Supersedes no. 11

ICRU REPORT 19

Radiation Quantities and Units

INTERNATIONAL COMMISSION
ON RADIATION UNITS
AND MEASUREMENTS

ICRU REPORT 19

Radiation Quantities and Units

Issued July 1, 1971

INTERNATIONAL COMMISSION ON RADIATION
UNITS AND MEASUREMENTS
7910 WOODMONT AVENUE
WASHINGTON, D.C. 20014
U.S.A.

Library of Congress Catalog Card Number 68-56968

Copies of this report can be purchased for U.S. $2.50 each from

ICRU Publications
P.O. Box 30165
Washington, D.C. 20014
U.S.A.

(For detailed information on the availability of this and other ICRU Reports see page 19)

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 recommendations in the field of radiation protection. 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 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 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 eleven technical areas and has assigned one or more members of the Commission to serve as sponsor for 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
Values of Factors—$\overline{W}$, S, etc.
Theoretical Aspects
Quantities and Units

The actual preparation of ICRU reports is carried out by ICRU report committees working in each of these technical areas. The currently active report committees in the various technical areas are as follows:

Radiation Therapy	Methods of Arriving at the Absorbed Dose at any Point in the Patient (In Vivo Dosimetry)
	Methods of Compensating for Body Shape and Inhomogeneity and of Beam Modification for Special Purposes (Beam Modification)
	Dose Specification for Reporting
Radiation Diagnosis	Modulation Transfer Function, Its Definition and Measurement
Nuclear Medicine	Scanning of Internally Deposited Radionuclides

	Methods of Assessment of Dose in Tracer Investigations
Radioactivity	Measurement of Low Level Radioactivity
Radiation Physics—X Rays, Gamma Rays and Electrons	Radiation Dosimetry—Electrons with Initial Energies Between 1 and 50 MeV
Radiation Physics—Neutrons and Heavy Particles	High Energy and Space Radiation Dosimetry
Radiation Protection	Radiation Protection Instrumentation and Its Application

In 1962, the Commission decided to abandon its past practice of holding a meeting together with all its subunits every three years. Instead, it was decided that the Commission would receive reports from the subgroups at the time of their completion rather than at fixed deadlines. Meetings of the Commission and of the subgroups are held as needed.

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 Report 10a, the other reports of the "10" series have continuing validity and, since none of the reports now in preparation is 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 19.

ICRU's Relationships With Other Organizations

The ICRU has developed relationships with other organizations interested in the problems of radiation quantities, units, and measurements. In addition to its close relationship with the International Commission on Radiological Protection and its financial relationships with the International Society of Radiology, the World Health Organization, and the International Atomic Energy Agency, the ICRU has also developed relationships of varying intensity with several other organizations. 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 worldwide 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
Council for International Organizations of Medical Sciences
Food and Agriculture Organization
International Council of Scientific Unions
International Electrotechnical Commission
International Labor Office
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 in addition to those supplied by the International Society of Radiology.

Prior to 1959, the principal financial assistance to the ICRU had been provided by the Rockefeller Foundation which supplied some $11,000 to make possible various meetings. In 1959 the International Society of Radiology increased its contribution to the Commission providing $3,000 for the period 1959–1962. For the periods 1962–1965 and 1965–1969 the Society's contributions were $5,000 and $7,500, respectively. In 1960 the Rockefeller Foundation supplied an additional sum of some $4,000 making possible a meeting of the Quantity and Units Committee in 1960.

In 1960 and 1961 the World Health Organization made available the sum of $3,000 each year. This was increased to $4,000 per year in 1962, $6,000 in 1969, and $8,000 in 1970. It is expected that this sum will be allocated annually, at least for the next several years.

In connection with the Commission's Joint Studies with the ICRP, the United Nations allocated the sum of $10,000 for the joint use of the two Commissions.

