ICRU REPORT 33

Radiation Quantities and Units

ICRU

INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS

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INTERNATIONAL COMMISSION ON RADIATION
UNITS AND MEASUREMENTS
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Preface

Scope of ICRU Activities

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,

(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 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 has divided its field of interest into twelve technical areas and has assigned one or more members of the Commission the responsibility for identification of potential topics for new ICRU activities in each area. A body of consultants has been constituted for each technical area to advise the Commission on the need for ICRU recommendations relating to the technical area and on the means for meeting an identified need. Each area is reviewed periodically by its sponsors and consultants. Recommendations of such groups for new reports are then reviewed by the Commission and a priority assigned.

The technical areas are:

Radiation Therapy
Radiation Diagnosis
Nuclear Medicine
Radiobiology
Radioactivity
Radiation Physics—X Rays, Gamma Rays and Electrons
Radiation Physics—Neutrons and Heavy Particles
Radiation Protection
Radiation Chemistry
Values of Factors—*W*, *S*, etc.
Theoretical Aspects
Quantities and Units

The actual preparation of ICRU reports is carried out by ICRU report committees. One or more Commission members serve as sponsors to each committee and provide close liaison with the Commission. The currently active report committees are:

- C_λ and C_E
- Clinical Dosimetry for Neutrons
- Computer Uses in Radiotherapy
- Definitions and Terminology for Computed Tomography
- Determination of Absorbed Dose Distribution Around a Source Used for Interstitial Therapy
- Dose Specification for Reporting Intracavitary and Intersititai Therapy
- Dosimetry of Pulsed Radiation
- High-Energy Electron Beam Dosimetry
- Measurement of Low-Level Radioactivity in Humans
- Microdosimetry
- Modulation Transfer Function for Screen-Film Systems
- Photographic Dosimetry in External Beam Therapy
- Practical Determination of Dose Equivalent Index
- Scanning
- Stopping Power

ICRU Reports

In 1962 the ICRU, in recognition of the fact that its triennial reports were becoming too extensive and in some cases too specialized to justify single-volume publication, initiated the publication of a series of reports, each dealing with a limited range of topics. This series was initiated with the publication of six reports:

- ICRU Report 10a, *Radiation Quantities and Units*
- ICRU Report 10b, *Physical Aspects of Irradiation*
- ICRU Report 10c, *Radioactivity*
- ICRU Report 10d, *Clinical Dosimetry*
- ICRU Report 10e, *Radiobiological Dosimetry*
- ICRU Report 10f, *Methods of Evaluating Radiological Equipment and Materials*

These reports were published, as had been many of the previous reports of the Commission, by the United States Government Printing Office as Handbooks of the National Bureau of Standards.

In 1967 the Commission determined that in the future the recommendations formulated by the ICRU would be published by the Commission itself. This report is published by the ICRU pursuant to this policy. With the exception of ICRU Reports 10a, 10d, and 10e, the other reports of the "10" series have continuing validity and, since no subsequent reports were designed specifically to supersede them, they will remain available until the material is essentially obsolete. All future reports of the Commission, however, will be published under the ICRU's own auspices. Information about the availability of ICRU Reports is given on page 23.

ICRU's Relationships With Other Organizations

In addition to its close relationship with the International Commission on Radiological Protection, 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 entered into consultative status with the International Atomic Energy Agency. 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 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 des Poids et Mesures
- Commission of the European Communities
- Council for International Organizations of Medical Sciences
- Food and Agriculture Organization
- International Council of Scientific Unions
- International Electrotechnical Commission
- International Labor Office
- 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 organizations of the participants. (Only token assistance was originally available from the International Society of Radiology.) Recognizing the impracticability of continuing this mode of operation on an indefinite basis, operating funds were sought from various sources.

Financial support has been received from the following organizations:

- Agfa-Gevaert, N.V.
- B.A.T. Cigaretten Fabriken GMBH
- Commission of the European Communities
- Council for International Organizations of Medical Sciences
- Dutch Society for Radiodiagnostics
- Eastman Kodak Company
- E. I. duPont de Nemours and Company
- Ford Foundation
- General Electric Company

Hitachi Medical Corporation
International Atomic Energy Agency
International Radiation Protection Association
International Society of Radiology
Japan Industries Association of Radiation Apparatus
John och Augusta Perssons stiftelse
National Cancer Institute of the U.S. Department of Health, Education and Welfare
N.V. Philips Gloeilampenfabrieken
Philips Medical Systems, Incorporated
Picker Corporation
Pyne X-Ray Corporation
Radiological Society of North America
Rockefeller Foundation
Shimadzu Corporation
Siemens Aktiengesellschaft
Society of Nuclear Medicine
Statens laegevidenskabelige Forskningsrad
United Nations
U.S. Bureau of Radiological Health of the Food and Drug Administration
World Health Organization
Xerox Corporation

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.

HAROLD O. WYCKOFF
Chairman, ICRU

Washington, D.C., U.S.A.
1 December 1979

Contents

Radiation Quantities and Units

Introduction

This report supersedes ICRU Report 19. Since ICRU Report 19 was published, a number of discussions have taken place between members of the Report Committee on Fundamental Quantities and Units and other workers in the field. Some of these discussions have resulted in the acceptance of certain modifications in the material set out in Report 19 and these modifications are incorporated in the current report. In addition, there has been some expansion and rearrangement of the material in the earlier report.

In 1948, the General Conference on Weights and Measures (a diplomatic conference responsible for the "international unification and development of the metric system") instructed its International Committee for Weights and Measures to develop a set of rules for the units of measurement. The "International System of Units" (SI) was developed under this charge and accepted by all signatories to the Metre Convention [1].

The special units, curie, röntgen, and rad are not coherent with this system and were listed among those units to be used for a limited time. The corresponding SI units are reciprocal second, coulomb per kilogram, and joule per kilogram, respectively. Recognizing that this shift to different units might cause difficulty, particularly in radiation therapy, the ICRU solicited comments on this matter in 1973 and 1974. From these comments, it appeared that the majority of workers in the field would find SI units acceptable if the transition period was sufficiently long and if there could be special names at least for reciprocal second and joule per kilogram. Therefore, the ICRU proposed special names for these units. The 1975 meeting of the General Conference adopted, for use with ionizing radiation, the special names of becquerel for reciprocal second and gray for joule per kilogram. The ICRU will use SI units and, where pertinent, special names. Currently, it will also include the relevant special units, but it plans to drop such usage by 1985.

The special unit of exposure has been röntgen. The approximate equality that exists between the numerical values of exposure in röntgens and absorbed dose to air, water, or soft tissue in rads under transient charged-particle equilibrium conditions is not retained when the SI units of these quantities, coulomb per kilogram and gray, are used. An approximate equality exists, however, between the numerical values of the air kerma expressed in grays and absorbed dose to air, water, or soft tissue in grays under transient charged-particle equilibrium conditions.

The special unit of dose equivalent has been rem since 1962. However, the SI unit of dose equivalent is joule per kilogram and a dose equivalent of one joule per kilogram is equal to 100 rems. It is desirable for purposes of radiation safety to have a special name for this SI unit. In 1977 the special name—sievert (Sv)—was proposed jointly by the ICRU and ICRP (International Commission on Radiological Protection) and this special name was approved by the General Conference of Weights and Measures in 1979. Sievert was used in ICRP Publication 26 (1977) and will be used in this document.

The Section on Radionuclides of the Consultative Committee on Standards Measurement for Ionizing Radiations of the International Committee for Weights and Measures suggested some modifications of the definition of activity given in ICRU Report 19. It recommended the insertion of "energy state" into the definition and the replacement of the word "transformation" by "transition." These modifications have now been incorporated into the current definition.

Helpful comments on the previous quantities and units report were received from a number of persons and some pertinent material has been published [2, 3]. As a result, clarification of several points has been incorporated in the present Report. The ICRU appreciates the assistance rendered by those who formulated comments.

In line with providing more didactic material and useful source material for other ICRU reports, the general considerations in subsection I.A of Report 19 have been expanded and placed in a separate subsection. The additional material includes discussions of four terms that are used in this document—quantity, unit, stochastic, and non-stochastic—along with a brief discussion of the mathematical formalism used in ICRU reports.

As in ICRU Report 19, the definitions of quantities and units specifically designed for radiation protection (Part B) are separated from those of the general quantities (Part A). The inclusion of the index concept outlined in ICRU Report 25 [4] required an extension of Part B.

Some of the quantities currently in use in the area of *ionizing radiation* are also used for other types of radiation and some quantities used for these radiations are very similar to those used for ionizing radiation. Generally, the names for such quantities are different in the various radiation areas. The names for similar quantities used by the Commission Internationale de l'Eclairage (CIE) and the Comité International de Photobiologie (CIP) are indicated in the notes following the pertinent ICRU definition. It is hoped that identification of such similarities will eventually lead to a common nomenclature. Closer ties between groups in related areas could minimize the spread of differences.

Prior ICRU reports on quantities and units have considered definitions of attenuation coefficient, energy transfer coefficient, and energy absorption coefficient primarily for photons although the last one included a brief treatment of cross sections for neutrons. The current document contains a broader treatment of cross sections and their relationship to the attenuation coefficient, which is a quantity of primary interest for ionizing radiation.

Part A

Quantities and Units for General Use

I. General Considerations

A. Introduction

This section deals with terms which are used throughout the remainder of the document. The Commission is of the opinion that the clarification of concepts and the definition of quantities are fundamental matters and that the choice of units is less important. Ambiguity can best be avoided if the quantities under consideration are clearly specified.

It is essential that one distinguishes between a quantity and a unit. A *physical quantity* characterizes a physical phenomenon in terms that are suitable for numerical specifications. For example, length, time, volume, and absorbed dose (of radiation) are all physical quantities. A *unit* is a selected reference sample of a quantity. Every physical quantity may be expressed as the product of a numerical value and a unit.

