ICRU REPORT 60

Fundamental Quantities and Units for Ionizing Radiation

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Preface

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 may arise from time to time when an expedient solution of a current problem may 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:

Absorbed Dose Standards for Photon Irradiation and Their Dissemination
Assessment of Image Quality in Nuclear Medicine
Beta Rays for Therapeutic Applications
Bone Densitometry
Chest Radiography—Assessment of Image Quality
Clinical Proton Dosimetry—Part II: Dose Specification for Reporting, Treatment Planning and Radiation Quality
Determination of Body Burdens for Radionuclides
Dose and Volume Specification for Reporting Intracavitary Therapy in Gynecology
Dose Specification in Nuclear Medicine
Dosimetric Procedures in Diagnostic Radiology
Mammography—Assessment of Image Quality
Measurement of Operational Quantities for Neutrons
Nuclear Data for Neutron and Proton Radiotherapy and for Radiation Protection
Prescribing, Recording and Reporting Electron Beam Therapy
Requirements for Radioecological Sampling
Retrospective Assessment of Exposure to Ionizing Radiation
ROC Analysis
Stopping Power for Heavy Ions
Tissue Substitutes, Characteristics of Biological Tissue and Phantoms for Ultrasound

In addition, the ICRU is evaluating the possibility of expanding its program to encompass nonionizing radiation, particularly the quantities and units aspects.

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

ICRU's Relationships with Other Organizations

In addition to its close relationship with the ICRP, the ICRU has developed relationships with other organizations interested in the problems of radiation quantities, units and measurements. Since 1955, the ICRU has had an official relationship with the World Health Organization (WHO), whereby the ICRU is looked to for primary guidance in matters of radiation units and measurements and, in turn, the WHO assists in the world-wide dissemination of the Commission's recommendations. In 1960, the ICRU en-

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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 effort which they devoted to this task and to express its appreciation to the organizations with which they are affiliated.

(For detailed information of the availability of this and other ICRU Reports, see page 20.)

tered 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 corresponds and exchanges final 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 Committee of Photobiology
International Council of Scientific Unions
International Electrotechnical Commission
International Labor 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. Relations with these other international bodies do not affect the basic affiliation of the ICRU with the International Society of Radiology.

Operating Funds

In the early days of its existence, the ICRU operated essentially on a voluntary basis, with the travel and operating costs being borne by the parent organization of the participants. (Only token assistance was originally available from the International Society of Radiology.) Recognizing the impractibility of continuing this mode of operation on an indefinite basis, operating funds were sought from various sources.

In recent years, principal financial support has been provided by the European Commission, the National Cancer Institute of the U.S. 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 Society for Therapeutic Radiology and Oncology
Atomic Energy Control Board
Bayer AG
Central Electricity Generating Board
Commissariat à l'Energie Atomique
Dutch Society for Radiodiagnostics
Eastman Kodak Company
Ebara Corporation
Électricité de France
Fuji Medical Systems
General Electric Company
Hitachi, Ltd.
International Radiation Protection Association
International Society of Radiology
Italian Radiological Association
Japan Industries Association of Radiological Systems
Konica Corporation
National Electrical Manufacturers Association
Philips Medical Systems, Incorporated
Radiation Research Society
Scanditronix AB
Siemens Aktiengesellschaft
Sumitomo Heavy Industries, Ltd
Theratronics
Toshiba Corporation
University Hospital Lund, Sweden
World Health Organization

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.

André Wambersie
Chairman, ICRU

Bruxelles, Belgium
15 October 1998

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Fundamental Quantities and Units for Ionizing Radiation

Introduction

This report supersedes Part A of ICRU Report 33 (ICRU, 1980), dealing with quantities and units for general use. Part B of ICRU Report 33, covering quantities and units for use in radiation protection, has already been replaced by ICRU Report 51 (ICRU, 1993a) entitled *Quantities and Units in Radiation Protection Dosimetry.*

The present report deals with the fundamental quantities and units for ionizing radiation. Drafts of its main sections, namely radiometry, interaction coefficients and dosimetry, have been published for comment in the ICRU News. The ICRU appreciates the assistance rendered by scientific bodies and individuals who submitted comments, and hopes that this process will facilitate the acceptance of the report.

The report is structured in five major sections, each of which is followed by tables summarizing, for each quantity, its symbol, unit and the relation used in its definition.

Section 1 deals with terms and mathematical conventions used throughout the report.

Section 2, 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 vectorial quantities are defined.

Interaction coefficients and related quantities are covered in Section 3. 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 definition of the linear energy transfer (LET) given in the present report differs from that given previously (ICRU, 1980) by the inclusion of the binding energy for all collisions.

Section 4 deals with dosimetric quantities which describe the 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 a new quantity, cema (*c*onverted *e*nergy per unit *ma*ss) for charged particles, paralleling kerma (*k*inetic *e*nergy *r*eleased per unit *ma*ss) for uncharged particles. Cema differs from kerma in that cema involves the energy lost in electronic collisions by the incoming charged particles while kerma involves the energy imparted to outgoing charged particles. In the second part on deposition of energy, a new quantity termed energy deposit is introduced. Energy deposit, *i.e.*, the energy deposited in a single interaction, is the fundamental quantity in terms of which all other quantities presented in the section can be defined. These are the traditional stochastic quantities, 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 5.

Much work has been devoted to the current document to ensure it is scientifically rigorous and as consistent as possible with similar publications used in other fields of physics. It is hoped that this report represents a modest step towards a universal scientific language.

1. General Considerations

This section deals with terms and mathematical conventions used throughout the report.

1.1 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 may be 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, 1998). In this system, the base units are metre, 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 currently in use in this restricted category are becquerel (equal to reciprocal second for activity of a radionuclide) and gray (equal to joule per kilogram for absorbed dose, kerma, cema and specific energy). Some examples of SI units are given in Table 1.1.

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 1.2).

Decimal multiples and submultiples of SI units can be formed using the SI prefixes (see Table 1.3).

TABLE 1.1—*SI units used in this report*

Category of units	Quantity	Name	Symbol
SI base units	length	metre	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

1.2 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 may 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 remain-

TABLE 1.2—*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 = 1.602 177 33(49) · 10^{-19} J. 1 u = 1.660 540 2(10) · 10^{-27} kg. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value (CODATA, 1986).