The most substantial contribution to the work of the ICRU has come from the Ford Foundation. In December 1960, the Ford Foundation made available to the Commission the sum of $37,000 per year for a period of five years. This grant was to provide for such items as travel expenses to meetings, for secretarial services and other operating expenses. In 1965 the Foundation agreed to a time extension of this grant making available for the period 1966–1970 the unused portion of the original grant. To a large extent, it is because of this grant that the Commission has been able to move forward actively with its program.

In 1963 the International Atomic Energy Agency allocated the sum of $6,000 per year for use by the ICRU. This was increased to $9,000 in 1967. It is expected that this sum will be allocated annually at least for the next several years.

In 1970 the Statens lægevidenskabelige Forskningsråd of Denmark contributed $1,000 in support of the Commission's work.

From 1934 through 1964 valuable indirect contributions were made by the U.S. National Bureau of Standards where the Secretariat resided. The Bureau provided substantial secretarial services, publication services and travel costs in the amount of several thousands of dollars.

The Commission wishes to express its deep appreciation to all of these and other organizations that have contributed so importantly to its work.

Composition of the ICRU

It is of interest to note that the membership of the Commission and its subgroups totals 91 persons drawn from 14 countries. This gives some indication of the extent to which the ICRU has achieved international breadth of membership within its basic selection requirement of high technical competence of individual participants.

The current membership of the Commission is as follows:

H. O. Wyckoff, *Chairman*
A. Allisy, *Vice Chairman*
K. Lidén, *Secretary*
F. P. Cowan
F. Gauwerky
J. R. Greening
A. M. Kellerer
R. H. Morgan
H. H. Rossi
W. K. Sinclair
F. W. Spiers
A. Tsuya
A. Wambersie

Composition of ICRU Committee Responsible for the Initial Drafting of this Report

Serving on the Committee on Fundamental Quantities and Units during the preparation of this report were:

H. O. Wyckoff, *Chairman*
A. Allisy
H. Fränz
W. A. Jennings
A. M. Kellerer
K. Lidén
H. H. Rossi

Consultants

T. Axton
J. W. Boag
W. G. Marley
F. D. Sowby
A. Wambersie

The Commission wishes to express its appreciation to the individuals involved in the preparation of this report for the time and effort they devoted to this task.

Harold O. Wyckoff
Chairman, ICRU

Washington, D.C.
March 1, 1971

Contents

Radiation Quantities and Units

Introduction

This report supersedes ICRU Report 11. The major changes are: (a) introduction of additional quantities particularly in the areas of microdosimetry and radiation protection; and (b) more rigorous definitions of the quantities resulting in a somewhat different formalism without altering their meaning or range of applicability. The quantities defined are listed in Tables 1 and 2.

It is recognized that certain terms for which definitions are given here are of interest in other fields of science and that they are already variously defined elsewhere. The precise wording of the definition and even the name and symbol of any quantity may, at some future date, require alteration if discussions with representatives of other interested groups of scientists should lead to agreement on a common definition or symbol. Although the definitions represent some degree of compromise, they are believed to meet requirements in the field of radiation measurement.

The Commission is of the opinion that the definition of concepts and quantities is a fundamental matter and that the choice of units is less important. Ambiguity can best be avoided if the quantity under consideration is clearly specified. The system of units recommended here is the International System of Units (SI). Nevertheless, special units do exist in this as in many other fields. For example, the hertz is restricted, by established convention, to the measurement of temporal frequency, and the curie to the measurement of the activity of a quantity of a nuclide. One does not measure activity in hertz nor temporal frequency in curies although these quantities have the same dimension.

The Commission considers that the establishment of additional special units in the field of radiation dosimetry is undesirable, but continues to recognize the existing special units. It recommends that the use of these special units be restricted as follows:

rad—for specific energy, absorbed dose, absorbed dose index, and kerma
roentgen—for exposure
curie—for activity
rem—for dose equivalent and dose equivalent index.

