THE DOSIMETRY OF IONIZING RADIATION

VOLUME I

Edited by

Kenneth R. Kase

Bengt E. Bjärngard

Frank H. Attix

THE DOSIMETRY OF IONIZING RADIATION

Volume I

Contributors

Gudrun Alm Carlsson
André Bridier
Johan J. Broerse
Andrée Dutreix
Elis Holm
John R. Johnson
Albrecht M. Kellerer
Kurt Lidén
John T. Lyman
Johannes Zoetelief

THE DOSIMETRY OF IONIZING RADIATION

Volume I

Edited by KENNETH R. KASE

Joint Center for Radiation Therapy
Harvard Medical School
Boston, Massachusetts

BENGT E. BJÄRNGARD

Joint Center for Radiation Therapy
Harvard Medical School
Boston, Massachusetts

FRANK H. ATTIX

Department of Medical Physics
University of Wisconsin Medical School
Madison, Wisconsin

1985

ACADEMIC PRESS, INC.

Harcourt Brace Jovanovich, Publishers

Orlando San Diego New York Austin

London Montreal Sydney Tokyo Toronto

ACADEMIC PRESS, INC.
Orlando, Florida 32887

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
24–28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data
Main entry under title:

The Dosimetry of ionizing radiation.

Includes index.
1. Ionizing radiation–Measurement. 2. Radiation dosimetry. I. Kase, Kenneth R., Date
II. Bjärngard, Bengt. III. Attix, Frank H.
[DNLM: 1. Radiation, Ionizing. 2. Radiometry.
WN 650 D7726]
QC795.42.D67 1985 539.7'7 84-28251
ISBN 0–12–400401–6 (alk. paper : v. 1)
ISBN 0–12–392651–3 (paperback)

PRINTED IN THE UNITED STATES OF AMERICA

85 86 87 88 9 8 7 6 5 4 3 2 1

Contents

List of Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

GUDRUN ALM CARLSSON (1), Department of Radiation Physics, The Medical School, University of Linköping, S–581 85 Linköping, Sweden

ANDRE BRIDIER (163), Service de Radiophysique, Institut Gustave-Roussy, 94800 Villejuif, France

JOHAN J. BROERSE (229), Radiobiological Institute TNO, 2280 HV Rijswijk, The Netherlands

ANDREE DUTREIX (163), Service de Radiophysique, Institut Gustave-Roussy, 94800 Villejuif, France

ELIS HOLM (291), Department of Radiation Physics, Lund University, Lund, Sweden

JOHN R. JOHNSON (369), Biomedical Research Branch, Atomic Energy of Canada Limited Research Company, Chalk River Nuclear Laboratories, Chalk River, Ontario KOJ 1JO, Canada

ALBRECHT M. KELLERER (77), Institut für Medizinische Strahlenkunde, Julius-Maximilians-Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany

KURT LIDEN (291), Department of Radiation Physics, Lasarettet, Lund University, S-22185 Lund, Sweden

JOHN T. LYMAN (229), Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

JOHANNES ZOETELIEF (229), Radiobiological Institute TNO, 2280 HV Rijswijk, The Netherlands

This page intentionally left blank

Preface

Since 1956 Academic Press has published some of the most authoritative, respected, and widely used references in the field of radiation dosimetry. These have included ''Radiation Dosimetry,'' First Edition (1956), edited by Gerald J. Hine and Gordon L. Brownell; Second Edition (1966–1969, 3 volumes), edited by Frank H. Attix, William C. Roesch, and Eugene Tochilin; and ''Topics in Radiation Dosimetry,'' Supplement 1 (1972), edited by Frank H. Attix. It is the goal of the present work to fill the need for newer reference material of comparable quality.

There were two major questions that faced the editors and publisher when this project was being considered: whether to undertake a full-scale third edition, and if not, what to call the new books.

It was decided that this would not be considered a third edition, because much of the material in the second edition of ''Radiation Dosimetry'' is still timely and useful, and because of the extraordinary editorial difficulties encountered in producing a very large multivolume, multiauthor work that is fully comprehensive and thoroughly cross-referenced. Instead, the new work is planned to be at least three volumes that will cover a variety of dosimetry subjects, including theory, instrumentation, methods, and applications.