TABLE 1.3—*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 $\text{fm}^2 = (10^{-15}\ \text{m})^2 = 10^{-30}\ \text{m}^2$.

ing energy in other processes such as excitation or elastic scattering. Thus, near the end of their range, charged particles that were ionizing become 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. 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 at the locations called *energy transfer points* (see Section 4.2.1). This implies cut-off energies below which charged particles are not considered to be ionizing. Below such energies, their ranges are minute. Hence, the choice of the cut-off energies does not materially affect the spatial distribution of energy deposition except at the smallest distances that may be of concern in microdosimetry. The choice of the threshold value depends on the application; for example, a value of 10 eV may be appropriate for radiobiology.

1.3 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. Thus, one distinguishes 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. Although similar considerations often apply to radiation, fluctuations can play a significant role, and may need to be considered explicitly.

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. 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*, ϵ_i (see Section 4.2.1), *energy imparted*, ϵ (see Section 4.2.2), *lineal energy*, y (see Section 4.2.3), and *specific energy*, z (see Section 4.2.4).

For example, the specific energy, z, is defined as the quotient of the energy imparted, ϵ, and the mass, m. Repeated measurements would provide an estimate of the probability distribution of z and of its first moment, $\bar{z}$, which approaches the *absorbed dose*, D, (see Section 4.2.5) as the mass becomes small. Knowledge of the distribution of z may not be 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 are 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).

1.4 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 2.1.1) will be treated as if it were continuous, since N is usually a very large number. Distributions with respect to energy are frequently required. For example, the distribution of *fluence* (see Section 2.1.3) with respect to particle energy is given by (see Eq. 2.1.6a)

$$\Phi_E = \mathrm{d}\Phi/\mathrm{d}E, \tag{1.3.1}$$

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 Φ is m^{-2}, whereas the unit of Φ_E is $\mathrm{m}^{-2}\,\mathrm{J}^{-1}$ (see Tables 2.1 and 2.2).

Quantities related to interactions, such as the mass attenuation coefficient, μ/ρ, (see Section 3.2) or the mass stopping power, S/ρ, (see Section 3.4), are functions of the particle energy and one may, if necessary, use a more explicit notation such as $\mu(E)/\rho$ or $S(E)/\rho$. For a radiation field with an energy spectrum, mean values such as $\overline{\mu}/\rho$ and $\overline{S}/\rho$, weighted according to the distribution of the relevant quantity, are often useful. For example,

$$\begin{aligned}\overline{\mu}/\rho &= \left\{\int [\mu(E)/\rho]\Phi_E\,\mathrm{d}E\right\}\Big/\int \Phi_E\,\mathrm{d}E \\ &= \frac{1}{\Phi}\int [\mu(E)/\rho]\Phi_E\,\mathrm{d}E\end{aligned} \tag{1.3.2}$$

is the fluence-weighted mean value of μ/ρ.

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 $F(y)$, and $f(y)$ is the probability that the lineal energy is between y and $y + \mathrm{d}y$.

2. 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 which 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 vectorial 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 which 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. An extended set of quantities relevant to radiometry is presented in Tables 2.1 and 2.2.

2.1 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 2.1.1). The full description of the radiation field, however, requires information on the type and the energy of the particles as well as on their spatial, directional and temporal distributions. In the present report, the specification of the radiation field is achieved with increasing detail, by defining radiometric quantities through successive differentiations of N and R with respect to time, area, volume, direction or energy. 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 2.1.3), often used in the common situation where radiation interactions are independent of the direction and temporal 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. The equivalence between the various terminologies is noted in connection with the relevant definitions.

2.1.1 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

$$N_E = \mathrm{d}N/\mathrm{d}E \tag{2.1.1a}$$

and

$$R_E = \mathrm{d}R/\mathrm{d}E, \tag{2.1.1b}$$

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

$$R_E = EN_E. \tag{2.1.2}$$

The *volumic particle number,* n, is given by

$$n = \mathrm{d}N/\mathrm{d}V, \tag{2.1.3}$$

where $\mathrm{d}N$ is the number of particles in the volume $\mathrm{d}V$. n is also termed number density of particles (ISO, 1993).

2.1.2 Flux, Energy Flux

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

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

Unit: s^{-1}

The **energy flux,** $\dot{R}$, is the quotient of $\mathrm{d}R$ by $\mathrm{d}t$, where $\mathrm{d}R$ is the increment of radiant energy in the time interval $\mathrm{d}t$, 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 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 for the quantity termed fluence rate in the present report (see Section 2.1.4). This usage is discouraged because of the possible confusion with the above definition of flux.

2.1.3 Fluence, Energy Fluence

The **fluence**, $\varPhi$, is the quotient of dN by da, where dN is the number of particles incident on a sphere of cross-sectional area da, thus

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

Unit: m^{-2}

The **energy fluence**, $\varPsi$, is the quotient of dR by da, where dR is the radiant energy incident on a sphere of cross-sectional area da, thus

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

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

The use of a sphere of cross sectional area da expresses in the simplest manner the fact that one considers an area da 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, dΩ, 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 that the fluence, $\varPhi$, is given by

$$\varPhi = \mathrm{d}l/\mathrm{d}V, \qquad (2.1.4)$$

where dl is the sum of the particle trajectory lengths in the volume dV.

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

$$\varPhi = nvt, \qquad (2.1.5)$$

where n is the volumic particle number.

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

$$\varPhi_E = \mathrm{d}\varPhi/\mathrm{d}E \qquad (2.1.6a)$$

and

$$\varPsi_E = \mathrm{d}\varPsi/\mathrm{d}E, \qquad (2.1.6b)$$

where d$\varPhi$ is the fluence of particles of energy between E and E + dE and d$\varPsi$ is their energy fluence.

The relationship between the two distributions is given by

$$\varPsi_E = E\varPhi_E. \qquad (2.1.7)$$

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 θ with the normal direction to a given surface element, the radiant exposure is equal to $\varPsi \cos \theta$.

2.1.4 Fluence Rate, Energy Fluence Rate

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

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

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

The **energy fluence rate**, $\dot{\varPsi}$, is the quotient of d$\varPsi$ by dt, where d$\varPsi$ is the increment of the energy fluence in the time interval dt, thus

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

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

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. The symbols $\dot{\varPhi}$ and $\dot{\varPsi}$ replace the symbols ϕ and ψ used previously (ICRU, 1980).