The Commission has been aware of the need for the formulation of quantities and units suitable for radiation protection. It is also mindful of the fact that there are widespread differences of opinion in this area. However, the disagreement involves in essence only matters of concept and interpretation and there is a general consensus on how the quantities in question are to be determined and applied. Since it is only these operational aspects that are pressing, it has been decided to provide pragmatic definitions. Thus, the definition of the dose equivalent is sufficiently explicit for effective utilization, although the nature of the quantity remains largely unspecified. Since this approach is quite different from that employed for most of the quantities defined here, the recommendations related to radiation protection are incorporated into a separate part of this report. Two new quantities are also introduced in this part together with explanatory material.

Part I

Fundamental Quantities and Units

A. Detailed Considerations Relating to Physical Radiation Quantities

1. Stochastic Quantities and Non-stochastic Quantities

Because radiations and their interaction with matter are of a discrete nature, certain radiation quantities can only be described in statistical terms. This mode of description is analyzed here in some detail to provide a foundation for the system of recommended definitions. A study of these considerations is, however, not a requirement for the practical use of the definitions given in Section B.

Statistical fluctuations are commonly encountered in physics and in the case of radiation they can be extreme. Since, in any given instance, the action of radiation is determined by the actual rather than the mean (expectation) values of such quantities, it is desirable to devote special attention to the former. It is therefore necessary to consider *stochastic quantities* in addition to those that are not stochastic. The difference between these two types of quantities and the relations between them are best illustrated by an example.

The *energy imparted*, ϵ (see definition 5), is subject to random fluctuations which become large if the volume of interest is small, or the fluence of charged particles is low. The stochastic quantity *specific energy*, z (see definition 7), which is the quotient of the energy imparted, ϵ, by the mass, m, contained in a volume, may deviate considerably from the non-stochastic quantity *absorbed dose*, D (see definition 8). Repeated measurements of z can establish an experimental distribution. This is an estimate of the probability distribution of z; similarly, 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.

Thus the specific energy, z, being a stochastic quantity, has the following characteristics:

a. It is defined for finite domains only. Its values vary discontinuously in space and time, and one cannot speak of its rate of change.

b. Its values cannot be predicted. However, the probability of any particular value is determined by a probability distribution.

c. In principle, its values can be measured with an arbitrarily small error.

Like other non-stochastic quantities the absorbed dose, D, has the following characteristics:

a. It is, in general, a continuous and differentiable function of space and time and one may speak of 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 nonuniform radiation field one has to derive the limiting value of this average for vanishingly small mass. The experimental errors are commonly larger than the statistical variations considered here, but the latter always exist.

The above considerations are given in place of the section entitled "Limiting Procedures" in ICRU Report 11. The introduction of the concept of stochastic quantities leads to a more rigorous definition of absorbed dose. In the present report only three stochastic quantities, ϵ, z, y, are defined (for y see definition 23). All other quantities defined are non-stochastic quantities. Contrary to the approach chosen in ICRU Report 11, where difference quotients were employed, the definitions of non-stochastic quantities, that are point functions, are now 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, if the differential quotient dN/da is termed: "the quotient of dN by da, where dN is the number of particles which enter a sphere of cross sectional area da", then dN is understood to be the differential of N, the expectation value of the number of particles. A detailed analysis of the characteristics of such expectation values has to be based on a consideration of the corresponding stochastic quantities and their probability distributions. In many applications these considerations can be disregarded and all definitions of non-stochastic quantities can be adequately understood without consideration of random fluctuations.

2. Spectra and Mean Values

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[1] of a quantity with respect to another quantity can be defined. For example, the fluence, Φ (see definition 10), is the number of particles of all energies which have entered a sphere of vanishing volume, divided by the cross-sectional area of that sphere. The sum distribution, $\Phi(E)$, is that part of the fluence 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 stopping power, S (see definition 21), or the attenuation coefficient, μ (see definition 18), are functions of the particle energy. For a radiation field having a complex energy spectrum, mean values such as $\bar{\mu}$ and $\bar{S}$, weighted according to the spectral distribution of the relevant quantity, may be useful. For example:

$$\bar{\mu} = \int_0^\infty \mu \, \Phi_E \, \mathrm{d}E \Big/ \int_0^\infty \Phi_E \, \mathrm{d}E = \frac{1}{\Phi} \int_0^\infty \mu \, \Phi_E \, \mathrm{d}E$$

is the mean value of μ weighted by fluence.