The ICRU recommends the use of SI units [1].

SI units are divided into three classes—base units, derived units, and supplementary units. The base units are metre, kilogram, second, ampere, kelvin, mole, and candela for the quantities, length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity, respectively.

Derived units are formed by combining base units according to the algebraic relations linking the corresponding quantities.

The current supplementary units are radian and steradian for the quantities plane angle and solid angle, respectively.

These three classes form a coherent system of units[1]. The ICRU uses the term "special units" for units with special names that are not coherent with SI. The curie, röntgen, rad, and rem are special units for the quantities activity, exposure, absorbed dose, and dose equivalent, respectively. Rad may also be used as a special unit for kerma, specific energy imparted, and absorbed dose index and rem may also be used for dose equivalent index. The ICRU recommends that the use of these special units be phased out by 1985 and that they be replaced by the appropriate SI units.

Some derived SI units are given special names, such as coulomb for ampere second. In addition, other derived units have been given special names when they are used only with a restricted number of quantities. The special names currently in use in this category are hertz (equal to reciprocal second for frequency), becquerel (equal to reciprocal second for activity of a radionuclide), gray (equal to joule per kilogram for absorbed dose, kerma, and specific energy imparted), and sievert (equal to joule per kilogram for dose equivalent).

There are also a few units that may be used *with* SI [1]. For some of these, their values in terms of SI units are obtained experimentally. Two of these are used in current ICRU documents—electronvolt (symbol eV) and unified atomic mass unit (symbol u). Others, such as day, hour and minute, are not coherent with SI but, because of long usage, are permitted to be used with SI.

Some of the definitions given in this document incorporate terms that require specification. These terms are ionization, ionizing radiation, nuclide, and energy deposition event.

Ionization is a process in which one or more electrons are liberated from a parent atom or molecule or other bound state.

Ionizing radiation consists of *charged particles* (for example, positive or negative electrons, protons or other heavy ions) and/or *uncharged particles* (for example, photons or neutrons) capable of causing ionization by primary or secondary processes. However, the ionization process is not the only process by which energy of the radiation may be transferred to a material. A second important phenomenon is excitation, a process which can also have physical, chemical, or biological consequences. A radiation, such as low energy photons, may be ionizing in one medium but not in another. Hence, the choice of a suitable energy cutoff, below which a radiation is considered as non-ionizing, will depend on circumstances. The definitions given in this report apply to a specified fixed cutoff value where relevant.

A *nuclide* is a species of atom having specified numbers of neutrons and protons in its nucleus.

The term *energy deposition event* denotes an event in which energy is imparted to the matter in a specified volume by an ionizing particle or a group of associated ionizing particles. The word "associated" refers to a particle and/or its secondaries. Examples of energy deposition events include energy deposition by an alpha particle and/or its delta rays and by one or both electrons arising from a pair production. For a given spectral distribution and type of ionizing radiation, the energy delivered by an event is independent of the fluence and absorbed dose or their rates.

B. Stochastic and Non-Stochastic Nature of Quantities

Statistical fluctuations between repeated observations are a well-known phenomenon in physics. In many situations one considers only the average value of a

[1] A *coherent system of units* is one in which all derived units can be obtained from a selected set of base units (by multiplication or division of base units) without the introduction of any numerical factors.

number of observations. It is assumed that, as the number of observations increases, the average value approaches the expectation value of the quantity. The expectation value will also be called "mean value" in this report.

It is often important to take into account the statistical fluctuations associated with energy deposition events, or other discrete events, and, therefore, of the varying values of a quantity and its mean.

A quantity subject to statistical fluctuations is termed stochastic and its mean a non-stochastic quantity. The differences between stochastic and non-stochastic quantities can best be illustrated by an example.

The *energy imparted,* ϵ (see Definition C.1), is subject to random fluctuations which become significant if the mass of interest is small, or the fluence of charged particles is low. The stochastic quantity *specific energy,* z (see Definition C.3), which is the quotient of the energy imparted, ϵ, by the specified mass, m, may deviate considerably from the associated non-stochastic quantity *absorbed dose,* D (see Definition C.4). Repeated measurements of z can establish an experimental distribution. This is an estimate of the probability distribution of z; the average of the experimental values of z is an estimate of the expectation value, $\bar{z}$. The limit of $\bar{z}$ as the mass approaches zero is D. The introduction of the stochastic quantity, specific energy, leads to a more rigorous definition of absorbed dose.

A *stochastic quantity* (such as the specific energy, z) has the following characteristics:

a. It is defined for finite domains only. Its values vary discontinuously in space and time and, generally, one does not refer to its rate of change.
b. Its value cannot be predicted. However, the probability of any particular value is determined by a probability distribution.
c. The fact of its randomness does not prejudice the accuracy with which single values of this quantity can be determined.