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

$$\dot{\varPhi} = nv, \qquad (2.1.8)$$

where n is the volumic particle number.

2.1.5 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 symbols $\dot{\Phi}_\Omega$ and $\dot{\Psi}_\Omega$ replace the symbols p and r used previously (ICRU, 1980).

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

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

$$\dot{\Phi}_{\Omega,E} = \frac{\mathrm{d}\dot{\Phi}_\Omega}{\mathrm{d}E} \tag{2.1.9a}$$

and

$$\dot{\Psi}_{\Omega,E} = \frac{\mathrm{d}\dot{\Psi}_\Omega}{\mathrm{d}E}, \tag{2.1.9b}$$

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

$$\dot{\Psi}_{\Omega,E} = E\dot{\Phi}_{\Omega,E}. \tag{2.1.10}$$

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

Apart from aspects which 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, since 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.

2.2 Vectorial Radiometric Quantities

Since radiometric quantities are primarily concerned with the flow of radiation, it is appropriate to consider some of them as vectorial quantities. Vectorial quantities are not needed in those cases where the corresponding scalar quantities are appropriate, *e.g.*, in deriving dosimetric quantities that are independent of the particle direction. In other instances, vectorial 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 vectorial quantity. However, in the case of a unidirectional field, they are of equal magnitude.

The vectorial quantities, defined in this section, are obtained by successive integrations of the quantities vectorial particle radiance and vectorial energy radiance (see Section 2.2.1). Vectorial quantities are used extensively in radiation-transport theory, but often with a different terminology. The equivalences are indicated for the convenience of the reader.

2.2.1 Vectorial Particle Radiance, Vectorial Energy Radiance

The **vectorial 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 $\dot{\Phi}_\Omega$, thus

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

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

The **vectorial 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 $\dot{\Psi}_\Omega$, 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 vectorial particle radiance and the vectorial energy radiance, with respect to energy, are given by

$$\dot{\boldsymbol{\Phi}}_{\Omega,E} = \boldsymbol{\Omega}\dot{\Phi}_{\Omega,E} \tag{2.2.1a}$$

and

$$\dot{\boldsymbol{\Psi}}_{\Omega,E} = \boldsymbol{\Omega}\dot{\Psi}_{\Omega,E}, \tag{2.2.1b}$$

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

2.2.2 Vectorial Fluence Rate, Vectorial Energy Fluence Rate

The **vectorial 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 vectorial 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 **vectorial 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 vectorial 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 vectorial fluence rate and of the vectorial energy fluence rate. The scalar quantities fluence rate and energy fluence rate can be obtained in a similar way according to

$$\dot{\Phi} = \int \dot{\Phi}_\Omega \, \mathrm{d}\Omega \qquad (2.2.2a)$$

and

$$\dot{\Psi} = \int \dot{\Psi}_\Omega \, \mathrm{d}\Omega. \qquad (2.2.2b)$$

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

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

2.2.3 Vectorial Fluence, Vectorial Energy Fluence

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

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

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

The **vectorial energy fluence**, $\boldsymbol{\Psi}$, is the integral of $\dot{\boldsymbol{\Psi}}$ with respect to time, t, where $\dot{\boldsymbol{\Psi}}$ is the vectorial 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 vectorial fluence and vectorial energy fluence, with respect to energy are given by

$$\boldsymbol{\Phi}_E = \mathrm{d}\boldsymbol{\Phi}/\mathrm{d}E = \int \dot{\boldsymbol{\Phi}}_E \, \mathrm{d}t \qquad (2.2.3a)$$

and

$$\boldsymbol{\Psi}_E = \mathrm{d}\boldsymbol{\Psi}/\mathrm{d}E = \int \dot{\boldsymbol{\Psi}}_E \, \mathrm{d}t, \qquad (2.2.3b)$$

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

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

$$\boldsymbol{\Psi} = \iiint \boldsymbol{\Omega} E \dot{\Phi}_{\Omega,E} \, \mathrm{d}t \, \mathrm{d}\Omega \, \mathrm{d}E. \qquad (2.2.4)$$

It should be noted that the (vectorial) integration of $\dot{\boldsymbol{\Phi}}_{\Omega,E}$ 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 2.1—*Scalar radiometric quantities*

Name[a]	Symbol	Unit	Definition	Where it appears in the report
particle number	N	1	—	Sect. 2.1.1
radiant energy	R	J	—	Sect. 2.1.1
energy distribution of particle number	N_E	J^{-1}	$\mathrm{d}N/\mathrm{d}E$	Eq. 2.1.1a
energy distribution of radiant energy	R_E	1	$\mathrm{d}R/\mathrm{d}E$	Eq. 2.1.1b
volumic particle number	n	m^{-3}	$\mathrm{d}N/\mathrm{d}V$	Eq. 2.1.3
volumic radiant energy	w	$\mathrm{J\,m}^{-3}$	$\mathrm{d}R/\mathrm{d}V$	—
energy distribution of volumic particle number	n_E	$\mathrm{m}^{-3}\,\mathrm{J}^{-1}$	$\mathrm{d}n/\mathrm{d}E$	—
energy distribution of volumic radiant energy	w_E	m^{-3}	$\mathrm{d}R/\mathrm{d}E$	—
flux	$\dot{N}$	s^{-1}	$\mathrm{d}N/\mathrm{d}t$	Sect. 2.1.2
energy flux	$\dot{R}$	W	$\mathrm{d}R/\mathrm{d}t$	Sect. 2.1.2
energy distribution of flux	$\dot{N}_E$	$\mathrm{s}^{-1}\,\mathrm{J}^{-1}$	$\mathrm{d}N/\mathrm{d}E$	—
energy distribution of energy flux	$\dot{R}_E$	s^{-1}	$\mathrm{d}R/\mathrm{d}E$	—
fluence	Φ	m^{-2}	$\mathrm{d}N/\mathrm{d}a$	Sect. 2.1.3
energy fluence	Ψ	$\mathrm{J\,m}^{-2}$	$\mathrm{d}R/\mathrm{d}a$	Sect. 2.1.3
energy distribution of fluence	Φ_E	$\mathrm{m}^{-2}\,\mathrm{J}^{-1}$	$\mathrm{d}\Phi/\mathrm{d}E$	Eq. 2.1.6a
energy distribution of energy fluence	Ψ_E	m^{-2}	$\mathrm{d}\Psi/\mathrm{d}E$	Eq. 2.1.6b
fluence rate	$\dot{\Phi}$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$	$\mathrm{d}\Phi/\mathrm{d}t$	Sect. 2.1.4
energy fluence rate	$\dot{\Psi}$	$\mathrm{W\,m}^{-2}$	$\mathrm{d}\Psi/\mathrm{d}t$	Sect. 2.1.4
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	$\dot{\Phi}_\Omega$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$	$\mathrm{d}\dot{\Phi}/\mathrm{d}\Omega$	Sect. 2.1.5
energy radiance	$\dot{\Psi}_\Omega$	$\mathrm{W\,m}^{-2}\,\mathrm{sr}^{-1}$	$\mathrm{d}\dot{\Psi}/\mathrm{d}\Omega$	Sect. 2.1.5
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. 2.1.9a
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. 2.1.9b