The new books are titled ''The Dosimetry of Ionizing Radiation;'' this title is certainly descriptive of their content. We do not mean to imply, however, that this set will cover all possible subjects under such a broad heading. It is also assumed that the second edition of ''Radiation Dosimetry'' (hereafter referred to as ''Radiation Dosimetry'') will continue to be available for some time to come, so that authors of the present work may freely make reference to it.

This first volume has been planned and organized to present several broad topics in dosimetry that can serve as foundations for what follows in later volumes. There are two chapters dealing with theoretical aspects of dosimetry. These are followed by two chapters concerning measurement of radiation fields, which will be applicable to radiation protection as well as to research, medical, and industrial uses of radiation beams. The final two chapters discuss determination of radioactivity in the environment and analysis of internal dose.

The first chapter by Gudrun Alm Carlsson presents her unique theoretical treatment of dosimetry. Albrecht M. Kellerer's chapter on microdosimetry updates and extends the earlier work of Harald Rossi in Volume I of "Radiation Dosimetry," and of William A. Glass and William A. Gross in "Topics in Radiation Dosimetry."

The chapter by Andrée Dutreix and André Bridier presents a timely summary of photon and electron beam dosimetry, taking into account the recent wave of protocols published in several countries. It supplements the chapters by John S. Laughlin on electron beam dosimetry and H. E. Johns on photon beam dosimetry in Volume III of "Radiation Dosimetry."

Johan Broerse, John Lyman, and Johannes Zoetelief have provided a chapter dealing with heavy-particle dosimetry. It provides important up-to-date information in the areas covered by the chapters by Mudundi R. Raju *et al.*, E. Tochilin and B. W. Shumway, and J. DePangher and Eugene Tochilin in Volume III of "Radiation Dosimetry."

The chapter by Kurt Lidén and Elis Holm is a thorough and well-documented reference on environmental radioactivity that largely replaces the chapter by W. V. Mayneord and C. R. Hill in "Radiation Dosimetry," Volume III.

Finally, John R. Johnson has written an excellent and much-needed chapter on internal dosimetry in reference to radiation protection.

Clearly this book is a valuable collection of work by outstanding authorities in their fields of specialty. In quality it measures up to the best of what has been published before. In any event, the editors cannot be accused of a parochial choice of authors: Canada, France, Germany, The Netherlands, Sweden, and the United States are represented!

Finally, we express our appreciation to our wives for their continued support and encouragement during the preparation of this book. In particular, Herb Attix thanks his wife, Shirley, for her unflagging patience and understanding, and for outstanding secretarial assistance in carrying out this and other writing and editing projects.

Kenneth R. Kase is now affiliated with the Department of Radiation Oncology, University of Massachusetts Medical Center, Worcester, Massachusetts.

1

Theoretical Basis for Dosimetry

GUDRUN ALM CARLSSON

DEPARTMENT OF RADIATION PHYSICS
THE MEDICAL SCHOOL
UNIVERSITY OF LINKÖPING
LINKÖPING, SWEDEN

I. Introduction

Radiation dosimetry has its origin in the medical application of ionizing radiation starting with the discovery of x rays by Röntgen (1895). In particular, the application in radiation therapy called for methods to predict and reproduce clinical results. Physical techniques soon proved superior to biological ones for executing reproducible radiation measurements. Radiation dosimetry has developed into a pure physical science.

The concept "dose" was introduced as the quantity of interest in relating physical measurements with the biological effect of radiation. "Dose" was meant to be a measure of the radiation emitted from an x-ray tube and given to the patient. The instrument used to measure x-ray output was called a "dosage meter." The connection to the medical profession is obvious. The term "dose" was used in a pharmacological sense analogously to its meaning when used in prescribing a dose of medicine.