A *non-stochastic quantity* (such as the absorbed dose, D) has the following characteristics:

a. It is defined as a point function and is, in general, a continuous and differentiable function of space and time and one may refer to its gradient and its rate.
b. For given conditions, its value can, in principle, be calculated.
c. It can be estimated as the average of observed values of the associated stochastic quantity. In the case of a spatially non-uniform field, one has to derive the limiting values of this average for vanishingly small mass. The systematic uncertainties in an experimental determination may be larger than the statistical variations considered here, but the latter always exist.

Not all stochastic quantities that are associated with non-stochastic quantities are given separate definitions. For example, the (particle) fluence (see Definition A.3a) is defined in terms of the expectation value of the number of particles entering a sphere. In this instance, the associated random variable usually follows a simple Poisson distribution. As this can be readily calculated, it need not be considered in detail. Thus, in many applications the statistical fluctuations can be disregarded and all definitions of non-stochastic quantities can be adequately understood without such considerations. On the other hand, the variations of energy deposition are more complex, and in view of their evident importance in radiobiology, ϵ, z and y (see Definition C.2) are given separate names and symbols.

C. Mathematical Formalism

Mathematical formalism and terminology are less important than the definition of quantities and units, and no general rules need, therefore, be adopted. However, certain conventions are followed throughout this report. These relate to differentials in the definitions, and to spectral and probability distributions.

The definitions of non-stochastic quantities that are point functions are given in differential form. In accordance with common usage in physics, it will be understood that the arguments of differential quotients are always non-stochastic quantities. For example, in Definition A.3a the differential quotient $\mathrm{d}N/\mathrm{d}a$ is termed: "the quotient of $\mathrm{d}N$ by $\mathrm{d}a$, where $\mathrm{d}N$ is the number of particles which enter a sphere of cross-sectional area $\mathrm{d}a$," and $\mathrm{d}N$ is understood to be the differential of an expectation value of the particle number, N.

Activity of a radionuclide and absorbed dose are quantities of special practical importance and it is desirable that their definitions be provided in a form that does not require reference to the above considerations. They are, therefore, given in a slightly altered form by stating explicitly that the differential in the numerator is that of an expectation value.

In practice, many of the quantities defined below, to permit characterization of a radiation field and its interactions with matter, are used for radiations having a range of energies. In such instances, the distribution[2]

[2] In this report the term *distribution* is used in two senses: (a) to denote spectral distributions as in the present section; and (b) to denote probability distributions. Throughout this report, probability distributions, in contrast to spectral distributions, are assumed to be normalized; also, different symbolism is used to distinguish between the two types of distribution. To indicate specifically the cases where one deals with probability distributions, the proper mathematical terms *probability density* and *distribution function,* instead of the terms *differential distribution* and *sum* (or *integral*) *distribution,* respectively, are employed. Use of the latter terms has been reserved to identify different types of spectral distributions.

of a quantity with respect to another quantity can be defined. For example, the sum distribution, $\Phi(E)$, is that part of the fluence Φ (see Definition A.3a) due to particles with energy between 0 and E. The differential distribution, Φ_E, of the fluence with respect to the particle energy, E, is the derivative of $\Phi(E)$, with respect to E.

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

The integral of this differential distribution over all particle energies from zero to infinity is the fluence, Φ.

$$\Phi = \Phi(\infty) = \int_0^\infty \Phi_E \mathrm{d}E$$

The independent quantity need not always be energy; one can specify, for instance, the spectral distribution of the absorbed dose with respect to linear energy transfer.

In this report, spectral distributions of the type $\Phi(E)$ are termed integral or sum distributions and those of the type Φ_E are termed differential distributions. Since the dimension of the differential distribution of one quantity with respect to another is equal to the dimension of the quotient of the two quantities, the dimension of $\Phi(E)$ differs from that of Φ_E.

Interaction coefficients, such as the mass stopping power, S/ρ (see Definition B.5), or the mass attenuation coefficient, μ/ρ (see Definition B.2), are functions of the particle energy. For a radiation field having a complex energy spectrum, mean values such as $(\overline{\mu}/\rho)$ and $(\overline{S}/\rho)$, weighted according to the spectral distribution of the relevant quantity, may be useful. For example:

$$\overline{\mu}/\rho = \int_0^\infty (\mu/\rho)\,\Phi_E\,\mathrm{d}E \Big/ \int_0^\infty \Phi_E\,\mathrm{d}E$$
$$= \frac{1}{\Phi}\int_0^\infty (\mu/\rho)\,\Phi_E\,\mathrm{d}E$$

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

II. Definitions

The general pattern adopted in this subsection is to give a short definition for each quantity and to indicate in an explanatory note following the definition the precise meaning of any special phrase or term used. Only those definitions that are central to the consideration of radiation quantities and units are included and no attempt has been made to give a comprehensive list of all possible related definitions.