[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 2.2—*Vectorial radiometric quantities*

Name[a]	Symbol	Unit	Definition	Where it appears in the report
vectorial particle radiance	$\dot{\boldsymbol{\Phi}}_\Omega$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$	$\boldsymbol{\Omega}\dot{\Phi}_\Omega$	Sect. 2.2.1
vectorial energy radiance	$\dot{\boldsymbol{\Psi}}_\Omega$	$\mathrm{W\,m}^{-2}\,\mathrm{sr}^{-1}$	$\boldsymbol{\Omega}\dot{\Psi}_\Omega$	Sect. 2.2.1
energy distribution of vectorial particle radiance	$\dot{\boldsymbol{\Phi}}_{\Omega,E}$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{J}^{-1}$	$\boldsymbol{\Omega}\dot{\Phi}_{\Omega,E}$	Eq. 2.2.1a
energy distribution of vectorial energy radiance	$\dot{\boldsymbol{\Psi}}_{\Omega,E}$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$	$\boldsymbol{\Omega}\dot{\Psi}_{\Omega,E}$	Eq. 2.2.1b
vectorial fluence rate	$\dot{\boldsymbol{\Phi}}$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$	$\int \dot{\boldsymbol{\Phi}}_\Omega\,\mathrm{d}\Omega$	Sect. 2.2.2
vectorial energy fluence rate	$\dot{\boldsymbol{\Psi}}$	$\mathrm{W\,m}^{-2}$	$\int \dot{\boldsymbol{\Psi}}_\Omega\,\mathrm{d}\Omega$	Sect. 2.2.2
energy distribution of vectorial fluence rate	$\dot{\boldsymbol{\Phi}}_E$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{J}^{-1}$	$\int \dot{\boldsymbol{\Phi}}_{\Omega,E}\,\mathrm{d}\Omega$	—
energy distribution of vectorial energy fluence rate	$\dot{\boldsymbol{\Psi}}_E$	$\mathrm{m}^{-2}\,\mathrm{s}^{-1}$	$\int \dot{\boldsymbol{\Psi}}_{\Omega,E}\,\mathrm{d}\Omega$	—
vectorial fluence	$\boldsymbol{\Phi}$	m^{-2}	$\int \dot{\boldsymbol{\Phi}}\,\mathrm{d}t$	Sect. 2.2.3
vectorial energy fluence	$\boldsymbol{\Psi}$	$\mathrm{J\,m}^{-2}$	$\int \dot{\boldsymbol{\Psi}}\,\mathrm{d}t$	Sect. 2.2.3
energy distribution of vectorial fluence	$\boldsymbol{\Phi}_E$	$\mathrm{m}^{-2}\,\mathrm{J}^{-1}$	$\int \dot{\boldsymbol{\Phi}}_E\,\mathrm{d}t$	Eq. 2.2.3a
energy distribution of vectorial energy fluence	$\boldsymbol{\Psi}_E$	m^{-2}	$\int \dot{\boldsymbol{\Psi}}_E\,\mathrm{d}t$	Eq. 2.2.3b

[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."

3. 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 may 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, target or material.

The fundamental interaction coefficient is the *cross section* (see Section 3.1). 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 3.1.

3.1 Cross Section

The **cross section,** σ, of a target entity, for a particular interaction produced by incident charged or uncharged particles, is the quotient of P by Φ, where P is the probability of that interaction for a single target entity when subjected to the particle fluence, Φ, thus

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

Unit: 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, inter alia, 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 σ with respect to energy and solid angle (see Eq. 3.4.2).

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, σ, is expressed by the sum of the component cross sections, σ_J, hence

$$\sigma = \sum_J \sigma_J = \frac{1}{\Phi}\sum_J P_J, \qquad (3.1.1)$$

where P_J is the probability of an interaction of type J for a single target entity when subjected to the particle fluence Φ and σ_J is the component cross section relating to an interaction of type J.

3.2 Mass Attenuation Coefficient

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

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

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

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

The reciprocal of μ is called the *mean free path* of an uncharged particle.

The linear attenuation coefficient, μ, depends on the density, ρ, of the absorber. This dependence is largely removed by using the mass attenuation coefficient, μ/ρ.

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

$$\frac{\mu}{\rho} = \frac{N_\mathrm{A}}{M}\sigma = \frac{N_\mathrm{A}}{M}\sum_J \sigma_J, \qquad (3.2.1)$$

where σ_J is the component cross section relating to interaction of type J.

Relation 3.2.1 can be written as

$$\frac{\mu}{\rho} = \frac{n_\mathrm{t}}{\rho}\sigma, \qquad (3.2.2)$$

where n_t is the *volumic number 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,

$$\frac{\mu}{\rho} = \frac{1}{\rho}\sum_L (n_\mathrm{t})_L\sigma_L = \frac{1}{\rho}\sum_L (n_\mathrm{t})_L \sum_J \sigma_{L,J}, \qquad (3.2.3)$$

where $(n_\mathrm{t})_L$ is the volumic number of target entities of type L, σ_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. Relation 3.2.3, which ignores the changes in 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).