B. Definitions

The general pattern adopted in this section 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.

Symbols for quantities are not used as subscripts in this section as they were in ICRU Report 11. Possible confusion with differential distributions (see Section A.2) is thus eliminated.

1. **Directly ionizing particles** are charged particles (electrons, protons, alpha particles, etc.) having sufficient kinetic energy to produce ionization by collision.

2. **Indirectly ionizing particles** are uncharged particles (neutrons, photons, etc.) which can liberate directly ionizing particles or can initiate nuclear transformations.

3. **Ionizing radiation** is any radiation consisting of directly or indirectly ionizing particles or a mixture of both.

4. **Energy deposition event** denotes the deposition of energy in the mass of interest by correlated ionizing particles.

NOTES: (a) The term "correlated" signifies statistical dependence.

(b) Examples of energy deposition events include energy deposition by an alpha particle and/or its delta rays, by one or both electrons arising from a pair production and by one or more products of a nuclear disintegration.

(c) The energy delivered in an energy deposition event is independent of fluence rate or absorbed dose rate.

[1] 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 commonly used 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 distribution.

5. The stochastic quantity **energy imparted,** ϵ, by ionizing radiation to the matter in a volume is:

$$\epsilon = \Sigma\epsilon_{in} - \Sigma\epsilon_{ex} + \Sigma Q$$

where

$\Sigma\epsilon_{in}$ = the sum of the energies (excluding rest energies) of all those directly and indirectly ionizing particles which have entered the volume,

$\Sigma\epsilon_{ex}$ = the sum of the energies (excluding rest energies) of all those directly and indirectly ionizing particles which have left the volume,

and ΣQ = the sum of all the energies released, minus the sum of all the energies expended, in any transformations of nuclei and elementary particles which have occurred within the volume.

6. The **mean energy imparted,** $\bar{\epsilon}$, is the expectation value of the energy imparted.

NOTE: $\bar{\epsilon}$ has sometimes been called the "*integral dose*" in the volume.

7. The stochastic quantity **specific energy** or **specific energy imparted**[2], z, is the quotient of ϵ by m, where ϵ is the energy imparted by ionizing radiation to the matter in a volume element and m is the mass of the matter in that volume element.

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

The special unit of specific energy is the rad.[3]

$$1 \text{ rad} = 10^{-2}\text{J kg}^{-1}$$

NOTES: (a) Because z is a stochastic quantity, it necessitates the use of probability distributions. The value of the distribution function, $F(z)$, is given by the probability that the specific energy, z', is equal to or less than z.

$$F(z) = P(z' \leq z)$$

The probability density, $f(z)$, is the derivative of $F(z)$ with respect to z.

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

$f(z)$ always includes a discrete component (a Dirac delta function) at $z = 0$ for the probability of no energy deposition.

(b) The mean specific energy, $\bar{z}$, is a non-stochastic quantity.

$$\bar{z} = \int_0^\infty z\, f(z)\, \mathrm{d}z$$

(c) Specific energy may be due to one or more energy deposition events. The distribution function of the specific energy deposited in a single event, $F_1(z)$, is given by the *conditional probability* that a specific energy, z', less than or equal to z is deposited if one event has occurred.

$$F_1(z) = P(z' \leq z \mid \nu = 1)$$

where ν designates the number of energy deposition events.

The probability density, $f_1(z)$ is the derivative of $F_1(z)$ with respect to z.

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

8. 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 by ionizing radiation to the matter in a volume element and $\mathrm{d}m$ is the mass of the matter in that volume element.

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

The special unit of absorbed dose is the rad.[3]

$$1 \text{ rad} = 10^{-2}\text{J kg}^{-1}$$

NOTE: The absorbed dose is the limit of the mean specific energy as the mass in the region under consideration approaches zero, i.e.,

$$D = \lim_{m \to 0} \bar{z}$$

This relation, which indicates the connections between D and z, could serve as an alternative definition of D.

9. 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 $\mathrm{d}t$.

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

A special unit of absorbed dose rate is any quotient of the rad or its multiple or submultiple by a suitable unit of time (rad s^{-1}, mrad h^{-1}, etc.).

10. The **fluence**[4], Φ, of particles is 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 $\mathrm{d}a$.

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

[2] In cases where this quantity might be confused with the thermodynamic quantity, *specific energy*, the term *specific energy imparted* is preferable.

[3] When rad may be confused with the symbol for radian, it is permissible to use rd as a symbol for rad.

[4] This quantity is the same as the quantity *nvt* commonly used in neutron physics.

11. The **flux density** or **fluence rate,** φ, of particles is the quotient of $d\Phi$ by dt where $d\Phi$ is the increment of particle fluence in the time interval dt.

$$\varphi = \frac{d\Phi}{dt}$$

12. The **energy fluence,** Ψ, of particles is the quotient of dE_{fl} by da, where dE_{fl} is the sum of the energies, exclusive of rest energies, of all the particles which enter a sphere of cross-sectional area da.

$$\Psi = \frac{dE_{fl}}{da}$$

13. The **energy flux density** or **energy fluence rate,** ψ, is the quotient of $d\Psi$ by dt, where $d\Psi$ is the increment of energy fluence in the time interval dt.

$$\psi = \frac{d\Psi}{dt}$$

14. The **kerma,** K, is the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of all the charged particles liberated by indirectly ionizing particles in a volume element of the specified material and dm is the mass of the matter in that volume element.

$$K = \frac{dE_{tr}}{dm}$$

The special unit of kerma is the rad.[5]

$$1 \text{ rad} = 10^{-2} \text{J kg}^{-1}$$

NOTES: (a) Since dE_{tr} is the sum of the initial kinetic energies of the charged particles liberated by the indirectly ionizing particles, it also includes the energy that these charged particles radiate in bremsstrahlung. The energies of any charged particles are also included when these are produced in secondary processes occurring within the volume element. Thus, the energy of Auger electrons is part of dE_{tr}.

(b) It may often be convenient to refer to a value of kerma or of kerma rate for a specified material in free space or at a point inside a different material. In such a case the value will be that which would be obtained if a small quantity of the specified material were placed at the point of interest. It is, therefore, permissible to make a statement such as: "The air kerma at the point P inside a water phantom is . . .".

(c) In actual determinations the mass element should be so small that its introduction does not appreciably disturb the field of the indirectly ionizing particles. This is important if the medium for which kerma is determined is different from the ambient medium; if the disturbance is appreciable, an appropriate correction must be applied.

(d) A fundamental physical description of a radiation field can be given in terms of the energy flux density (energy fluence rate) at all relevant points. For the purpose of dosimetry, however, it may be convenient to describe the field of indirectly ionizing particles in terms of the kerma rate for a suitable material. The material could be air for electromagnetic radiation of moderate energies, tissue for all indirectly ionizing radiations applied in medicine or biology, or any relevant material for studies of radiation effects.

(e) Kerma can also be a useful quantity in dosimetry when charged particle equilibrium exists in the material at the point of interest, and bremsstrahlung losses are negligible. It is then equal to the absorbed dose at that point. In beams of x or gamma rays or neutrons of moderately high energy, quasi-equilibrium of charged particles can occur; then the kerma is usually slightly less than the absorbed dose.

15. The **kerma rate,** $\dot{K}$, is the quotient of dK by dt, where dK is the increment of kerma in the time interval dt.

$$\dot{K} = \frac{dK}{dt}$$

A special unit of kerma rate is any quotient of the rad or its multiple or submultiple by a suitable unit of time (rad s^{-1}, rad min^{-1}, mrad h^{-1}, etc.).

16. The **exposure,** X, is the quotient of dQ by dm where dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in a volume element of air having mass dm are completely stopped in air.

$$X = \frac{dQ}{dm}$$

The special unit of exposure is the roentgen (R).

$$1 \text{ R} = 2.58 \times 10^{-4} \text{C kg}^{-1} \text{ (exactly)}$$

NOTES: (a) The ionization arising from the absorption of bremsstrahlung emitted by the secondary electrons liberated in the volume of interest is not to be included in dQ. Except for this difference, significant only at high energies, the exposure as defined above is the ionization equivalent of the kerma in air.

(b) With present techniques it is diffiicult to meas-

[5] When rad may be confused with the symbol for radian, it is permissible to use rd as a symbol for rad.

ure exposure when the photon energies involved lie above a few million electronvolts or below a few thousand electronvolts.

(c) As in the case of kerma (definition 14, note b), it may often 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. In such a case, the value will be that which would be determined for a small quantity of air placed at the point of interest. It is, therefore, permissible to make a statement such as: "The exposure at the point P inside a water phantom is . . .".

17. The **exposure rate,** $\dot{X}$, is the quotient of dX by dt where dX is the increment of exposure in the time interval dt.

$$\dot{X} = \frac{dX}{dt}$$

A special unit of exposure rate is any quotient of the roentgen or its multiple or submultiple by a suitable unit of time ($R\ s^{-1}$, $R\ min^{-1}$, $mR\ h^{-1}$, etc.).

18. The **mass attenuation coefficient,** μ/ρ, of a material for indirectly ionizing particles of specified energy is the quotient of dN/N by ρdl where dN/N is the fraction of particles that experience interactions in traversing a distance dl in a medium of density ρ.

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

NOTES: (a) The term *interactions* refers to processes whereby the energy or direction of the indirectly ionizing particles is altered.

(b) For x or gamma ray photons:[6]

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

where τ/ρ is the photoelectric mass attenuation coefficient, σ_c/ρ is the total Compton mass attenuation coefficient, σ_{coh}/ρ is the mass attenuation coefficient for coherent scattering, and κ/ρ is the pair production mass attenuation coefficient.

(c) An alternative approach which is identical in principle and widely used in neutron calculations is based on the definition of the cross section, σ. This cross section,[7] with dimension L^{-2}, is the probability of interaction in a mass element divided by the product of the number of nuclei and the fluence.

The mass attenuation coefficient is related to the cross section by:

$$\mu/\rho = N_A\,\sigma/M$$

where N_A is the Avogadro constant and M is the molar mass of the target element.

The quantity μ, sometimes denoted by Σ, of a material is the probability of interaction in a mass element divided by the product of its volume and the fluence.

(d) By analogy with Note (b) above, the cross section, σ, can be expressed as the sum of partial cross sections for the various neutron reactions relevant to the problem. For example:

$$\sigma = \sigma_a + \sigma_s$$

where σ_a is the neutron absorption cross section and σ_s is the neutron scattering cross section; or

$$\sigma = \sigma_e + \sigma_{n,n'} + \sigma_{n,\gamma} + \sigma_{n,\alpha} + \sigma_{n,p}$$

where e represents elastic scattering,
n, n′ represent inelastic scattering,
n, γ; n, α and n, p represent neutron capture followed by γ ray emission, by α particle emission, or by proton emission respectively.

This list of examples is not intended to be comprehensive as the number of possible interactions is large and depends on the neutron energy and the nature of the target nucleus.

19. The **mass energy transfer coefficient,** μ_{tr}/ρ, of a material for indirectly ionizing particles of specified energy is the quotient of dE_{tr}/E by ρdl where dE_{tr}/E is the fraction of incident particle energy (excluding rest energies) that is transferred to kinetic energy of charged particles by interactions in traversing a distance dl in a medium of density ρ.

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

NOTES: (a) For a given monoenergetic radiation the relation between energy fluence and kerma may be written as:

$$K = \Psi\frac{\mu_{tr}}{\rho}$$

(b) For x or gamma ray photons[8] of energy $h\nu$

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

[6] This equation applies if the nuclear interactions are not important. An extra term for such interactions may be required for x or gamma ray energies in excess of a few million electron volts.

[7] In neutron physics σ and Σ are commonly termed the microscopic and macroscopic cross sections, respectively.

[8] This equation applies if the nuclear interactions are not important. An extra term for such interactions may be required for x or gamma ray energies in excess of a few million electronvolts.

where:

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

(τ/ρ = the photoelectric mass attenuation coefficient, δ = average energy emitted as fluorescent radiation per photon absorbed) and:

$$\frac{\sigma_{ca}}{\rho} = \frac{\sigma_c}{\rho}\frac{E_e}{h\nu}$$

(σ_c/ρ = total Compton mass attenuation coefficient, E_e = average energy of the Compton electrons per scattered photon) and:

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

(κ/ρ = mass attenuation coefficient for pair production, mc^2 = rest energy of the electron).

(c) Equivalent expressions can be derived for neutrons. See ICRU Report 13 [1][9] for their formulation and discussion.

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

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

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

(b) When the material is air, the radiation is monoenergetic x or gamma rays and the mean energy expended in air per ion pair formed (see definition 24) is independent of electron energy, μ_{en}/ρ is proportional to the quotient of exposure by energy fluence.

21. The **total mass stopping power,** S/ρ, of a material for charged particles is the quotient of dE by ρdl, where dE is the energy lost by a charged particle of specified energy in traversing a distance dl, and ρ is the density of the medium.

$$\frac{S}{\rho} = \frac{1}{\rho}\frac{dE}{dl}$$

NOTE: For energies at which nuclear interactions can be neglected the total mass stopping power is:

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{col} + \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{rad}$$

where

$\left(\frac{dE}{dl}\right)_{col}$ = S_{col} is the linear collision stopping power

and

$\left(\frac{dE}{dl}\right)_{rad}$ = S_{rad} is the liner radiative stopping power.

22. The **linear energy transfer** or **restricted linear collision stopping power,** L_Δ, of charged particles in a medium is the quotient of dE by dl, where dl is the distance traversed by the particle and dE is the energy loss due to collisions with energy transfers less than some specified value Δ.

$$L_\Delta = \left(\frac{dE}{dl}\right)_\Delta$$

NOTES: (a) Although the definition specifies an energy cutoff and not a range cutoff, the energy losses are sometimes called "energy locally imparted".

(b) In order to simplify notation and to ensure uniformity it is recommended that Δ be expressed in electronvolts. Thus, L_{100} is the linear energy transfer for an energy cutoff of 100 electronvolts.

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

23. The stochastic quantity **lineal energy,**[10] y, is the the quotient of ϵ by $\bar{d}$, where ϵ is the energy imparted to the matter in a volume during an energy deposition event and $\bar{d}$ is the mean chord length in the volume of interest.

$$y = \frac{\epsilon}{\bar{d}}$$

NOTES: (a) The mean chord length in a volume is the mean length of randomly oriented chords in that volume. For a convex body, $\bar{d}$ equals $4\ V/a$, where V is the volume and a is the surface area [2].

(b) The distribution function, $F(y)$, is given by the probability that the lineal energy, y', is equal to or less than y:

$$F(y) = P(y' \leq y)$$

The probability density, $f(y)$, is the derivative of $F(y)$ with respect to y:

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

(c) Since only single energy deposition events are involved, the distribution of lineal energy is in-

[9] Numbers in brackets refer to literature references listed on page 18.

[10] In a commonly accepted formulation restricted to spherical volumes, a similar quantity (Y) is defined as the quotient of ϵ by the sphere diameter. In the case of a spherical volume, $y = 3/2\ Y$.