Following the definition of each quantity, its SI unit is indicated. If a special name for the SI unit has been approved, it is then given, together with its symbol and definition in terms of the SI unit. When a special unit has been used for the quantity, this is indicated, together with its relationship to the appropriate SI unit; it is also stated that the special unit may be used *temporarily*. While the ICRU has recommended that the special units be gradually abandoned over a period extending to 1985, some jurisdictions plan to complete the transition by an earlier date. Table 1 gives the symbol for each of the SI units used in this Report. Table 2 gives the name and symbol of each general use quantity defined here, together with the unit symbols used with it. Table 3 lists the SI prefixes.

The quantities defined in this subsection are divided into four categories. The first category is entitled "Radiometry" and deals with quantities associated with the radiation itself. The second category entitled "Interaction Coefficients" deals with quantities associated with the interaction of radiation and matter. The third category is entitled "Dosimetry" and deals with quantities that are generally products of quantities in the first and second categories. The fourth category is "Radioactivity."

A. Radiometry

Radiation measurements and investigations of radiation effects require various degrees of specification of the radiation field at points of interest. This subsection starts with the definition of the most elementary quantities associated with the radiation field and definitions of further quantities are developed from them which specify the radiation field with increasing detail.

These quantities deal with either particle number or energy and this is denoted in their names, e.g., particle flux or energy flux, etc. The word particle can be replaced by the more specific term for the considered entity, e.g., neutron flux, electron fluence, etc. Similarly, one may use neutron energy flux, electron energy fluence, etc.

If the radiation field is constituted by particles of various energies, the spectral distribution with respect to particle energy of any of the quantities defined in this subsection may be required. They are obtained as the derivatives of the quantities with respect to energy, E.

Thus:

$$R_E = \frac{\mathrm{d}R(E)}{\mathrm{d}E} \text{ and } p_E = \frac{\mathrm{d}p(E)}{\mathrm{d}E}$$

are, respectively, the spectral distributions of the radiant energy, R (see Definition A.1b), and the particle radiance, p (see Definition A.5a), with respect to particle energy.

A.1a. The *particle number, N,* is the number of particles emitted, transferred, or received.
Unit: 1

A.1b. The *radiant energy, R,* is the energy of particles (excluding rest energy) emitted, transferred, or received.
Unit: J

A.2a. The *(particle) flux,* $\dot{N}$, is the quotient of dN by dt, where dN is the increment of particle number in the time interval dt.

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

Unit: s^{-1}

A.2b. The *energy flux*[3], $\dot{R}$, is the quotient of dR by dt, where dR is the increment of radiant energy in the time interval dt.

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

Unit: W

A.3a. The *(particle) fluence*[4], Φ, is the quotient of dN by da, where dN is the number of particles incident on a sphere[5] of cross-sectional area da.

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

Unit: m^{-2}

A.3b. The *energy fluence*[6], Ψ, is the quotient of dR

[3] The Commission Internationale de l'Eclairage (CIE) and the International Organization for Standardization (ISO) define this quantity as "power emitted, transferred or received in the form of radiation" and call it "radiant flux" or "radiant power."

[4] This quantity is the same as the quantity nvt commonly used in neutron physics, where n is the (volume) density of neutrons, v their velocity and t the time.

[5] The area da must be perpendicular to each radiation's direction. A sphere arranges this in the simplest manner.

[6] This quantity is related to the quantity defined as the energy falling on a given plane surface element divided by the area of that surface element and called *radiant exposure, H,* by CIE and *dose* by Comité International de Photobiologie (CIP). When a parallel beam is incident at an angle θ with the normal to a given surface element, the radiant exposure H is equal to $\Psi \cos \theta$.

by da, where dR is the radiant energy incident on a sphere[7] of cross-sectional area da.

$$\Psi = \frac{dR}{da}$$

Unit: J m^{-2}

A.4a. The *(particle) fluence rate*, φ, is the quotient of dΦ by dt, where dΦ is the increment of particle fluence in the time interval dt.

$$\varphi = \frac{d\Phi}{dt} = \frac{d^2N}{da\,dt}$$

Unit: m^{-2} s^{-1}

Note: The term particle flux density is also used as the name for this quantity. As the word density has several connotations, the term particle fluence rate is preferable.

A.4b. The *energy fluence rate*[8], ψ, is the quotient of dΨ by dt, where dΨ is the increment of energy fluence in the time interval dt.

$$\psi = \frac{d\Psi}{dt} = \frac{d^2R}{da\,dt}$$

Unit: W m^{-2}

Note: The term energy flux density is also used as the name for this quantity. As the word density has several connotations, the term energy fluence rate is preferable.

A.5a. The *particle radiance*[9], *p*, is the quotient of dφ by dΩ, where dφ is the fluence rate of particles propagating in a specified direction within a solid angle dΩ.

$$p = \frac{d\varphi}{d\Omega} = \frac{d^3N}{da\,dt\,d\Omega}$$

Unit: m^{-2} s^{-1} sr^{-1}

A.5b. The *energy radiance*[9], *r*, is the quotient of dψ by dΩ, where dψ is the energy fluence rate of particles propagating in a specified direction within a solid angle dΩ.

$$r = \frac{d\psi}{d\Omega} = \frac{d^3R}{da\,dt\,d\Omega}$$

Unit: W m^{-2} sr^{-1}

All quantities defined in this section can be obtained by successive integrations of the *spectral distribution*, p_E, of the particle radiance, p, with respect to particle energy, E, solid angle, Ω, and time, t.