3.3 Mass Energy Transfer Coefficient

The **mass energy transfer coefficient**, μ_{tr}/ρ, of a material, for uncharged particles, is the quotient of $\mathrm{d}R_{\mathrm{tr}}/R$ by $\rho\,\mathrm{d}l$, where $\mathrm{d}R_{\mathrm{tr}}/R$ is the fraction of incident radiant energy that is transferred to kinetic energy of charged particles by interactions, in traversing a distance $\mathrm{d}l$ in the material of density ρ, thus

$$\frac{\mu_{\mathrm{tr}}}{\rho} = \frac{1}{\rho\,\mathrm{d}l}\frac{\mathrm{d}R_{\mathrm{tr}}}{R}\,.$$

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

In calculations relating to photons, the binding energy is usually included in the mass energy transfer coefficient. In materials consisting of elements of modest atomic number, this is generally significant below photon energies of 1 keV.

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, σ_J, by the relation

$$\frac{\mu_{\mathrm{tr}}}{\rho} = \frac{N_{\mathrm{A}}}{M}\sum_J f_J\,\sigma_J, \qquad (3.3.1)$$

where f_J is the average fraction of the incident particle energy that is transferred to kinetic energy of charged particles in an interaction of type J, 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, μ/ρ, by the equation

$$\frac{\mu_{\mathrm{tr}}}{\rho} = \frac{\mu}{\rho}\,f, \qquad (3.3.2)$$

where

$$f = \frac{\sum\limits_J f_J\,\sigma_J}{\sum\limits_J \sigma_J}\,.$$

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

$$\frac{\mu_{\mathrm{tr}}}{\rho} = \frac{1}{\rho}\sum_L (n_{\mathrm{t}})_L \sum_J f_{L,J}\,\sigma_{L,J}, \qquad (3.3.3)$$

where $(n_{\mathrm{t}})_L$ and $\sigma_{L,J}$ have the same meaning as in Eq. 3.2.3 and $f_{L,J}$ is the average fraction of the incident particle energy that is transferred to kinetic energy of charged particles in an interaction of type J with a target entity of type L. Relation 3.3.3 implies the same approximations as relation 3.2.3.

The product of μ_{tr}/ρ for a material and $(1 - g)$, where g is the fraction of the energy of liberated charged particles that is lost in radiative processes in the material, is called the *mass energy absorption coefficient*, μ_{en}/ρ, of the material for uncharged particles.

The mass energy absorption coefficient of a compound material depends on the stopping power (see Section 3.4) 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.

3.4 Mass Stopping Power

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

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

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

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

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

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

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{el}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{rad}} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{\mathrm{nuc}}, \qquad (3.4.1)$$

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) stopping power* due to collisions with electrons,

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

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

In addition, one can consider energy losses due to inelastic nuclear processes.

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

$$\frac{1}{\rho} S_{\mathrm{el}} = \frac{N_{\mathrm{A}}}{M} Z \int w \frac{\mathrm{d}\sigma}{\mathrm{d}w} \mathrm{d}w, \qquad (3.4.2)$$

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

Forming the quotient S_{el}/ρ 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).

3.5 Linear Energy Transfer (LET)

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

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

Unit: J m^{-1}

E_Δ may be expressed in eV and hence L_Δ may be expressed in eV m^{-1}, or some convenient multiples or submultiples, such as keV μm^{-1}.

The linear energy transfer, L_Δ, can also be expressed by

$$L_\Delta = S_{\mathrm{el}} - \frac{\mathrm{d}E_{\mathrm{ke},\Delta}}{\mathrm{d}l}, \qquad (3.5.1)$$

where S_{el} is the linear electronic stopping power and $\mathrm{d}E_{\mathrm{ke},\Delta}$ is the sum of the kinetic energies, greater than Δ, of all the electrons released by the charged particle traversing a distance $\mathrm{d}l$.

The definition expresses the following energy balance: energy lost by the primary charged particle in collisions with electrons, along a track segment $\mathrm{d}l$, minus energy carried away by secondary electrons having kinetic energies greater than Δ, equals energy considered as 'locally transferred', although the definition specifies an energy cutoff, Δ, and not a range cutoff.

This definition differs from that previously given (ICRU, 1980) in two respects. First, L_Δ now includes the binding energy for all collisions. As a consequence, L_0 refers to the energy lost that does not reappear as kinetic energy of released electrons. Second, the threshold of the kinetic energy of the released electrons is now Δ as opposed to Δ minus the binding energy.

In order to simplify notation, Δ may be expressed in eV. Then L_{100} is understood to be the linear energy transfer for an energy cutoff of 100 eV. L_∞, which is equal to S_{el}, may be replaced by L and is sometimes termed *unrestricted linear energy transfer.*

3.6 Radiation Chemical Yield

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

$$G(\mathrm{x}) = \frac{n(\mathrm{x})}{\epsilon}.$$

Unit: mol J^{-1}

The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon-12. The elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles or specified groups of such particles (BIPM, 1998).

A related quantity, called *G value,* has been de-

---

[1] The established term "mass nuclear stopping power" is a misnomer because it does not pertain to nuclear interactions.

fined 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 $(100\ \text{eV})^{-1}$. A G value of 1 $(100\ \text{eV})^{-1}$ corresponds to a radiation chemical yield of 0.104 μmol J^{-1}.

3.7 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 number of ion pairs formed when the initial kinetic energy E of a charged particle is completely dissipated in the gas, thus
>
> $$W = \frac{E}{N}.$$
>
> Unit: J

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 charged particles are included in N.

In certain cases, it may 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).