Although "dose" was not rigorously defined it was evidently thought of as something like radiant energy, i.e., a quantity of the radiation field (radiometric quantity). It was soon recognized that the effects of radiation on biological tissues are not correlated to the radiant energy incident on but rather to that actually imparted to it. Christen (1914) defined a concept of "dose" which comes close to what is now called absorbed dose. It was defined as the "roentgen energy absorbed by a unit volume" and could be calculated as the product of a radiometric quantity and coefficients describing the interactions between radiation and matter.

Use of the concept of "dose" with two different meanings, as a radiometric quantity and as absorbed dose, has been a continuing source of confusion. A contributing factor is that the air ionization chamber has been the instrument of choice for determining the output from x-ray machines. The quantity measured is called exposure (earlier, exposure dose). Exposure is proportional to the absorbed dose in air under electronic equilibrium conditions and is thus related to the product of a radiometric quantity, the energy fluence of photons, and the mass energy absorption coefficient describing the interactions of the photons and their secondary electrons with air. As long as determinations of absorbed dose in airlike materials such as soft tissues are the main interest, and not specification of the radiation field itself, the fact that exposure is not a true radiometric quantity has no serious practical consequences. In connection with determinations of absorbed dose or mean energy imparted to high-atomic-number detectors such as those frequently used in, e.g., diagnostic radiology, ambiguities are more likely to appear as a result of interpreting exposure as a parameter of the radiation field.

Radiation dosimetry is fundamental to all fields of science dealing with radiation effects and is concerned with problems which are often intricate as hinted above. A firm scientific basis is needed to face increasing demands on accurate dosimetry. This chapter is an attempt to review and to elucidate the elements for such a basis. Quantities suitable for radiation dosimetry have been defined in the unique work to coordinate radiation terminology and usage by the International Commission on Radiation Units and Measurements, ICRU. Basic definitions and terminology used in this chapter conform with the recent "Radiation Quantities and Units, Report 33" of the ICRU (1980).

A striking feature in early definitions of quantities for radiation measurements was their close connection to a particular experimental arrangement used in the measurements. With time the quantities have been given more general definitions such that they can be determined with a variety of experimental methods. Excellent reviews of the development of dosimetric quantities as reflected in the "Radiation Quantities and Units" reports of the ICRU have been given by Roesch and Attix (1968) and Wyckoff (1980). Quantities may also be defined which cannot be measured but which are helpful in calculations of other quantities or for the understanding of dosimetric problems. For instance, the vectorial quantities used extensively in radiation transport theory—a field of science closely related to radiation dosimetry—can be exploited to develop a vector formalism which is forceful in clarifying basic dosimetric quantities and experimental arrangements for their determination. It seems to be a trend that modern textbooks in radiation dosimetry contain a presentation of vectorial quantities and the connection to radiation transport theory (see, e.g., Stolz and Bernhardt, 1981), a trend which will be followed here.

The energy imparted by ionizing radiation to the matter in a volume (ICRU, 1980) is the fundamental quantity of radiation dosimetry, on the basis of which the quantity absorbed dose is derived to allow specification of the spatial distribution of the energy imparted to an irradiated medium. The definitions and physical significance of energy imparted and absorbed dose are treated in detail in Sections II and III.

A radiation detector responds to irradiation with a signal which is basically related to the energy imparted to the detector volume. This relation is treated in Section IV, the statistical fluctuations in the energy imparted to the detector in Section IV,A, and factors determining the conversion of the imparted energy into a detectable signal in Section IV,B.

Section V deals with the definitions of nonstochastic radiometric quantities, both scalar and vectorial. Expectation values of the energy imparted to a body and absorbed dose can by means of vectorial quantities be expressed in a way that clearly demonstrates the close connection between radiation dosimetry and radiation transport theory. Examples are given to demonstrate the usefulness of the vector formalism.

