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# FUNDAMENTAL QUANTITIES AND UNITS FOR IONIZING RADIATION (*Revised*)



THE INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS

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# Editor's Note

The original version of ICRU Report 85 published in the JICRU, Vol. 11, No. 1, 2011, had a number of unfortunate typographical errors. The ultimate responsibility for the failure to catch these errors on page proofs rests, of course, with the Editor. The basic nature of this Report and the errors in rather important summary tables of SI prefixes, quantities, and units, suggested strongly that a completely corrected Report be made available. Thus, this version (Report 85a) corrects those and other errors, and it is hoped that this corrected version is typographically error-free. If further errors are indeed detected, please contact the ICRU so that these can be corrected in a future update.

**Stephen M. Seltzer**
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# FUNDAMENTAL QUANTITIES AND UNITS FOR IONIZING RADIATION (*Revised*)

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The Commission wishes to express its appreciation to the individuals involved in the preparation of this Report for the time and efforts that they devoted to this task and to express its appreciation to the organizations with which they are affiliated.



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# The International Commission on Radiation Units and Measurements

## Introduction

The International Commission on Radiation Units and Measurements (ICRU), since its inception in 1925, has had as its principal objective the development of internationally acceptable recommendations regarding:

(1) quantities and units of radiation and radioactivity,
(2) procedures suitable for the measurement and application of these quantities in clinical radiology and radiobiology, and
(3) physical data needed in the application of these procedures, the use of which tends to assure uniformity in reporting.

The Commission also considers and makes similar types of recommendations for the radiation protection field. In this connection, its work is carried out in close cooperation with the International Commission on Radiological Protection (ICRP).

## Policy

The ICRU endeavors to collect and evaluate the latest data and information pertinent to the problems of radiation measurement and dosimetry and to recommend the most acceptable values and techniques for current use.

The Commission's recommendations are kept under continual review in order to keep abreast of the rapidly expanding uses of radiation.

The ICRU feels that it is the responsibility of national organizations to introduce their own detailed technical procedures for the development and maintenance of standards. However, it urges that all countries adhere as closely as possible to the internationally recommended basic concepts of radiation quantities and units.

The Commission feels that its responsibility lies in developing a system of quantities and units having the widest possible range of applicability. Situations can arise from time to time for which an expedient solution of a current problem might seem advisable. Generally speaking, however, the Commission feels that action based on expediency is inadvisable from a long-term viewpoint; it endeavors to base its decisions on the long-range advantages to be expected.

The ICRU invites and welcomes constructive comments and suggestions regarding its recommendations and reports. These may be transmitted to the Chairman.

## Current Program

The Commission recognizes its obligation to provide guidance and recommendations in the areas of radiation therapy, radiation protection, and the compilation of data important to these fields, and to scientific research and industrial applications of radiation. Increasingly, the Commission is focusing on the problems of protection of the patient and evaluation of image quality in diagnostic radiology. These activities do not diminish the ICRU's commitment to the provision of a rigorously defined set of quantities and units useful in a very broad range of scientific endeavors.

The Commission is currently engaged in the formulation of ICRU Reports treating the following subjects:

*Alternatives to Absorbed Dose for Quantification and Reporting of Low Doses and Other Heterogeneous Exposures*
*Bioeffect Modeling and Biologically Equivalent Dose Concepts in Radiation Therapy*
*Concepts and Terms for Recording and Reporting Gynecologic Brachytherapy*
*Harmonization of Prescribing, Recording, and Reporting Radiotherapy*
*Image Quality and Patient Dose in Computed Tomography*
*Key Data for Measurement Standards in the Dosimetry of Ionizing Radiation*
*Measurement and Reporting of Radon Exposure*
*Operational Radiation Protection Quantities for External Radiation*
*Prescribing, Recording, and Reporting Ion-Beam Therapy*

*Small-Field Photon Dosimetry and Applications in Radiotherapy*

The Commission continually reviews radiation science with the aim of identifying areas in which the development of guidance and recommendations can make an important contribution.

## The ICRU's Relationship with Other Organizations

In addition to its close relationship with the ICRP, the ICRU has developed relationships with national and international agencies and organizations. In these relationships, the ICRU is looked to for primary guidance in matters relating to quantities, units, and measurements for ionizing radiation, and their applications in the radiological sciences. In 1960, through a special liaison agreement, the ICRU entered into consultative status with the International Atomic Energy Agency (IAEA). The Commission has a formal relationship with the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), whereby ICRU observers are invited to attend annual UNSCEAR meetings. The Commission and the International Organization for Standardization (ISO) informally exchange notifications of meetings, and the ICRU is formally designated for liaison with two of the ISO technical committees. The ICRU also enjoys a strong relationship with its sister organization, the National Council on Radiation Protection and Measurements (NCRP). In essence, these organizations were founded concurrently by the same individuals. Presently, this long-standing relationship is formally acknowledged by a special liaison agreement. The ICRU also exchanges reports with the following organizations:

Bureau International de Métrologie Légale
Bureau International des Poids et Mesures
European Commission
Council for International Organizations of Medical Sciences
Food and Agriculture Organization of the United Nations
International Council for Science
International Electrotechnical Commission
International Labour Office
International Organization for Medical Physics
International Radiation Protection Association
International Union of Pure and Applied Physics
United Nations Educational, Scientific and Cultural Organization

The Commission has found its relationship with all of these organizations fruitful and of substantial benefit to the ICRU program.

## Operating Funds

In recent years, principal financial support has been provided by the European Commission, the National Cancer Institute of the US Department of Health and Human Services, and the International Atomic Energy Agency. In addition, during the last 10 years, financial support has been received from the following organizations:

American Association of Physicists in Medicine
Belgian Nuclear Research Centre
Canadian Nuclear Safety Commission
Electricité de France
Helmholtz Zentrum München
Hitachi, Ltd.
International Radiation Protection Association
International Society of Radiology
Ion Beam Applications, S.A.
Japanese Society of Radiological Technology
MDS Nordion
National Institute of Standards and Technology
Nederlandse Vereniging voor Radiologie
Philips Medical Systems, Incorporated
Radiological Society of North America
Siemens Medical Solutions
US Department of Energy
Varian Medical Systems

In addition to the direct monetary support provided by these organizations, many organizations provide indirect support for the Commission's program. This support is provided in many forms, including, among others, subsidies for (1) the time of individuals participating in ICRU activities, (2) travel costs involved in ICRU meetings, and (3) meeting facilities and services.

In recognition of the fact that its work is made possible by the generous support provided by all of the organizations supporting its program, the Commission expresses its deep appreciation.

**Hans-Georg Menzel**
**Chairman, ICRU**
**Geneva, Switzerland**

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# Fundamental Quantities and Units for Ionizing Radiation

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# Preface

The International Commission on Radiation Units and Measurements (ICRU) was originally conceived at the First International Congress of Radiology in 1925 as the International X-Ray Unit Committee, later to become the International Commission on Radiological Units before adopting its current name. Its primary objective was to provide an internationally agreed upon unit for measurement of radiation as applied in medicine. The ICRU established the first internationally acceptable unit for exposure, the röntgen, in 1928. In 1950, the ICRU expanded its role to consider all concepts, quantities, and units for ionizing radiation, encompassing not only medical applications but also those in industry, radiation protection, and nuclear energy. The ICRU has continued to recommend new quantities and units as the need arose, for example, absorbed dose (1950), the rad (1953), fluence (1962), kerma (1968), and cema (1998).

Thus, quantities and units for ionizing radiation represent the most basic element of the core mission of the ICRU. This is evidenced by the series of Reports on fundamental quantities and units: Report 10a, *Radiation Quantities and Units* (1962); Report 11, *Radiation Quantities and Units* (1968); Report 19, *Radiation Quantities and Units* (1971); Report 33, *Radiation Quantities and Units* (1980); and Report 60, *Fundamental Quantities and Units for Ionizing Radiation* (1998). This list excludes those Reports that primarily include recommendations for quantities and units specifically intended for radiation protection, which are developed in liaison and collaboration with the International Commission on Radiation Protection (ICRP).

The development of the present Report was prompted by a few criticisms of Report 60, and while basically introducing no new quantities it does strive for more-precisely worded definitions and clarity.

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# Abstract

Definitions of fundamental quantities, and their units, for ionizing radiation are given, which represent the recommendation of the International Commission on Radiation Units and Measurements (ICRU).

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# 1. Introduction

There has been a gradual evolution in the establishment and definitions of fundamental quantities for ionizing radiation since the formation of the ICRU (see, *e.g.*, the series of separate Reports on quantities and units: ICRU, 1962; 1968; 1971; 1980; 1998). The goal is a set of quantities (and their units) of use in the measurement of and in transport calculations for ionizing radiation in practical applications. The definitions of these quantities should be precise and logically consistent, and possess the utmost scientific validity and mathematical rigor. Although much progress has been made toward this goal, the effort has no doubt fallen short of perfection due to compromises among the unavoidable ambiguities inherent in the real natural world and the need nonetheless for a basic set of useful quantities.

This Report supersedes ICRU Report 60, *Fundamental Quantities and Units for Ionizing Radiation* (1998). Definitions are not radically changed: rather, the refinements presented in this Report mainly correct oversights in the previous Report and in some cases provide additional clarification. It was felt, however, that a new Report would establish a complete current reference for fundamental quantities and units for ionizing radiation. This Report does not deal with quantities and units specifically intended for use in radiation protection, which were covered in ICRU Report 51 (1993a) and which are currently under review by the ICRU.

The quantities and units for ionizing radiation dealt with in this Report include those for radiometry, interaction coefficients, dosimetry, and radioactivity. The ICRU appreciates the assistance rendered by scientific bodies and individuals who commented on aspects of ICRU Report 60, and a number of these comments have informed the refinements included in the present Report. The remainder of this Report is structured in five subsequent major Sections, each of the last four of which is followed by tables summarizing for each quantity its symbol, unit, and the relationship used in its definition.

Section 2 deals with terms and mathematical conventions used throughout the Report.

Section 3, entitled Radiometry, presents quantities required for the specification of radiation fields. Two classes of quantities are used, referring either to the number of particles or to the energy transported by them. Accordingly, the definitions of radiometric quantities are grouped into pairs. Both scalar and vector quantities are defined.

Interaction coefficients and related quantities are covered in Section 4. The fundamental interaction coefficient is the cross section. All other coefficients defined in this Section can be expressed in terms of cross section or differential cross section. The current Report adds the definition of the ionization yield, $Y$, to provide a logical connection between the radiation chemical yield and the mean energy expended in a gas per ion pair formed. Explicit language is now included in the definition of $W$, the mean energy expended in a gas per ion pair formed, to clarify what is meant by "ion pair" (ICRU, 1979) in order to avoid possible confusion.

Section 5 deals with dosimetric quantities that describe the results of processes by which particle energy is converted and finally deposited in matter. Accordingly, the definitions of dosimetric quantities are presented in two parts entitled Conversion of Energy and Deposition of Energy, respectively. The first part includes refinement of the definition of $g$ as the fraction of the *kinetic* energy of liberated charged particles that is lost in radiative processes in the material, and explicit specification of *dry* air in the definition of exposure. In the second part on deposition of energy, the definitions of kerma and of exposure are refined to explicitly include the kinetic energy of all charged particles emitted in the decay of excited atoms/molecules or nuclei, and consideration of elapsed time is acknowledged in the specifications of energy imparted, particularly in cases involving the production of radionuclides by the incident particle(s). Energy deposit, *i.e.*, the energy deposited in a single interaction, is the basis in terms of which all other quantities presented in the Section can be defined. These are the traditional stochastic quantities (which are now so labeled as they are defined): energy imparted, lineal energy, and specific energy, the latter leading to the non-stochastic quantity absorbed dose.

Quantities related to radioactivity are defined in Section 6.

The current document strives for an incremental improvement in scientific rigor and yet to remain as consistent as possible with earlier ICRU Reports in this series and in similar publications used in other fields of physics. It is hoped that this Report represents a modest step toward a universal scientific language.

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# 2. General Considerations

This Section deals with terms and mathematical conventions used throughout the Report.

## 2.1 Quantities and Units

*Quantities*, when used for the quantitative description of physical phenomena or objects, are generally called physical quantities. A *unit* is a selected reference sample of a quantity with which other quantities of the same kind are compared. Every quantity is expressed as the product of a *numerical value* and a unit. As a quantity remains unchanged when the unit in which it is expressed changes, its numerical value is modified accordingly.

Quantities can be multiplied or divided by one another resulting in other quantities. Thus, all quantities can be derived from a set of *base quantities*. The resulting quantities are called *derived quantities*.

A *system of units* is obtained in the same way by first defining units for the base quantities, the *base units*, and then forming *derived units*. A system is said to be *coherent* if no numerical factors other than the number 1 occur in the expressions of derived units.

The ICRU recommends the use of the *International System of Units* (SI) (BIPM, 2006). In this system, the base units are meter, kilogram, second, ampere, kelvin, mole, and candela, for the base quantities length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity, respectively.

Some derived SI units are given special names, such as coulomb for ampere second. Other derived units are given special names only when they are used with certain derived quantities. Special names pertaining to ionizing radiation currently in use in this restricted category are becquerel (equal to reciprocal second for activity of a radionuclide), gray (equal to joule per kilogram for absorbed dose, kerma, cema, and specific energy), and sievert (equal to joule per kilogram for dose equivalent, ambient dose equivalent, directional dose equivalent, and personal dose equivalent). Some examples of SI units are given in Table 2.1.

There are also a few units outside of the international system that may be used with SI. For some of these, their values in terms of SI units are obtained experimentally. Two of these are used in current ICRU documents: electron volt (symbol eV) and (unified) atomic mass unit (symbol u). Others, such as day, hour, and minute, are not coherent with the system but, because of long usage, are permitted to be used with SI (see Table 2.2).

Decimal multiples and submultiples of SI units can be formed using the SI prefixes (see Table 2.3).

## 2.2 Ionizing Radiation

*Ionization* produced by particles is the process by which one or more electrons are liberated in collisions of the particles with atoms or molecules. This can be distinguished from *excitation*, which is a transfer of electrons to higher energy levels in atoms or molecules and generally requires less energy.

When charged particles have slowed down sufficiently, ionization becomes less likely or impossible, and the particles increasingly dissipate their remaining energy in other processes such as excitation or elastic scattering. Thus, near the end of their range, charged particles that were ionizing can be considered to be non-ionizing.

The term *ionizing radiation* refers to charged particles (*e.g.*, electrons or protons) and uncharged particles (*e.g.*, photons or neutrons) that can produce ionizations in a medium or can initiate nuclear or elementary-particle transformations that then result in ionization or the production of ionizing radiation. In the condensed phase, the difference between ionization and excitation can become blurred. A pragmatic approach for dealing with this ambiguity is to adopt a threshold for the energy that can be transferred to the medium. This implies cutoff energies below which charged particles may be assumed not to be ionizing (unless they can initiate nuclear or elementary-particle transformations). Below such energies, their ranges are minute. Hence, the choice of the cutoff energies does not materially affect the spatial

Table 2.1. SI units used in this Report

| Category of units | Quantity | Name | Symbol |
|---|---|---|---|
| SI base units | length | meter | m |
| | mass | kilogram | kg |
| | time | second | s |
| | amount of substance | mole | mol |
| SI derived units with special names (general use) | electric charge | coulomb | C |
| | energy | joule | J |
| | solid angle | steradian | sr |
| | power | watt | W |
| SI derived units with special names (restricted use) | activity | becquerel | Bq |
| | absorbed dose, kerma, cema, specific energy | gray | Gy |

Table 2.2. Some units used with the SI

| Category of units | Quantity | Name | Symbol |
|---|---|---|---|
| Units widely used | time | minute | min |
| | | hour | h |
| | | day | d |
| Units whose values in SI are obtained experimentally | energy | electron volt[a] | eV |
| | mass | (unified) atomic mass unit[a] | u |

[a]1 eV = 1.602176487(40) $\times$ $10^{-19}$ J, and 1 u = 1.660538782(83) $\times$ $10^{-27}$ kg. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value (Mohr *et al.,* 2008).

Table 2.3. SI prefixes[a]

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

[a]The prefix symbol attached to the unit symbol constitutes a new symbol, *e.g.*, 1 $fm^2 = (10^{-15}\ m)^2 = 10^{-30}\ m^2$.

distribution of energy deposition except at the smallest distances that can be of concern in microdosimetry. The choice of the threshold value depends on the application; for example, a value of 10 eV might be appropriate for radiobiology.

## 2.3 Stochastic and Non-Stochastic Quantities

Differences between results from repeated observations are common in physics. These can arise from imperfect measurement systems, or from the fact that many physical phenomena are subject to inherent fluctuations. Quantum-mechanical issues aside, one often needs to distinguish between a *non-stochastic* quantity with its unique value and a *stochastic* quantity, the values of which follow a probability distribution. In many instances, this distinction is not significant because the probability distribution is very narrow. For example, the measurement of an electric current commonly involves so many electrons that fluctuations contribute negligibly to inaccuracy in the measurement. However, as the limit of zero electric current is approached, fluctuations can become manifest. This case of course requires a more careful measurement procedure, but perhaps more importantly illustrates that the significance of stochastic variations of a quantity can depend on the magnitude of the quantity. Similar considerations apply to ionizing radiation; fluctuations can play a significant role, and in some cases need to be considered explicitly. On a practical level, this Report adopts the convention that a quantity whose underlying distribution at microscopic levels is normally of little interest and that is customarily expressed in terms of a mean value will not be defined explicitly as stochastic.

Certain stochastic processes follow a Poisson distribution, a distribution uniquely determined by its mean value. A typical example of such a process is radioactive decay.[1] However, more complex distributions are involved in energy deposition. In this Report, because of their relevance, four stochastic quantities are defined explicitly, namely *energy deposit*, $\varepsilon_i$ (see Section 5.2.1), *energy imparted*, $\varepsilon$ (see Section 5.2.2), *lineal energy*, $y$ (see Section 5.2.3), and *specific energy*, $z$ (see Section 5.2.4). For example, the specific energy, $z$, is defined as the quotient of the energy imparted, $\varepsilon$, and the mass, $m$. Repeated measurements would provide an estimate of the probability distribution of $z$ and of its first moment or mean, $\bar{z}$, the latter approaching the *absorbed dose*, $D$ (see Section 5.2.5), as the mass becomes small. Knowledge of the distribution of $z$ is not required for the determination of the absorbed dose, $D$. However, knowledge of the distribution of $z$ corresponding to a known $D$ can be important because in the irradiated mass element, $m$, the effects of radiation can be more closely related to $z$ than to $D$, and the values of $z$ can differ greatly from $D$ for small values of $m$ (*e.g.*, biological cells).

## 2.4 Mathematical Conventions

To permit characterization of a radiation field and its interactions with matter, many of the quantities defined in this Report are considered as functions of other quantities. For simplicity in presentation, the arguments on which a quantity depends often will not be stated explicitly. In some instances, the *distribution* of a quantity with respect to another quantity can be defined. The distribution function of a discrete quantity, such as the particle number $N$ (see Section 3.1.1), will be treated as if it were continuous, as $N$ is usually a very large number. Distributions with respect to energy are frequently required, as are other differential forms of defined quantities. This Report follows the previous practice of often introducing integral forms of quantities prior to their representation in differential forms. For example, *fluence* is defined at the start of Section 3.1.3, followed by that of the distribution of fluence with respect to particle energy, given by (see Eq. 3.1.8a)

$$\Phi_E = \mathrm{d}\Phi/\mathrm{d}E, \tag{2.4.1}$$

where $\mathrm{d}\Phi$ is the fluence of particles of energy between $E$ and $E + \mathrm{d}E$. Such distributions with respect to energy are denoted in this Report by adding the subscript $E$ to the symbol of the distributed quantity. This results in a change of physical dimensions; thus, the unit of $\Phi$ is $\mathrm{m}^{-2}$, whereas the unit of $\Phi_E$ is $\mathrm{m}^{-2}\ \mathrm{J}^{-1}$ (see Tables 3.1 and 3.2).

Quantities related to interactions, such as the mass attenuation coefficient, $\mu/\rho$, (see Section 4.2) or the mass stopping power, $S/\rho$ (see Section 4.4), are functions of the particle type and energy, and one might, if necessary, use a more explicit notation such as $\mu(E)/\rho$ or $S(E)/\rho$. For a radiation field with an energy distribution, mean values such as $\bar{\mu}/\rho$ and $\bar{S}/\rho$, weighted according to the distribution of the relevant quantity, are often useful. For example,

$$\begin{aligned}\frac{\bar{\mu}}{\rho} &= \frac{\int [\mu(E)/\rho]\,\Phi_E\,\mathrm{d}E}{\int \Phi_E\,\mathrm{d}E} \\ &= \frac{1}{\Phi}\left\{\int [\mu(E)/\rho]\,\Phi_E\,\mathrm{d}E\right\}\end{aligned} \tag{2.4.2}$$

is the fluence-weighted mean value of $\mu/\rho$.

Stochastic quantities are associated with *probability distributions*. Two types of such distributions are considered in this Report, namely the *distribution function* (symbol $F$) and the *probability density* (symbol $f$). For example, $F(y)$ is the probability that the lineal energy is equal to or less than $y$. The probability density $f(y)$ is the derivative of $F(y)$, with $f(y)$ being the probability that the lineal energy is between $y$ and $y + \mathrm{d}y$.

[1]Radioactive decay is inherently governed by the binomial distribution. However, for sufficiently large values of the number of radioactive atoms that one usually deals with, the Poisson distribution is an excellent approximation of the binomial distribution.

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# 3. Radiometry

Radiation measurements and investigations of radiation effects require various degrees of specification of the radiation field at the point of interest. Radiation fields consisting of various types of particles, such as photons, electrons, neutrons, or protons, are characterized by radiometric quantities that apply in free space and in matter.

Two classes of quantities are used in the characterization of a radiation field, referring either to the number of particles or to the energy transported by them. Accordingly, most of the definitions of radiometric quantities given in this Report can be grouped into pairs.

Both scalar and vector quantities are used in radiometry, and here they are treated separately. Formal definitions of quantities deemed to be of particular relevance are presented in boxes. Equivalent definitions that are used in particular applications are given in the text. Distributions of some radiometric quantities with respect to energy are given when they will be required later in the Report. This extended set of quantities relevant to radiometry is summarized in Tables 3. 1 and 3. 2.

## 3.1 Scalar Radiometric Quantities

Consideration of radiometric quantities begins with the definition of the most general quantities associated with the radiation field, namely the particle number, $N$, and the radiant energy, $R$ (see Section 3.1.1). The full description of the radiation field, however, requires information on the type and the energy of the particles as well as on their distributions in space, direction, and time. This most differential form is the basic field quantity from a radiation-transport perspective, and definitions of quantities in terms of integrals of such a quantity might seem to better represent mathematical rigor. However, the physical processes relevant here do not preclude differentiation. Thus, in the present Report, the specification of the radiation field is achieved with increasing detail by defining scalar radiometric quantities through successive differentiations of $N$ and $R$ with respect to time, area, volume, direction, or energy.[2] Thus, these quantities relate to a particular value of each variable of differentiation. This procedure provides the simplest definitions of quantities such as fluence and energy fluence (see Section 3.1.3), often used in the common situation in which radiation interactions are independent of the direction and time distribution of the incoming particles.

The scalar radiometric quantities defined in this Report are used also for fields of optical and ultraviolet radiations, sometimes under different names. In this Report, the equivalence between the various terminologies is often noted in connection with the relevant definitions.

### 3.1.1 Particle Number, Radiant Energy

The *particle number*, $N$, is the number of particles that are emitted, transferred, or received.

Unit: 1

The *radiant energy*, $R$, is the energy (excluding rest energy) of the particles that are emitted, transferred or received.

Unit: J

For particles of energy $E$ (excluding rest energy), the radiant energy, $R$, is equal to the product $NE$.

The distributions, $N_E$ and $R_E$, of the particle number and the radiant energy with respect to energy are given by

$$N_E = \mathrm{d}N/\mathrm{d}E, \qquad (3.1.1a)$$

and

$$R_E = \mathrm{d}R/\mathrm{d}E, \qquad (3.1.1b)$$

where $\mathrm{d}N$ is the number of particles with energy between $E$ and $E + \mathrm{d}E$, and $\mathrm{d}R$ is their radiant energy. The two distributions are related by

$$R_E = EN_E. \qquad (3.1.2)$$

[2]Mathematically, the differentials are understood to be of expected or mean values of the quantities.

The *particle number density*[3], $n$, is given by

$$n = \mathrm{d}N/\mathrm{d}V, \quad (3.1.3a)$$

where d$N$ is the number of particles in the volume d$V$. Similarly, the *radiant energy density*, $u$, is given by

$$u = \mathrm{d}R/\mathrm{d}V. \quad (3.1.3b)$$

The distributions, $n_E$ and $u_E$, of the particle number density and the radiant energy density with respect to energy are given by

$$n_E = \mathrm{d}n/\mathrm{d}E, \quad (3.1.4a)$$

and

$$u_E = \mathrm{d}u/\mathrm{d}E. \quad (3.1.4b)$$

The two distributions are related by

$$u_E = E n_E. \quad (3.1.5)$$

### 3.1.2 Flux, Energy Flux

The *flux*, $\dot{N}$, is the quotient of d$N$ by d$t$, where d$N$ is the increment of the particle number in the time interval d$t$, thus

$$\dot{N} = \frac{\mathrm{d}N}{\mathrm{d}t}.$$

Unit: $\mathrm{s}^{-1}$

The *energy flux*, $\dot{R}$, is the quotient of d$R$ by d$t$, where d$R$ is the increment of radiant energy in the time interval d$t$, thus

$$\dot{R} = \frac{\mathrm{d}R}{\mathrm{d}t}.$$

Unit: W

These quantities frequently refer to a limited spatial region, *e.g.*, the flux of particles emerging from a collimator. For source emission, the flux of particles emitted in all directions is generally considered.

For visible light and related electromagnetic radiations, the energy flux is defined as power emitted, transmitted, or received in the form of radiation and termed radiant flux or radiant power (CIE, 1987).

The term flux has been employed in other texts for the quantity termed fluence rate in the present Report (see Section 3.1.4). This usage is discouraged because of the possible confusion with the above definition of flux.

### 3.1.3 Fluence, Energy Fluence

The *fluence*, $\Phi$, is the quotient of d$N$ by d$a$, where d$N$ is the number of particles incident on a sphere of cross-sectional area d$a$, thus

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a}.$$

Unit: $\mathrm{m}^{-2}$

The *energy fluence*, $\Psi$, the quotient of d$R$ by d$a$, where d$R$ is the radiant energy incident on a sphere of cross-sectional area d$a$, thus

$$\Psi = \frac{\mathrm{d}R}{\mathrm{d}a}.$$

Unit: J $\mathrm{m}^{-2}$

The use of a sphere of cross-sectional area d$a$ expresses in the simplest manner the fact that one considers an area d$a$ perpendicular to the direction of each particle. The quantities fluence and energy fluence are applicable in the common situation in which radiation interactions are independent of the direction of the incoming particles. In certain situations, quantities (defined below) involving the differential solid angle, d$\Omega$, in a specified direction are required.

In dosimetric calculations, fluence is frequently expressed in terms of the lengths of the particle trajectories. It can be shown (Papiez and Battista, 1994; and references therein) that the fluence, $\Phi$, is given by

$$\Phi = \frac{\mathrm{d}l}{\mathrm{d}V}, \quad (3.1.6)$$

where d$l$ is the sum of the lengths of particle trajectories in the volume d$V$.

For a radiation field that does not vary over the time interval, $t$, and is composed of particles with velocity $v$, the fluence, $\Phi$, is given by

$$\Phi = nvt, \quad (3.1.7)$$

where $n$ is the particle number density.

[3]This quantity was previously termed *volumic particle number* (ICRU, 1998). Recognizing that the terms *volumic* and *massic* are not commonly used in English, this Report reverts to the convention (IUPAC, 1997) that *density* indicates *per volume* and *specific* indicates *per mass* (additionally, *surface … density* indicates *per area*, *linear … density* indicates *per length*, and *rate* indicates *per time*). However, the adjectives *massic* = *per mass*, *volumic* = *per volume*, *areic* = *per area*, and *lineic* = *per length* (ISO, 1993) are acceptable and recognized for their convenience.

The distributions, $\Phi_E$ and $\Psi_E$, of the fluence and energy fluence with respect to energy are given by

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E}, \qquad (3.1.8a)$$

and

$$\Psi_E = \frac{\mathrm{d}\Psi}{\mathrm{d}E}, \qquad (3.1.8b)$$

where $\mathrm{d}\Phi$ is the fluence of particles of energy between $E$ and $E + \mathrm{d}E$, and $\mathrm{d}\Psi$ is their energy fluence. The relationship between the two distributions is given by

$$\Psi_E = E\Phi_E. \qquad (3.1.9)$$

The energy fluence is related to the quantity radiant exposure defined, for fields of visible light, as the quotient of the radiant energy incident on a surface element by the area of that element (CIE, 1987). When a parallel beam is incident at an angle $\theta$ with the normal direction to a given surface element, the radiant exposure is equal to $\Psi \cos\theta$.

### 3.1.4 Fluence Rate, Energy-Fluence Rate

The *fluence rate*, $\dot{\Phi}$, is the quotient of $\mathrm{d}\Phi$ by $\mathrm{d}t$, where $\mathrm{d}\Phi$ is the increment of the fluence in the time interval $\mathrm{d}t$, thus

$$\dot{\Phi} = \frac{\mathrm{d}\Phi}{\mathrm{d}t}.$$

Unit: $\mathrm{m^{-2}\ s^{-1}}$

The *energy-fluence rate*, $\dot{\Psi}$, is the quotient of $\mathrm{d}\Psi$ by $\mathrm{d}t$, where $\mathrm{d}\Psi$ is the increment of the energy fluence in the time interval $\mathrm{d}t$, thus

$$\dot{\Psi} = \frac{\mathrm{d}\Psi}{\mathrm{d}t}.$$

Unit: $\mathrm{W\ m^{-2}}$

In radiation-transport literature, these quantities have also been termed particle flux density and energy flux density, respectively. Because the word density has several connotations, the term fluence rate is preferred.

For a radiation field composed of particles of velocity $v$, the fluence rate, $\dot{\Phi}$, is given by

$$\dot{\Phi} = nv, \qquad (3.1.10)$$

where $n$ is the particle number density.

### 3.1.5 Particle Radiance, Energy Radiance

The *particle radiance*, $\dot{\Phi}_\Omega$, is the quotient of $\mathrm{d}\dot{\Phi}$ by $\mathrm{d}\Omega$, where $\mathrm{d}\dot{\Phi}$ is the fluence rate of particles propagating within a solid angle $\mathrm{d}\Omega$ around a specified direction, thus

$$\dot{\Phi}_\Omega = \frac{\mathrm{d}\dot{\Phi}}{\mathrm{d}\Omega}.$$

Unit: $\mathrm{m^{-2}\ s^{-1}\ sr^{-1}}$

The *energy radiance*, $\dot{\Psi}_\Omega$, is the quotient of $\mathrm{d}\dot{\Psi}$ by $\mathrm{d}\Omega$, where $\mathrm{d}\dot{\Psi}$ is the energy fluence rate of particles propagating within a solid angle $\mathrm{d}\Omega$ around a specified direction, thus

$$\dot{\Psi}_\Omega = \frac{\mathrm{d}\dot{\Psi}}{\mathrm{d}\Omega}.$$

Unit: $\mathrm{W\ m^{-2}\ sr^{-1}}$

The specification of a direction requires two variables. In a spherical coordinate system with polar angle $\theta$ and azimuthal angle $\varphi$, $\mathrm{d}\Omega$ is equal to $\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi$.

For visible light and related electromagnetic radiations, the particle radiance and energy radiance are termed photon radiance and radiance, respectively (CIE, 1987).

The distributions of particle radiance and energy radiance with respect to energy are given by

$$\dot{\Phi}_{\Omega,E} = \frac{\mathrm{d}\dot{\Phi}_\Omega}{\mathrm{d}E}, \qquad (3.1.11a)$$

and

$$\dot{\Psi}_{\Omega,E} = \frac{\mathrm{d}\dot{\Psi}_\Omega}{\mathrm{d}E}, \qquad (3.1.11b)$$

where $\mathrm{d}\dot{\Phi}_\Omega$ is the particle radiance for particles of energy between $E$ and $E + \mathrm{d}E$, and $\mathrm{d}\dot{\Psi}_\Omega$ is their energy radiance. The two distributions are related by

$$\dot{\Psi}_{\Omega,E} = E\dot{\Phi}_{\Omega,E}. \qquad (3.1.12)$$

The quantity $\dot{\Phi}_{\Omega E}$ is sometimes termed angular flux or phase flux in radiation-transport theory.

Apart from aspects that are of minor importance in the present context (*e.g.*, polarization), the field of any radiation of a given particle type is completely specified by the distribution, $\dot{\Phi}_{\Omega,E}$, of the particle radiance with respect to particle energy, as this defines number, energy, local density, and arrival rate of particles propagating in a given direction. This quantity, as well as the distribution of the energy radiance with respect to energy, can be considered as basic in radiometry.

### 3.2 Vector Radiometric Quantities

As radiometric quantities are primarily concerned with the flow of radiation, it is appropriate to consider some of them as vector quantities. Vector quantities are not needed in those cases for which the corresponding scalar quantities are appropriate, *e.g.*, in deriving dosimetric quantities that are independent of the particle direction. In other instances, vector quantities are useful, and they are important in theoretical considerations related to radiation fields and dosimetric quantities. There is, in general, no simple relationship between the magnitudes of a scalar quantity and the corresponding vector quantity. However, in the case of a unidirectional field, they are of equal magnitude. The use of boldface symbols distinguishes the vector quantities introduced in this Section from the corresponding scalar quantities.

The vector quantities, defined in this Section, are obtained by successive integrations of the quantities vector particle radiance and vector energy radiance (see Section 3.2.1). Vector quantities are used extensively in radiation-transport theory, but often with a different terminology. The equivalences are indicated for the convenience of the reader.

#### 3.2.1 Vector Particle Radiance, Vector Energy Radiance

The *vector particle radiance*, $\dot{\boldsymbol{\Phi}}_\Omega$, is the product of $\boldsymbol{\Omega}$ by $\dot{\Phi}_\Omega$, where $\boldsymbol{\Omega}$ is the unit vector in the direction specified for the particle radiance $\dot{\boldsymbol{\Phi}}_\Omega$, thus

$$\dot{\boldsymbol{\Phi}}_\Omega = \boldsymbol{\Omega}\dot{\Phi}_\Omega.$$

Unit: $\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$

The *vector energy radiance*, $\dot{\boldsymbol{\Psi}}_\Omega$, is the product of $\boldsymbol{\Omega}$ by $\dot{\Psi}_\Omega$, where $\boldsymbol{\Omega}$ is the unit vector in the direction specified for the energy radiance $\dot{\boldsymbol{\Psi}}_\Omega$, thus

$$\dot{\boldsymbol{\Psi}}_\Omega = \boldsymbol{\Omega}\dot{\Psi}_\Omega.$$

Unit: $\mathrm{W\,m^{-2}\,sr^{-1}}$

The magnitudes $|\dot{\boldsymbol{\Phi}}_\Omega|$ and $|\dot{\boldsymbol{\Psi}}_\Omega|$ are equal to $\dot{\Phi}_\Omega$ and $\dot{\Psi}_\Omega$, respectively.

The distributions $\dot{\boldsymbol{\Phi}}_{\Omega,E}$ and $\dot{\boldsymbol{\Psi}}_{\Omega,E}$ of the vector particle radiance and the vector energy radiance, with respect to energy, are given by

$$\dot{\boldsymbol{\Phi}}_{\Omega,E} = \boldsymbol{\Omega}\dot{\Phi}_{\Omega,E}, \quad (3.2.1a)$$

and

$$\dot{\boldsymbol{\Psi}}_{\Omega,E} = \boldsymbol{\Omega}\dot{\Psi}_{\Omega,E}, \quad (3.2.1b)$$

where $\dot{\Phi}_{\Omega,E}$ and $\dot{\Psi}_{\Omega,E}$ are the distributions of the particle radiance and the energy radiance, respectively, with respect to energy.

In radiation-transport theory, $\dot{\boldsymbol{\Phi}}_{\Omega,E}$ is sometimes called angular current density, phase-space current density, or directional flux.

#### 3.2.2 Vector Fluence Rate, Vector Energy-Fluence Rate

The *vector fluence rate*, $\dot{\boldsymbol{\Phi}}$, is the integral of $\dot{\boldsymbol{\Phi}}_\Omega$ with respect to solid angle, where $\dot{\boldsymbol{\Phi}}_\Omega$ is the vector particle radiance in the direction specified by the unit vector $\boldsymbol{\Omega}$, thus

$$\dot{\boldsymbol{\Phi}} = \int \dot{\boldsymbol{\Phi}}_\Omega \,\mathrm{d}\Omega.$$

Unit: $\mathrm{m^{-2}\,s^{-1}}$

The *vector energy-fluence rate*, $\dot{\boldsymbol{\Psi}}$, is the integral of $\dot{\boldsymbol{\Psi}}_\Omega$ with respect to solid angle, where $\dot{\boldsymbol{\Psi}}_\Omega$ is the vector energy radiance in the direction specified by the unit vector $\boldsymbol{\Omega}$, thus

$$\dot{\boldsymbol{\Psi}} = \int \dot{\boldsymbol{\Psi}}_\Omega \,\mathrm{d}\Omega.$$

Unit: $\mathrm{W\,m^{-2}}$

The vectorial integration determines both direction and magnitude of the vector fluence rate and of the vector energy-fluence rate. The scalar quantities fluence rate and energy-fluence rate can be obtained in a similar way according to

$$\dot{\Phi} = \int \dot{\Phi}_\Omega \,\mathrm{d}\Omega, \quad (3.2.2a)$$

and

$$\dot{\Psi} = \int \dot{\Psi}_\Omega \,\mathrm{d}\Omega. \quad (3.2.2b)$$

It is important that these quantities not be confused with the vector counterparts. In particular, it needs to be recognized that the magnitude of vector fluence rate and of vector energy-fluence rate change from zero in an isotropic field to $\dot{\Phi}$ and $\dot{\Psi}$ in a unidirectional field.

The vector fluence rate is sometimes referred to as current density in radiation-transport theory.

### 3.2.3 Vector Fluence, Vector Energy Fluence

The *vector fluence*, $\boldsymbol{\Phi}$, is the integral of $\dot{\boldsymbol{\Phi}}$ with respect to time, $t$, where $\dot{\boldsymbol{\Phi}}$ is the vector fluence rate, thus

$$\boldsymbol{\Phi} = \int \dot{\boldsymbol{\Phi}} \mathrm{d}t.$$

Unit: $\mathrm{m}^{-2}$

The *vector energy fluence*, $\boldsymbol{\Psi}$, is the integral of $\dot{\boldsymbol{\Psi}}$ with respect to time, $t$, where $\dot{\boldsymbol{\Psi}}$ is the vector energy-fluence rate, thus

$$\boldsymbol{\Psi} = \int \dot{\boldsymbol{\Psi}} \mathrm{d}t.$$

Unit: $\mathrm{J\ m}^{-2}$

The distributions $\boldsymbol{\Phi}_E$ and $\boldsymbol{\Psi}_E$ of the vector fluence and vector energy fluence, with respect to energy are given by

$$\boldsymbol{\Phi}_E = \frac{\mathrm{d}\boldsymbol{\Phi}}{\mathrm{d}E} = \int \dot{\boldsymbol{\Phi}}_E \mathrm{d}t, \qquad (3.2.3a)$$

and

$$\boldsymbol{\Psi}_E = \frac{\mathrm{d}\boldsymbol{\Psi}}{\mathrm{d}E} = \int \dot{\boldsymbol{\Psi}}_E \mathrm{d}t, \qquad (3.2.3b)$$

where $\mathrm{d}\boldsymbol{\Phi}$ is the vector fluence of particles of energy between $E$ and $E + \mathrm{d}E$, and $\mathrm{d}\boldsymbol{\Psi}$ is their vector energy fluence.

The vector energy fluence, $\boldsymbol{\Psi}$, can be obtained from the distribution $\dot{\Phi}_{\Omega,E}$ according to

$$\boldsymbol{\Psi} = \iiint \boldsymbol{\Omega} E \dot{\Phi}_{\Omega,E} \mathrm{d}t\ \mathrm{d}\Omega\ \mathrm{d}E. \qquad (3.2.4)$$

It should be noted that the (vectorial) integration of $\dot{\Phi}_{\Omega,E}$ over time, energy, and solid angle results in a point function in space, but this is not the case when the integration is over area. It is meaningful to integrate, for instance, the scalar product $\boldsymbol{\Psi} \cdot \mathrm{d}\boldsymbol{a}$ over a given area $a$ to obtain the net flow of radiant energy through this area. Integration with respect to a particular surface must take account of the (three-dimensional) shape of the surface and its orientation, because the number of particles in a given direction, intercepted by a surface, depends on the angle of incidence.

Table 3.1. Scalar radiometric quantities

| Name[a] | Symbol | Unit | Definition | Appearance in the Report |
|---|---|---|---|---|
| particle number | $N$ | 1 | – | Section 3.1.1 |
| radiant energy | $R$ | J | – | Section 3.1.1 |
| energy distribution of particle number | $N_E$ | $\mathrm{J}^{-1}$ | $\mathrm{d}N/\mathrm{d}E$ | Eq. 3.1.1a |
| energy distribution of radiant energy | $R_E$ | 1 | $\mathrm{d}R/\mathrm{d}E$ | Eq. 3.1.1b |
| particle number density | $n$ | $\mathrm{m}^{-3}$ | $\mathrm{d}N/\mathrm{d}V$ | Eq. 3.1.3a |
| radiant energy density | $u$ | $\mathrm{J\ m}^{-3}$ | $\mathrm{d}R/\mathrm{d}V$ | Eq. 3.1.3b |
| energy distribution of particle number density | $n_E$ | $\mathrm{m}^{-3}\ \mathrm{J}^{-1}$ | $\mathrm{d}n/\mathrm{d}E$ | Eq. 3.1.4a |
| energy distribution of radiant energy density | $u_E$ | $\mathrm{m}^{-3}$ | $\mathrm{d}u/\mathrm{d}E$ | Eq. 3.1.4b |
| flux | $\dot{N}$ | $\mathrm{s}^{-1}$ | $\mathrm{d}n/\mathrm{d}t$ | Section 3.1.2 |
| energy flux | $\dot{R}$ | W | $\mathrm{d}R/\mathrm{d}t$ | Section 3.1.2 |
| energy distribution of flux | $\dot{N}_E$ | $\mathrm{s}^{-1}\ \mathrm{J}^{-1}$ | $\mathrm{d}\dot{N}/\mathrm{d}E$ | – |
| energy distribution of energy flux | $\dot{R}_E$ | $\mathrm{s}^{-1}$ | $\mathrm{d}\dot{R}/\mathrm{d}E$ | – |
| fluence | $\Phi$ | $\mathrm{m}^{-2}$ | $\mathrm{d}N/\mathrm{d}a$ | Section 3.1.3 |
| energy fluence | $\Psi$ | $\mathrm{J\ m}^{-2}$ | $\mathrm{d}R/\mathrm{d}a$ | Section 3.1.3 |
| energy distribution of fluence | $\Phi_E$ | $\mathrm{m}^{-2}\ \mathrm{J}^{-1}$ | $\mathrm{d}\Phi/\mathrm{d}E$ | Eq. 3.1.8a |
| energy distribution of energy fluence | $\Psi_E$ | $\mathrm{m}^{-2}$ | $\mathrm{d}\Psi/\mathrm{d}E$ | Eq. 3.1.8b |
| fluence rate | $\dot{\Phi}$ | $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ | $\mathrm{d}\Phi/\mathrm{d}t$ | Section 3.1.4 |
| energy-fluence rate | $\dot{\Psi}$ | $\mathrm{W\ m}^{-2}$ | $\mathrm{d}\Psi/\mathrm{d}t$ | Section 3.1.4 |
| energy distribution of fluence rate | $\dot{\Phi}_E$ | $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{J}^{-1}$ | $\mathrm{d}\dot{\Phi}/\mathrm{d}E$ | – |
| energy distribution of energy-fluence rate | $\dot{\Psi}_E$ | $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ | $\mathrm{d}\dot{\Psi}/\mathrm{d}E$ | – |
| particle radiance | $\dot{\Phi}_\Omega$ | $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ | $\mathrm{d}\dot{\Phi}/\mathrm{d}\Omega$ | Section 3.1.5 |
| energy radiance | $\dot{\Psi}_\Omega$ | $\mathrm{W\ m}^{-2}\ \mathrm{sr}^{-1}$ | $d\dot{\Psi}/\mathrm{d}\Omega$ | Section 3.1.5 |
| energy distribution of particle radiance | $\dot{\Phi}_{\Omega,E}$ | $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{J}^{-1}$ | $\mathrm{d}\dot{\Phi}_\Omega/\mathrm{d}E$ | Eq. 3.1.11a |
| energy distribution of energy radiance | $\dot{\Psi}_{\Omega,E}$ | $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ | $\mathrm{d}\dot{\Psi}_\Omega/\mathrm{d}E$ | Eq. 3.1.11b |

[a]The expression "distribution of a quantity with respect to energy" has been replaced in this table by the shorthand expression "energy distribution of the quantity."

Table 3.2. Vector radiometric quantities

| Name[a] | Symbol | Unit | Definition | Appearance in the Report |
|---|---|---|---|---|
| vector particle radiance | $\dot{\boldsymbol{\Phi}}_{\Omega}$ | $m^{-2}$ $s^{-1}$ $sr^{-1}$ | $\boldsymbol{\Omega}\dot{\Phi}_{\Omega}$ | Section 3.2.1 |
| vector energy radiance | $\dot{\boldsymbol{\Psi}}_{\Omega}$ | W $m^{-2}$ $sr^{-1}$ | $\boldsymbol{\Omega}\dot{\Psi}_{\Omega}$ | Section 3.2.1 |
| energy distribution of vector particle radiance | $\dot{\boldsymbol{\Phi}}_{\Omega,E}$ | $m^{-2}$ $s^{-1}$ $sr^{-1}$ $J^{-1}$ | $\boldsymbol{\Omega}\dot{\Phi}_{\Omega,E}$ | Eq. 3.2.1a |
| energy distribution of vector energy radiance | $\dot{\boldsymbol{\Psi}}_{\Omega,E}$ | $m^{-2}$ $s^{-1}$ $sr^{-1}$ | $\boldsymbol{\Omega}\dot{\Psi}_{\Omega,E}$ | Eq. 3.2.1b |
| vector fluence rate | $\dot{\boldsymbol{\Phi}}$ | $m^{-2}$ $s^{-1}$ | $\int \dot{\boldsymbol{\Phi}}_{\Omega}\mathrm{d}\Omega$ | Section 3.2.2 |
| vector energy-fluence rate | $\dot{\boldsymbol{\Psi}}$ | W $m^{-2}$ | $\int \dot{\boldsymbol{\Psi}}_{\Omega}\mathrm{d}\Omega$ | Section 3.2.2 |
| energy distribution of vector fluence rate | $\dot{\boldsymbol{\Phi}}_{E}$ | $m^{-2}$ $s^{-1}$ $J^{-1}$ | $\int \dot{\boldsymbol{\Phi}}_{\Omega,E}\mathrm{d}\Omega$ | – |
| energy distribution of vector energy-fluence rate | $\dot{\boldsymbol{\Psi}}_{E}$ | $m^{-2}$ $s^{-1}$ | $\int \dot{\boldsymbol{\Psi}}_{\Omega,E}\mathrm{d}\Omega$ | – |
| vector fluence | $\boldsymbol{\Phi}$ | $m^{-2}$ | $\int \dot{\boldsymbol{\Phi}}\mathrm{d}t$ | Section 3.2.3 |
| vector energy fluence | $\boldsymbol{\Psi}$ | J $m^{-2}$ | $\int \dot{\boldsymbol{\Psi}}\mathrm{d}t$ | Section 3.2.3 |
| energy distribution of vector fluence | $\boldsymbol{\Phi}_{E}$ | $m^{-2}$ $J^{-1}$ | $\int \dot{\boldsymbol{\Phi}}_{E}\mathrm{d}t$ | Eq. 3.2.3a |
| energy distribution of vector energy fluence | $\boldsymbol{\Psi}_{E}$ | $m^{-2}$ | $\int \dot{\boldsymbol{\Psi}}_{E}\mathrm{d}t$ | Eq. 3.2.3b |

[a]The expression "distribution of a quantity with respect to energy" has been replaced in this table by the shorthand expression "energy distribution of the quantity."

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# 4. Interaction Coefficients and Related Quantities

Interaction processes occur between radiation and matter. In an interaction, the energy or the direction (or both) of the incident particle is altered or the particle is absorbed. The interaction might be followed by the emission of one or several secondary particles. The likelihood of such interactions is characterized by interaction coefficients. They refer to a specific interaction process, type and energy of radiation, and target or material.

The fundamental interaction coefficient is the cross section (see Section 4.1). All other interaction coefficients defined in this Report can be expressed in terms of cross sections or differential cross sections.

Interaction coefficients and related quantities discussed in this Section are listed in Table 4.1.

## 4.1 Cross Section

The *cross section*, $\sigma$, of a target entity, for a particular interaction produced by incident charged or uncharged particles of a given type and energy, is the quotient of $N$ by $\Phi$, where $N$ is the mean number of such interactions per target entity subjected to the particle fluence $\Phi$, thus

$$\sigma = \frac{N}{\Phi}.$$

Unit: $\mathrm{m}^2$

A special unit often used for the cross section is the barn, b, defined by

$$1\,\mathrm{b} = 10^{-28}\,\mathrm{m}^2 = 100\,\mathrm{fm}^2.$$

A full description of an interaction process requires, among other things, the knowledge of the distributions of cross sections in terms of energy and direction of all emergent particles resulting from the interaction. Such distributions, sometimes called *differential cross sections*, are obtained by differentiations of $\sigma$ with respect to energy of emergent particles and solid angle.

If incident particles of a given type and energy can undergo different and independent types of interaction in a target entity, the resulting cross section, sometimes called the total cross section, $\sigma$, is expressed by the sum of the component cross sections, $\sigma_j$, hence

$$\sigma = \sum_J \sigma_J = \frac{1}{\Phi}\sum_J N_J, \qquad (4.1.1)$$

where $N_J$ is the mean number of interactions of type $J$ per target entity subjected to the particle fluence $\Phi$, and $\sigma_J$ is the component cross section relating to an interaction of type $J$.

## 4.2 Mass Attenuation Coefficient

The *mass attenuation coefficient*, $\mu/\rho$, of a material, for uncharged particles of a given type and energy, is the quotient of $\mathrm{d}N/N$ by $\rho\mathrm{d}l$, where $\mathrm{d}N/N$ is the mean fraction of the particles that experience interactions in traversing a distance $\mathrm{d}l$ in the material of density $\rho$, thus

$$\frac{\mu}{\rho} = \frac{1}{\rho\,\mathrm{d}l}\frac{\mathrm{d}N}{N}.$$

Unit: $\mathrm{m}^2\,\mathrm{kg}^{-1}$

The quantity $\mu$ is the *linear attenuation coefficient*. The probability that at normal incidence an uncharged particle undergoes an interaction in a material layer of thickness $\mathrm{d}l$ is $\mu\mathrm{d}l$.

The reciprocal of $\mu$ is called the *mean free path* of an uncharged particle.

The linear attenuation coefficient, $\mu$, depends on the density, $\rho$, of the material. This dependence is largely removed by using the mass attenuation coefficient, $\mu/\rho$.

The mass attenuation coefficient can be expressed in terms of the total cross section, $\sigma$. The mass attenuation coefficient is the product of $\sigma$ and $N_A/M$, where $N_A$ is the Avogadro constant, and $M$ is the molar mass of the target material, thus

$$\frac{\mu}{\rho} = \frac{N_A}{M}\sigma = \frac{N_A}{M}\sum_J \sigma_J, \qquad (4.2.1)$$

where $\sigma_J$ is the component cross section relating to an interaction of type $J$.

Relationship 4.2.1 can be written as

$$\frac{\mu}{\rho} = \frac{n_t}{\rho}\sigma, \qquad (4.2.2)$$

where $n_t$ is the number density of target entities, *i.e.*, the number of target entities in a volume element divided by its volume.

The mass attenuation coefficient of a compound material is usually treated as if the latter consisted of independent atoms. Thus,

$$\frac{\mu}{\rho} = \frac{1}{\rho}\sum_L (n_t)_L\,\sigma_L = \frac{1}{\rho}\sum_L (n_t)_L \sum_J \sigma_{L,J}, \qquad (4.2.3)$$

where $(n_t)_L$ is the *number density of target entities* of type $L$, $\sigma_L$ the total cross section for an entity $L$, and $\sigma_{L,J}$ the cross section of an interaction of type $J$ for a single target entity of type $L$. Relationship 4.2.3, which ignores the effects on the cross sections of the molecular, chemical, or crystalline environment of an atom, is justified in most cases, but can occasionally lead to errors, for example, in the interaction of low-energy photons with molecules (Hubbell, 1969) and in the interaction of slow neutrons with molecules, particularly those containing hydrogen (see, *e.g.*, Caswell *et al.*, 1982; Houk and Wilson, 1967; Rauch, 1994).

## 4.3 Mass Energy-Transfer Coefficient

The *mass energy-transfer coefficient*, $\mu_{tr}/\rho$, of a material, for uncharged particles of a given type and energy, is the quotient of $dR_{tr}/R$ by $\rho dl$, where $dR_{tr}$ is the mean energy that is transferred to kinetic energy of charged particles by interactions of the uncharged particles of incident radiant energy $R$ in traversing a distance $dl$ in the material of density $\rho$, thus

$$\frac{\mu_{tr}}{\rho} = \frac{1}{\rho\, dl}\frac{dR_{tr}}{R}.$$

Unit: $m^2\,kg^{-1}$

The binding energies of the liberated charged particles are not to be included in $dR_{tr}$. However, binding energies are usually assumed negligible and thus included in calculations of the mass energy-transfer coefficient for photons. In materials consisting of elements of modest atomic number, such an inconsistency with the definition can become important for photons with energies below 1 keV. In addition, the decay of excited nuclear states produced by interactions can contribute charged particles; this process is usually not included in evaluation of the mass energy-transfer coefficient for photons, but rather is treated as a separate source term in dosimetry calculations.

If incident uncharged particles of a given type and energy can produce several types of independent interactions in a target entity, the mass energy-transfer coefficient can be expressed in terms of the component cross sections, $\sigma_J$, by the relationship

$$\frac{\mu_{tr}}{\rho} = \frac{N_A}{M}\sum_J f_J\sigma_J, \qquad (4.3.1)$$

where $f_J$ is the quotient of the mean energy transferred to kinetic energy of charged particles in an interaction of type $J$ by the kinetic energy of the incident uncharged particle, $N_A$ is the Avogadro constant, and $M$ is the molar mass of the target material.

The mass energy-transfer coefficient is related to the mass attenuation coefficient, $\mu/\rho$, by the equation

$$\frac{\mu_{tr}}{\rho} = \frac{\mu}{\rho}f, \qquad (4.3.2)$$

where

$$f = \frac{\sum_J f_J\sigma_J}{\sum_J \sigma_J}.$$

The mass energy-transfer coefficient of a compound material is usually treated as if the latter consisted of independent atoms. Thus,

$$\frac{\mu_{tr}}{\rho} = \frac{1}{\rho}\sum_L (n_t)_L \sum_J f_{L,J}\sigma_{L,J}, \qquad (4.3.3)$$

where $(n_t)_L$ and $\sigma_{L,J}$ have the same meaning as in Eq. 4.2.3, and $f_{L,J}$ is the quotient of the mean energy transferred to kinetic energy of charged particles in an interaction of type $J$ with a target entity of type $L$ by the kinetic energy of the incident uncharged particle. Relationship 4.3.3 implies the same approximations as relationship 4.2.3.

A fraction $g$ of the kinetic energy transferred to charged particles is subsequently lost on average in radiative processes (bremsstrahlung, in-flight annihilation, and fluorescence radiations) as the charged particles slow to rest in the material, and this fraction $g$ is specific to the material. The product of $\mu_{tr}/\rho$ for a material and $(1-g)$ is called the *mass energy-absorption coefficient*, $\mu_{en}/\rho$, of the material for uncharged particles,

$$\frac{\mu_{en}}{\rho} = \frac{\mu_{tr}}{\rho}(1-g). \qquad (4.3.4)$$

The mass energy-absorption coefficient of a compound material depends on the stopping power (see Section 4.4) of the material. Thus, its evaluation cannot, in principle, be reduced to a simple summation of the mass energy-absorption coefficient of the atomic constituents (Seltzer, 1993). Such a summation can provide an adequate approximation when the value of $g$ is sufficiently small.

## 4.4 Mass Stopping Power

The *mass stopping power*, $S/\rho$, of a material, for charged particles of a given type and energy, is the quotient of $\mathrm{d}E$ by $\rho\mathrm{d}l$, where $\mathrm{d}E$ is the mean energy lost by the charged particles in traversing a distance $\mathrm{d}l$ in the material of density $\rho$, thus

$$\frac{S}{\rho} = \frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}l}.$$

Unit: J m$^2$ kg$^{-1}$

The quantity $E$ may be expressed in eV, and hence $S/\rho$ may be expressed in eV m$^2$ kg$^{-1}$ or some convenient multiples or submultiples, such as MeV cm$^2$ g$^{-1}$.

The quantity $S = \mathrm{d}E/\mathrm{d}l$ denotes the *linear stopping power*.

The mass stopping power can be expressed as a sum of independent components by

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{rad}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{nuc}}, \qquad (4.4.1)$$

where

$\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} = \frac{1}{\rho}S_{\mathrm{el}}$ is the *mass electronic (or collision*[4]*) stopping power* due to interactions with atomic electrons resulting in ionization or excitation,

$\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{rad}} = \frac{1}{\rho}S_{\mathrm{rad}}$ is the *mass radiative stopping power* due to emission of bremsstrahlung in the electric fields of atomic nuclei or atomic electrons, and

$\frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{nuc}} = \frac{1}{\rho}S_{\mathrm{nuc}}$ is the *mass nuclear stopping power*[5] due to elastic Coulomb interactions in which recoil energy is imparted to atoms.

In addition, one can consider energy losses due to nonelastic nuclear interactions, but such processes are not usually described by a stopping power.

The separate mass stopping-power components can be expressed in terms of cross sections. For example, the mass electronic stopping power for an atom can be expressed as

$$\frac{1}{\rho}S_{\mathrm{el}} = \frac{N_{\mathrm{A}}}{M}Z\int \varepsilon\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon}\mathrm{d}\varepsilon, \qquad (4.4.2)$$

where $N_{\mathrm{A}}$ is the Avogadro constant, $M$ the molar mass of the atom, $Z$ its atomic number, $\mathrm{d}\sigma/\mathrm{d}\varepsilon$ the differential cross section (per atomic electron) for interactions, and $\varepsilon$ is the energy loss.

Forming the quotient $S_{\mathrm{el}}/\rho$ greatly reduces, but does not eliminate, the dependence on the density of the material (see ICRU, 1984; 1993b, where the density effect and the stopping powers for compounds are discussed).

## 4.5 Linear Energy Transfer (LET)

The *linear energy transfer* or *restricted linear electronic stopping power*, $L_\Delta$, of a material, for charged particles of a given type and energy, is the quotient of $\mathrm{d}E_\Delta$ by $\mathrm{d}l$, where $\mathrm{d}E_\Delta$ is the mean energy lost by the charged particles due to electronic interactions in traversing a distance $\mathrm{d}l$, minus the mean sum of the kinetic energies in excess of $\Delta$ of all the electrons released by the charged particles, thus

$$L_\Delta = \frac{\mathrm{d}E_\Delta}{\mathrm{d}l}.$$

Unit: J m$^{-1}$

The quantity $E_\Delta$ may be expressed in eV, and hence $L_\Delta$ may be expressed in eV m$^{-1}$ or some convenient multiples or submultiples, such as keV µm$^{-1}$.

[4]The older term was "collision stopping power." Because all interactions can be considered "collisions," the more specific term "electronic" is strongly preferred.

[5]The established term "mass nuclear stopping power" can be misleading because this quantity does not pertain to nuclear interactions.

The linear energy transfer, $L_\Delta$, can also be expressed by

$$L_\Delta = S_{el} - \frac{dE_{ke,\Delta}}{dl}, \qquad (4.5.1)$$

where $S_{el}$ is the linear electronic stopping power, and $dE_{ke,\Delta}$ is the mean sum of the kinetic energies, greater than $\Delta$, of all the electrons released by the charged particle in traversing a distance $dl$.

The definition expresses the following energy balance: energy lost by the primary charged particle in interactions with electrons, along a distance $dl$, minus energy carried away by energetic secondary electrons having initial kinetic energies greater than $\Delta$, equals energy considered as "locally transferred," although the definition specifies an energy cutoff, $\Delta$, and not a distance cutoff.

Note that $L_\Delta$ includes the binding energy of electrons for all interactions. As a consequence, $L_0$ refers to the energy lost that does not reappear as kinetic energy of released electrons. Thus, the threshold of the kinetic energy of the released electrons is $\Delta$ as opposed to $\Delta$ minus the binding energy.

In order to simplify notation, $\Delta$ may be expressed in eV. Then $L_{100}$ is understood to be the linear energy transfer for an energy cutoff of 100 eV. If no energy cutoff is imposed, the *unrestricted linear energy transfer*, $L_\infty$, is equal to $S_{el}$, and may be denoted simply as $L$.

## 4.6 Radiation Chemical Yield

The *radiation chemical yield*, $G(x)$, of an entity, x, is the quotient of $n(x)$ by $\bar{\varepsilon}$, where $n(x)$ is the mean amount of substance of that entity produced, destroyed, or changed in a system by the mean energy imparted, $\bar{\varepsilon}$, to the matter of that system, thus

$$G(x) = \frac{n(x)}{\bar{\varepsilon}}.$$

Unit: mol $J^{-1}$

The mole is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kg of $^{12}C$. The elementary entities must be specified and can be atoms, molecules, ions, electrons, other particles, or specified groups of such particles (BIPM, 2006).

A related quantity, called *G value*, has been defined as the mean number of entities produced, destroyed, or changed by an energy imparted of 100 eV. The unit in which the $G$ value is expressed is $(100\ eV)^{-1}$. A $G$ value of 1 $(100\ eV)^{-1}$ corresponds to a radiation chemical yield of approximately 0.1036 μmol $J^{-1}$.

## 4.7 Ionization Yield in a Gas

The *ionization yield in a gas*, $Y$, is the quotient of $N$ by $E$, where $N$ is the mean total liberated charge of either sign, divided by the elementary charge, when the initial kinetic energy $E$ of a charged particle of a given type is completely dissipated in the gas, thus

$$Y = \frac{N}{E}.$$

Unit: $J^{-1}$

The quantity $Y$ may also be expressed in $eV^{-1}$.

The ionization yield in a gas is a particular case of the radiation chemical yield. It follows from the definition of $Y$ that the charge produced by bremsstrahlung or other secondary radiation emitted by the initial and secondary charged particles is included in $N$. The charge of the initial charged particle is not included in $N$, as this charge is not liberated in the energy-dissipation process.

## 4.8 Mean Energy Expended in a Gas per Ion Pair Formed

The *mean energy expended in a gas per ion pair formed*, $W$, is the quotient of $E$ by $N$, where $N$ is the mean total liberated charge of either sign, divided by the elementary charge, when the initial kinetic energy $E$ of a charged particle introduced into the gas is completely dissipated in the gas, thus

$$W = \frac{E}{N}.$$

Unit: J

The quantity $W$ may also be expressed in eV.

It follows from the definition of $W$ that the ions produced by bremsstrahlung or other secondary radiation emitted by the initial and secondary charged particles are included in $N$. The charge of the initial charged particle is not included in $N$.

In certain cases, it could be necessary to focus attention on the variation in the mean energy expended per ion pair along the path of the particle; then the concept of a differential $W$ is required, as defined in ICRU Report 31 (ICRU, 1979). The differential value, $w$, of the mean energy expended in a gas per ion pair formed is the quotient of d$E$ by d$N$; thus

$$w = \frac{\mathrm{d}E}{\mathrm{d}N}, \qquad (4.8.1)$$

where d$E$ is the mean energy lost by a charged particle of kinetic energy $E$ in traversing a layer of gas of infinitesmal thickness, and d$N$ is the mean total liberated charge of either sign divided by the elementary charge when d$E$ is completely dissipated in the gas.

The relationship between $W$ and $w$ is given by

$$W(E) = \frac{E}{\int_I^E [\mathrm{d}E'/w(E')]}, \qquad (4.8.2)$$

where $I$ is the lowest ionization potential of the gas, and $E'$ is the instantaneous kinetic energy of the charged particle as it slows down.

In solid-state theory, a concept similar to $W$ is the average energy required for the formation of a hole−electron pair.

Table 4.1. Interaction coefficients and related quantities

| Name | Symbol | Unit | Definition | Appearance in the Report |
|---|---|---|---|---|
| cross section | $\sigma$ | $m^2$ | $N/\Phi$ | Section 4.1 |
| mass attenuation coefficient | $\mu/\rho$ | $m^2\,kg^{-1}$ | $\mathrm{d}N/(N\,\rho\,\mathrm{d}l)$ | Section 4.2 |
| linear attenuation coefficient | $\mu$ | $m^{-1}$ | $\mathrm{d}N/(N\,\mathrm{d}l)$ | Section 4.2 |
| mean free path | $\mu^{-1}$ | m | $N\,\mathrm{d}l/\mathrm{d}N$ | Section 4.2 |
| mass energy-transfer coefficient | $\mu_{tr}/\rho$ | $m^2\,kg^{-1}$ | $\mathrm{d}R_{tr}/(R\,\rho\,\mathrm{d}l)$ | Section 4.3 |
| mass energy-absorption coefficient | $\mu_{en}/\rho$ | $m^2\,kg^{-1}$ | $(\mu_{tr}/\rho)(1-g)$ | Section 4.3 |
| mass stopping power | $S/\rho$ | $J\,m^2\,kg^{-1}$ | $\mathrm{d}E/(\rho\,\mathrm{d}l)$ | Section 4.4 |
| linear stopping power | $S$ | $J\,m^{-1}$ | $\mathrm{d}E/\mathrm{d}l$ | Section 4.4 |
| linear energy transfer | $L_\Delta$ | $J\,m^{-1}$ | $\mathrm{d}E_\Delta/\mathrm{d}l$ | Section 4.5 |
| radiation chemical yield | $G$(x) | mole $J^{-1}$ | $n(\mathrm{x})/\bar{\varepsilon}$ | Section 4.6 |
| ionization yield in a gas | $Y$ | $J^{-1}$ | $N/E$ | Section 4.7 |
| mean energy expended in a gas per ion pair formed | $W$ | J | $E/N$ | Section 4.7 |
| differential mean energy expended in a gas per ion pair formed | $w$ | J | $\mathrm{d}E/\mathrm{d}N$ | Eq. 4.8.1 |

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# 5. Dosimetry

The effects of radiation on matter depend on the radiation field, as specified by the radiometric quantities defined in Sections 3.1 and 3.2, and on the interactions between radiation and matter, as characterized by the interaction quantities defined in Sections 4.1 to 4.5. Dosimetric quantities, which are selected to provide a physical measure to correlate with actual or potential effects, are products of radiometric quantities and interaction coefficients. In calculations, the values of these quantities and coefficients must be known, while measurements might not require this information.

Radiation interacts with matter in a series of processes in which particle energy is converted and finally deposited in matter. The dosimetric quantities that describe these processes are presented below in two Sections dealing with the conversion and with the deposition of energy. The evaluation of the quantities defined in this Section requires, in general, consideration of elapsed time. Most applications and measurements of ionizing radiation involve time scales of the order of seconds or minutes, so at a practical level the decay of an excited atomic state usually can be assumed to have occurred. This might not be the case for nuclear de-excitations or spontaneous nuclear decays, with the obvious example of a radionuclide produced in an interaction or pre-existing in a volume of interest.

## 5.1 Conversion of Energy

The term conversion of energy refers to the transfer of energy from ionizing particles to secondary ionizing particles. The quantity *kerma* pertains to the kinetic energy of the charged particles liberated by uncharged particles; the energy expended to overcome the binding energies, usually a relatively small component, is, by definition, not included. In addition to kerma, the quantity *cema* is defined that pertains to the energy lost by charged particles (*e.g.*, electrons, protons, alpha particles) in interactions with atomic electrons; by definition, the binding energies are included. Cema differs from kerma in that cema involves the energy lost in electronic interactions by the incoming charged particles, while kerma involves the energy of outgoing charged particles as a result of interactions by incoming uncharged particles. Both quantities, in conditions of charged-particle equilibrium, serve as approximations to absorbed dose, kerma for uncharged and cema for charged ionizing particles.

### 5.1.1 Kerma[6]

The *kerma*, $K$, for ionizing uncharged particles, is the quotient of $\mathrm{d}E_{\mathrm{tr}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\mathrm{tr}}$ is the mean sum of the initial kinetic energies of all the charged particles liberated in a mass $\mathrm{d}m$ of a material by the uncharged particles incident on $\mathrm{d}m$, thus

$$K = \frac{\mathrm{d}E_{tr}}{\mathrm{d}m}.$$

Unit: J kg$^{-1}$

The special name for the unit of kerma is gray (Gy).

The quantity $\mathrm{d}E_{\mathrm{tr}}$ includes the kinetic energy of the charged particles emitted in the decay of excited atoms/molecules[7] or in nuclear de-excitation or disintegration.

For a fluence, $\Phi$, of uncharged particles of energy $E$, the kerma, $K$, in a specified material is given by

$$K = \Phi E \mu_{\mathrm{tr}}/\rho = \Psi \mu_{\mathrm{tr}}/\rho, \qquad (5.1.1)$$

where $\mu_{\mathrm{tr}}/\rho$ is the mass energy-transfer coefficient of the material for these particles.

The kerma per fluence, $K/\Phi$, is termed the *kerma coefficient* for uncharged particles of energy $E$ in a specified material. The term kerma coefficient is used in preference to the older term kerma factor, as the word coefficient implies a physical dimension whereas the word factor does not.

In dosimetric calculations, the kerma, $K$, is usually expressed in terms of the distribution, $\Phi_E$, of the

[6]Kinetic energy released per mass.
[7]For example, Auger, Coster-Kronig, shake-off electrons.

uncharged-particle fluence with respect to energy (see Eq. 3.l.8a). The kerma, $K$, is then given by

$$K = \int \Phi_E E \frac{\mu_{tr}}{\rho}\, \mathrm{d}E = \int \Psi_E \frac{\mu_{tr}}{\rho} \mathrm{d}E, \tag{5.1.2}$$

where $\mu_{tr}/\rho$ is the mass energy-transfer coefficient of the material for uncharged particles of energy $E$.

The expression of kerma in terms of fluence makes it clear that one can refer to a value of kerma or kerma rate for a specified material at a point in free space, or inside a different material. Thus, one can speak, for example, of the air kerma at a point inside a water phantom.

Although kerma is a quantity that concerns the initial transfer of energy to matter, it is sometimes used as an approximation to absorbed dose. The numerical value of the kerma approaches that of the absorbed dose to the degree that *charged-particle equilibrium* exists, that radiative losses are negligible, and that the kinetic energy of the uncharged particles is large compared with the binding energy of the liberated charged particles. Charged-particle equilibrium exists at a point if the distribution of the charged-particle radiance with respect to energy (see Eq. 3.1.11a) is constant within distances equal to the maximum charged-particle range.

A quantity related to the kerma, termed the *collision kerma*, has long been in use as an approximation to absorbed dose (Attix, 1979a; 1979b) when radiative losses are not negligible. The collision kerma, $K_{col}$, excludes the radiative losses by the liberated charged particles, and – for a fluence, $\Phi$, of uncharged particles of energy $E$ in a specified material – is given by

$$K_{col} = \Phi E \frac{\mu_{en}}{\rho} = \Phi E \frac{\mu_{tr}}{\rho}(1-g) = K(1-g), \tag{5.1.3}$$

where $\mu_{en}/\rho$ is the mass energy-absorption coefficient of the material for uncharged particles of energy $E$, and $g$ is the fraction of the kinetic energy of liberated charged particles that would be lost in radiative processes in that material (see Section 4.3).

In dosimetric calculations, the collision kerma, $K_{col}$, can be expressed in terms of the distribution, $\Phi_E$, of the uncharged-particle fluence with respect to energy as

$$\begin{aligned} K_{col} &= \int \Phi_E E \frac{\mu_{en}}{\rho}\, \mathrm{d}E = \int \Phi_E E \frac{\mu_{tr}}{\rho}(1-g)\, \mathrm{d}E \\ &= K(1-\bar{g}), \end{aligned} \tag{5.1.4}$$

where $\bar{g}$ is the mean value of $g$ averaged over the distribution of the kerma with respect to the electron energy.

The expression of collision kerma in terms of the product of the kerma and a radiative-loss correction factor evaluated for the same material as the kerma suggests that one can refer to a value of collision kerma or collision kerma rate for a specified material at a point in free space, or inside a different material.

### 5.1.2 Kerma Rate

The *kerma rate*, $\dot{K}$, is the quotient of $\mathrm{d}K$ by $\mathrm{d}t$, where $\mathrm{d}K$ is the increment of kerma in the time interval $\mathrm{d}t$, thus

$$\dot{K} = \frac{\mathrm{d}K}{\mathrm{d}t}.$$

Unit: J kg$^{-1}$ s$^{-1}$

If the special name gray is used, the unit of kerma rate is gray per second (Gy s$^{-1}$).

### 5.1.3 Exposure

The *exposure*, $X$, is the quotient of $\mathrm{d}q$ by $\mathrm{d}m$, where $\mathrm{d}q$ is the absolute value of the mean total charge of the ions of one sign produced when all the electrons and positrons liberated or created by photons incident on a mass $\mathrm{d}m$ of dry air are completely stopped in dry air, thus

$$X = \frac{\mathrm{d}q}{\mathrm{d}m}.$$

Unit: C kg$^{-1}$

The ionization produced by electrons emitted in atomic/molecular relaxation processes is included in $\mathrm{d}q$. The ionization due to photons emitted by radiative processes (*i.e.*, bremsstrahlung and fluorescence photons) is not to be included in $\mathrm{d}q$. Except for this difference, significant at high energies, the exposure, as defined above, is the ionization analogue of the dry-air kerma. Exposure can be expressed in terms of the distribution, $\Phi_E$, of the fluence with respect to the photon energy, $E$, and the mass energy-transfer coefficient, $\mu_{tr}/\rho$, for dry air and for that energy as follows:

$$\begin{aligned} X &\approx \frac{e}{W}\int \Phi_E E \frac{\mu_{tr}}{\rho}(1-g)\mathrm{d}E \\ &\approx \frac{e}{W}\int \Phi_E E \frac{\mu_{en}}{\rho}\mathrm{d}E, \end{aligned} \tag{5.1.5}$$

where $e$ is the elementary charge, $W$ is the mean energy expended in dry air per ion pair formed, and $g$ is the fraction of the kinetic energy of the electrons liberated by photons that is lost in radiative processes in air. The approximation symbol in Eq. 5.1.5 reflects the fact that the exposure includes the charge of electrons or ions liberated by the incident photons whereas $W$ pertains only to the charge produced during the slowing down of these electrons.[8]

For photon energies of the order of 1 MeV or below, for which the value of $g$ is small, Eq. 5.1.5 can be further approximated by $X \approx (e/W)K_{\text{air}}(1-\bar{g}) = (e/W)K_{\text{col,air}}$, where $K_{\text{air}}$ is the dry-air kerma for primary photons and $\bar{g}$ is the mean value of $g$ averaged over the distribution of the air kerma with respect to the electron energy.

As in the case of collision kerma, it can be convenient to refer to a value of exposure or of exposure rate in free space or at a point inside a material different from air; one can speak, for example, of the exposure at a point inside a water phantom.

### 5.1.4 Exposure Rate

The *exposure rate*, $\dot{X}$, is the quotient of $\mathrm{d}X$ by $\mathrm{d}t$, where $\mathrm{d}X$ is the increment of exposure in the time interval $\mathrm{d}t$, thus

$$\dot{X} = \frac{\mathrm{d}X}{\mathrm{d}t}.$$

Unit: C kg$^{-1}$ s$^{-1}$

### 5.1.5 Cema[9]

The *cema*, $C$, for ionizing charged particles, is the quotient of $\mathrm{d}E_{\text{el}}$ by $\mathrm{d}m$, where $\mathrm{d}E_{\text{el}}$ is the mean energy lost in electronic interactions in a mass $\mathrm{d}m$ of a material by the charged particles, except secondary electrons, incident on $\mathrm{d}m$, thus

$$C = \frac{\mathrm{d}E_{\text{el}}}{\mathrm{d}m}.$$

Unit: J kg$^{-1}$

The special name of the unit of cema is gray (Gy).

[8]This difference, although relatively small, tends to become more significant as the photon energy decreases. Additionally, $W$ is not constant as perhaps implied in Eq. 5.1.5, but known to increase at low energies (ICRU, 1979). At energies for which the variation of $W$ with energy becomes important, one should consider the effect of this increase on the relationship between exposure and air kerma.

[9]Converted energy per mass.

The energy lost by charged particles in electronic interactions includes the energy expended to overcome the binding energy and the initial kinetic energy of the liberated electrons, referred to as secondary electrons. Thus, energy subsequently lost by all secondary electrons is excluded from $\mathrm{d}E_{\text{el}}$.

The cema, $C$, can be expressed in terms of the distribution, $\Phi_E$, of the charged-particle fluence, with respect to energy (see Eq. 3.1.8a). According to the definition of cema, the distribution $\Phi_E$ does not include the contribution of secondary electrons to the fluence, but the contributions of all other charged particles, such as secondary protons, alpha particles, tritons, and ions produced in nuclear interactions, are included in the cema. The cema, $C$, is thus given by

$$C = \int \Phi_E \frac{S_{\text{el}}}{\rho} \mathrm{d}E = \int \Phi_E \frac{L_\infty}{\rho} \mathrm{d}E, \qquad (5.1.6)$$

where $S_{\text{el}}/\rho$ is the mass electronic stopping power of a specified material for charged particles of energy $E$, and $L_\infty$ is the corresponding unrestricted linear energy transfer. In general, the cema is evaluated as the sum of contributions by all species of charged particles, except liberated secondary electrons.

For charged particles of high energies, it might be undesirable to disregard energy transport by secondary electrons of all energies. A modified concept, *restricted cema*, $C_\Delta$, (Kellerer *et al.*, 1992) is then defined as

$$C_\Delta = \int \Phi_E' \frac{L_\Delta}{\rho} \mathrm{d}E. \qquad (5.1.7)$$

This differs from the integral in Eq. 5.1.6 in that $L_\infty$ is replaced by $L_\Delta$ and that the distribution $\Phi_E'$ now includes secondary electrons liberated in $\mathrm{d}m$ with kinetic energies greater than $\Delta$. For $\Delta = \infty$, restricted cema is identical to cema.

The expression of cema and restricted cema in terms of fluence makes it clear that one can refer to their values for a specified material at a point in free space, or inside a different material. Thus, one can speak, for example, of tissue cema in air (Kellerer *et al.*, 1992).

The quantities cema and restricted cema can be used as approximations to absorbed dose from charged particles. Equality of absorbed dose and cema is approached to the degree that *secondary-charged-particle equilibrium* exists and that radiative losses and those due to elastic nuclear interactions are negligible. Secondary-charged-particle equilibrium is achieved at a point if the fluence of secondary charged particles is constant within distances equal to their maximum range. For restricted cema, only partial secondary-charged-particle equilibrium, up to kinetic energy $\Delta$, is required.

### 5.1.6 Cema Rate

The *cema rate*, $\dot{C}$, is the quotient of d$C$ by d$t$, where d$C$ is increment of cema in the time interval d$t$, thus

$$\dot{C} = \frac{\mathrm{d}C}{\mathrm{d}t}.$$

Unit: J kg$^{-1}$ s$^{-1}$

If the special name gray is used, the unit of cema rate is gray per second (Gy s$^{-1}$).

## 5.2 Deposition of Energy

In this Section, certain stochastic quantities are introduced. Energy deposit is the basis in terms of which all other quantities presented here can be defined.

### 5.2.1 Energy Deposit

The *energy deposit*, $\varepsilon_i$, is the energy deposited in a single interaction, $i$, thus

$$\varepsilon_i = \varepsilon_{\text{in}} - \varepsilon_{\text{out}} + Q,$$

where $\varepsilon_{\text{in}}$ is the energy of the incident ionizing particle (excluding rest energy), $\varepsilon_{\text{out}}$ is the sum of the energies of all charged and uncharged ionizing particles leaving the interaction (excluding rest energy), and $Q$ is the change in the rest energies of the nucleus and of all elementary particles involved in the interaction ($Q > 0$: decrease of rest energy; $Q < 0$: increase of rest energy).

Unit: J

The quantity $\varepsilon_i$ may also be expressed in eV. Note that $\varepsilon_i$ is a stochastic quantity.

Interactions with atomic electrons resulting in atomic excitation (and subsequent de-excitation) do not involve a change in rest energies of the nucleus or of elementary particles and thus have $Q = 0$. The restriction of $\varepsilon_{\text{in}}$ and $\varepsilon_{\text{out}}$ to energies of ionizing particles can in principle lead to a slight energy imbalance by ignoring the net energy transport by non-ionizing particles; thus, energy of non-ionizing particles, *e.g.*, very-low-energy photons, that can leave the interaction are included in the energy deposit. The dimensions over which that energy is re-absorbed can be thought to define a spatial region associated with a single interaction.

### 5.2.2 Energy Imparted

The *energy imparted*, $\varepsilon$ , to the matter in a given volume is the sum of all energy deposits in the volume, thus

$$\varepsilon = \sum_i \varepsilon_i,$$

where the summation is performed over all energy deposits, $\varepsilon_i$, in that volume.

Unit: J

The quantity $\varepsilon$ may also be expressed in eV. Note that $\varepsilon$ is a stochastic quantity.

The energy deposits over which the summation is performed can belong to one or more *energy-deposition events*; for example, they might belong to one or several independent particle trajectories. The term energy-deposition event denotes the imparting of energy to matter by correlated particles. Examples include a proton and its secondary electrons, an electron-positron pair, or the primary and secondary particles in nuclear reactions.

If the energy imparted to the matter in a given volume is due to a single energy-deposition event, it is equal to the sum of the energy deposits in the volume associated with the energy-deposition event. If the energy imparted to the matter in a given volume is due to several energy-deposition events, it is equal to the sum of the individual energies imparted to the matter in the volume due to each energy-deposition event.

The mean energy imparted, $\bar{\varepsilon}$, to the matter in a given volume equals the mean radiant energy, $R_{\text{in}}$, of all charged and uncharged ionizing particles that enter the volume minus the mean radiant energy, $R_{\text{out}}$, of all charged and uncharged ionizing particles that leave the volume, plus the mean sum, $\sum Q$, of all changes of the rest energy of nuclei and elementary particles that occur in the volume ($Q > 0$: decrease of rest energy; $Q < 0$: increase of rest energy); thus

$$\bar{\varepsilon} = R_{\text{in}} - R_{\text{out}} + \sum Q. \qquad (5.2.1)$$

### 5.2.3 Lineal Energy

The *lineal energy*, $y$, is the quotient of $\varepsilon_s$ by $\bar{l}$, where $\varepsilon_s$ is the energy imparted to the matter in a given volume by a single energy-deposition event, and $\bar{l}$ is the mean chord length of that volume, thus

$$y = \frac{\varepsilon_s}{\bar{l}}.$$

Unit: J $m^{-1}$

The quantity $y$ is a stochastic quantity. The numerator $\varepsilon_s$ may be expressed in eV; hence $y$ may be expressed in multiples and submultiples of eV and m, *e.g.*, in keV $\mu m^{-1}$.

The mean chord length of a volume is the mean length of randomly oriented chords (uniform isotropic randomness) through that volume. For a convex body, it can be shown that the mean chord length, $\bar{l}$, equals $4V/A$, where $V$ is the volume and $A$ is the surface area (Cauchy, 1850; Kellerer, 1980); thus, for a sphere the mean chord length is 2/3 of the sphere diameter.

It is useful to consider the probability distribution of $y$. The value of the *distribution function*, $F(y)$, is the probability that the lineal energy due to a single energy-deposition event is equal to or less than $y$. The *probability density*, $f(y)$, is the derivative of $F(y)$; thus

$$f(y) = \frac{dF(y)}{dy}. \quad (5.2.2)$$

$F(y)$ and $f(y)$ are independent of absorbed dose and absorbed-dose rate, but are dependent on the size and shape of the volume.

### 5.2.4 Specific Energy

The *specific energy* (imparted), $z$, is the quotient of $\varepsilon$ by $m$, where $\varepsilon$ is the energy imparted by ionizing radiation to matter in a volume of mass $m$, thus

$$z = \frac{\varepsilon}{m}.$$

Unit: J $kg^{-1}$

The special name for the unit of speific energy is gray (Gy).

The quantity $z$ is a stochastic quantity. The specific energy can be due to one or more energy-deposition events. The distribution function, $F(z)$, is the probability that the specific energy is equal to or less than $z$. The probability density, $f(z)$, is the derivative of $F(z)$; thus

$$f(z) = \frac{dF(z)}{dz}. \quad (5.2.3)$$

$F(z)$ and $f(z)$ depend on absorbed dose in the mass, $m$. The probability density $f(z)$ includes a discrete component (in terms of a Dirac delta function) at $z = 0$ for the probability of no energy deposition.

The distribution function of the specific energy deposited in a single energy-deposition event, $F_s(z)$, is the conditional probability that a specific energy less than or equal to $z$ is deposited if one energy-deposition event has occurred. The probability density, $f_s(z)$, is the derivative of $F_s(z)$; thus

$$f_s(z) = \frac{dF_s(z)}{dz}. \quad (5.2.4)$$

For convex volumes, $y$ and the increment, $z$, of specific energy due to a single energy-deposition event are related by

$$y = \frac{\rho A}{4} z, \quad (5.2.5)$$

where $A$ is the surface area of the volume, and $\rho$ is the density of matter in the volume.

### 5.2.5 Absorbed Dose

The *absorbed dose*, $D$, is the quotient of $d\bar{\varepsilon}$ by $dm$, where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass $dm$, thus

$$D = \frac{d\bar{\varepsilon}}{dm}.$$

Unit: J $kg^{-1}$

The special name for the unit of absorbed dose is gray (Gy).

In the limit of a small domain[10], the mean specific energy $\bar{z}$ is equal to the absorbed dose $D$.

[10] The absorbed dose, $D$, is considered a point quantity, but it should be recognized that the physical process does not allow $dm$ to approach zero in the mathematical sense.

### 5.2.6 Absorbed-Dose Rate

The *absorbed-does rate*, $\dot{D}$, is the quotient of d$D$ by d$t$, where d$D$ is the increment of absorbed does in the time interval d$t$, thus

$$\dot{D} = \frac{\mathrm{d}D}{\mathrm{d}t}.$$

Unit: J kg$^{-1}$ s$^{-1}$

If the special name gray is used, the unit of absorbed-does rate is gray per second (Gy s$^{-1}$).

Table 5.1. Dosimetric quantities: conversion of energy

| Name | Symbol | Unit | | Definition | Appearance in the Report |
|---|---|---|---|---|---|
| kerma | $K$ | J kg$^{-1}$ | Gy | $\mathrm{d}E_{\mathrm{tr}}/\mathrm{d}m$ | Section 5.1.1 |
| collision kerma | $K_{\mathrm{col}}$ | J kg$^{-1}$ | Gy | $K(1-g)$ | Section 5.1.1 |
| kerma coefficient | – | J m$^2$ kg$^{-1}$ | Gy m$^2$ | $K/\Phi$ | Section 5.1.1 |
| kerma rate | $\dot{K}$ | J kg$^{-1}$ s$^{-1}$ | Gy s$^{-1}$ | $\mathrm{d}K/\mathrm{d}t$ | Section 5.1.2 |
| exposure | $X$ | C kg$^{-1}$ | | $\mathrm{d}q/\mathrm{d}m$ | Section 5.1.3 |
| exposure rate | $\dot{X}$ | C kg$^{-1}$ s$^{-1}$ | | $\mathrm{d}X/\mathrm{d}t$ | Section 5.1.4 |
| cema | $C$ | J kg$^{-1}$ | Gy | $\mathrm{d}E_{\mathrm{el}}/\mathrm{d}m$ | Section 5.1.5 |
| restricted cema | $C_{\Delta}$ | J kg$^{-1}$ | Gy | – | Section 5.1.5 |
| cema rate | $\dot{C}$ | J kg$^{-1}$ s$^{-1}$ | Gy s$^{-1}$ | $\mathrm{d}C/\mathrm{d}t$ | Section 5.1.6 |

Table 5.2. Dosimetric quantities: deposition of energy

| Name | Symbol | Unit | | Definition | Appearance in the Report |
|---|---|---|---|---|---|
| energy deposit | $\varepsilon_i$ | J | | $\varepsilon_{\mathrm{in}} - \varepsilon_{\mathrm{out}} + Q$ | Section 5.2.1 |
| energy imparted | $\varepsilon$ | J | | $\sum_i \varepsilon_i$ | Section 5.2.2 |
| lineal energy | $y$ | J m$^{-1}$ | | $\varepsilon_s/\bar{l}$ | Section 5.2.3 |
| specific energy | $z$ | J kg$^{-1}$ | Gy | $\varepsilon/m$ | Section 5.2.4 |
| absorbed dose | $D$ | J kg$^{-1}$ | Gy | $\mathrm{d}\bar{\varepsilon}/\mathrm{d}m$ | Section 5.2.5 |
| absorbed-dose rate | $\dot{D}$ | J kg$^{-1}$ s$^{-1}$ | Gy s$^{-1}$ | $\mathrm{d}D/\mathrm{d}t$ | Section 5.2.6 |

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# 6. Radioactivity

The term *radioactivity* refers to the phenomena associated with spontaneous transformations that involve changes in the nuclei of atoms or of the energy states of the nuclei of atoms. The energy released in such transformations is emitted as nuclear particles (*e.g.*, alpha particles, electrons, and positrons) and/or photons.

Such transformations represent a *stochastic process*. The whole atom is involved in this process because nuclear transformations can also affect the atomic shell structure and cause emission or capture of electrons, the emission of photons, or both.

A *nuclide* is a species of atoms having a specified number of protons and neutrons in its nucleus. Unstable nuclides, which transform to stable or unstable progeny, are called *radionuclides*. The transformation results in another nuclide or in a transition to a lower energy state of the same nuclide.

## 6.1 Decay Constant

> The *decay constant*, $\lambda$, of a radionuclide in a particular energy state is the quotient of $-\mathrm{d}N/N$ by $\mathrm{d}t$, where $\mathrm{d}N/N$ is the mean fractional change in the number of nuclei in that energy state due to spontaneous nuclear transformations in the time interval $\mathrm{d}t$, thus
>
> $$\lambda = \frac{-\mathrm{d}N/N}{\mathrm{d}t}.$$
>
> Unit: $\mathrm{s}^{-1}$

The quantity $(\ln 2)/\lambda$, commonly called the *half life*, $T_{1/2}$, of a radionuclide, is the mean time taken for the radionuclides in the particular energy state to decrease to one half of their initial number.

## 6.2 Activity

> The *activity*, $A$, of an amount of a radionuclide in a particular energy state at a given time is the quotient of $-\mathrm{d}N$ by $\mathrm{d}t$, where $\mathrm{d}N$ is the mean change in the number of nuclei in that energy state due to spontaneous nuclear transformations in the time interval $\mathrm{d}t$, thus
>
> $$A = -\frac{\mathrm{d}N}{\mathrm{d}t}.$$
>
> Unit: $\mathrm{s}^{-1}$
>
> The special name for the unit of activity is becquerel (Bq).

The "particular energy state" is the ground state of the radionuclide unless otherwise specified.

The activity, $A$, of an amount of a radionuclide in a particular energy state is equal to the product of the decay constant, $\lambda$, for that state, and the number $N$ of nuclei in that state, thus,

$$A = \lambda N. \qquad (6.2.1)$$

## 6.3 Air-kerma-Rate Constant

> The *air-kerma-rate constant*, $\Gamma_\delta$, of a radionuclide emitting photons is the quotient of $l^2\dot{K}_\delta$ by $A$, where $\dot{K}_\delta$ is the air-kerma rate due to photons of energy greater than $\delta$, at a distance $l$ *in vacuo* from a point source of this nuclide having an activity $A$, thus
>
> $$\Gamma_\delta = \frac{l^2\dot{K}_\delta}{A}.$$
>
> Unit: $\mathrm{m^2\,J\,kg^{-1}}$
>
> If the special names gray (Gy) and becquerel (Bq) are used, the unit of air-kerma-rate constant is $\mathrm{m^2\,Gy\,Bq^{-1}\,s^{-1}}$.

The photons referred to in the definition include gamma rays, characteristic x rays, and internal bremsstrahlung.

The air-kerma-rate constant, a characteristic of a radionuclide, is defined in terms of an ideal point source, and the term is not strictly applicable to a source of finite extent. In a source of finite size, attenuation and scattering occur, and annihilation radiation and external bremsstrahlung can be produced. In many cases, these processes require significant corrections.

Any medium intervening between the source and the point of measurement will give rise to absorption and scattering for which corrections are needed.

The selection of the value of $\delta$ depends upon the application. To simplify notation and ensure uniformity, it is recommended that $\delta$ be expressed in keV. For example, $\Gamma_5$ is understood to be the air-kerma-rate constant for a photon-energy cutoff of 5 keV.

Table 6.1. Quantities related to radioactivity

| Name | Symbol | Unit | | Definition | Appearance in the Report |
|---|---|---|---|---|---|
| decay constant | $\lambda$ | $s^{-1}$ | | $-(\mathrm{d}N/N)/\mathrm{d}t$ | Section 6.1 |
| half life | $T_{1/2}$ | s | | $(\ln 2)/\lambda$ | Section 6.1 |
| activity | $A$ | $s^{-1}$ | Bq | $-\mathrm{d}N/\mathrm{d}t$ | Section 6.2 |
| air-kerma-rate constant | $\Gamma_\delta$ | $m^2$ J $kg^{-1}$ | $m^2$ Gy $Bq^{-1}$ $s^{-1}$ | $l^2\dot{K}_\delta/A$ | Section 6.3 |

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