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

TABLE 3.1—*Interaction coefficients and related quantities*

Name	Symbol	Unit	Definition	Where it appears in the report
cross section	σ	m^2	P/Φ	Sect. 3.1
mass attenuation coefficient	μ/ρ	$\text{m}^2\ \text{kg}^{-1}$	$\text{d}N/\rho\ \text{d}l\ N$	Sect. 3.2
linear attenuation coefficient	μ	m^{-1}	$\text{d}N/N\ \text{d}l$	Sect. 3.2
mean free path	$1/\mu$	m	$N\ \text{d}l/\text{d}N$	Sect. 3.2
mass energy transfer coefficient	μ_{tr}/ρ	$\text{m}^2\ \text{kg}^{-1}$	$\text{d}R_{\text{tr}}/\rho\ \text{d}l\ R$	Sect. 3.3
mass energy absorption coefficient	μ_{en}/ρ	$\text{m}^2\ \text{kg}^{-1}$	$(\mu_{\text{tr}}/\rho)\,(1-g)$	Sect. 3.3
mass stopping power	S/ρ	$\text{J m}^2\ \text{kg}^{-1}$	$\text{d}E/\rho\ \text{d}l$	Sect. 3.4
linear stopping power	S	J m^{-1}	$\text{d}E/\text{d}l$	Sect. 3.4
linear energy transfer	L_Δ	J m^{-1}	$\text{d}E_\Delta/\text{d}l$	Sect. 3.5
radiation chemical yield	$G(\text{x})$	mol J^{-1}	$n(\text{x})/\epsilon$	Sect. 3.6
mean energy expended in a gas per ion pair formed	W	J	E/N	Sect. 3.7

4. Dosimetry

The effects of radiation on matter depend on the radiation field, as specified by the radiometric quantities defined in Sections 2.1 and 2.2, and on the interactions between radiation and matter, as characterized by the interaction quantities defined in Sections 3.1 to 3.5. Dosimetric quantities, which are devised to provide a physical measure to correlate with actual or potential effects, are, in essence, products of radiometric quantities and interaction coefficients. In calculations, the values of the relevant quantities of each type must be known, while measurements often do 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 which describe these processes are presented below in two sections dealing with the conversion and with the deposition of energy.

4.1 Conversion of Energy

The term conversion of energy refers to the transfer of energy from ionizing particles to secondary ionizing particles. The quantity *kerma* relates to the kinetic energy of the charged particles liberated by uncharged particles; the energy expended against the binding energies, usually a relatively small component, is, by definition, not included. In addition to kerma, a quantity called *cema* is defined which relates to the energy lost by charged particles (*e.g.*, electrons, protons, alpha particles) in collisions with atomic electrons. By definition, the binding energies are included. Cema differs from kerma in that cema involves the energy lost in electronic collisions by the incoming charged particles while kerma involves the energy imparted to outgoing charged particles.

4.1.1 Kerma[2]

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

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

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 Auger electrons.

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

$$K = \Phi E \mu_{\mathrm{tr}}/\rho, \qquad (4.1.1)$$

where μ_{tr}/ρ is the mass energy transfer coefficient of the material for these particles.

The kerma per unit fluence, K/Φ, 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 term kerma factor previously used 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, Φ_E, of the uncharged particle fluence with respect to energy (see Eq. 2.1.6a). The kerma, K, is then given by

$$K = \int \Phi_E E \frac{\mu_{\mathrm{tr}}}{\rho} \mathrm{d}E, \qquad (4.1.2)$$

where μ_{tr}/ρ is the mass energy transfer coefficient of the material for uncharged particles of energy E.

The expression of kerma in terms of fluence implies 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 which concerns initial transfer of energy to matter, it is sometimes used as an approximation to absorbed dose. Equality of absorbed dose and kerma is approached to the degree that *charged particle equilibrium* exists, that radiative losses are negligible, and that the energy of the uncharged particles is large compared to the binding energy of the released charged particles. Charged particle equilibrium exists at a point if the distribution of the charged particle radiance with respect to energy (see Eq. 2.1.9a) is constant within distances equal to the maximum charged particle range.

4.1.2 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}).

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[2] Kinetic energy released per unit mass.

4.1.3 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 total charge of the ions of one sign produced in air when all the electrons and positrons liberated or created by photons in air of mass $\mathrm{d}m$ are completely stopped in air, thus

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

Unit: C kg^{-1}

The ionization produced by Auger electrons 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 air kerma. Exposure can be expressed in terms of the distribution, Φ_E, of the fluence with respect to the photon energy, E, and the mass energy transfer coefficient, μ_{tr}/ρ, for air and for that energy as follows

$$X = \frac{e}{W} \int \Phi_E E \frac{\mu_{\mathrm{tr}}}{\rho} (1 - g)\, \mathrm{d}E, \qquad (4.1.3)$$

where e is the elementary charge, W is the mean energy expended in air per ion pair formed, g is the fraction of the energy of the electrons liberated by photons that is lost in radiative processes in air.

For photon energies of the order of 1 MeV or below, where the value of g is small, Eq. 4.1.3 may be approximated by $X = e/W\, K(1 - \bar{g})$, where K is the 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 kerma, it may 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.

4.1.4 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}

4.1.5 Cema[3]

The **cema**, C, is the quotient of $\mathrm{d}E_c$ by $\mathrm{d}m$, where $\mathrm{d}E_c$ is the energy lost by charged particles, except secondary electrons, in electronic collisions in a mass $\mathrm{d}m$ of a material, thus

$$C = \frac{\mathrm{d}E_c}{\mathrm{d}m}.$$

Unit: J kg^{-1}

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

The energy lost by charged particles in electronic collisions includes the energy expended against binding energy and any kinetic energy of the liberated electrons, referred to as secondary electrons. Thus, energy subsequently lost by all secondary electrons is excluded from $\mathrm{d}E_c$.

The cema, C, can be expressed in terms of the distribution Φ_E, of the charged particle fluence, with respect to energy (see Eq. 2.1.6a). According to the definition of cema, the distribution Φ_E does not include the contribution of secondary electrons to the fluence. The cema, C, is thus given by

$$C = \int \Phi_E \frac{S_{\mathrm{el}}}{\rho}\, \mathrm{d}E = \int \Phi_E \frac{L_\infty}{\rho}\, \mathrm{d}E, \qquad (4.1.4)$$

where S_{el}/ρ is the mass electronic stopping power of a specified material for charged particles of energy E, and L_∞ is the corresponding unrestricted linear energy transfer.

For charged particles of high energies, it may be undesirable to disregard energy transport by secondary electrons of all energies. A modified concept, *restricted cema*, C_Δ, (Kellerer *et al.*, 1992) is then defined as the integral

$$C_\Delta = \int \Phi'_E \frac{L_\Delta}{\rho}\, \mathrm{d}E. \qquad (4.1.5)$$

This differs from the integral in Eq. 4.1.4 in that L_∞ is replaced by L_Δ and that the distribution Φ'_E now includes secondary electrons with kinetic energies greater than Δ. For $\Delta = \infty$, restricted cema is identical to cema.

