique* | $j,\ J$ |

[3] When symbols for both time and Celsius temperature are required, $t$ should be used for time and $\theta$ for temperature.

| | | |
|---|---|---|
| electric potential; *potentiel électrique* | $V,\ \phi$ | |
| potential difference; *différence de potentiel, tension* | $U,\ V$ | |
| electromotive force; *force électromotrice* | $E,\ \mathcal{E}$ | |
| electric field (strength); *champ électrique* | $\boldsymbol{E}$ | |
| electric flux; *flux électrique* | $\Psi$ | |
| magnetic potential difference; *différence de potentiel magnétique* | $U_{\mathrm{m}}$ | |
| magnetomotive force; *force magnétomotrice* : $\oint H_s\,\mathrm{d}s$ | $F_{\mathrm{m}}$ | |
| magnetic field (strength); *champ magnétique* | $\boldsymbol{H}$ | |
| electric dipole moment; *moment dipolaire électrique* | $\boldsymbol{p}$ | |
| dielectric polarization; *polarisation électrique* | $\boldsymbol{P}$ | |
| electric susceptibility; *susceptibilité électrique* | $\chi_{\mathrm{e}}$ | [4] |
| polarizability; *polarisabilité* | $\alpha,\ \gamma$ | [4] |
| electric displacement; *induction électrique* : $\epsilon_\circ \boldsymbol{E} + \boldsymbol{P}$ | $\boldsymbol{D}$ | |
| permittivity; *permittivité* : $\boldsymbol{D} = \epsilon \boldsymbol{E}$ | $\epsilon$ | [4] |
| relative permittivity; *permittivité relative* : $\epsilon/\epsilon_\circ$ | $\epsilon_{\mathrm{r}},\ K$ | |
| magnetic vector potential; *potentiel vecteur magnétique* | $\boldsymbol{A}$ | |
| magnetic induction, magnetic flux density; *induction magnétique, densité de flux magnétique* | $\boldsymbol{B}$ | |
| magnetic flux; *flux magnétique* | $\Phi$ | |
| permeability; *perméabilité* : $\boldsymbol{B} = \mu \boldsymbol{H}$ | $\mu$ | [4] |
| relative permeability; *perméabilité relative* : $\mu/\mu_\circ$ | $\mu_{\mathrm{r}}$ | |
| magnetization; *aimantation* : $\boldsymbol{B}/\mu_\circ - \boldsymbol{H}$ | $\boldsymbol{M}$ | |
| magnetic susceptibility; *susceptibilité magnétique* | $\chi,\ (\chi_{\mathrm{m}})$ | [4] |
| magnetic dipole moment; *moment dipolaire magnétique* | $\boldsymbol{m},\ \boldsymbol{\mu}$ | |
| capacitance; *capacité* | $C$ | |
| resistance; *résistance* | $R$ | |
| reactance; *réactance* | $X$ | |
| impedance; *impédance* : $R + \mathrm{j}X$ | $Z$ | |
| loss angle; *angle de pertes* : $\arctan X/R$ | $\delta$ | |
| conductance; *conductance* | $G$ | |
| susceptance; *susceptance* | $B$ | |
| admittance; *admittance* : $Y = 1/Z = G + \mathrm{j}B$ | $Y$ | |
| resistivity; *resistivité* | $\rho$ | |
| conductivity; *conductivité* : $1/\rho$ | $\gamma,\ \sigma$ | |
| self-inductance; *inductance propre* | $L$ | |
| mutual inductance; *inductance mutuelle* | $M,\ L_{12}$ | |
| coupling coefficient; *facteur de couplage* : $k = L_{12}/(L_1 L_2)^{\frac{1}{2}}$ | $k$ | |

[4] In anisotropic media quantities such as permittivity, susceptibility and polarizability are second-rank tensors; component notation should be used if the tensor character of these quantities is significant, e.g., $\chi_{ij}$.

electromagnetic energy density;
*énergie électromagnétique volumique* — $w,\ u$
Poynting vector; *vecteur de Poynting* — $\boldsymbol{S}$

## 4.6 Radiation and light

The word 'light' is used to refer both to the electromagnetic spectrum of all wavelengths and to that portion of it that produces a response in the human eye. In describing light, the same symbols are often used for the corresponding radiant, luminous and photonic quantities. Although the symbols are the same, the units and dimensions of these three quantities are different; subscripts e (energetic), v (visible) and p (photon) should be added when it is necessary to distinguish among them.

| | |
|---|---|
| radiant energy; *énergie rayonnante* | $Q,\ (Q_\mathrm{e}),\ W$ |
| radiant energy density; *énergie rayonnante volumique* | $w$ |
| spectral concentration of radiant energy density (in terms of wavelength); *énergie rayonnante volumique spectrique (en longueur d'onde)*: $w = \int w_\lambda \,\mathrm{d}\lambda$ | $w_\lambda$ |
| radiant (energy) flux, radiant power; *flux énergétique, puissance rayonnante*: $\int \Phi_\lambda \,\mathrm{d}\lambda$ | $\Phi,\ (\Phi_\mathrm{e}),\ P$ |
| radiant flux density; *flux énergétique surfacique*: $\Phi = \int \phi \,\mathrm{d}S$ | $\phi$ |
| radiant intensity; *intensité énergétique*: $\Phi = \int I \,\mathrm{d}\Omega$ | $I,\ (I_\mathrm{e})$ |
| spectral concentration of radiant intensity (in terms of frequency); *intensité énergétique spectrique (en fréquence)*: $I = \int I_\nu \,\mathrm{d}\nu$ | $I_\nu,\ (I_{\mathrm{e},\nu})$ |
| irradiance; *éclairement énergétique*: $\Phi = \int E \,\mathrm{d}S$ | $E,\ (E_\mathrm{e})$ |
| radiance; *luminance énergétique*: $I = \int L \cos\vartheta \,\mathrm{d}S$ | $L,\ (L_\mathrm{e})$ |
| radiant exitance; *exitance énergétique*: $\Phi = \int M \,\mathrm{d}S$ | $M,\ (M_\mathrm{e})$ |
| emissivity; *emissivité*: $M/M_\mathrm{B}$ ($M_\mathrm{B}$: radiant exitance of a blackbody radiator) | $\epsilon$ |
| luminous efficacy; *efficacité lumineuse*: $\Phi_\mathrm{v}/\Phi_\mathrm{e}$ | $K$ |
| spectral luminous efficacy; *efficacité lumineuse spectrale*: $\Phi_{\mathrm{v},\lambda}/\Phi_{\mathrm{e},\lambda}$ | $K(\lambda)$ |
| maximum spectral luminous efficacy; *efficacité lumineuse spectrale maximale* | $K_\mathrm{m}$ |
| luminous efficiency; *efficacité lumineuse relative*: $K/K_\mathrm{m}$ | $V$ |
| spectral luminous efficiency; *efficacité lumineuse relative spectrale*: $K(\lambda)/K_m$ | $V(\lambda)$ |
| quantity of light; *quantité de lumière* | $Q,\ (Q_\mathrm{v})$ |
| luminous flux; *flux lumineux* | $\Phi,\ (\Phi_\mathrm{v})$ |
| luminous intensity; *intensité lumineuse*: $\Phi = \int I \,\mathrm{d}\Omega$ | $I, (I_\mathrm{v})$ |
| spectral concentration of luminous intensity (in terms of wave number); *intensité lumineuse spectrique (en nombre d'onde)*: $I = \int I_\sigma \,\mathrm{d}\sigma$ | $I_\sigma,\ (I_{\mathrm{v},\sigma})$ |

illuminance, illumination; *éclairement lumineux* : $\Phi = \int E \,\mathrm{d}S$ — $E,\ (E_\mathrm{v})$
luminance; *luminance* : $I = \int L \cos\vartheta \,\mathrm{d}S$ — $L,\ (L_\mathrm{v})$
luminous exitance; *exitance lumineuse* : $\Phi = \int M \,\mathrm{d}S$ — $M,\ (M_\mathrm{v})$
linear attenuation coefficient; *coefficient d'atténuation linéique* — $\mu$
linear absorption coefficient; *coefficient d'absorption linéique* — $a$
absorptance; *facteur d'absorption* : $\Phi_\mathrm{a}/\Phi_\mathrm{o}$ — $\alpha$ [5]
reflectance; *facteur de réflexion* : $\Phi_\mathrm{r}/\Phi_\mathrm{o}$ — $\rho$
transmittance; *facteur de transmission* : $\Phi_\mathrm{tr}/\Phi_\mathrm{o}$ — $\tau$

## 4.7 Acoustics

acoustic pressure; *pression acoustique* — $p$
sound particle velocity; *vitesse particulaire acoustique* — $\boldsymbol{u}$
velocity of sound; *vitesse du son, célérité* — $c$
velocity of longitudinal waves; *célérité longitudinale* — $c_\mathrm{l}$
velocity of transverse waves; *célérité transversale* — $c_\mathrm{t}$
group velocity; *vitesse de groupe* — $c_\mathrm{g}$
sound energy flux, acoustic power; *flux d'énergie acoustique, puissance acoustique* — $W$
reflection coefficient; *facteur de réflexion* : $P_\mathrm{r}/P_0$ — $\rho$
acoustic absorption coefficient; *facteur d'absorption acoustique* : $1-\rho$ — $\alpha_\mathrm{a},\ (\alpha)$
transmission coefficient; *facteur de transmission* : $P_\mathrm{tr}/P_0$ — $\tau$
dissipation factor; *facteur de dissipation* : $\alpha_\mathrm{a} - \tau$ — $\psi,\ \delta$
loudness level; *niveau d'isosonie* — $L_\mathrm{N}$
sound power level; *niveau de puissance acoustique* — $L_W$
sound pressure level; *niveau de pression acoustique* — $L_p$

## 4.8 Quantum mechanics

wave function; *fonction d'onde* — $\Psi$
complex conjugate of $\Psi$; *complexe conjugué de* $\Psi$ — $\Psi^*$
probability density; *densité de probabilité* : $\Psi^*\Psi$ — $P$
probability current density; *densité de courant de probabilité* : $(\hbar/2\mathrm{i}m)(\Psi^*\boldsymbol{\nabla}\Psi - \Psi\boldsymbol{\nabla}\Psi^*)$ — $\boldsymbol{S}$
charge density of electrons; *charge volumique d'électrons* : $-eP$ — $\rho$
current density of electrons; *densité de courant électrique d'électrons* : $-e\boldsymbol{S}$ — $\boldsymbol{j}$

[5] $\alpha(\lambda)$, $\rho(\lambda)$, and $\tau(\lambda)$ designate spectral absorptance $\Phi_\mathrm{a}(\lambda)/\Phi_\mathrm{o}(\lambda)$, spectral reflectance $\Phi_\mathrm{r}(\lambda)/\Phi_\mathrm{o}(\lambda)$, and spectral transmittance $\Phi_\mathrm{tr}(\lambda)/\Phi_\mathrm{o}(\lambda)$, respectively.

| | |
|---|---|
| Dirac bra vector; *vecteur bra de Dirac* | $\langle ... \vert$ |
| Dirac ket vector; *vecteur ket de Dirac* | $\vert ... \rangle$ |
| commutator of $A$ and $B$; *commutateur de $A$ et $B$*: $AB - BA$ | $[A, B]$, $[A, B]_-$ |
| anticommutator of $A$ and $B$; *anticommutateur de $A$ et $B$*: $AB + BA$ | $[A, B]_+$ |
| matrix element; *element de matrice*: $\int \phi_i^* (A\phi_j)\, \mathrm{d}\tau$ | $A_{ij}$ |
| expectation value of $A$; *valeur moyenne de $A$*: $\mathrm{Tr}\,(A)$ | $\langle\, A \,\rangle$ |
| Hermitian conjugate of operator $A$; *conjugué Hermitien de l'opérateur $A$*: $(A^\dagger)_{ij} = A^*_{ji}$ | $A^\dagger$ |
| momentum operator in coordinate representation; *opérateur de quantité de mouvement* | $(\hbar/\mathrm{i})\boldsymbol{\nabla}$ |
| annihilation operators; *opérateurs d'annihilation* | $a,\ b,\ \alpha,\ \beta$ |
| creation operators; *opérateurs de création* | $a^\dagger,\ b^\dagger,\ \alpha^\dagger,\ \beta^\dagger$ |
| Pauli matrices; *matrices de Pauli*: | $\boldsymbol{\sigma}$ |
| $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},\ \sigma_y = \begin{pmatrix} 0 & -\mathrm{i} \\ \mathrm{i} & 0 \end{pmatrix},\ \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ | $\sigma_x,\ \sigma_y,\ \sigma_z$ <br> $\sigma_1,\ \sigma_2,\ \sigma_3$ |
| unit matrix; *matrice unité*: $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ | $I$ |
| Dirac $(4 \times 4)$ matrices; *matrices (4×4) de Dirac*: [6] | |
| $\alpha_x = \begin{pmatrix} 0 & \sigma_x \\ \sigma_x & 0 \end{pmatrix},\ \alpha_y = \begin{pmatrix} 0 & \sigma_y \\ \sigma_y & 0 \end{pmatrix},\ \alpha_z = \begin{pmatrix} 0 & \sigma_z \\ \sigma_z & 0 \end{pmatrix}$ | $\boldsymbol{\alpha}$ <br> $\alpha_x,\ \alpha_y,\ \alpha_z$ |
| $\beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$ | $\beta$ |

### 4.9 Atomic and nuclear physics

| | |
|---|---|
| nucleon number, mass number; *nombre de nucléons, nombre de masse* | $A$ |
| proton number, atomic number; *nombre de protons, numéro atomique* | $Z$ |
| neutron number; *nombre de neutrons*: $A - Z$ | $N$ |
| nuclear mass (of nucleus $^A\mathrm{X}$); *masse nucléaire (du noyau $^A\mathrm{X}$)* | $m_\mathrm{N},\ m_\mathrm{N}(^A\mathrm{X})$ |
| atomic mass (of nuclide $^A\mathrm{X}$); *masse atomique (du nucléide $^A\mathrm{X}$)* | $m_\mathrm{a},\ m_\mathrm{a}(^A\mathrm{X})$ |
| (unified) atomic mass constant; *constante (unifiée) de masse atomique*: $\frac{1}{12} m_\mathrm{a}(^{12}\mathrm{C})$ | $m_\mathrm{u}$ |
| relative atomic mass; *masse atomique relative*: $m_\mathrm{a}/m_\mathrm{u}$ | $A_\mathrm{r},\ M_\mathrm{r}$ |
| mass excess; *excès de masse*: $m_\mathrm{a} - A m_\mathrm{u}$ | $\mathit{\Delta}$ |

[6] Sometimes a different representation is used.

| | |
|---|---|
| principal quantum number (q.n.); *nombre quantique (n.qu.) principal* | $n,\ n_i$ |
| orbital angular momentum q.n.; *n.qu. de moment angulaire orbital* | $L,\ l_i$ |
| spin q.n.; *n.qu. de spin* | $S,\ s_i$ |
| total angular momentum q.n.; *n.qu. de moment angulaire total* | $J,\ j_i$ |
| magnetic q.n.; *n.qu. magnétique* | $M,\ m_i$ |
| nuclear spin q.n.; *n.qu. de spin nucléaire* | $I,\ J$ [7] |
| hyperfine q.n.; *n.qu. hyperfin* | $F$ |
| rotational q.n.; *n.qu. de rotation* | $J,\ K$ |
| vibrational q.n.; *n.qu. de vibration* | $v$ |
| quadrupole moment; *moment quadripolaire* | $Q$ [8] |
| magnetic moment of a particle; *moment magnétique d'une particule* | $\mu$ |
| $g$-factor; *facteur* $g$ : $\mu/I\mu_{\mathrm{N}}$ | $g$ |
| gyromagnetic ratio, gyromagnetic coefficient; *rapport gyromagnétique, coefficient gyromagnétique* : $\omega/B$ | $\gamma$ |
| Larmor circular frequency; *pulsation de Larmor* | $\omega_{\mathrm{L}}$ |
| level width; *largeur d'un niveau* | $\mathit{\Gamma}$ |
| reaction energy, disintegration energy; *énergie de réaction, énergie de désintégration* | $Q$ |
| cross section; *section efficace* | $\sigma$ |
| macroscopic cross section; *section efficace macroscopique* : $n\sigma$ | $\mathit{\Sigma}$ |
| impact parameter; *paramètre de collision* | $b$ |
| scattering angle; *angle de diffusion* | $\vartheta,\ \theta$ |
| internal conversion coefficient: *coefficient de conversion interne* | $\alpha$ |
| mean life; *vie moyenne* | $\tau,\ \tau_{\mathrm{m}}$ |
| half life; *demi-vie, période radioactive* | $T_{\frac{1}{2}},\ \tau_{\frac{1}{2}}$ |
| decay constant, disintegration constant; *constante de désintégration* | $\lambda$ |
| activity; *activité* | $A$ |
| Compton wavelength; *longueur d'onde de Compton* : $h/mc$ | $\lambda_{\mathrm{C}}$ |
| linear attenuation coefficient; *coefficient d'atténuation linéique* | $\mu,\ \mu_{\mathrm{l}}$ |
| atomic attenuation coefficient; *coefficient d'atténuation atomique* | $\mu_{\mathrm{a}}$ |

[7] $I$ is used in atomic physics, $J$ in nuclear physics.

[8] A quadrupole moment is actually a second-rank tensor; if the tensor character is significant the symbol should be $\boldsymbol{Q}$ or $Q_{ij}$.

mass attenuation coefficient; *coefficient d'atténuation massique* $\mu_{\text{m}}$
linear stopping power; *pouvoir d'arrêt linéaire* $S,\ S_{\text{l}}$
atomic stopping power; *pouvoir d'arrêt atomique* $S_{\text{a}}$
linear range; *distance de pénétration linéaire* $R,\ R_{\text{l}}$
recombination coefficient; *coefficient de recombinaison* $\alpha$

## 4.10 Molecular spectroscopy

*Remark*: LM = linear molecules. STM = symmetric top molecules. DM = diatomic molecules. PM = polyatomic molecules. For further details see: *Report on Notation for the Spectra of Polyatomic Molecules* (Joint Commission for Spectroscopy of IUPAP and IAU 1954), J. Chem. Phys. **23** (1955) 1997.

quantum number (q.n.) of component electronic orbital angular momentum vector along the symmetry axis; *nombre quantique (n.qu.) de la composante du moment angulaire orbital électronique suivant l'axe de symétrie* $\Lambda,\ \lambda_i$
q.n. of component of electronic spin along the symmetry axis; *n.qu. de la composante du spin électronique suivant l'axe de symétrie* $\Sigma,\ \sigma_i$
q.n. of total electronic angular momentum vector along the symmetry axis; *n.qu. du moment angulaire total électronique suivant l'axe de symétrie*: $\Omega = |\Lambda + \Sigma|$ $\Omega,\ \omega_i$
q.n. of electronic spin; *n.qu. du spin électronique* $S$
q.n. of nuclear spin; *n.qu. du spin nucléaire* $I$
q.n. of vibrational mode; *n.qu. d'une mode de vibration* $v$
degeneracy of vibrational mode; *degré de dégénérescence d'une mode de vibration* $d$
q.n. of vibrational angular momentum; *n.qu. du moment angulaire vibrationnel* (LM) $l$
q.n. of total angular momentum; *n.qu. du moment angulaire total*
(LM and STM; excluding electron and nuclear spin) $N$
(excluding nuclear spin): $\boldsymbol{J} = \boldsymbol{N} + \boldsymbol{S}$ [9] $J$
(including nuclear spin): $\boldsymbol{F} = \boldsymbol{J} + \boldsymbol{I}$ $F$
q.n. of component of $\boldsymbol{J}$ in the direction of an external field; *n.qu. de la composante de* $\boldsymbol{J}$ *dans la direction du champ extérieur* $M,\ M_J$

[9] Case of loosely coupled electron spin.

| | |
|---|---|
| q.n. of component of $\boldsymbol{X}$ ($\boldsymbol{X} = \boldsymbol{S}$, $\boldsymbol{F}$ or $\boldsymbol{I}$) in the direction of an external field; *n.qu. de la composante de* $\boldsymbol{X}$ *(*$\boldsymbol{X} = \boldsymbol{S}$, $\boldsymbol{F}$ *ou* $\boldsymbol{I}$*) dans la direction du champ extérieur* | $M_X$ |
| q.n. of component of angular momentum along the symmetry axis; *n.qu. de la composante du moment angulaire suivant l'axe de symétrie* | |
| (for LM, excluding electron and nuclear spin) : $K = \lvert \Lambda + l \rvert$ | $K$ |
| (excluding nuclear spin) :[10] for LM : $P = \lvert \Lambda \pm l \rvert$; for STM : $P = \lvert K + \Sigma \rvert$ | $P$ |
| electronic term; *terme électronique* : $E_\mathrm{e}/hc$ | $T_\mathrm{e}$ [11] |
| vibrational term; *terme de vibration* : $E_\mathrm{vibr}/hc$ | $G$ |
| coefficients in the expression for the vibrational term; *coefficients de l'expression d'un terme de vibration* : | |
| for DM : $G = \sigma_\mathrm{e}[(v + \frac{1}{2}) - x(v + \frac{1}{2})^2]$ | $\sigma_\mathrm{e},\ x$ |
| for PM : $G = \Sigma\sigma_j(v_j + \frac{1}{2}d_j) + \frac{1}{2}\Sigma_{j,k}x_{jk}(v_j + \frac{1}{2}d_j)(v_k + \frac{1}{2}d_k)$ | $\sigma_j,\ x_{jk}$ |
| rotational term; *terme de rotation* : $E_\mathrm{rot}/hc$ | $F$ |
| total term; *terme total* : $T_\mathrm{e} + G + F$ | $T$ |
| principal moments of inertia; *moments principaux d'inertie* : $I_A \le I_B \le I_C$ [12] | $I_A,\ I_B,\ I_C$ |
| rotational constants; *constantes de rotation* : $A = h/8\pi^2 cI_A$, etc. [12] | $A,\ B,\ C$ |

## 4.11 Solid state physics

| | |
|---|---|
| lattice vector: a translation vector which maps the crystal lattice onto itself; *vecteur du réseau; vecteur qui reproduit par translation le réseau cristallin sur lui-même* | $\boldsymbol{R},\ \boldsymbol{R}_0$ |
| fundamental translation vectors for the crystal lattice; *vecteurs de base de la maille cristalline* : $\boldsymbol{R} = n_1\boldsymbol{a}_1 + n_2\boldsymbol{a}_2 + n_3\boldsymbol{a}_3$, ($n_1, n_2, n_3$, integers) | $\boldsymbol{a}_1, \boldsymbol{a}_2, \boldsymbol{a}_3$<br>$\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$ |
| (circular) reciprocal lattice vector; *vecteur du réseau réciproque* : $\boldsymbol{G} \cdot \boldsymbol{R} = 2\pi m$, where $m$ is an integer | $\boldsymbol{G}$ |
| (circular) fundamental translation vectors for the reciprocal lattice; *vecteur de base de la maille du réseau réciproque* : $\boldsymbol{a}_i \cdot \boldsymbol{b}_k = 2\pi\delta_{ik}$, [13] where $\delta_{ik}$ is the Kronecker delta symbol | $\boldsymbol{b}_1, \boldsymbol{b}_2, \boldsymbol{b}_3$<br>$\boldsymbol{a}^*, \boldsymbol{b}^*, \boldsymbol{c}^*$ |

[10] Case of tightly coupled electron spin.
[11] All energies are taken with respect to the ground state as the reference level.
[12] For diatomic molecules, use $I$ and $B = h/8\pi^2 cI$.
[13] In crystallography, however, $\boldsymbol{a}_i \cdot \boldsymbol{b}_k = \delta_{ik}$.

| | |
|---|---|
| lattice plane spacing; *espacement entre plans réticulaires* | $d$ |
| Miller indices; *indices de Miller* | $h_1, h_2, h_3$<br>$h, k, l$ |
| single plane or set of parallel planes in a lattice;<br>*plan simple ou famille de plans réticulaires parallèles dans un réseau* | $(h_1, h_2, h_3)$<br>$(h, k, l)$ |
| full set of planes in a lattice equivalent by symmetry;<br>*famille de plans réticulaires équivalents par symétrie* | $\{h_1, h_2, h_3\}$<br>$\{h, k, l\}$ |
| direction in a lattice; *rangée réticulaire* | $[u, v, w]$ |
| full set of directions in a lattice equivalent by symmetry;<br>*famille de rangées réticulaires equivalentes par symétrie* | $\langle u, v, w\rangle$ |

*Note*: When the letter symbols in the bracketed expressions are replaced by numbers, the commas are usually omitted. A negative numerical value is commonly indicated by a bar above the number, e.g., $(\bar{1}10)$.

| | |
|---|---|
| Bragg angle; *angle de Bragg* | $\vartheta$ |
| order of reflexion; *ordre de réflexion* | $n$ |
| short range order parameter; *paramètre d'ordre local* | $\sigma$ |
| long range order parameter; *paramètre d'ordre à grande distance* | $s$ |
| Burgers vector; *vecteur de Burgers* | $\boldsymbol{b}$ |
| particle position vector; *vecteur de position d'une particule* | $\boldsymbol{r}, \boldsymbol{R}$ [14] |
| equilibrium position vector of an ion;<br>*vecteur de position d'équilibre d'un ion* | $\boldsymbol{R}_0$ |
| displacement vector of an ion; *vecteur de déplacement d'un ion* | $\boldsymbol{u}$ |
| normal coordinates; *coordonnées normales* | $Q_i$ |
| polarization vector; *vecteur de polarisation* | $\boldsymbol{e}$ |
| Debye–Waller factor; *facteur de Debye–Waller* | $D$ |
| Debye angular wave number; *nombre d'onde angulaire de Debye* | $q_{\mathrm{D}}$ |
| Debye angular frequency; *pulsation de Debye* | $\omega_{\mathrm{D}}$ |
| Grüneisen parameter; *paramètre de Grüneisen*: $\alpha/\kappa\rho c_V$<br>($\alpha$: cubic expansion coefficient; $\kappa$: compressibility) | $\gamma, \mathit{\Gamma}$ |
| Madelung constant; *constante de Madelung* | $\alpha$ |
| mean free path of electrons; *libre parcours moyen des électrons* | $l,\ l_{\mathrm{e}}$ |
| mean free path of phonons; *libre parcours moyen des phonons* | $\mathit{\Lambda},\ l_{\mathrm{ph}}$ |
| drift velocity; *vitesse de mouvement* | $v_{\mathrm{dr}}$ |
| mobility; *mobilité* | $\mu$ |
| one-electron wave function; *fonction d'onde monoélectronique* | $\psi(\boldsymbol{r})$ |
| Bloch wave function; *fonction d'onde de Bloch*:<br>$\psi_{\boldsymbol{k}}(\boldsymbol{r}) = u_{\boldsymbol{k}}(\boldsymbol{r}) \exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r})$ | $u_{\boldsymbol{k}}(\boldsymbol{r})$ |
| density of states; *densité (électronique) d'états*: $\mathrm{d}N(E)/\mathrm{d}E$ | $N_E,\ \rho$ |

[14] Lower case and capital letters are used, respectively, to distinguish between electron and ion position vectors.

| | |
|---|---|
| (spectral) density of vibrational modes; *densité spectrale de modes de vibration* | $g, N_\omega$ |
| exchange integral; *intégrale d'échange* | $J$ |
| resistivity tensor; *tenseur de résistivité* | $\rho_{ik}$ |
| electric conductivity tensor; *tenseur de conductivité électrique* | $\sigma_{ik}$ |
| thermal conductivity tensor; *tenseur de conductivité thermique* | $\lambda_{ik}$ |
| residual resistivity; *résistivité résiduelle* | $\rho_\mathrm{R}$ |
| relaxation time; *temps de relaxation* | $\tau$ |
| Lorenz coefficient; *coefficient de Lorenz* : $\lambda/\sigma T$ | $L$ |
| Hall coefficient; *coefficient de Hall* | $R_\mathrm{H},\ A_\mathrm{H}$ |
| Ettinghausen coefficient; *coefficient d'Ettinghausen* | $A_\mathrm{E},\ P_\mathrm{E}$ |
| first Ettinghausen–Nernst coefficient; *premier coefficient d'Ettinghausen–Nernst* | $A_\mathrm{N}$ |
| first Righi–Leduc coefficient; *premier coefficient de Righi–Leduc* | $A_\mathrm{RL},\ S_\mathrm{RL}$ |
| thermoelectromotive force between substances a and b; *force thermoeléctromotrice entre deux substances* a *et* b | $E_\mathrm{ab},\ \Theta_\mathrm{ab}$ |
| Seebeck coefficient for substances a and b; *coefficient de Seebeck pour deux substances* a *et* b : $\mathrm{d}E_\mathrm{ab}/\mathrm{d}T$ | $S_\mathrm{ab},\ \epsilon_\mathrm{ab}$ |
| Peltier coefficient for substances a and b; *coefficient de Peltier pour deux substances* a *et* b | $\Pi_\mathrm{ab}$ |
| Thomson coefficient; *coefficient de Thomson* | $\mu,\ (\tau)$ |
| work function; *travail d'extraction* : $\Phi = e\phi$ [15] | $\phi,\ \Phi$ |
| Richardson constant; *constante de Richardson* : $j = AT^2 \exp(-\Phi/kT)$ | $A$ |
| electron number density; *nombre volumique électronique (densité électronique)* | $n,\ n_\mathrm{n},\ n_-$ [16] |
| hole number density; *nombre volumique de trous (densité de trous)* | $p,\ n_\mathrm{p},\ n_+$ [16] |
| donor number density; *nombre volumique de donneurs (densité de donneurs)* | $n_\mathrm{d}$ |
| acceptor number density; *nombre volumique d'accepteurs (densité d'accepteurs)* | $n_\mathrm{a}$ |
| instrinsic number density; *nombre volumique intrinsèque, densité intrinsèque* : $(n \cdot p)^{1/2}$ | $n_\mathrm{i}$ |
| energy gap; *bande d'énergie interdite* | $E_\mathrm{g}$ |
| donor ionization energy; *énergie d'ionisation de donneur* | $E_\mathrm{d}$ |
| acceptor ionization energy; *énergie d'ionisation d'accepteur* | $E_\mathrm{a}$ |
| Fermi energy; *énergie de Fermi* | $E_\mathrm{F},\ \epsilon_\mathrm{F}$ |

[15] The symbol $W$ is used for the quantity $\Phi+\mu$, where $\mu$ is the electron chemical potential which, at $T = 0$ K, is equal to the Fermi energy $E_\mathrm{F}$.
[16] In general, the subscripts n and p or $-$ and $+$ may be used to denote electrons and holes, respectively.

angular wave vector, propagation vector (of particles);
*vecteur d'onde angulaire,*
*vecteur de propagation (de particules)* $\boldsymbol{k}$

angular wave vector, propagation vector (of phonons);
*vecteur d'onde angulaire, vecteur de propagation (de phonons)* $\boldsymbol{q}$

Fermi angular wave vector; *vecteur de Fermi* $\boldsymbol{k}_{\mathrm{F}}$

electron annihilation operator;
*opérateur d'annihilation d'électron* $a$

electron creation operator; *opérateur de création d'électron* $a^{\dagger}$

phonon annihilation operator;
*opérateur d'annihilation de phonon* $b$

phonon creation operator; *opérateur de création de phonon* $b^{\dagger}$

effective mass; *masse effective* $m_{\mathrm{n}}^{*}, m_{\mathrm{p}}^{*}$

mobility; *mobilité* $\mu_{\mathrm{n}}, \mu_{\mathrm{p}}$

mobility ratio; *rapport de mobilité*: $\mu_{\mathrm{n}}/\mu_{\mathrm{p}}$ $b$

diffusion coefficient; *coefficient de diffusion* $D_{\mathrm{n}}, D_{\mathrm{p}}$

diffusion length; *longueur de diffusion* $L_{\mathrm{n}},\ L_{\mathrm{p}}$

carrier life time; *durée de vie de porteur* $\tau_{\mathrm{n}}, \tau_{\mathrm{p}}$

characteristic (Weiss) temperature;
*température caractéristique (de Weiss)* $\Theta, \Theta_{\mathrm{W}}$

Néel temperature; *température de Néel* $T_{\mathrm{N}}$

Curie temperature;*température de Curie* $T_{\mathrm{C}}$

superconductor critical transition temperature;
*température critique de transition supraconductrice* $T_{\mathrm{c}}$

superconductor (thermodynamic) critical field strength;
*champ critique (thermodynamique) d'un supraconducteur* $H_{\mathrm{c}}$

superconductor critical field strength (type II);
*champ critique d'un supraconducteur (type II)* $H_{\mathrm{c1}}, H_{\mathrm{c2}}, H_{\mathrm{c3}}$ [17]

superconductor energy gap;
*bande interdite du supraconducteur* $\Delta$

London penetration depth;
*profondeur de pénétration de London* $\lambda_{\mathrm{L}}$

coherence length; *longueur de cohérence* $\xi$

Landau–Ginzburg parameter;
*paramètre de Landau–Ginzburg*: $\lambda_{\mathrm{L}}/\sqrt{2}\,\xi$ $\kappa$

## 4.12 Chemical physics

*Remark*: In general, the attribute $X$ of chemical species B is denoted by the symbol $X_{\mathrm{B}}$, but in specific instances it is more convenient to use the notation $X(\mathrm{B})$, *e.g.*, $X(\mathrm{CaCO_3})$ or $X(\mathrm{H_2O};\ 250\ °\mathrm{C})$.

---

[17] $H_{\mathrm{c1}}$: for magnetic flux entering the superconductor;
$H_{\mathrm{c2}}$: for disappearance of bulk superconductivity;reak $H_{\mathrm{c3}}$: for disappearance of surface superconductivity.

| | |
|---|---|
| relative atomic mass; *masse atomique relative* | $A_r$ |
| relative molar mass; *masse molaire relative* | $M_r$ |
| amount of substance; *quantité de matière* | $n,\ \nu$ [18] |
| molar mass; *masse molaire* | $M$ |
| concentration; *concentration (en quantité de matière)* : $c = n/V$ | $c$ |
| molar fraction; *fraction molaire* | $x$ |
| mass fraction; *fraction massique* | $w$ |
| volume fraction; *fraction volumique* | $\phi$ |
| molar ratio of solution; *rapport molaire d'une solution* | $r$ |
| molality of solution; *molalité d'une solution* | $m$ |
| chemical potential; *potentiel chimique* [19] | $\mu$ |
| absolute activity; *activité absolue* : $\exp(\mu/kT)$ | $\lambda$ |
| relative activity; *activité relative* | $a$ |
| reduced activity; *activité réduite* : $(2\pi mkT/h^2)^{3/2}\lambda$ | $z$ |
| osmotic pressure; *pression osmotique* | $\Pi$ |
| osmotic coefficient; *coefficient osmotique* | $g, \phi$ |
| stoichiometric number of substance B; *nombre stœchiométrique de la substance* B | $\nu_B$ |
| affinity; *affinité* | $A$ |
| extent of reaction; *état d'avancement d'une réaction* : $d\xi_B = dn_B/\nu_B$ | $\xi$ |
| equilibrium constant; *constante d'équilibre* | $K$ |
| charge number of an ion; *nombre de charge d'un ion, électrovalence* | $z$ |

### 4.13 Plasma physics

| | |
|---|---|
| energy of particle; *énergie d'une particule* | $\epsilon$ |
| dissociation energy (of molecule X); *énergie de dissociation (d'une molécule* X*)* | $E_d,\ E_d(X)$ |
| electron affinity; *affinité électronique* | $E_{ea}$ |
| ionization energy; *énergie d'ionisation* | $E_i$ |
| degree of ionization; *degré d'ionisation* | $x$ |
| charge number of ion (positive or negative); *nombre de charge ionique(positif ou négatif)* | $z$ |
| number density of ions of charge number $z$; *densité ionique des ions de nombre de charge z* | $n_z$ [20] |
| degree of ionization for charge number $z \geq 1$; *degré d'ionisation pour un nombre de charge* $z \geq 1$ : $n_z/(n_z + n_{z-1})$ | $x_z$ |

[18] $\nu$ may be used as an alternative symbol for amount of substance when $n$ is used for number density of particles.

[19] Referred to one particle.

[20] If only singly charged ions need to be considered, $n_{-1}$ and $n_{+1}$ may be represented by $n_-$ and $n_+$.

neutral particle temperature; *température des neutres* $T_{\mathrm{n}}$
ion temperature; *température ionique* $T_{\mathrm{i}}$
electron temperature; *température électronique* $T_{\mathrm{e}}$
electron number density; *densité électronique* $n_{\mathrm{e}}$
electron plasma circular frequency; *pulsation de plasma* :
$\omega_{\mathrm{pe}}^2 = n_{\mathrm{e}} e^2 / \epsilon_{\circ} m_{\mathrm{e}}$ $\omega_{\mathrm{pe}}$
Debye length; *longueur de Debye* $\lambda_{\mathrm{D}}$
charge of particle; *charge d'une particule* $q$
electron cyclotron circular frequency;
*pulsation cyclotron électronique* : $(e/m_{\mathrm{e}})B$ $\omega_{\mathrm{ce}}$
ion cyclotron circular frequency;
*pulsation cyclotron ionique* : $(ze/m_{\mathrm{i}})B$ $\omega_{\mathrm{ci}}$
reduced mass; *masse réduite* : $m_1 m_2/(m_1 + m_2)$ $\mu,\ m_{\mathrm{r}}$
impact parameter; *paramètre d'impact* $b$
mean free path; *libre parcours moyen* $l,\ \lambda$
collision frequency; *fréquence de collision* $\nu_{\mathrm{coll}},\ \nu_{\mathrm{c}}$
mean time interval between collisions;
*intervalle de temps moyen entre collisions* : $1/\nu_{\mathrm{coll}}$ $\tau_{\mathrm{coll}},\ \tau_{\mathrm{c}}$
cross section; *section efficace* : $1/nl$ $\sigma$
(electron) ionization efficiency;
*efficacité d'ionisation (électronique)* : $(\rho_{\circ}/\rho)\mathrm{d}N/\mathrm{d}x$ $s_{\mathrm{e}}$
(d$N$ : number of ion pairs formed by an ionizing electron traveling through d$x$ in the plasma at gas density $\rho$;
$\rho_{\circ}$ : gas density at $p_{\circ} = 133.322$ Pa, $T_{\circ} = 273.15$ K)
rate coefficient; *taux de réaction* $k$
one-body rate coefficient; *taux de réaction unimoléculaire* :
$-\mathrm{d}n_{\mathrm{A}}/\mathrm{d}t = k_{\mathrm{m}} n_{\mathrm{A}}$ $k_{\mathrm{m}}$
relaxation time; *temps de relaxation* : (e.g., $\tau = 1/k_{\mathrm{m}}$) $\tau$
binary rate coefficient, two-body rate coefficient;
*taux de réaction binaire* (e.g., $\mathrm{X} + \mathrm{Y} \rightarrow \mathrm{XY} + h\nu$) :
$\mathrm{d}n_{\mathrm{XY}}/\mathrm{d}t = k_{\mathrm{b}} n_{\mathrm{X}} n_{\mathrm{Y}}$ $k_{\mathrm{b}}$
ternary rate coefficient, three-body rate coefficient ;
*taux de réaction ternaire* (e.g., $\mathrm{X} + \mathrm{Y} + \mathrm{M} \rightarrow \mathrm{XY} + \mathrm{M}^*$) :
$\mathrm{d}n_{\mathrm{XY}}/\mathrm{d}t = k_{\mathrm{t}} n_{\mathrm{M}} n_{\mathrm{X}} n_{\mathrm{Y}}$ $k_{\mathrm{t}}$
Townsend (electron) ionization coefficient;
*coefficient de Townsend* [21] $\alpha$
Townsend (ion) ionization coefficient;
*coefficient ionique de Townsend* $\beta$
secondary electron emission coefficient;
*taux d'émission secondaire* $\gamma$
drift velocity; *vitesse de mouvement* $v_{\mathrm{dr}}$

[21] The same name is also used for the quantity $\eta = \alpha/E$, where $E$ is the electric field strength.

mobility; *mobilité* : $v_{\mathrm{dr}}/E$ — $\mu$

positive or negative ion diffusion coefficient;
*coefficient de diffusion des ions* — $D_+,\ D_-$

electron diffusion coefficient;
*coefficient de diffusion des électrons* — $D_{\mathrm{e}}$

ambipolar (ion–electron) diffusion coefficient;
*coefficient de diffusion ambipolaire* :
$(D_+\mu_{\mathrm{e}} + D_{\mathrm{e}}\mu_+)/(\mu_+ + \mu_{\mathrm{e}})$ — $D_{\mathrm{a}},\ D_{\mathrm{amb}}$

characteristic diffusion length;
*longueur caractéristique de diffusion* — $L_{\mathrm{D}},\ \mathit{\Lambda}$

ionization frequency; *fréquence d'ionisation* — $\nu_{\mathrm{i}}$

ion–ion recombination coefficient;
*coefficient de recombinaison ion–ion* :
$\mathrm{d}n_-/\mathrm{d}t = -\alpha_{\mathrm{i}} n_- n_+$ — $\alpha_{\mathrm{i}}$

electron–ion recombination coefficient;
*coefficient de recombinaison électron–ion* :
$\mathrm{d}n_{\mathrm{e}}/\mathrm{d}t = -\alpha_{\mathrm{e}} n_{\mathrm{e}} n_+$ — $\alpha_{\mathrm{e}}$

plasma pressure; *pression cinétique du plasma* — $p$

magnetic pressure; *pression magnétique* :
$B^2/2\mu$ ($\mu$: permeability) — $p_{\mathrm{m}}$

magnetic pressure ratio; *coefficient* $\beta$ : $p/p_{\mathrm{m}}$
($p_{\mathrm{m}}$: magnetic pressure outside the plasma) — $\beta$

magnetic diffusivity; *diffusivité magnétique* : $1/\mu\sigma$
($\sigma$: electric conductivity; $\mu$: permeability) — $\nu_{\mathrm{m}},\ \eta_{\mathrm{m}}$

Alfvén speed; *vitesse d'Alfvén* : $B/(\mu\rho)^{1/2}$
($\rho$: (mass) density; $\mu$: permeability) — $v_{\mathrm{A}}$

### 4.14 Dimensionless parameters

The symbols given here are those recommended in the International Standard ISO 31, Part XII (second edition, 1981). The ISO recommendation is that two-letter dimensionless parameters be printed in *sloping* type in the same way as single-letter quantities. When such a symbols is a factor in a product it should be separated from other symbols by a thin space, a multiplicaton sign or brackets. This disagrees with some journals that set two-letter symbols in roman type to distiguish them from ordinary products. In this report *sloping roman* is used to distiguish a two-letter symbol from the product of two *italic* single-letter symbols.

The symbols used in these definitions have the following meanings:

- $a$, thermal diffusivity ($\lambda/\rho c_p$)
- $c$, velocity of sound
- $c_p$, specific heat capacity at constant pressure
- $f$, a characteristic frequency
- $g$, acceleration of free fall

$h$, heat transfer coefficient :
heat/(time × cross sectional area × temperature difference)
$k$, mass transfer coefficient :
mass/(time × cross sectional area × mole fraction difference)
$l$, a characteristic length
$v$, a characteristic speed
$x$, mole fraction
$B$, magnetic flux density
$D$, diffusion coefficient
$\beta' = -\rho^{-1}(\partial\rho/\partial x)_{T,p}$
$\gamma$, cubic expansion coefficient : $-\rho^{-1}(\partial\rho/\partial T)_p$
$\eta$, viscosity
$\lambda$, mean free path (*par.* b); thermal conductivity (*par.* c)
$\mu$, magnetic permeability
$\nu$, kinematic viscosity : $\eta/\rho$
$\rho$, (mass) density
$\sigma$, surface tension; electric conductivity
$\Delta p$, pressure difference
$\Delta t$, a characteristic time interval
$\Delta x$, a characteristic difference of mole fraction
$\Delta T$, a characteristic temperature difference

a. Dimensionless constants of matter

| | |
|---|---|
| Prandtl number; *nombre de Prandtl* : $\nu/a$ | *Pr* |
| Schmidt number; *nombre de Schmidt* : $\nu/D$ | *Sc* |
| Lewis number; *nombre de Lewis* : $a/D = Sc/Pr$ | *Le* |

b. Momentum transport

| | |
|---|---|
| Reynolds number; *nombre de Reynolds* : $vl/\nu$ | *Re* |
| Euler number; *nombre d'Euler* : $\Delta p/\rho v^2$ | *Eu* |
| Froude number; *nombre de Froude* : $v(lg)^{-1/2}$ | *Fr* |
| Grashof number; *nombre de Grashof* : $l^3 g\gamma\Delta T/\nu^2$ | *Gr* |
| Weber number; *nombre de Weber* : $\rho v^2 l/\sigma$ | *We* |
| Mach number; *nombre de Mach* : $v/c$ | *Ma* |
| Knudsen number; *nombre de Knudsen* : $\lambda/l$ | *Kn* |
| Strouhal number; *nombre de Strouhal* : $lf/v$ | *Sr* |

c. Transport of heat

| | |
|---|---|
| Fourier number; *nombre de Fourier* : $a\Delta t/l^2$ | *Fo* |
| Péclet number; *nombre de Péclet:* $vl/a = Re \cdot Pr$ | *Pe* |
| Rayleigh number; *nombre de Rayleigh* : $l^3 g\gamma\Delta T/\nu a = Gr \cdot Pr$ | *Ra* |
| Nusselt number; *nombre de Nusselt* : $hl/\lambda$ | *Nu* |
| Stanton number; *nombre de Stanton* : $h/\rho v c_p = Nu/Pe$ | *St* |

d. Transport of matter in a binary mixture

Fourier number for mass transfer;
*nombre de Fourier pour transfert de masse*: $D\Delta t/l^2 = \mathrm{Fo}/Le$ — $Fo^*$

Péclet number for mass transfer;
*nombre de Péclet pour transfert de masse*: $vl/D = Pe \cdot Le$ — $Pe^*$

Grashof number for mass transfer;
*nombre de Grashof pour transfert de masse*: $l^3 g\beta'\Delta x/\nu^2$ — $Gr^*$

Nusselt number for mass transfer;
*nombre de Nusselt pour transfert de masse*: $kl/\rho D$ — $Nu^*$

Stanton number for mass transfer;
*nombre de Stanton pour transfert de masse*: $k/\rho v = \mathrm{Nu}^*/Pe^*$ — $St^*$

e. Magnetohydrodynamics

Magnetic Reynolds number; *nombre de Reynolds magnetique*: $v\mu\sigma l$ — $Rm$

Alfvén number; *nombre d'Alfvén*: $v(\rho\mu)^{1/2}/B$ — $Al$

Hartmann number; *nombre de Hartmann*: $Bl(\sigma/\rho\nu)^{1/2}$ — $Ha$

Cowling number (second Cowling number); *nombre de Cowling (deuxième nombre de Cowling)*: $B^2/\mu\rho v^2 = Al^{-2}$ — $Co$, $Co_2$

first Cowling number; *premier nombre de Cowling*:
$B^2 l\sigma/\rho v = Rm \cdot Co_2 = Ha^2/Re$ — $Co_1$

## 5 RECOMMENDED MATHEMATICAL SYMBOLS

### 5.1 General symbols

| | |
|---|---|
| ratio of the circumference of a circle to its diameter; *rapport de la circonférence d'un cercle à son diamètre* | $\pi$ |
| base of natural logarithms; *base des logarithmes népériens* | $\mathrm{e}$ |
| infinity; *infini* | $\infty$ |
| equal to; *égal à* | $=$ |
| not equal to; *différent de* | $\neq$ |
| identically equal to; *égal identiquement à* | $\equiv$ |
| by definition equal to; *égal par définition à* | $\stackrel{\mathrm{def}}{=}$, $(:=)$ |
| corresponds to; *correspond à* | $\hat{=}$ |
| approximately equal to; *égal environ à* | $\approx$ |
| asymptotically equal to; *asymptotiquement égal à* | $\simeq$ |
| proportional to; *proportionnel à* | $\propto$ |
| approaches; *tend vers* | $\rightarrow$ |
| greater than; *supérieur à* | $>$ |
| less than; *inférieur à* | $<$ |
| much greater than; *trés supérieur à* | $\gg$ |
| much less than; *trés inférieur à* | $\ll$ |
| greater than or equal to; *supérieur ou égal à* | $\geq$ |
| less than or equal to; *inférieur ou égal à* | $\leq$ |
| plus; *plus* | $+$ |
| minus; *moins* | $-$ |
| plus or minus; *plus ou moins* | $\pm$ |
| $a$ multiplied by $b$; *$a$ multiplié par $b$* | $ab,\ a \cdot b,\ a \times b$ |
| $a$ divided by $b$; *$a$ divisé par $b$* | $a/b,\ \frac{a}{b},\ ab^{-1}$ |
| $a$ raised to the power $n$; *$a$ puisance $n$* | $a^n$ |
| magnitude of $a$; *valeur absolue de $a$* | $\|a\|$ |
| square root of $a$; *racine carrée de $a$* | $\sqrt{a},\ \surd a,\ a^{\frac{1}{2}}$ |
| mean value of $a$; *valeur moyenne de $a$* | $\bar{a},\ \langle a \rangle$ |
| factorial $p$; *factorielle $p$* | $p!$ |
| binomial coefficient; *coefficient binomial* : $n!/[p!(n-p)!]$ | $\binom{n}{p}$ |

### 5.2 Letter symbols

Although the symbols for mathematical *variables* are usually set in sloping or italic type, the symbols for the common mathematical *functions* are always set in roman (upright) type.

| | |
|---|---|
| exponential of $x$; *exponentielle de x* | $\exp x,\ \mathrm{e}^x$ |
| logarithm to the base $a$ of $x$; *logarithme de base a de x* | $\log_a x$ |
| natural logarithm of $x$; *logarithme népérien de x* | $\ln x,\ \log_{\mathrm{e}} x$ |
| common logarithm of $x$; *logarithme décimal de x* | $\lg x,\ \log_{10} x$ |
| binary logarithm of $x$; *logarithme binaire de x* | $\mathrm{lb}\, x,\ \log_2 x$ |
| sine of $x$; *sinus x* | $\sin x$ |
| cosine of $x$; *cosinus x* | $\cos x$ |
| tangent of $x$; *tangente x* | $\tan x,\ \mathrm{tg}\, x$ |
| cotangent of $x$; *cotangente x* | $\cot x,\ \mathrm{ctg}\, x$ |
| secant of $x$; *sécante x* | $\sec x$ |
| cosecant of $x$; *cosécant x* | $\mathrm{cosec}\, x,\ \csc x$ |

For the *hyperbolic functions* the symbolic expressions for the corresponding circular functions are followed by the letter: h.
*Examples*: $\sinh x, \cosh x, \tanh x$, etc.
(The shortened forms $\mathrm{sh}\, x$, $\mathrm{ch}\, x$, and $\mathrm{th}\, x$ are also permitted.)

For the *inverse circular functions* the symbolic expressions for the corresponding circular functions are preceded by the letters: arc.
*Examples*: $\arcsin x, \arccos x, \arctan x$, etc.

For the *inverse hyperbolic functions* the symbolic expression for the corresponding hyperbolic function should be preceded by the letters: ar.
*Examples*: $\mathrm{arsinh}\, x$, $\mathrm{arcosh}\, x$, etc. (or $\mathrm{arsh}\, x$, $\mathrm{arch}\, x$, etc.)

| | |
|---|---|
| summation; *somme* | $\Sigma$ |
| product; *produit* | $\Pi$ |
| finite increase of $x$; *accroissement fini de x* | $\Delta x$ [1] |
| variation of $x$; *variation de x* | $\delta x$ |
| total differential of $x$; *différentielle totale de x* | $\mathrm{d}x$ |
| function of $x$; *fonction de x* | $f(x)$ |
| composite function of $f$ and $g$; *fonction composée de f et g* : $(g \circ f)(x) = g(f(x))$ | $g \circ f$ |
| convolution of $f$ and $g$; *convolution de f et g*: $f * g = (f * g)(x) = (g * f)(x) = \int_{-\infty}^{\infty} f(x-t)g(t)\,\mathrm{d}t$ | $f * g$ |
| limit of $f(x)$; *limite de f(x)* | $\lim_{x\to a} f(x),\ \lim\limits_{x\to a} f(x)$ |
| derivative of $f$; *dérivée de f* | $\dfrac{\mathrm{d}f}{\mathrm{d}x},\ \mathrm{d}f/\mathrm{d}x,\ f'$ |
| time derivative of $f$; *dérivée temporelle de f* | $\dot{f}$ |
| partial derivative of $f$; *dérivée partielle de f* | $\dfrac{\partial f}{\partial x},\ \partial f/\partial x,\ \partial_x f,\ f_x$ |
| total differential of $f$; *différentielle totale de f*: $\mathrm{d}f(x,y) = (\partial f/\partial x)_y \mathrm{d}x + (\partial f/\partial y)_x \mathrm{d}y$ | $\mathrm{d}f$ |
| variation of $f$; *variation de f* | $\delta f$ |

[1] Greek capital delta, not a triangle.

| | | |
|---|---|---|
| Dirac delta function; *fonction delta de Dirac*: $\delta(\boldsymbol{r}) = \delta(x)\delta(y)\delta(z)$ | $\delta(x), \delta(\boldsymbol{r})$ | |
| Kronecker delta symbol; *symbole delta de Kronecker* | $\delta_{ij}$ | |
| signum $a$; *signum* $a$: $\begin{cases} a/\lvert a\rvert & \text{for } a \neq 0, \\ 0 & \text{for } a = 0 \end{cases}$ | $\operatorname{sgn} a$ | |
| greatest integer $\leq a$; *le plus grand entier* $\leq a$ | $\operatorname{ent} a,\ [a]$ | [2] |

### 5.3 Complex quantities

| | | |
|---|---|---|
| imaginary unit; *unité imaginaire*: $(\mathrm{i}^2 = -1)$ | $\mathrm{i},\ \mathrm{j}$ | |
| real part of $z$; *partie réelle de* $z$ | $\operatorname{Re} z,\ z'$ | [3] |
| imaginary part of $z$; *partie imaginaire de* $z$ | $\operatorname{Im} z,\ z''$ | [3] |
| modulus of $z$; *module de* $z$ | $\lvert z\rvert$ | |
| phase, argument of $z$; *phase, argument de* $z$: $z = \lvert z\rvert \mathrm{e}^{\mathrm{i}\phi}$ | $\phi,\ \arg z$ | |
| complex conjugate of $z$, conjugate of $z$; *complexe conjugué de* $z$*, conjugué de* $z$ | $z^*,\ \bar{z}$ | |

### 5.4 Vector calculus [4]

| | | |
|---|---|---|
| vector; *vecteur* | $\boldsymbol{A},\ \boldsymbol{a}$ | |
| absolute value; *valeur absolue* | $\lvert\boldsymbol{A}\rvert,\ A$ | |
| unit vector; *vecteur unitaire*: $\boldsymbol{a}/\lvert\boldsymbol{a}\rvert$ | $\boldsymbol{e_a},\ \hat{\boldsymbol{a}}$ | |
| unit coordinate vectors; *vecteurs coordonnés unitaires* | $\boldsymbol{e}_x, \boldsymbol{e}_y, \boldsymbol{e}_z,\ \boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$ | [5] |
| scalar product of $\boldsymbol{a}$ and $\boldsymbol{b}$; *produit scalaire de* $\boldsymbol{a}$ *et* $\boldsymbol{b}$ | $\boldsymbol{a} \cdot \boldsymbol{b}$ | |
| vector product of $\boldsymbol{a}$ and $\boldsymbol{b}$; *produit vectoriel de* $\boldsymbol{a}$ *et* $\boldsymbol{b}$ | $\boldsymbol{a} \times \boldsymbol{b},\ \boldsymbol{a} \wedge \boldsymbol{b}$ | |
| dyadic product of $\boldsymbol{a}$ and $\boldsymbol{b}$; *produit extérieur de* $\boldsymbol{a}$ *et* $\boldsymbol{b}$ | $\boldsymbol{ab}$ | |
| differential vector operator, nabla; *(opérateur) nabla* | $\partial/\partial\boldsymbol{r},\ \nabla$ | |
| gradient; *gradient* | $\operatorname{grad}\phi,\ \nabla\phi$ | |
| divergence; *divergence* | $\operatorname{div}\boldsymbol{A},\ \boldsymbol{\nabla}\cdot\boldsymbol{A}$ | |
| curl; *rotationnel* | $\operatorname{curl}\boldsymbol{A},\ \operatorname{rot}\boldsymbol{A},\ \boldsymbol{\nabla}\times\boldsymbol{A}$ | |
| Laplacian; *Laplacien* | $\triangle\phi,\ \nabla^2\phi$ | |
| Dalembertian; *Dalembertien*: $\nabla^2\phi - c^{-2}\partial^2\phi/\partial t^2$ | $\Box\phi$ | |
| second order tensor; *tenseur du second ordre* | $\mathsf{A}$ | |
| scalar product of tensors $\mathsf{S}$ and $\mathsf{T}$; *produit scalaire des tenseurs* $\mathsf{S}$ *et* $\mathsf{T}$: $(\Sigma_{i,k} S_{ik} T_{ki})$ | $\mathsf{S} : \mathsf{T}$ | |
| tensor product of tensors $\mathsf{S}$ and $\mathsf{T}$; *produit tensoriel des tenseurs* $\mathsf{S}$ *et* $\mathsf{T}$: $(\Sigma_k S_{ik} T_{kl})$ | $\mathsf{S} \cdot \mathsf{T}$ | |

---

[2] For $a \neq$ integer, $[-a] = -([a] + 1)$;   *e.g.*, $[-3.14] = -4$.

[3] The notation $z',\ z''$ is used primarily for physical quantities, *e.g.*, the complex representation of the dielectric constant: $\epsilon = \epsilon' + \mathrm{i}\epsilon''$.

[4] See also section **1.1.2**.

[5] $\boldsymbol{1}_x$, $\boldsymbol{1}_y$, $\boldsymbol{1}_z$ are also used.

product of tensor $\boldsymbol{S}$ and vector $\boldsymbol{A}$;
*produit du tenseur* $\boldsymbol{S}$ *et du vecteur* $\boldsymbol{A}$: $(\Sigma_k S_{ik} A_k)$ — $\boldsymbol{S} \cdot \boldsymbol{A}$

## 5.5 Matrix calculus

| | |
|---|---|
| matrix; *matrice* | $A,\ \{a_{ij}\}$ |
| | $\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix}$ |
| product of $A$ and $B$; *produit de* $A$ *et* $B$ | $AB$ |
| inverse of $A$; *inverse de* $A$ | $A^{-1}$ |
| unit matrix; *matrice unité* | $E,\ I$ |
| transpose of matrix $A$; *matrice transposée de* $A$: $(A^{\mathrm{T}})_{ij} = A_{ji}$ | $A^{\mathrm{T}},\ \tilde{A}$ |
| complex conjugate of $A$; *matrice complexe conjuguée de* $A$: $(A^*)_{ij} = A^*_{ij}$ | $A^*$ |
| Hermitian conjugate of $A$; *matrice adjointe de* $A$: $(A^\dagger)_{ij} = A^*_{ji}$ | $A^\dagger$ |
| determinant of $A$; *déterminant de* $A$ | $\det A$ |
| trace of $A$; *trace de* $A$: $\Sigma_{ii} A_{ii}$ | $\mathrm{Tr}\, A$ |

## 5.6 Symbolic logic

| | |
|---|---|
| conjunction: $p \wedge q$ means "$p$ and $q$"; *conjonction: $p \wedge q$ signifie "$p$ et $q$"* | $\wedge$ |
| disjunction: $p \vee q$ means "$p$ or $q$ or both"; *disjonction: $p \vee q$ signifie "$p$ ou $q$ ou les deux"* | $\vee$ |
| negation; *négation* | $\neg$ |
| implication; *implication* | $\Rightarrow$ |
| equivalence, bi-implication; *équivalence, bi-implication* | $\Leftrightarrow$ |
| universal quantifier; *quantificateur universel* | $\forall$ |
| existential quantifier; *quantificateur existentiel* | $\exists$ |

## 5.7 Theory of sets

| | |
|---|---|
| is an element of; *est un élément de*: $x \in A$ | $\in$ |
| is not an element of; *n'est pas un élément de*: $x \notin A$ | $\notin$ |
| contains as element; *contient comme élément*: $A \ni x$ | $\ni$ |
| set of elements; *ensemble des éléments* | $\{a_1, a_2, \cdots\}$ |
| empty set; *l'ensemble vide* | $\emptyset,\ \varnothing$ |
| the set of positive integers and zero; *ensemble des nombres entiers positifs et zero* | $\mathsf{N}$ |
| the set of all integers; *ensemble de tous les nombres entiers* | $\mathsf{Z}$ [6] |

[6] $\mathsf{Z} = \{\ldots, -2, -1, 0, 1, 2, \ldots\}$

| | |
|---|---|
| the set of rational numbers; *ensemble des nombres rationnels* | $\mathsf{Q}$ |
| the set of real numbers; *ensemble des nombres réels* | $\mathsf{R}$ |
| the set of complex numbers; *ensemble des nombres complexes* | $\mathsf{C}$ |
| set of elements of $A$ for which $p(x)$ is true; *ensemble des éléments de $A$ pour lequels $p(x)$ est vrai* | $\{ x \in A \mid p(x) \}$ |
| is included in; *est contenu comme sous-ensemble dans* : $B \subseteq A$ | $\subseteq$, $(\subset)$ |
| contains; *contient* : $A \supseteq B$ | $\supseteq$, $(\supset)$ |
| is properly contained in; *est strictement contenu dans* | $\subset$, $(\subsetneq)$ |
| contains properly; *contient strictement* | $\supset$, $(\supsetneq)$ |
| union; *réunion* : $A \cup B = \{ x \mid (x \in A) \vee (x \in B) \}$ | $\cup$ |
| intersection; *intersection* : $A \cap B = \{ x \mid (x \in A) \wedge (x \in B) \}$ | $\cap$ |
| difference; *différence* : $A \setminus B = \{ x \mid (x \in A) \wedge (x \notin B) \}$ | $\setminus$ |
| complement of; *complément de* : $\mathcal{C}A = \{ x \mid x \notin A \}$ | $\mathcal{C}$ |

### 5.8 Symbols for special values of periodic quantities

A quantity whose time dependence is such that $x(t+T) = x(t)$, where $T$ is the smallest strictly positive constant value for which this relation holds for all $t$, is said to vary periodically with period $T$.

| | |
|---|---|
| instantaneous value; *valeur instantanée* | $x,\ x(t)$ |
| maximum value; *valeur maximale* | $\hat{x},\ x_{\max}$ |
| minimum value; *valeur minimale* | $\check{x},\ x_{\min}$ |
| mean value; *valeur moyenne* : $\dfrac{1}{T}\displaystyle\int_0^T x(t)\,\mathrm{d}t$ | $\bar{x},\ \langle x \rangle$ |
| rms value; *valeur efficace* : $\left[\dfrac{1}{T}\displaystyle\int_0^T [x(t)]^2\,\mathrm{d}t\right]^{\frac{1}{2}}$ | $X,\ \tilde{x},\ x_{\mathrm{rms}},\ (x_{\mathrm{eff}})$ |

## 6 RECOMMENDED VALUES OF THE FUNDAMENTAL PHYSICAL CONSTANTS

This report is primarily concerned with establishing recognized standards of usage for symbols, units and nomenclature in physics, thus improving comprehension and understanding. However, communication is simplified not only if there are standards for symbols, but also if there is a uniformity of usage of the numerical values of the basic physical quantities that enter into data analysis in all branches of science and technology. To this end, the Committee on Data for Science and Technology (CODATA), through its Task Group on Fundamental Constants, has recommended a set of values of the physical constants for general use. These numerical values have the advantage that they are consistent in the sense that they properly reflect all known physical interrelationships among the constants and take into account the constraints imposed by the results of all evaluated experimental measurements and theoretical calculations.

The tables in this section are drawn from the Task Group report* , and are based on a least-squares adjustment with 17 degrees of freedom. The digits in parentheses following the numerical values are the one-standard-deviation uncertainty in the last digits of the given value.

Table 9 gives a listing of CODATA recommended values of important physical and chemical constants; table 10 gives the values of some conversion constants and standards which, although they cannot be considered to be 'fundamental' constants, are nonetheless important in pure and applied physics.

Since the uncertainties of many of these entries are correlated, the full variance matrix must be used in evaluating the uncertainties of quantities computed from them. An expanded variance matrix for the variables of tables 9 and 10 is given in table 11. To use this table note that the covariance between two quantities $Q_k$ and $Q_s$ which are functions of a common set of variables $x_i$ $(i = 1, \ldots, N)$ is given by

$$v_{ks} = \sum_{i,j=1}^{N} \frac{\partial Q_k}{\partial x_i} \frac{\partial Q_s}{\partial x_j} v_{ij}, \qquad (1)$$

where $v_{ij}$ is the covariance of $x_i$ and $x_j$. In this general form, the units of $v_{ij}$ are the product of the units of $x_i$ and $x_j$ and the units of $v_{ks}$ are the

* *The 1986 Adjustment of the Fundamental Physical Constants*, E. Richard Cohen and Barry N. Taylor, CODATA Bulletin Number 63 (Pergamon Press, Elmsford, NY 10523, USA, and Headinghill Hall, Oxford OX3 0BW, UK, November, 1986). CODATA is a Committee of the International Council of Scientific Unions, 51 Blvd de Montmorency, 75016 Paris, France.

product of the units of $Q_k$ and $Q_s$. For most cases of interest involving the fundamental constants, the variables $x_i$ may be taken to be the fractional change in the physical quantity from some fiducial value, and the quantities $Q$ can be expressed as powers of physical constants $Z_j$ according to

$$Q_k = q_k \prod_{j=1}^{N} Z_j^{Y_{kj}}, \tag{2}$$

where $q_k$ is a auxiliary constant or a numerical factor. If the variances and covariances are then expressed in relative units, eq. (1) becomes

$$v_{ks} = \sum_{i,j=1}^{N} Y_{ki} Y_{sj} v_{ij}. \tag{3}$$

Equation (3) is the basis for the expansion of the variance matrix to include $e$, $h$, $m_\mathrm{e}$, $N_\mathrm{A}$, and $F$.

In terms of correlation coefficients defined by $r_{ij} = v_{ij}(v_{ii}v_{jj})^{-\frac{1}{2}} = v_{ij}/\epsilon_i\epsilon_j$, where $\epsilon_i$ is the standard deviation ($\epsilon_i^2 = v_{ii}$) we may write, from eq. (3),

$$\epsilon_k^2 = \sum_{i=1}^{N} Y_{ki}^2 \epsilon_i^2 + 2\sum_{j<i}^{N} Y_{ki} Y_{kj} r_{ij} \epsilon_i \epsilon_j. \tag{4}$$

Table 9. 1986 recommended values of the fundamental physical constants.

The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value. Since the uncertainties of many of these entries are correlated, the full variance matrix must be used in evaluating the uncertainties of quantities computed from them.

| Quantity | Symbol | Value | Relative uncertainty, parts in $10^6$ |
|---|---|---|---|
| **GENERAL CONSTANTS** | | | |
| Universal constants | | | |
| speed of light in vacuum; *vitesse de la lumière dans le vide* | $c$ | $299\,792\,458$ m s$^{-1}$ | (exact) |
| permeability of vacuum; *perméabilité du vide* | $\mu_\circ$ | $4\pi\times10^{-7}$ N A$^{-2}$ $=12.566\,370\,614\ldots\times10^{-7}$ N A$^{-2}$ | (exact) |
| permittivity of vacuum; *permittivité du vide* : $1/\mu_\circ c^2$ | $\epsilon_\circ$ | $8.854\,187\,817\ldots\times10^{-12}$ F m$^{-1}$ | (exact) |
| gravitational constant; *constante de gravitation* | $G$ | $6.672\,59(85)\times10^{-11}$ m$^3$ kg$^{-1}$ s$^{-2}$ | 128 |
| Planck constant; *constante de Planck* | $h$ | $6.626\,0755(40)\times10^{-34}$ J s | 0.60 |
| | | $4.135\,6692(12)\times10^{-15}$ eV s | 0.30 |
| $h/2\pi$ | $\hbar$ | $1.054\,572\,66(63)\times10^{-34}$ J s | 0.60 |
| | | $6.582\,1220(20)\times10^{-16}$ eV s | 0.30 |
| Planck mass; *masse de Planck* : $(\hbar c/G)^{\frac{1}{2}}$ | $m_{\rm P}$ | $2.176\,71(14)\times10^{-8}$ kg | 64 |
| Planck length; *longueur de Planck* : $\hbar/m_{\rm P}c = (\hbar G/c^3)^{\frac{1}{2}}$ | $l_{\rm P}$ | $1.616\,05(10)\times10^{-35}$ m | 64 |
| Planck time; *temps de Planck* : $l_{\rm P}/c = (\hbar G/c^5)^{\frac{1}{2}}$ | $t_{\rm P}$ | $5.390\,56(34)\times10^{-44}$ s | 64 |
| Electromagnetic constants | | | |
| elementary charge; *charge élémentaire* | $e$ | $1.602\,177\,33(49)\times10^{-19}$ C | 0.30 |
| | $e/h$ | $2.417\,988\,36(72)\times10^{14}$ A J$^{-1}$ | 0.30 |
| magnetic flux quantum; *quantum de flux magnétique* : $h/2e$ | $\Phi_\circ$ | $2.067\,834\,61(61)\times10^{-15}$ Wb | 0.30 |
| Josephson frequency–voltage quotient; *quotient fréquence–tension dans l'effet Josephson* | $2e/h$ | $4.835\,9767(14)\times10^{14}$ Hz V$^{-1}$ | 0.30 |
| quantized Hall conductance; *conductance quantifiée de Hall* | $e^2/h$ | $3.874\,046\,14(17)\times10^{-5}$ S | 0.045 |
| quantized Hall resistance; *résistance quantifiée de Hall* : $h/e^2 = \mu_\circ c/2\alpha$ | $R_{\rm H}$ | $25\,812.8056(12)$ Ω | 0.045 |
| Bohr magneton; *magnéton de Bohr* : $e\hbar/2m_{\rm e}$ | $\mu_{\rm B}$ | $9.274\,0154(31)\times10^{-24}$ J T$^{-1}$ | 0.34 |
| | | $5.788\,382\,63(52)\times10^{-5}$ eV T$^{-1}$ | 0.089 |
| | $\mu_{\rm B}/h$ | $1.399\,624\,18(42)\times10^{10}$ Hz T$^{-1}$ | 0.30 |
| | $\mu_{\rm B}/hc$ | $46.686\,437(14)$ m$^{-1}$ T$^{-1}$ | 0.30 |
| | $\mu_{\rm B}/k$ | $0.671\,7099(57)$ K T$^{-1}$ | 8.5 |
| nuclear magneton; *magnéton nucléaire* : $e\hbar/2m_{\rm p}$ | $\mu_{\rm N}$ | $5.050\,7866(17)\times10^{-27}$ J T$^{-1}$ | 0.34 |
| | | $3.152\,451\,66(28)\times10^{-8}$ eV T$^{-1}$ | 0.089 |
| | $\mu_{\rm N}/h$ | $7.622\,5914(23)$ MHz T$^{-1}$ | 0.30 |
| | $\mu_{\rm N}/hc$ | $2.542\,622\,81(77)\times10^{-2}$ m$^{-1}$ T$^{-1}$ | 0.30 |
| | $\mu_{\rm N}/k$ | $3.658\,246(31)\times10^{-4}$ K T$^{-1}$ | 8.5 |

## ATOMIC CONSTANTS

| | | | |
|---|---|---|---|
| fine-structure constant; *constante de structure fine* : | | | |
| $\mu_\circ ce^2/2h$ | $\alpha$ | $0.007\,297\,353\,08(33)$ | 0.045 |
| | $\alpha^{-1}$ | $137.035\,9895(61)$ | 0.045 |
| | $\alpha^2$ | $5.325\,136\,20(48)\times10^{-5}$ | 0.090 |
| Rydberg constant; *constante de Rydberg* : | | | |
| $m_e c\alpha^2/2h$ | $R_\infty$ | $10\,973\,731.534(13)\ \mathrm{m^{-1}}$ | 0.0012 |
| | $R_\infty c$ | $3.289\,841\,9499(39)\times10^{15}$ Hz | 0.0012 |
| | $R_\infty hc$ | $2.179\,8741(13)\times10^{-18}$ J | 0.60 |
| | | $13.605\,6981(40)$ eV | 0.30 |
| Bohr radius; *rayon de Bohr* : | | | |
| $\alpha/4\pi R_\infty$ | $a_\circ$ | $0.529\,177\,249(24)\times10^{-10}$ m | 0.045 |
| quantum of circulation; *quantum de circulation* | $h/2m_e$ | $3.636\,948\,07(33)\times10^{-4}\ \mathrm{m^2\,s^{-1}}$ | 0.089 |
| | $h/m_e$ | $7.273\,896\,14(65)\times10^{-4}\ \mathrm{m^2\,s^{-1}}$ | 0.089 |

### Electron

| | | | |
|---|---|---|---|
| electron mass; *masse de l'électron* | $m_e$ | $9.109\,3897(54)\times10^{-31}$ kg | 0.59 |
| | | $5.485\,799\,03(13)\times10^{-4}$ u | 0.023 |
| | | $0.510\,999\,06(15)$ MeV | 0.30 |
| electron–muon mass ratio; *rapport de la masse du muon à celle de l'électron* | $m_e/m_\mu$ | $0.004\,836\,332\,18(71)$ | 0.15 |
| electron–proton mass ratio; *rapport de la masse de l'électron à celle du proton* | $m_e/m_p$ | $5.446\,170\,13(11)\times10^{-4}$ | 0.020 |
| electron–deuteron mass ratio; *rapport de la masse du deuteron à celle de l'électron* | $m_e/m_d$ | $2.724\,437\,07(6)\times10^{-4}$ | 0.020 |
| electron–$\alpha$-particle mass ratio; *rapport de la masse de la particule $\alpha$ à celle de l'électron* | $m_e/m_\alpha$ | $1.370\,933\,54(3)\times10^{-4}$ | 0.021 |
| electron specific charge; *charge massique de l'électron* | $-e/m_e$ | $-1.758\,819\,62(53)\times10^{11}\ \mathrm{C\,kg^{-1}}$ | 0.30 |
| electron molar mass; *masse molaire de l'électron* | $M(\mathrm{e}), M_e$ | $5.485\,799\,03(13)\times10^{-7}$ kg/mol | 0.023 |
| Compton wavelength; *longueur d'onde de Compton* : | | | |
| $h/m_e c$ | $\lambda_C$ | $2.426\,310\,58(22)\times10^{-12}$ m | 0.089 |
| $\lambda_C/2\pi = \alpha a_\circ = \alpha^2/4\pi R_\infty$ | $\bar{\lambda}_C$ | $3.861\,593\,23(35)\times10^{-13}$ m | 0.089 |
| classical electron radius; *rayon classique de l'électron* : | | | |
| $\alpha^2 a_\circ$ | $r_e$ | $2.817\,940\,92(38)\times10^{-15}$ m | 0.13 |
| Thomson cross section; *section efficace de Thomson* : | | | |
| $(8\pi/3)r_e^2$ | $\sigma_e$ | $0.665\,246\,16(18)\times10^{-28}\ \mathrm{m^2}$ | 0.27 |

| | | | |
|---|---|---|---|
| electron magnetic moment; *moment magnétique de l'électron* | $\mu_e$ | $9.284\,7701(31)\times10^{-24}$ J T$^{-1}$ | 0.34 |
| | $\mu_e/\mu_B$ | 1.001 159 652 193(10) | $1\times10^{-5}$ |
| | $\mu_e/\mu_N$ | 1838.282 000(37) | 0.020 |
| electron–muon magnetic moment ratio; *rapport du moment magnétique de l'électron à celui du muon* | $\mu_e/\mu_\mu$ | 206.766967(30) | 0.15 |
| electron–proton magnetic moment ratio; *rapport du moment magnétique de l'électron à celui du proton* | $\mu_e/\mu_p$ | 658.210 6881(66) | 0.010 |
| | Muon | | |
| muon mass; *masse du muon* | $m_\mu$ | $1.883\,5327(11)\times10^{-28}$ kg | 0.61 |
| | | 0.113 428 913(17) u | 0.15 |
| | | 105.658 389(34) MeV | 0.32 |
| muon–electron mass ratio; *rapport de la masse du muon à celle de l'électron* | $m_\mu/m_e$ | 206.768 262(30) | 0.15 |
| muon molar mass; *masse molaire du muon* | $M(\mu), M_\mu$ | $1.134\,289\,13(17)\times10^{-4}$ kg/mol | 0.15 |
| muon magnetic moment; *moment magnétique du muon* | $\mu_\mu$ | $4.490\,4514(15)\times10^{-26}$ J T$^{-1}$ | 0.33 |
| | $\mu_\mu/\mu_B$ | 0.004 841 970 97(71) | 0.15 |
| | $\mu_\mu/\mu_N$ | 8.890 5981(13) | 0.15 |
| muon magnetic moment anomaly; *anomalie du moment magnétique du muon*: $[\mu_\mu/(e\hbar/2m_\mu)]-1$ | $a_\mu$ | 0.001 165 9230(84) | 7.2 |
| muon–proton magnetic moment ratio; *rapport du moment magnétique du muon à celui du proton* | $\mu_\mu/\mu_p$ | 3.183 345 47(47) | 0.15 |
| | Proton | | |
| proton mass; *masse du proton* | $m_p$ | $1.672\,6231(10)\times10^{-27}$ kg | 0.59 |
| | | 1.007 276 470(12) u | 0.012 |
| | | 938.272 31(28) MeV | 0.30 |
| proton–electron mass ratio; *rapport de la masse du proton à celle de de l'électron* | $m_p/m_e$ | 1836.152 701(37) | 0.020 |
| proton–muon mass ratio; *rapport de la masse du proton à celle du muon* | $m_p/m_\mu$ | 8.880 2444(13) | 0.15 |
| proton specific charge; *charge massique du proton* | $e/m_p$ | $9.578\,8309(29)\times10^{7}$ C kg$^{-1}$ | 0.30 |
| proton molar mass; *masse molaire du proton* | $M(p), M_p$ | $1.007\,276\,470(12)\times10^{-3}$ kg/mol | 0.012 |
| proton Compton wavelength; *longueur d'onde de Compton du proton*: $h/m_pc$ | $\lambda_{C,p}$ | $1.321\,410\,02(12)\times10^{-15}$ m | 0.089 |
| $\lambda_{C,p}/2\pi$ | $\bar{\lambda}_{C,p}$ | $2.103\,089\,37(19)\times10^{-16}$ m | 0.089 |

| | | | |
|---|---|---|---|
| proton magnetic moment; *moment magnétique du proton* | $\mu_p$ | $1.410\,607\,61(47)\times10^{-26}\ \mathrm{J\,T^{-1}}$ | 0.34 |
| | $\mu_p/\mu_B$ | $0.001\,521\,032\,202(15)$ | 0.010 |
| | $\mu_p/\mu_N$ | $2.792\,847\,386(63)$ | 0.023 |
| diamagnetic shielding correction; *facteur d'écran diamagnétique* : ($H_2O$, sph., 25 °C): $1-\mu_p'/\mu_p$ | $\sigma_{H_2O}$ | $25.689(15)\times10^{-6}$ | – |
| shielded proton moment; *moment magnétique du proton non corrigé* : ($H_2O$, sph., 25 °C) | $\mu_p'$ | $1.410\,571\,38(47)\times10^{-26}\ \mathrm{J\,T^{-1}}$ | 0.34 |
| | $\mu_p'/\mu_B$ | $0.001\,520\,993\,129(17)$ | 0.011 |
| | $\mu_p'/\mu_N$ | $2.792\,775\,642(64)$ | 0.023 |
| proton gyromagnetic ratio; *coefficient gyromagnétique du proton* | $\gamma_p$ | $26\,752.2128(81)\times10^4\ \mathrm{s^{-1}\,T^{-1}}$ | 0.30 |
| | $\gamma_p/2\pi$ | $42.577\,469(13)\ \mathrm{MHz\,T^{-1}}$ | 0.30 |
| uncorrected; *non corrigé* : ($H_2O$, sph., 25 °C) | $\gamma_p'$ | $26\,751.5255(81)\times10^4\ \mathrm{s^{-1}\,T^{-1}}$ | 0.30 |
| | $\gamma_p'/2\pi$ | $42.576\,375(13)\ \mathrm{MHz\,T^{-1}}$ | 0.30 |

Neutron

| | | | |
|---|---|---|---|
| neutron mass; *masse du neutron* | $m_n$ | $1.674\,9286(10)\times10^{-27}\ \mathrm{kg}$ | 0.59 |
| | | $1.008\,664\,904(14)\ \mathrm{u}$ | 0.014 |
| | | $939.565\,63(28)$ Mev | 0.30 |
| neutron–electron mass ratio; *rapport de la masse du neutron à celle de l'électron* | $m_n/m_e$ | $1838.683\,662(40)$ | 0.022 |
| neutron–proton mass ratio; *rapport de la masse du neutron à celle du proton* | $m_n/m_p$ | $1.001\,378\,404(9)$ | 0.009 |
| neutron molar mass; *masse molaire du neutron* | $M(\mathrm{n}), M_n$ | $1.008\,664\,904(14)\times10^{-3}\ \mathrm{kg/mol}$ | 0.014 |
| neutron Compton wavelength; *longueur d'onde de Compton du neutron* : $h/m_nc$ | $\lambda_{C,n}$ | $1.319\,591\,10(12)\times10^{-15}\ \mathrm{m}$ | 0.089 |
| $\lambda_{C,n}/2\pi$ | $\bar{\lambda}_{C,n}$ | $2.100\,194\,45(19)\times10^{-16}\ \mathrm{m}$ | 0.089 |
| neutron magnetic moment; *moment magnétique du neutron* | $\mu_n$ | $0.966\,237\,07(40)\times10^{-26}\ \mathrm{J\,T^{-1}}$ | 0.41 |
| | $\mu_n/\mu_B$ | $0.001\,041\,875\,63(25)$ | 0.24 |
| | $\mu_n/\mu_N$ | $1.913\,042\,75(45)$ | 0.24 |
| neutron–electron magnetic moment ratio; *rapport du moment magnétique du neutron à celui de l'électron* | $\mu_n/\mu_e$ | $0.001\,040\,668\,82(25)$ | 0.24 |
| neutron–proton magnetic moment ratio; *rapport du moment magnétique du neutron à celui du proton* | $\mu_n/\mu_p$ | $0.684\,979\,34(16)$ | 0.24 |

Deuteron

| | | | |
|---|---|---|---|
| deuteron mass; *masse du deutéron* | $m_d$ | $3.343\,5860(20)\times10^{-27}\ \mathrm{kg}$ | 0.59 |
| | | $2.013\,553\,214(24)\ \mathrm{u}$ | 0.012 |
| | | $1875.613\,39(57)\ \mathrm{MeV}$ | 0.30 |

| | | | |
|---|---|---|---|
| deuteron–electron mass ratio; *rapport de la masse du deutéron à celle de l'électron* | $m_d/m_e$ | $3670.483\,014(75)$ | 0.020 |
| deuteron–proton mass ratio; *rapport de la masse du deutéron à celle du proton* | $m_d/m_p$ | $1.999\,007\,496(6)$ | 0.003 |
| deuteron molar mass; *masse molaire du deutéron* | $M(\mathrm{d}), M_d$ | $2.013\,553\,214(24)\times10^{-3}$ kg/mol | 0.012 |
| deuteron magnetic moment; *moment magnétique du deutéron* | $\mu_d$ | $0.433\,073\,75(15)\times10^{-26}\ \mathrm{J\,T^{-1}}$ | 0.34 |
| | $\mu_d/\mu_B$ | $0.466\,975\,4479(91)\times10^{-3}$ | 0.019 |
| | $\mu_d/\mu_N$ | $0.857\,438\,230(24)$ | 0.028 |
| deuteron–electron magnetic moment ratio; *rapport du moment magnétique du deutéron à celui de l'électron* | $\mu_d/\mu_e$ | $4.664\,345\,460(91)\times10^{-4}$ | 0.019 |
| deuteron–proton magnetic moment ratio; *rapport du moment magnétique du deutéron à celui du proton* | $\mu_d/\mu_p$ | $0.307\,012\,2035(51)$ | 0.017 |

## PHYSICO-CHEMICAL CONSTANTS

| | | | |
|---|---|---|---|
| Avogadro constant; *constante d'Avogadro* | $N_A, L$ | $6.022\,1367(36)\times10^{23}\ \mathrm{mol^{-1}}$ | 0.59 |
| atomic mass constant; *constante de masse atomique* : $\frac{1}{12}m(^{12}\mathrm{C})$ | $m_u$ | $1.660\,5402(10)\times10^{-27}$ kg | 0.59 |
| | | $931.494\,32(28)$ MeV | 0.30 |
| Faraday constant; *constante de Faraday* | $F$ | $96\,485.309(29)\ \mathrm{C\,mol^{-1}}$ | 0.30 |
| molar Planck constant; *constante molaire de Planck* | $N_A h$ | $3.990\,313\,23(36)\times10^{-10}\ \mathrm{J\,s\,mol^{-1}}$ | 0.089 |
| | $N_A hc$ | $0.119\,626\,58(11)\ \mathrm{J\,m\,mol^{-1}}$ | 0.089 |
| molar gas constant; *constante molaire de gaz* | $R$ | $8.314\,510(70)\ \mathrm{J\,mol^{-1}\,K^{-1}}$ | 8.4 |
| Boltzmann constant; *constante de Boltzmann* : $R/N_A$ | $k$ | $1.380\,658(12)\times10^{-23}\ \mathrm{J\,K^{-1}}$ | 8.5 |
| | | $8.617\,385(73)\times10^{-5}\ \mathrm{eV\,K^{-1}}$ | 8.4 |
| | $k/h$ | $2.083\,674(18)\times10^{10}\ \mathrm{Hz\,K^{-1}}$ | 8.4 |
| | $k/hc$ | $69.503\,87(59)\ \mathrm{m^{-1}\,K^{-1}}$ | 8.4 |
| molar volume (ideal gas); *volume molaire (gaz parfait)* : $RT/p$ $T = 273.15\,\mathrm{K},\ p = 101\,325\,\mathrm{Pa}$ | $V_m$ | $22\,414.10(19)\ \mathrm{cm\,mol^{-1}}$ | 8.4 |
| Loschmidt constant; *constante de Loschmidt* : $N_A/V_m$ | $n_\circ$ | $2.686\,763(23)\times10^{25}\ \mathrm{m^{-3}}$ | 8.5 |
| Sackur–Tetrode (absolute entropy) constant; *constante de Sackur–Tetrode (entropie absolue)* : * $\frac{5}{2} + \ln\{(2\pi m_u kT_1/h^2)^{\frac{3}{2}} kT_1/p_\circ\}$ $T_1 = 1\ \mathrm{K},\quad p_\circ = 100\ \mathrm{kPa}$ | $S_\circ/R$ | $-1.151\,693(21)$ | 18 |
| $p_\circ = 101\,325$ Pa | | $-1.164\,856(21)$ | 18 |

RADIATION CONSTANTS

| | | | |
|---|---|---|---|
| Stefan–Boltzmann constant; *constante de Stefan–Boltzmann* : $(\pi^2/60)k^4/\hbar^3c^2$ | $\sigma$ | $5.670\,51(19)\times10^{-8}$ W m$^{-2}$ K$^{-4}$ | 34 |
| first radiation constant; *première constante de rayonnement* : $2\pi hc^2$ | $c_1$ | $3.741\,7749(22)\times10^{-16}$ W m$^2$ | 0.60 |
| second radiation constant; *deuxième constante de rayonnement* : $hc/k$ | $c_2$ | 0.014 387 69(12) m K | 8.4 |
| Wien displacement law constant; *constante de la loi du déplacement de Wien* : $\lambda_{\mathrm{max}}T = c_2/4.965\,114\,23\ldots$ | $b$ | 0.002 897 756(24) m K | 8.4 |

* The molar entropy of an ideal monatomic gas of relative atomic weight $A_\mathrm{r}$ is given by

$$S = S_\circ + \tfrac{3}{2}R\ln A_\mathrm{r} - R\ln(p/p_\circ) + \tfrac{5}{2}R\ln(T/\mathrm{K}).$$

Table 10. Maintained units and standard values.

| Quantity | Symbol | Value | Relative uncertainty, parts in $10^6$ |
|---|---|---|---|
| electron volt: $(e/\mathrm{C})\,\mathrm{J} = \{e\}\,\mathrm{J}$ | eV | $1.602\,177\,33(49)\times10^{-19}$ J | 0.30 |
| | | $11\,604.45(10)$ K | 8.5 |
| | | $1.073\,543\,85(33)\times10^{-9}$ u | 0.30 |
| (unified) atomic mass unit: | u | $1.660\,5402(10)\times10^{-27}$ kg | 0.59 |
| $1\ \mathrm{u} = m_\mathrm{u} = \frac{1}{12}m(^{12}\mathrm{C})$ | | $931.494\,32(28)$ MeV | 0.30 |
| standard atmosphere | atm | $101\,325$ Pa | (exact) |
| standard acceleration of gravity | $g_\mathrm{n}$ | $9.806\,65\ \mathrm{m\,s^{-2}}$ | (exact) |
| ‘As-maintained’ electrical units | | | |
| BIPM maintained ohm, $\Omega_{69-\mathrm{BI}}$: | | | |
| $\Omega_{\mathrm{BI85}} \equiv \Omega_{69-\mathrm{BI}}(1985\ \mathrm{Jan}\ 1)$ | $\Omega_{\mathrm{BI85}}$ | $0.999\,998\,437(50)\ \Omega$ | 0.050 |
| Drift rate: $\mathrm{d}\Omega_{69-\mathrm{BI}}/\mathrm{d}t$ | | $-0.0566(15)\ \mu\Omega/\mathrm{a}$ | — |
| BIPM maintained volt: | | | |
| $2e/h \equiv 483\,594.0\ \mathrm{GHz}/V_{76-\mathrm{BI}}$ | $V_{76-\mathrm{BI}}$ | $0.999\,992\,41(30)$ V | 0.30 |
| BIPM maintained ampere: | | | |
| $A_{\mathrm{BIPM}} = V_{76-\mathrm{BI}}/\Omega_{69-\mathrm{BI}}$ | $A_{\mathrm{BI85}}$ | $0.999\,993\,97(30)$ A | 0.30 |
| X-ray standards | | | |
| x-unit: $\lambda(\mathrm{Cu\,K}\alpha_1)/1537.400$ | xu(Cu) | $1.002\,077\,89(70)\times10^{-13}$ m | 0.70 |
| x-unit: $\lambda(\mathrm{Mo\,K}\alpha_1)/707.831$ | xu(Mo) | $1.002\,099\,38(45)\times10^{-13}$ m | 0.45 |
| Å*: $\lambda(\mathrm{W\,K}\alpha_1)/0.209\,100$ | Å* | $1.000\,014\,81(92)\times10^{-10}$ m | 0.92 |

Table 11. Expanded matrix of variances, covariances and correlation coefficients for the 1986 recommended set of fundamental physical constants.

The elements of the variance matrix appear on and above the major diagonal in (parts in $10^8)^2$; correlation coefficients appear in *italics* below the diagonal. The variances and covariances in thid table have been rounded from those given in CODATA Bulletin No. 63.

The correlation coefficient between $m_e$ and $N_A$ appears as *−1.000* in this table because the auxiliary constants were considered to be exact in carryi and $N_A$ appears as *−1.000* in this table because the auxiliary constants were considered to be exact in carrying out the least-squares adjustment. When the uncertainties of $m_p/m_e$ and $M_p$ are properly taken into account, the correlation coefficient is *−0.999* and the variances of $m_e$ and $N_A$ are slightly increased.

| | $\alpha^{-1}$ | $e$ | $h$ | $m_e$ | $N_A$ | $F$ | $\mu_\mu/\mu_p$ |
|---|---|---|---|---|---|---|---|
| $\alpha^{-1}$ | 20 | −31 | −41 | −1 | 1 | −29 | 33 |
| $e$ | *−0.226* | 921 | 1812 | 1750 | −1750 | −829 | −50 |
| $h$ | *−0.154* | *0.997* | 3582 | 3500 | −3500 | −1688 | −67 |
| $m_e$ | *−0.005* | *0.975* | *0.989* | 3497 | −3497 | −1747 | −2 |
| $N_A$ | *0.005* | *−0.975* | *−0.989* | *−1.000* | 3497 | 1747 | 2 |
| $F$ | *−0.217* | *−0.902* | *−0.931* | *−0.975* | *0.975* | 917 | −48 |
| $\mu_\mu/\mu_p$ | *0.498* | *−0.112* | *−0.077* | *−0.002* | *0.002* | *−0.108* | 215 |

## APPENDIX. NON-SI SYSTEMS OF QUANTITIES AND UNITS

Although the Système International is the recommended system for representing quantities and units, a great deal of the existing literature in physics has been expressed in terms of older systems. It is thus necessary to understand the relationship between SI and these systems if the older literature is to be fully utilized. The discussion here is not intended to be a complete review of these systems, nor to advance their use; its only purpose is to provide a basis for their translation into SI.

### A.1 Systems of equations with three base quantities

During the 19th century, when physics was dominated by Newtonian mechanics, electromagnetism was forced into an artificially restrictive three-dimensional framework. As a consequence, at least three different systems have been developed from the base quantities length, mass and time:

1a. The "electrostatic" system defines electric charge to be a derived quantity based on Coulomb's law for the force between two electric charges,

$$\boldsymbol{F} = k_{\mathrm{e}} \frac{q_1 q_2 \boldsymbol{r}}{\epsilon r^3}, \tag{1}$$

by choosing $k_{\mathrm{e}} = 1$ and defining the permittivity $\epsilon$ to be a dimensionless quantity, taking its value to be unity for a vacuum.

1b. The "electromagnetic" system defines electric current to be a derived quantity based on Ampère's law for the force between two electric current elements,

$$\mathrm{d}^2\boldsymbol{F} = k_{\mathrm{m}} \mu \frac{i_1 \mathrm{d}\boldsymbol{l}_1 \times (i_2 \mathrm{d}\boldsymbol{l}_2 \times \boldsymbol{r})}{r^3}, \tag{2}$$

by choosing $k_{\mathrm{m}} = 1$ and defining the permeability $\mu$ to be a dimensionless quantity, taking its value to be unity for a vacuum.

1c. The "symmetrical" Gaussian system uses electric quantities (including electric current) from system (1a) and magnetic quantities from system (1b).

In systems (1a) and (1b) a factor of the square of the speed of light in vacuum appears explicitly in some of the equations among quantities. In system (1c) the first power of the speed of light appears in many of the equations relating electric and magnetic quantities.

These systems are "non-rationalized" because the choices $k_{\mathrm{e}} = 1$ and $k_{\mathrm{m}} = 1$ in eqs. (1) and (2) leads to the appearance of factors of $2\pi$ and $4\pi$ in situations that involve plane geometry, and to their absence in situations that

Table 12. Non-rationalized and rationalized systems.

| Non-rationalized symmetrical (Gaussian) system with three base quantities (1.c) | Rationalized system with four base quantities |
|---|---|
| Equations | |
| $c\boldsymbol{\nabla}\times\boldsymbol{E}^* = -\partial\boldsymbol{B}^*/\partial t$ | $\boldsymbol{\nabla}\times\boldsymbol{E} = -\partial\boldsymbol{B}/\partial t$ |
| $c\boldsymbol{\nabla}\times\boldsymbol{H}^* = 4\pi\boldsymbol{j}^* + \partial\boldsymbol{D}^*/\partial t$ | $\boldsymbol{\nabla}\times\boldsymbol{H} = \boldsymbol{j} + \partial\boldsymbol{D}/\partial t$ |
| $\boldsymbol{\nabla}\cdot\boldsymbol{D}^* = 4\pi\rho^*$ | $\boldsymbol{\nabla}\cdot\boldsymbol{D} = \rho$ |
| $\boldsymbol{\nabla}\cdot\boldsymbol{B}^* = 0$ | $\boldsymbol{\nabla}\cdot\boldsymbol{B} = 0$ |
| $\boldsymbol{F} = q^*(\boldsymbol{E}^* + \boldsymbol{v}\times\boldsymbol{B}^*/c)$ | $\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B})$ |
| $w = (\boldsymbol{E}^*\cdot\boldsymbol{D}^* + \boldsymbol{B}^*\cdot\boldsymbol{E}^*)/8\pi$ | $w = \frac{1}{2}(\boldsymbol{E}\cdot\boldsymbol{D} + \boldsymbol{B}\cdot\boldsymbol{E})$ |
| $\boldsymbol{S} = c(\boldsymbol{E}^*\times\boldsymbol{H}^*)/4\pi$ | $\boldsymbol{S} = \boldsymbol{E}\times\boldsymbol{H}$ |
| $\boldsymbol{E}^* = -(\boldsymbol{\nabla} V^* + (1/c)\partial\boldsymbol{A}^*/\partial t)$ | $\boldsymbol{E} = -(\boldsymbol{\nabla} V + \partial\boldsymbol{A}/\partial t)$ |
| $\boldsymbol{B}^* = \boldsymbol{\nabla}\times\boldsymbol{A}^*$ | $\boldsymbol{B} = \boldsymbol{\nabla}\times\boldsymbol{A}$ |
| $\boldsymbol{D}^* = \epsilon_\mathrm{r}\boldsymbol{E}^*$ | $\boldsymbol{D} = \epsilon\boldsymbol{E} = \epsilon_\circ\epsilon_\mathrm{r}\boldsymbol{E}$ |
| $= \boldsymbol{E}^* + 4\pi\boldsymbol{P}^*$ | $= \epsilon_\circ\boldsymbol{E} + \boldsymbol{P}$ |
| $\boldsymbol{B}^* = \mu_\mathrm{r}\boldsymbol{H}^*$ | $\boldsymbol{B} = \mu\boldsymbol{H} = \mu_\circ\mu_\mathrm{r}\boldsymbol{H}$ |
| $= \boldsymbol{H}^* + 4\pi\boldsymbol{M}^*$ | $= \mu_\circ(\boldsymbol{H} + \boldsymbol{M})$ |
| $\epsilon_\mathrm{r} = 1 + 4\pi\chi_\mathrm{e}^*$ | $\epsilon_\mathrm{r} = 1 + \chi_\mathrm{e}$ |
| $\mu_\mathrm{r} = 1 + 4\pi\chi_\mathrm{m}^*$ | $\mu_\mathrm{r} = 1 + \chi_\mathrm{m}$ |
| Physical constants | |
| $\alpha = e^{*2}/\hbar c$ | $\alpha = e^2/4\pi\epsilon_\circ\hbar c = \mu_\circ ce^2/2h$ |
| $a_\circ = \hbar^2/m_\mathrm{e}e^{*2}$ | $a_\circ = 4\pi\epsilon_\circ\hbar^2/m_\mathrm{e}e^2$ |
| $hcR_\infty = e^{*2}/2a_\circ$ | $hcR_\infty = e^2/8\pi\epsilon_\circ a_\circ$ |
| $r_\mathrm{e} = e^{*2}/m_\mathrm{e}c^2$ | $r_\mathrm{e} = \mu_\circ e^2/m_\mathrm{e}$ |
| $\mu_\mathrm{B}^* = e^*\hbar/2m_\mathrm{e}c$ | $\mu_\mathrm{B} = e\hbar/2m_\mathrm{e}$ |
| $\omega_\mathrm{L} = (q^*/2mc)B^*$ | $\omega_\mathrm{L} = (q/2m)B$ |
| $\gamma^* = gI(e^*/mc)$ | $\gamma = gI(e/m)$ |

have cylindrical or spherical symmetry where these factors might normally be expected. On the other hand, if the factors $k_\mathrm{e}$ and $k_\mathrm{m}$ are set equal to $1/4\pi$ in eqs. (1) and (2), respectively (recognizing the spherical symmetry of these equations), then the factors of $2\pi$ and $4\pi$ appear explicitly only in those equations where they would be expected from the geometry of the system. In this form the equations are said to be “rationalized”.

### A.2 Systems of equations with four base quantities

The system of quantities is enlarged to four dimensions by including an electrical quantity as a fourth base quantity. In SI and in its older relative, the MKSA system, the fourth quantity is taken to be electric current, and in the Système International eqs. (1) and (2) are rationalized ($k_{\rm e} = k_{\rm m} = 1/4\pi$). As a result, permeability $\mu$ and permittivity $\epsilon$ are dimensional physical quantities. If electrostatics and electrodynamics are to be coherent, thus avoiding the explicit introduction of the factor $c$ asymmetrically into the expressions for electric and magnetic quantities, $\epsilon_\circ$ and $\mu_\circ$ must satisfy the condition

$$\epsilon_\circ \mu_\circ c^2 = 1.$$

In SI the permeability of vacuum $\mu_\circ$ is defined to have the value

$$\mu_\circ = 4\pi{\times}10^{-7}\,{\rm N/A^2} = 4\pi{\times}10^{-7}\,{\rm H/m}.$$

### A.3 Relations between quantities in different systems

The basic equations between quantities in the non-rationalized symmetrical (Gaussian) system (1c) and the corresponding equations in the rationalized four-dimensional system are given in table 12. In order to distinguish the physical quantities in the two systems, those in the three-dimensional system are indicated with an asterisk ($^*$) when they differ from their corresponding quantities of the rationalized four-dimensional system.[+] The relationships between the two sets of quantities are determined by setting $X^* = a_X X$ in the first column and comparing the resultant equations with the corresponding ones in the second column. These substitutions lead to:

$$\begin{aligned}
(4\pi\epsilon_\circ)^{\frac{1}{2}} &= \frac{E^*}{E} = \frac{V^*}{V} = \frac{Q}{Q^*} = \frac{\rho}{\rho^*} = \frac{j}{j^*} = \frac{I}{I^*} = \frac{P}{P^*},\\
(4\pi/\epsilon_\circ)^{\frac{1}{2}} &= \frac{D^*}{D},\\
(4\pi\mu_\circ)^{\frac{1}{2}} &= \frac{H^*}{H},\\
(4\pi/\mu_\circ)^{\frac{1}{2}} &= \frac{B^*}{B} = \frac{A^*}{A} = \frac{M}{M^*},\\
4\pi &= \frac{\chi_{\rm e}}{\chi_{\rm e}^*} = \frac{\chi_{\rm m}}{\chi_{\rm m}^*}.
\end{aligned}$$

### A.4 The CGS system of units

The centimetre-gram-second (CGS) system of units is a coherent system based on the three base units: centimeter, gram and second. These base units

[+] Symbols for Gaussian quantities may also be distinguished from those for the four-dimensional quantities by the superscript $^{\rm s}$ or subscript $_{\rm s}$ (for symmetric) instead of the asterisk.

Table 13. CGS base units and derived units with special names.

| Quantity<br>*Grandeur* | Unit; *Unité*<br>Name<br>*Nom* | <br>Symbol<br>*Symbole* | <br>Expression in terms of base units<br>*Expression en unités de base* |
|---|---|---|---|
| length<br>*longueur* | centimetre<br>*centimètre* | cm | |
| mass<br>*masse* | gram<br>*gramme* | g | |
| time<br>*temps* | second<br>*seconde* | s | |
| force;<br>*force* | dyne | dyn | cm g $s^{-2}$ |
| energy;<br>*énergie* | erg | erg | $cm^2$ g $s^{-2}$ |
| viscosity;<br>*viscosité* | poise | P | $cm^{-1}$ g $s^{-1}$ |
| kinematic viscosity;<br>*viscosité cinématique* | stokes | St | $cm^2$ $s^{-1}$ |
| acceleration of free fall;<br>*accélération de la pesanteur* [a] | gal | Gal | cm $s^{-2}$ |

[a] The gal is a unit used in geophysics to express the earth's gravitational field; it should not be used as a unit of acceleration other than in this specific sense.

and their symbols, as well as the names and symbols of derived units having special names in the CGS system are given in table 13.

The CGS "electrostatic" system of units (esu) forms a coherent system of units in combination with the three-dimensional "electrostatic" system of quantities of (1a). In its less common form as a four-dimensional system, the electrostatic unit of charge (sometimes called the franklin; symbol, Fr ) is introduced and the permittivity of vacuum is set equal to $\epsilon_\circ = 1\ \mathrm{Fr}^2\ \mathrm{dyn}^{-1}\ \mathrm{cm}^{-2}$. Other units may then be derived using the usual rules for constructing a coherent set of units from a set of base units.

The CGS "electromagnetic" system of units (emu) forms a coherent system of units in combination with the three-dimensional "electromagnetic" system of quantities of (1b). In its four-dimensional form, the fourth base unit is taken to be the current unit, abampere (symbol, abamp), by defining the permeability

Table 14. CGS magnetic units with special names.

| Quantity *Grandeur* | Unit; *Unité* Name *Nom* | Symbol *Symbole* | Dimension[a] | Equivalence between CGS units and corresponding 4-dimensional SI units |
|---|---|---|---|---|
| $H^*$ | oersted | Oe | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1}$ | $\frac{1}{4\pi}$ abamp/cm $= 10^{-4}$ T/$\mu_\circ$ |
| $B^*$ | gauss | G, (Gs) | $L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1}$ | $10^{-4}$ T |
| $\Phi^*$ | maxwell | Mx | $L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1}$ | $10^{-8}$ Wb |
| $F_\mathrm{m}^*$ | gilbert | Gi, (Gb) | $L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1}$ | $\frac{1}{4\pi}$ abamp $= 10^{-6}$ T m/$\mu_\circ$ |

[a] $L$ = length; $M$ = mass; $T$ = time.

of vacuum to be $\mu_\circ = 1$ g cm s$^{-2}$ abamp$^{-2}$. The force between two parallel infinitely long wires, 1 cm apart in vacuum, each carrying a current of 1 abamp, is 2 dyn per cm of length.

The “mixed”, “symmetrized”, or “Gaussian” CGS units, consisting of the set of electric units of the esu system and the magnetic units of the emu system, form a coherent system of units when used in combination with the three-dimensional “symmetrical system” or “Gaussian system” of equations (1c).

Special names and symbols have been given to four of the magnetic emu or Gaussian CGS units. These are given in table 14. In evaluating the relationship between a CGS non-rationalized unit and an SI rationalized unit one must include not only the transformation of the *quantities* given in the preceding section but also the transformation of the *units* from centimetre and gram to metre and kilogram. In addition, the relationship between a four-dimensional unit involving the ampere and its corresponding three-dimensional unit includes the quantity $\mu_\circ$, recognizing that its value is unity in the latter system.

The CGS system enlarged by the kelvin (K) as unit of thermodynamic temperature, and by the mole (mol) as unit of amount of substance or by the candela (cd) as unit of luminous intensity has been used in thermodynamics and photometry, respectively. The two units in the field of photometry derived from cm, g, s, cd and sr that have been given special names and symbols are listed in table 15.

## A.5 Atomic units

It is often appropriate in theoretical physics and in numerical computations to use a system of “dimensionless” quantities obtained by setting the numerical values of $\hbar$, $c$ and either $m_\mathrm{e}$ or $m_\mathrm{u}$ equal to unity. It is more correct, however, to maintain the description of Section **1** and to treat this as a unit system in which the units are fundamental physical quantities rather than arbitrary

Table 15.  CGS units in photometry with special names.

| Quantity *Grandeur* | Derived unit; *Unité derivée* Name *Nom* | Symbol *Symbole* | Expression *Expression* |
|---|---|---|---|
| luminance; *luminance* | stilb | sb | $\mathrm{cm}^{-2}$ cd |
| illuminance; *éclairement lumineux* | phot | ph | $\mathrm{cm}^{-2}$ cd sr |

artifacts such as the metre or the second. It is, in fact, strongly recommended that physical computations be carried out and reported in terms of such units in order that the results should be independent (to the greatest possible extent) of any uncertainties in the values of the physical constants.

The standard choice of units in quantum electrodynamics takes $\hbar$ and $c$ as the units of action and velocity respectively, so that the elementary charge is $(4\pi\epsilon_{\circ}\alpha)^{\frac{1}{2}}$ (charge units) where the fine-structure constant $\alpha$ is the natural measure of the electromagnetic interaction.

For computations in atomic and molecular physics a more appropriate choice (known as 'atomic units' or 'au') takes the electron mass $m_{\mathrm{e}}$ to be the unit of mass, the Bohr radius, $a_{\circ} = \hbar/(m_{\mathrm{e}}c\alpha)$ to be the unit of length and $\hbar/(m_{\mathrm{e}}c^2\alpha^2)$ to be the unit of time. As a result the unit of velocity is $\alpha c$ and the unit of energy is $E_{\mathrm{h}} = m_{\mathrm{e}}c^2\alpha^2 = 2R_{\infty}hc$, which has been given the name 'hartree'. The atomic units form an unrationalized, three-dimensional coherent system with $\epsilon_{\circ}$ set equal to unity and the elementary charge $e$ as the unit of charge.

Since atomic units are natural physical quantities rather than artificial constructs, it is appropriate to write them in italic (*sloping*) type rather than in the roman (upright) type normally used for units: the physical quantities are represented as multiples of physical constants.