The *particle radiance, p,*

$$p = \int_E p_E\,dE$$

The *(particle) fluence rate,* φ,

$$\varphi = \int_E \int_\Omega p_E\,d\Omega\,dE$$

The *(particle) fluence,* Φ,

$$\Phi = \int_E \int_\Omega \int_t p_E\,dt\,d\Omega\,dE$$

The *energy radiance, r,*

$$r = \int_E E p_E\,dE$$

The *energy fluence rate,* ψ,

$$\psi = \int_E \int_\Omega E p_E\,d\Omega\,dE$$

The *energy fluence,* Ψ,

$$\Psi = \int_E \int_\Omega \int_t E p_E\,dt\,d\Omega\,dE$$

Similar integrations can be performed with respect to area. However, their form will depend on circumstances.

B. Interaction Coefficients

Interaction coefficients are non-stochastic quantities. They characterize interactions between radiation and matter. Therefore, they are usually given for specified radiations (also, often, for specified radiation energies), specified materials and, when applicable, also for specified types of interactions. Such specifications, while not required in the definitions, are essential when numerical values are quoted.

B.1. The *cross section*, σ, of a target entity, for an interaction produced by incident charged or uncharged particles is the quotient of P by Φ, where P is the probability of the interaction for one target entity when subjected to the particle fluence Φ.

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

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[7] The area da must be perpendicular to each radiation's direction. A sphere arranges this in the simplest manner.

[8] This quantity is related to the quantities *radiant flux (surface) density, radiant exitance,* and *irradiance* defined by the CIE and *dose rate* defined by the CIP, which refer to a given plane surface element, in contrast with energy fluence rate, which refers to a cross-sectional area of a sphere.

[9] The same quantity has been defined in a somewhat different way and named *radiance* by the CIE. In order to promote the unification of nomenclature for all radiations, the same name has been adopted here, together with the modifier "energy" or "particle."

Unit: m^2

The special unit of cross section is the barn, b,

$$1\ \text{b} = 10^{-28}\ \text{m}^2$$

Notes: (a) The term *interaction* refers to processes whereby the energy and/or the direction of the incident particle is altered. The interaction may be followed by the emission of a secondary particle or particles. In the case of nuclear reactions, the type of interaction is frequently expressed by specifying the incoming particle type and the outgoing particle type(s): e.g., $\sigma_{\gamma,n}$, the photo-neutron emission cross section; $\sigma_{n,n'}$, the inelastic scattering cross section . . . By analogy, the same notation can also be used for atomic interactions: e.g., $\sigma_{\gamma,e}$, the photoelectric cross section; $\sigma_{\gamma,\gamma}$, the Rayleigh scattering cross section . . .

Additional symbolism may be needed to distinguish between nuclear and extranuclear interactions.

(b) If several independent interactions are possible for a given target entity, the total cross section, σ, can be expressed as the sum of the individual cross sections, σ_J,

$$\sigma = \sum_J \sigma_J = \frac{1}{\Phi} \sum P_J$$

where P_J is the probability of an interaction of type J.

(c) The cross section of compound target entities such as molecules, are usually treated as if they were mixtures of independent atoms. This is justified in most cases, but can occasionally lead to errors, for example, for low-energy photons [5].

B.2. The *mass attenuation coefficient, μ/ρ,* of a material for uncharged ionizing particles is the quotient of dN/N by $\rho\, dl$, where dN/N is the fraction of particles that experience interactions in traversing a distance dl in a material of density ρ.

$$\frac{\mu}{\rho} = \frac{1}{\rho N} \frac{dN}{dl}$$

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

Notes: (a) μ is the *total linear attenuation coefficient.*

(b) Alternatively, if interactions between target entities contained in a target of a given atomic species can be disregarded, 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 element.

$$\frac{\mu}{\rho} = \frac{N_A}{M}\sigma$$

(c) For photons, one may write:

$$\frac{\mu}{\rho} = \frac{N_A}{M}(\sigma_{\gamma,e} + \sigma_{\gamma,\gamma'e} + \sigma_{\gamma,\gamma} + \sigma_{\gamma,ee^+})$$

where the component cross sections refer to those for the photoelectric effect, Compton effect, coherent scattering, and pair production, respectively. At energies in excess of a few MeV, further terms for nuclear interactions may need to be added, e.g., $\sigma_{\gamma,n}$, $\sigma_{\gamma,p}$ . . .