The expression of cema and restricted cema in terms of fluence implies 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 called cema and restricted cema can be used as approximations to absorbed dose from charged particles. Equality of absorbed dose and

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[3] Converted energy per unit mass.

cema is approached to the degree that *secondary electron equilibrium* exists and that radiative losses and those due to elastic nuclear collisions are negligible. Such an equilibrium is achieved at a point if the fluence of secondary electrons is constant within distances equal to their maximum range. For restricted cema, only partial secondary electron equilibrium, up to kinetic energy Δ, is required.

4.1.6 Cema Rate

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

$$\dot{C} = \frac{dC}{dt}.$$

Unit: $\text{J kg}^{-1}\,\text{s}^{-1}$

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

4.2 Deposition of Energy

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

4.2.1 Energy Deposit

The **energy deposit**, ϵ_i, is the energy deposited in a single interaction, i, thus

$$\epsilon_i = \epsilon_{\text{in}} - \epsilon_{\text{out}} + Q,$$

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

Unit: J

ϵ_i may also be expressed in eV.

ϵ_i may be considered as the energy deposited at the point of interaction, which is called the *transfer point, i.e.*, the location where an ionizing particle loses kinetic energy. The quantum-mechanical uncertainties of this location are ignored.

The energy deposits and transfer points, without further details of the interactions that cause them, are sufficient for a description of the spatial distribution of energy deposition by ionizing particles.

4.2.2 Energy Imparted

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

$$\epsilon = \sum_i \epsilon_i,$$

where the summation is performed over all energy deposits, ϵ_i, in that volume.

Unit: J

ϵ may also be expressed in eV.

The energy deposits over which the summation is performed may belong to one or more (*energy deposition) events;* for example, they may belong to one or several statistically independent particle tracks. The term event denotes the imparting of energy to matter by statistically 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 event, it is equal to the sum of the energy deposits in the volume associated with the event. If the energy imparted to the matter in a given volume is due to several events, it is equal to the sum of the individual energies imparted to the matter in the volume due to each event.

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

$$\bar{\epsilon} = R_{\text{in}} - R_{\text{out}} + \Sigma Q. \qquad (4.2.1)$$

4.2.3 Lineal Energy

The **lineal energy**, y, is the quotient of ϵ_s by $\bar{l}$, where ϵ_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

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

Unit: J m^{-1}

ϵ_s is the sum of the energy deposits ϵ_i in a volume from a single event and may be expressed in eV. Hence y may be expressed in multiples and submultiples of eV and m, *e.g.*, in keV μm^{-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).

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

$$f(y) = \frac{\mathrm{d}F(y)}{\mathrm{d}y}. \tag{4.2.2}$$

$F(y)$ and $f(y)$ are independent of absorbed dose and absorbed dose rate.

4.2.4 Specific Energy

The **specific energy (imparted)**, z, is the quotient of ϵ by m, where ϵ is the energy imparted to matter of mass m, thus

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

Unit: J kg^{-1}

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

The specific energy may 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

$$f(z) = \frac{\mathrm{d}F(z)}{\mathrm{d}z}. \tag{4.2.3}$$

$F(z)$ and $f(z)$ depend on absorbed dose. The probability density $f(z)$ includes a discrete component (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 event, $F_1(z)$, is the conditional probability that a specific energy less than or equal to z is deposited if one event has occurred. The probability density, $f_1(z)$, is the derivative of $F_1(z)$, thus

$$f_1(z) = \frac{\mathrm{d}F_1(z)}{\mathrm{d}z}. \tag{4.2.4}$$

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

$$y = \frac{\rho A}{4} z, \tag{4.2.5}$$

where A is the surface area of the volume, and ρ is the density of matter in the volume.

4.2.5 Absorbed Dose

The **absorbed dose**, D, is the quotient of $\mathrm{d}\bar{\epsilon}$ by $\mathrm{d}m$, where $\mathrm{d}\bar{\epsilon}$ is the mean energy imparted to matter of mass $\mathrm{d}m$, thus

$$D = \frac{\mathrm{d}\bar{\epsilon}}{\mathrm{d}m}.$$

Unit: J kg^{-1}

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

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

4.2.6 Absorbed Dose Rate

The **absorbed dose rate**, $\dot{D}$, is the quotient of $\mathrm{d}D$ by $\mathrm{d}t$, where $\mathrm{d}D$ is the increment of absorbed dose in the time interval $\mathrm{d}t$, 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 dose rate is gray per second (Gy s^{-1}).

TABLE 4.1—*Dosimetric quantities—Conversion of energy*

Name	Symbol	Unit		Definition	Where it appears in the report
kerma	K	J kg^{-1}	Gy	$\mathrm{d}E_{\mathrm{tr}}/\mathrm{d}m$	Sect. 4.1.1
kerma coefficient	—	J m^2 kg^{-1}	Gy m^2	K/Φ	Sect. 4.1.1
kerma rate	$\dot{K}$	J kg^{-1} s^{-1}	Gy s^{-1}	$\mathrm{d}K/\mathrm{d}t$	Sect. 4.1.2
exposure	X	C kg^{-1}		$\mathrm{d}Q/\mathrm{d}m$	Sect. 4.1.3
exposure rate	$\dot{X}$	C kg^{-1} s^{-1}		$\mathrm{d}X/\mathrm{d}t$	Sect. 4.1.4
cema	C	J kg^{-1}	Gy	$\mathrm{d}E_c/\mathrm{d}m$	Sect. 4.1.5
restricted cema	C_Δ	J kg^{-1}	Gy	—	Sect. 4.1.5
cema rate	$\dot{C}$	J kg^{-1} s^{-1}	Gy s^{-1}	$\mathrm{d}C/\mathrm{d}t$	Sect. 4.1.6

TABLE 4.2—*Dosimetric quantities—Deposition of energy*

Name	Symbol	Unit		Definition	Where it appears in the report
energy deposit	ϵ_i	J		$\epsilon_{\mathrm{in}} - \epsilon_{\mathrm{out}} + Q$	Sect. 4.2.1
energy imparted	ϵ	J		$\Sigma\, \epsilon_i$	Sect. 4.2.2
lineal energy	y	J m^{-1}		$\epsilon_s/\bar{l}$	Sect. 4.2.3
specific energy	z	J kg^{-1}	Gy	ϵ/m	Sect. 4.2.4
absorbed dose	D	J kg^{-1}	Gy	$\mathrm{d}\epsilon/\mathrm{d}m$	Sect. 4.2.5
absorbed dose rate	$\dot{D}$	J kg^{-1} s^{-1}	Gy s^{-1}	$\mathrm{d}D/\mathrm{d}t$	Sect. 4.2.6

5. Radioactivity

The term *radioactivity* refers to those spontaneous transformations that involve changes of the nuclei of atoms. The energy released in such transformations is emitted as photons and/or other radiations.