In Section VI, the quantity absorbed dose is defined in terms of the scalar quantity fluence (or energy fluence) and interaction coefficients allowing numerical calculations to be performed in specified conditions. When radiation equilibrium can be presumed, the calculations are considerably simplified. In particular, calculations of absorbed dose are relevant to the field of cavity theory dealing with determinations of the absorbed dose at a specified point in a medium by means of the signal from a radiation detector. The concept of radiation equilibrium is treated in detail (Section VI,C) and the geometrical arrangements needed to establish various kinds of approximate radiation equilibrium at a point in a medium and at all points of a detector volume are discussed. Problems of nonequilibrium inevitably arise when, e.g., a bare Bragg–Gray detector is used in a medium of differing atomic composition or when the ranges of secondary radiations are comparable with the ranges (or mean free paths) of the primary radiation. Calculations of absorbed dose in nonequilibrium require complete knowledge of the field of charged ionizing particles and are considered in the particular light of cavity theory.

In the final section, Section VII, some problems of cavity theory are touched on to explore the significance of the absorbed dose equations derived in Section VI to this field.

II. Energy Imparted: The Fundamental Quantity of Radiation Dosimetry

Most physical, chemical, and biological effects yielding detectable signals from a radiation detector are basically correlated to the physical quantity: the energy imparted (ICRU, 1980) to the detector. The signal may in addition depend on the microscopic distribution in space and time of the imparted energy. The signal from the detector is, for instance, temperature rise, the number of ions produced, the amount of light emitted upon subsequent heating (thermoluminescence), etc. In biological objects, ionizations are sometimes thought to be more effective than excitations in causing the biological changes; both effects are correlated to the energy imparted. The quantity "the energy imparted by ionizing radiation to the matter in a volume" is regarded as the fundamental quantity of radiation dosimetry.

A. Basic Processes of Energy Impartation

The concept of "energy imparted by ionizing radiation to the matter in a volume" has a well-defined meaning as stated in definitions by the ICRU (1980). More familiar expressions like "energy absorbed, deposited in, or transferred to" are frequently used as synonyms for energy imparted. This will be avoided here since the latter expressions are sometimes also used with other meanings. In the following, emphasis will be given to the specific expression of "energy imparted," which will be used exclusively in the sense of its ICRU definition.

The energy imparted ϵ to the matter in a volume is, due to the quantum nature of both radiation and matter, composed of discrete contributions $\delta\epsilon$ from a number of basic processes occurring in the volume (Alm Carlsson, 1979). The physical significance of the energy imparted is most clearly demonstrated by analyzing the contributions from the basic processes representing those elementary mechanisms by which energy is imparted to matter. One basic process of energy impartation is an interaction by an ionizing particle with the atomic constituents of matter; another is spontaneous nuclear or elementary particle transformation at which ionizing particles are created (source processes). The fundamental character of the basic processes of energy impartation arises from the fact that the *imparted energy* $\delta\epsilon$ in such a process can be determined from a detailed knowledge about interaction processes and spontaneous nuclear and elementary particle transformations only.* In contrast, "the *energy imparted* to the matter in a volume" requires that a volume and time interval be specified for its determination.

The imparted energy $\delta\epsilon$ in a basic process of energy impartation is given by

$$\delta\epsilon = T_\mathrm{b} - \sum_i T_{\mathrm{a},\,i} + Q \tag{1}$$

where T_b is the kinetic energy (energy excluding rest-mass energy: $T = E - m_0c^2$) of the interacting ionizing particle immediately before the interaction (in a spontaneous process such as nuclear decay, $T_\mathrm{b} = 0$), $\sum_i T_{\mathrm{a},\,i}$ the sum of the kinetic energies of all ionizing particles created in the process (including the residual kinetic energy of the primary particle if this is still an ionizing particle after interaction), and Q the release of rest-mass energy of nuclei and elementary particles in those basic processes in which transformations of nuclei and elementary particles occur.†

Secondary particles liberated in a basic process contribute to $\sum_i T_{\mathrm{a},\,i}$ only if they are considered to be ionizing particles. The value of the imparted energy $\delta\epsilon$ depends critically on the definition of an ionizing particle. *Ionizing particles* are charged or uncharged particles capable of causing ionization by primary or secondary processes [ICRU (1980): see also Alm Carlsson (1978) for a detailed discussion]. Ionization may occur directly through interactions with the atomic

*A distinction is made between "energy imparted," which refers to the "energy imparted to the matter in a volume," and "imparted energy," which refers to the fundamental processes of energy impartation and can be considered regardless of any volume. This is in accordance with a terminology suggested by Kellerer and Chmelevsky (1975a).

†Q is identical to the Q values used in nuclear physics to classify nuclear reactions as exoergic ($Q > 0$) or endoergic ($Q < 0$) (see, e.g., Evans, 1955).

electrons (primary processes) or indirectly through a nuclear reaction or spontaneous elementary particle transformation (e.g., neutron capture or π-meson decay) in which particles capable of ionizing directly are created (secondary processes). All charged particles can be characterized as ionizing on the basis of their ability to produce ionization through Coulomb collision with atomic electrons. However, when their kinetic energy drops below a certain cutoff value, T_{cut} (depending on particle type and the material considered), they cease to be ionizing unless they are still able to initiate nuclear or elementary particle reactions. For instance, positrons remain ionizing below the cutoff energy T_{cut} for ionizing through Coulomb collision because they can cause ionization by annihilation. Negatrons, protons, and other heavier nuclei, however, are important examples of charged particles which will cease to be ionizing when their kinetic energies drop below the cutoff energy T_{cut}. The same applies to photons but not to neutrons, which are able to produce ionization through secondary processes upon being captured by a nucleus.

B. The Imparted Energy $\delta\epsilon$ in a Basic Process

Determination of the imparted energy $\delta\epsilon$ in a basic process requires a detailed knowledge about the outcomes of interaction processes and spontaneous nuclear and elementary particle transformations. No complete treatment of the different processes which may occur will be given; the important interactions between ionizing particles and matter are described in a number of existing textbooks on radiation dosimetry (see, e.g., Whyte, 1959; Attix *et al.*, 1968, 1969; Kase and Nelson, 1978; ICRU, 1978; Greening, 1981). Instead, we focus attention in more general terms on those products of a basic process which constitute the imparted energy. It is instructive to distinguish between basic processes on the basis of their Q-values: $Q = 0$, $Q > 0$, $Q < 0$; cf. Eq. (1).

1. *Interactions with $Q = 0$*

Coulomb collision with atomic electrons, giving rise to excitations and ionizations, is the most important interaction of this kind. With $Q = 0$, the imparted energy $\delta\epsilon$ is given by

$$\delta\epsilon = T_{\text{b}} - \sum_i T_{\text{a},\,i} \tag{2}$$

In words, the imparted energy is that part of the kinetic energy of the interacting particle which is converted into energy forms other than the kinetic energy of ionizing particles. For a more concrete exposition, consider the following example, Fig. 1.

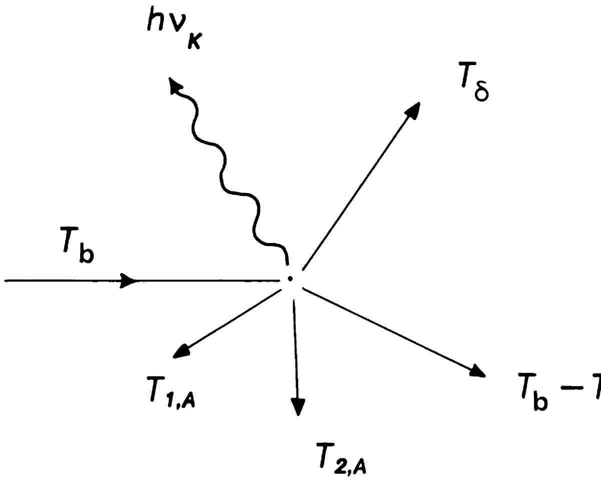

Fig. 1. A charged ionizing particle with kinetic energy T_b collides with an atomic electron and loses kinetic energy T. The atomic electron is knocked out and escapes with kinetic energy T_δ (δ particle). In the subsequent deexcitation of the electronic structure, one fluorescence photon with energy $h\nu_k$ and two Auger electrons with kinetic energies $T_{1,A}$ and $T_{2,A}$ are emitted. [After Alm Carlsson (1979).]

In Fig. 1, all particles which emerge from the interaction and the subsequent deexcitation processes as ionizing particles are depicted as waves (photons) or lines. Since the deexcitations of the electronic structure follow very closely in time (within $\sim 10^{-14}$ s) upon the interaction of the incident particle with the atomic electron, it is convenient to include them as a part of this interaction [treated as separate spontaneous ($T_b = 0$) basic processes they would yield negative values of imparted energy].* The imparted energy $\delta\epsilon$ is given by

$$\begin{aligned}\delta\epsilon &= T_b - (T_b - T + T_\delta + T_{1,A} + T_{2,A} + h\nu_k) \\ &= T - T_\delta - T_{1,A} - T_{2,A} - h\nu_k \qquad (3)\end{aligned}$$

and may deviate appreciably from the kinetic energy T lost by the interacting particle. Note that if the interacting particle loses so much energy that its residual kinetic energy drops below the cutoff energy of an ionizing particle, i.e., $(T_b - T) < T_{cut}$, the term $T_b - T$ in the parentheses of Eq. (3) disappears and T_b replaces T in the last equality. In this case, the residual kinetic energy

*As a result of multiple Auger and Coster–Kronig transitions, the atom may become highly charged. The energies of ionizing particles, mostly low-energy photons, emitted in subsequent (occurring within 10^{-13} to 10^{-11} s) neutralization processes (Charlton *et al.*, 1983) are also included in $\Sigma_i T_{a,i}$.

of the interacting particle becomes part of the imparted energy $\delta\epsilon$. Equation (3) also yields the imparted energy of an excitation, in which case $T_\delta = 0$.

The imparted energy $\delta\epsilon$ may appear in different ways, such as heat, visible light, chemical binding energy, etc. The subsequent disposition of this energy is not of interest from the pure dosimetric point of view, but must be considered in the design of practical measurements of the energy imparted to the matter in a volume (radiation detector).

The imparted energy $\delta\epsilon$ in an interaction of the type considered here ($Q = 0$) has been called an "energy transfer ϵ_i" by Kellerer and Chmelevsky (1975b). It forms the basic quantity in calculations of particle track structures (see, e.g., Paretzke, 1974) underlying evaluations of proximity functions (Kellerer and Chmelevsky 1975c; Chmelevsky *et al.*, 1978, 1980) in microdosimetry.*

2. *Interactions with $Q < 0$*

A negative value of Q means that part $|Q|$ of the kinetic energy of the interacting particle is expended to increase the rest mass of nuclei and elementary particles. The imparted energy $\delta\epsilon$ can be written

$$\delta\epsilon = T_b - \sum_i T_{a,i} - |Q| \tag{4}$$

Kinetic energy of ionizing particles (radiant energy) which is expended to increase the rest mass of nuclei and elementary particles is not counted as imparted energy. The imparted energy is defined in terms of conversions of radiant energy related to changes in the electronic structure only. Most physical, chemical, and biological effects of radiation are considered to depend on such changes (transmutations of nuclei may under some circumstances, however, be of significance). This is important and is probably the reason to adopt the specific expression "imparted energy" instead of simply "absorbed energy." There exists a definite distinction between "imparted energy" and "absorbed energy" in the sense of radiant energy absorbed, i.e., removed from the radiation field and converted into other energy forms.

As an example of an interaction with $Q < 0$, consider pair production of a photon in the field of an atomic nucleus, Fig. 2.

The imparted energy of the pair production process is

$$\delta\epsilon = h\nu - (T_+ + T_-) - 2m_0c^2 \tag{5}$$

*In recent track calculations of Zaider *et al.* (1983), electrons are followed down to a kinetic energy of only 0.4 eV in water, considerably below the cutoff energy (12.6 eV) of ionizing electrons. Their track pattern of "energy depositions" is not strictly a pattern of imparted energies $\delta\epsilon$. In radiobiology, the interesting cutoff energy depends on the biological model considered.

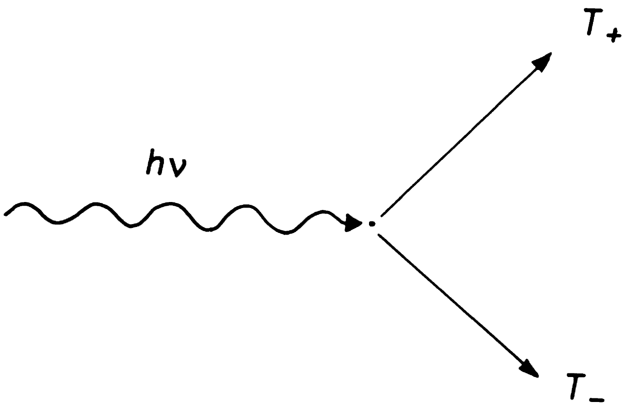

Fig. 2. A photon of energy $h\nu$ is absorbed in the field of an atomic nucleus by emission of a positron and a negatron (pair production) with kinetic energy T_+ and T_-. [After Alm Carlsson (1979).]

where $(T_+ + T_-)$ is obtained from the energy relation

$$T_+ + T_- = h\nu - 2m_0c^2 - T_R \tag{6}$$

and m_0c^2 is the rest-mass energy of an electron. Substituting Eq. (6) into Eq. (5) yields $\delta\epsilon = T_R$, the kinetic energy of the recoiling nucleus ($T_R \approx 0$). If the negatron is created with $T_- < T_{cut}$, T_- constitutes part of $\delta\epsilon$. The positron remains ionizing at all values of T_+.

3. *Processes with Q > 0*

A positive value of Q means that rest-mass energy of nuclei and elementary particles is released into other energy forms, such as the kinetic energy of ionizing particles. These processes—interactions by ionizing particles or spontaneous nuclear and elementary particle transformations—act as radiation sources.

It is convenient to write the imparted energy $\delta\epsilon$ of a process with $Q > 0$ in the form

$$\delta\epsilon = Q - \left(\sum_i T_{a,i} - T_b\right) \tag{7}$$

Here, $\sum_i T_{a,i} - T_b$ is that part of the released rest-mass energy Q that appears as kinetic or quantum energy of ionizing particles. The imparted energy $\delta\epsilon$ is the remaining part of Q, i.e., that which is not converted into the kinetic or quantum energy of ionizing particles.

As an example, consider a two-quantum annihilation of a positron, Fig. 3. The imparted energy $\delta\epsilon$ in the annihilation process is

$$\delta\epsilon = 2m_0c^2 - (h\nu_1 + h\nu_2 + h\nu_k + T_{1,A} + T_{2,A} - T_+) \tag{8}$$

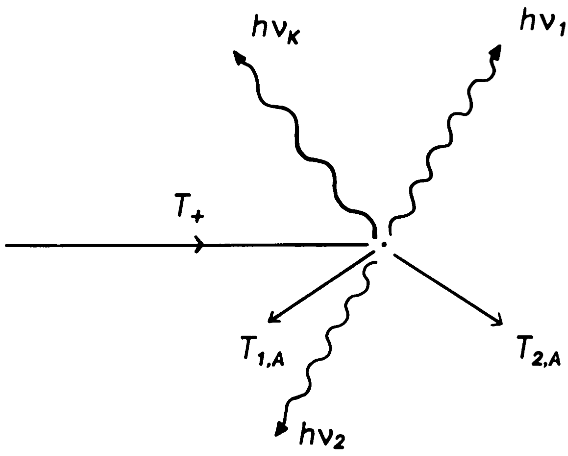

Fig. 3. A positron with kinetic energy T_+ annihilates with an atomic electron giving rise to two annihilation photons with energies $h\nu_1$ and $h\nu_2$. In subsequent deexcitations of the electronic structure, a characteristic roentgen ray with energy $h\nu_k$ and two Auger electrons with kinetic energies $T_{1,\,A}$ and $T_{2,\,A}$ are emitted.

The energies of the annihilation photons are given by the energy relation (E_B is the binding energy of the annihilated atomic electron)

$$h\nu_1 + h\nu_2 = 2m_0c^2 - E_B + T_+ \tag{9}$$

Substituting Eq. (9) into Eq. (8) yields

$$\delta\epsilon = E_B - T_{1,\,A} - T_{2,\,A} - h\nu_k \tag{10}$$

which is identical to the $\delta\epsilon$ in the example illustrated in Fig. 1, since $T - T_\delta$ in Eq. (3) can be identified with E_B. The imparted energy in an annihilation process is independent of whether the annihilation occurs in flight ($T_+ > 0$) or at rest ($T_+ = 0$) and equals the imparted energy of other processes causing the same type of ionization.

Spontaneous [$T_b = 0$ in Eqs. (1) and (7)] nuclear decay or isomeric nuclear transition are other examples of processes with $Q > 0$. Following the scheme of calculations in the preceding examples, it can be shown that the imparted energy in a nuclear decay equals the kinetic energy of the recoiling daughter nucleus plus the decrease in the total binding energy of the electrons bound to the mother nucleus before decay. The recoil energy of the daughter nucleus may be sufficient to cause some atomic electrons to be stripped off and the nucleus (possibly surrounded by some of its atomic electrons) to proceed as an ionizing particle. The imparted energy in the decay then reduces to the decrease in the total binding energy of atomic electrons. The same reasoning applies to nuclear reactions induced by ionizing particles.

The fact that a spontaneous nuclear decay is by itself a process of energy impartation apart from those subsequently occurring during the slowing down of the ionizing particles liberated in the decay may seem strange but is a consequence of the definition of the energy imparted to the matter in a volume. A conceptually interesting detail is that in decays which result in an increase in the atomic number, as in a β^--decay, the imparted energy may become negative due to the resulting increase in binding energy of the surrounding electrons. In the same way, the imparted energy of an initiated nuclear reaction may become negative. Practically, the imparted energy in processes like nuclear decays and initiated nuclear reactions is neglected in calculations of, e.g., absorbed dose (see Section VI, A), since it is negligible compared with the sum of the imparted energies in the interactions of the ionizing particles liberated in the processes.

C. The Energy Imparted to the Matter in a Volume

The energy imparted ϵ to the matter in a volume is the sum of the imparted energies in all those basic processes which have occurred in the volume during the time interval considered:

$$\epsilon = \sum_i \delta\epsilon_i \tag{11}$$

It may be convenient (cf. Section V,C) to express ϵ in an alternative way [identical to the formulation used by the ICRU (1980) in defining ϵ]. Consider an ionizing particle of kinetic energy T_{in} incident on a volume, Fig. 4.

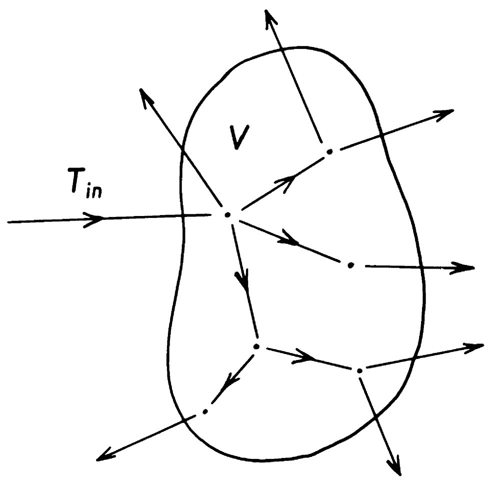

Fig. 4. An ionizing particle with kinetic energy T_{in} enters the volume V and gives rise to a series of correlated basic processes in it. Points indicate basic processes occurring during the time interval considered. In addition to interactions by ionizing particles, decays of radioactive nuclei created in a preceding interaction have to be considered. Freely moving ionizing particles are represented by lines, and the arrows indicate directions of motion. [After Alm Carlsson (1979).]