(d) For x rays and gamma rays, the separate components of μ/ρ are not usually expressed in terms of cross sections; the following notation is used:

$$\frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma_c}{\rho} + \frac{\sigma_{coh}}{\rho} + \frac{\kappa}{\rho}$$

where the component mass attenuation coefficients refer to those for the photoelectric effect, Compton effect, coherent scattering, and pair production, respectively. At energies in excess of a few MeV, extra terms for nuclear interactions may need to be added.

(e) In neutron physics, μ is sometimes given the symbol Σ and called the "macroscopic cross section." A separate symbol and the special name should be discouraged; the latter because the quantity does not have the dimensions of a cross section.

(f) The mass attenuation coefficients of compound target entities such as molecules, are usually treated as if they were mixtures of independent atoms. This is justified in most cases, but can occasionally lead to errors, for example, for low-energy photons [5].

B.3. The *mass energy transfer coefficient, μ_{tr}/ρ,* of a material for uncharged ionizing particles, is the quotient of dE_{tr}/EN by $\rho\, dl$, where E is the energy of each particle (excluding rest energy), N is the number of particles, and dE_{tr}/EN is the fraction of incident particle energy that is transferred to kinetic energy of charged particles by interactions in traversing a distance dl in the material of density ρ.

$$\frac{\mu_{tr}}{\rho} = \frac{1}{\rho E N} \frac{dE_{tr}}{dl}$$

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

Notes: (a) By convention, E does not include the rest energy of the particle. The sum of the initial kinetic energies of all the charged ionizing particles liberated by the uncharged ionizing particles is denoted by dE_{tr} (see Definition C.6).

(b) Alternatively, if interactions between target entities contained in a target of a given atomic species can be disregarded, the mass energy transfer coefficient can be expressed in terms of the cross sections:

$$\frac{\mu_{tr}}{\rho} = \frac{N_A}{M} \sum_J f_J \sigma_J$$

$$= \frac{\mu}{\rho} f$$

where f is a weighted average of f_J and f_J is the average of the fraction of the incident particle energy, E (excluding rest energy), that is transferred to kinetic energy of charged particles in each interaction of type J, μ/ρ is the mass attenuation coefficient, N_A is the Avogadro constant, and M is the molar mass of the target element.

(c) For photons, one may write:

$$\frac{\mu_{tr}}{\rho} = \frac{N_A}{M} (\sigma_{\gamma,e} f_{\gamma,e} + \sigma_{\gamma,\gamma'e} f_{\gamma,\gamma'e} + \sigma_{\gamma,ee^+} f_{\gamma,ee^+})$$

where the component[10] cross sections refer to those for the photoelectric effect, the Compton effect, and pair production, respectively, and

$$f_{\gamma,e} = 1 - \frac{\delta}{h\nu}$$

where δ is the average energy emitted as fluorescent radiation per photon absorbed and $h\nu$ is the energy of the incident photon,

$$f_{\gamma,\gamma'e} = 1 - \frac{\overline{h\nu'} + \delta}{h\nu}$$

where $\overline{h\nu'}$ is the average energy of the Compton scattered photons,

$$f_{\gamma,ee^+} = 1 - \frac{2mc^2}{h\nu}$$

where mc^2 is the rest mass energy of the electron.

(d) For x rays and gamma rays, the separate components of μ_{tr}/ρ are not usually expressed in terms of cross sections; instead, the following notation[10] is used,

$$\frac{\mu_{tr}}{\rho} = \frac{\tau_a}{\rho} + \frac{\sigma_{ca}}{\rho} + \frac{\kappa_a}{\rho}$$

where the component mass energy transfer coefficients refer to those for the photoelectric effect, Compton effect, and pair production, respectively, and

$$\frac{\tau_a}{\rho} = \frac{\tau}{\rho}\left(1 - \frac{\delta}{h\nu}\right)$$

where τ/ρ is the photoelectric mass attenuation coefficient,

$$\frac{\sigma_{ca}}{\rho} = \frac{\sigma_c}{\rho} \frac{\overline{E}_e}{h\nu}$$

where σ_c/ρ is the Compton mass attenuation coefficient, $\overline{E}_e$ is the average energy of the Compton recoil electron, and

$$\frac{\kappa_a}{\rho} = \frac{\kappa}{\rho}\left(1 - \frac{2mc^2}{h\nu}\right)$$

where κ/ρ is the mass attenuation coefficient for pair production.

(e) For neutrons, one may write:

$$\frac{\mu_{tr}}{\rho} = \frac{1}{E} \sum_L N_L \sum_J \epsilon_{LJ}(E)\sigma_{LJ}(E)$$

The index L identifies the nuclide, and the index J identifies the type of nuclear reaction (elastic scattering, inelastic scattering, (n,α), etc.). N_L is the quotient of the number of nuclei of the L-th species in a volume element by the mass of matter in this volume element; $\epsilon_{LJ}(E)$ is the average energy transferred to kinetic energy of charged particles in an interaction whose cross section is $\sigma_{LJ}(E)$. For elastic scattering the average recoil energy, ϵ_{el}, is

$$\epsilon_{el} = 2m_t m_n E(1 - f_1)/(m_t + m_n)^2$$

where m_t is the mass of the target nucleus, m_n is the mass of the neutron, and f_1 is the mean value of the cosine of the angle of deflection in the center of mass system. For other processes similar, but more complex, relations hold [6].

(f) The mass energy transfer coefficient of compound target entities such as molecules are usually treated as if they were mixtures of independent atoms. This is justified in most cases but can occasionally lead to errors, for example, for low-energy photons [5].

B.4. The *mass energy absorption coefficient*, μ_{en}/ρ, of a material for uncharged ionizing particles is the product of the mass energy transfer coefficient, μ_{tr}/ρ, and $(1 - g)$, where g is the fraction of the energy of secondary charged particles that is lost to bremsstrahlung in the material.

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

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

Notes: (a) Alternatively, if interactions between target entities contained in a target of a given atomic species can be disregarded, the mass energy absorption coefficient can be expressed in terms of the cross sections:

[10] For energies in excess of a few MeV, extra terms for nuclear interactions may need to be added.

$$\frac{\mu_{en}}{\rho} = \frac{N_A}{M} \sum_J f_J(1 - g_J)\sigma_J$$

where N_A is the Avogadro constant, M is the molar mass of the target element, f_J is the average of the fraction of the incident particle energy, E (excluding rest energy), that is transferred to kinetic energy of charged particles in each interaction of type J with an interaction cross section σ_J and g_J is the fraction of the energy of secondary charged particles produced in interaction J that is lost to bremsstrahlung.

(b) μ_{en}/ρ and μ_{tr}/ρ can differ appreciably when the kinetic energies of the secondary charged particles are comparable with, or larger than, their rest mass energies, particularly for interactions in high atomic number materials.

B.5. The *total 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.

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

Unit: $\mathrm{J\,m^2\,kg^{-1}}$
E may be expressed in eV and hence S/ρ may be expressed in $\mathrm{eV\,m^2\,kg^{-1}}$.

Notes: (a) S is the *total linear stopping power.*

(b) For energies at which nuclear interactions can be neglected, the total mass stopping power is

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{col} + \frac{1}{\rho}\left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_{rad}$$

where $(\mathrm{d}E/\mathrm{d}l)_{col} = S_{col}$ is the linear collision stopping power and $(\mathrm{d}E/\mathrm{d}l)_{rad} = S_{rad}$ is the linear radiative stopping power.

(c) Total mass stopping power can also be expressed in terms of cross sections in a manner analogous to that discussed for μ_{tr}/ρ.

B.6. The *linear energy transfer* or *restricted linear collision stopping power, L_Δ,* of a material for charged particles is the quotient of $\mathrm{d}E$ by $\mathrm{d}l$, where $\mathrm{d}E$ is the energy lost by a charged particle in traversing a distance $\mathrm{d}l$ due to those collisons with electrons in which the energy loss is less than Δ.

$$L_\Delta = \left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_\Delta$$

Unit: $\mathrm{J\,m^{-1}}$
E may be expressed in eV and hence L_Δ may be expressed in $\mathrm{eV\,m^{-1}}$, or some convenient submultiple or multiple, such as $\mathrm{keV\,\mu m^{-1}}$.

Notes: (a) Although the definition specifies an energy cut-off and not a range cutoff, the energy losses are sometimes referred to as "energy locally transferred."

(b) 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.

(c) $L_\infty = S_{col}$.

(d) The linear energy transfer can also be expressed in terms of cross sections in a manner analogous to that discussed for μ_{tr}/ρ.

B.7. The *radiation chemical yield, G*(x), is the quotient of n(x) by $\bar{\epsilon}$, where n(x) is the mean amount of substance of a specified entity, x, produced, destroyed, or changed by the mean energy imparted, $\bar{\epsilon}$, to the matter.

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

Unit: $\mathrm{mol\,J^{-1}}$

Note: A related quantity, *G-value,* has been defined as the quotient of the mean number of elementary entities produced, destroyed or changed and the energy imparted. It has been expressed in $(100\ \mathrm{eV})^{-1}$. For example, the G-value for Fe^{3+} of 15.5 $(100\ \mathrm{eV})^{-1}$ for cobalt-60 gamma rays becomes 1.61 $\mu\mathrm{mol\,J^{-1}}$.

B.8. The *mean energy expended in a gas per ion pair formed, W,* is the quotient of E by $\overline{N}$, where $\overline{N}$ is the mean number of ion pairs formed when the initial kinetic energy E of a charged particle is completely dissipated in the gas.

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

Unit: J
W may be expressed in eV.

Notes: (a) It follows from the definition that the ions produced by the bremsstrahlung or other secondary radiation emitted by the charged particles are included in $\overline{N}$.

(b) 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 a differential concept is indicated which is defined in ICRU Report 31 [7].

C. Dosimetry

The effects of radiation on matter depend on the magnitude of the radiation field, as specified by the quantities defined in Section IIA, and on the degree of