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

Atoms are subdivided into *nuclides*. A nuclide is a species of atoms having a specified number of protons and neutrons in its nucleus. Unstable nuclides, that 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.

5.1 Decay Constant

The **decay constant**, λ, of a radionuclide in a particular energy state is the quotient of $\mathrm{d}P$ by $\mathrm{d}t$, where $\mathrm{d}P$ is the probability that a given nucleus undergoes a spontaneous nuclear transformation from that energy state in the time interval $\mathrm{d}t$, thus

$$\lambda = \frac{\mathrm{d}P}{\mathrm{d}t}\,.$$

Unit: 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.

5.2 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 number of spontaneous nuclear transformations from that energy state in the time interval $\mathrm{d}t$, thus

$$A = \frac{\mathrm{d}N}{\mathrm{d}t}\,.$$

Unit: 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, λ, for that state, and the number N of nuclei in that state, thus

$$A = \lambda N. \tag{5.2.1}$$

5.3 Air Kerma-Rate Constant

The **air kerma-rate constant**, Γ_δ, 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 δ, 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: $\mathrm{m}^2\,\mathrm{J\,kg}^{-1}$

If the special names gray (Gy) and becquerel (Bq) are used, the unit of air kerma-rate constant is $\mathrm{m}^2\,\mathrm{Gy\,Bq}^{-1}\,\mathrm{s}^{-1}$.

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. In a source of finite size, attenuation and scattering occur, and annihilation radiation and external bremsstrahlung may be produced. In some 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 δ depends upon the application. To simplify notation and ensure uniformity, it is recommended that δ be expressed in keV. For example, Γ_5 is understood to be the air kerma-rate constant with a photon energy cutoff of 5 keV.

TABLE 5.1—*Quantities related to radioactivity*

Name	Symbol	Unit		Definition	Where it appears in the report
decay constant	λ	s^{-1}		$\mathrm{d}P/\mathrm{d}t$	Sect. 5.1
half life	$T_{1/2}$	s		$(\ln 2)/\lambda$	Sect. 5.1
activity	A	s^{-1}	Bq	$\mathrm{d}N/\mathrm{d}t$	Sect. 5.2
air kerma-rate constant	Γ_δ	$\mathrm{m}^2\,\mathrm{J\,kg}^{-1}$	$\mathrm{m}^2\,\mathrm{Gy\,Bq}^{-1}\,\mathrm{s}^{-1}$	$l^2\,\dot{K}_\delta/A$	Sect. 5.3

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The following ICRU Reports are now superseded and/or out of print:

ICRU Report No.	*Title and Reference**
1	*Discussion on International Units and Standards for X-ray work,* Br. J. Radiol. **23,** 64 (1927).
2	*International X-Ray Unit of Intensity,* Br. J. Radiol. (new series) **1,** 363 (1928).
3	*Report of Committee on Standardization of X-ray Measurements,* Radiology **22,** 289 (1934).
4	*Recommendations of the International Committee for Radiological Units,* Radiology **23,** 580 (1934).
5	*Recommendations of the International Committee for Radiological Units,* Radiology **29,** 634 (1937).
6	*Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units,* National Bureau of Standards Handbook 47 (U.S. Government Printing Office, Washington, D.C., 1951).
7	*Recommendations of the International Commission on Radiological Units,* Radiology **62,** 106 (1954).
8	*Report of the International Commission on Radiological Units and Measurements (ICRU) 1956,* National Bureau of Standards Handbook 62 (U.S. Government Printing Office, Washington, D.C., 1957).
9	*Report of the International Commission on Radiological Units and Measurements (ICRU) 1959,* National Bureau of Standards Handbook 78 (U.S. Government Printing Office, Washington, D.C., 1961).

10a *Radiation Quantities and Units,* National Bureau of Standards Handbook 84 (U.S. Government Printing Office, Washington, D.C., 1962).

10c *Radioactivity,* National Bureau of Standards Handbook 88 (U.S. Government Printing Office, Washington, D.C., 1963).

10d *Clinical Dosimetry,* National Bureau of Standards Handbook 87 (U.S. Government Printing Office, Washington, D.C., 1963).

10e *Radiobiological Dosimetry,* National Bureau of Standards Handbook 88 (U.S. Government Printing Office, Washington, D.C., 1963).

11 *Radiation Quantities and Units* (International Commission on Radiation Units and Measurements, Washington, D.C., 1968).

14 *Radiation Dosimetry: X Rays and Gamma Rays with Maximum Photon Energies Between 0.6 and 50 MeV* (1969).

19 *Radiation Quantities and Units* (International Commission on Radiation Units and Measurements, Washington, D.C., 1971).

19S *Dose Equivalent* [Supplement to ICRU Report 19] (International Commission on Radiation Units and Measurements, Washington, D.C., 1973).

21 *Radiation Dosimetry: Electrons with Initial Energies Between 1 and 50 MeV* (International Commission on Radiation Units and Measurements, Washington, D.C., 1972).

29 *Dose Specification for Reporting External Beam Therapy with Photons and Electrons* (International Commission on Radiation Units and Measurements, Washington, D.C., 1978).

33 *Radiation Quantities and Units* (International Commission on Radiation Units and Measurements, Bethesda, MD, 1980).

35 *Radiation Dosimetry: Electron Beams with Energies Between 1 and 50 MeV* (International Commission on Radiation Units and Measurements, Bethesda, MD, 1984).

*References given are in English. Some of the Reports were also published in other languages.

Index

Tables 2.1, 2.2, 3.1, 4.1, 4.2 and 5.1 provide guidance on where the definitions of quantities appear in the Report. They also provide information on symbols and units. They can be found on the pages indicated below: