INTRODUCTION TO RADIOLOGICAL PHYSICS AND RADIATION DOSIMETRY

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This book is dedicated to my parents
Ulysses Sheldon Attix and Alma Katherine Attix (nee Michelsen),
my wife Shirley Adeline Attix (nee Lohr),
my children Shelley Anne and Richard Haven,
and to radiological physics students everywhere

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Preface

This book is intended as a text for an introductory course at the graduate or senior undergraduate level. At the University of Wisconsin this is a three-credit course: Medical Physics 501—Radiological Physics and Dosimetry, consisting of about 45 lectures and 15 problem discussion sessions, each 50 minutes in length. By moving along briskly and by scheduling the exams at other times, the material in the book can be adequately covered in one semester. The chapters are designed to be taught in sequence from 1 through 16.

The book is written on the assumption that the student has previously studied integral calculus and atomic or modern physics. Thus integrals are used without apology wherever necessary, and no introductory chapter to review atomic structure and elementary particles is provided. Chapter 1 in Johns and Cunningham's book *The Physics of Radiology*, 3rd or 4th edition, for example, can be used for remedial review if needed.

The present text is pragmatic and classical in approach, not necessarily developing equations from first principles, as is more often done by Anderson (1984) in his admirable book *Absorption of Ionizing Radiation*. Missing details and derivations that are relevant to interaction processes may be found there, or in the incomparable classic *The Atomic Nucleus* by Robley Evans, recently republished by Krieger.

A challenging problem in writing this book was how to limit its scope so that it would fit a coherent course that could be taught in one semester and would not reach an impractical and unpublishable length. It had to be in a single volume for convenient use as a text, as it was not intended to be a comprehensive reference like the three-volume second edition of *Radiation Dosimetry*, edited by Attix, Roesch, and Tochilin. Although that treatise has been used for textbook purposes in some courses, it was never intended to be other than a reference. In limiting the scope of this text the following topic areas were largely omitted and are taught as separate courses in the University of Wisconsin Department of Medical Physics: radiotherapy physics, nuclear medicine, diagnostic radiological physics, health physics (radiation protection), and radiobiology. Other texts are used for those courses. Radiation-generating equipment is described in the courses on radiotherapy and diagnostic physics, as the design of such equipment is specific to its use.

What is included is a logical, rather than historical, development of radiological physics, leading into radiation dosimetry in its broadest sense. There is no such thing as a *perfect* sequence—one that always builds on material that has gone before and never has to reach ahead for some as yet untaught fact. However, the present order of chapters has evolved from several years of trial-and-error classroom testing and works quite well.

A few specifics deserve mentioning:

Extensive, but not exclusive, use is made of SI units. The older units in some instances offer advantages in convenience, and in any case they are not going to vanish down a "memory hole" into oblivion. The rad, rem, roentgen, curie, and erg will remain in the existing literature forever, and we should all be familiar with them. There is, moreover, no reason to restrain ourselves from using centimeters or grams when nature provides objects for which convenient-sized numbers will result. I believe that units should be working for us, not the other way around.

The recommendations of the International Commission on Radiation Units and Measurements (ICRU) are used as the primary basis for the radiological units in this book, as far as they go. However, additional quantities (e.g., collision kerma, energy transferred, net energy transferred) have been defined where they are needed in the logical development of radiological physics.

Several important concepts have been more clearly defined or expanded upon, such as radiation equilibrium, charged-particle equilibrium, transient charged-particle equilibrium, broadbeam attenuation, the reciprocity theorem (which has been extended to homogeneous but nonisotropic fields), and a rigorous derivation of the Kramers x-ray spectrum.

Relegating neutron dosimetry to the last chapter is probably the most arbitrary and least logical chapter assignment. Initially it was done when the course was taught in two halves, with the first half alone being prerequisite for radiotherapy physics. Time constraints and priorities dictated deferring all neutron considerations until the second half. Now that the course (and text) has been unified, that reason is gone, but the neutron chapter remains number 16 because it seems to fit in best after all the counting detectors have been discussed. Moreover it provides an appropriate setting for introducing microdosimetry, which finds its main application in characterizing neutron and mixed n–γ fields.

The tables in the appendixes have been made as extensive as one should hope to find in an introductory text. The references for all the chapters have been collected together at the back of the book to avoid redundancy, since some references are repeated in several chapters. Titles of papers have been included. A comprehensive table of contents and index should allow the easy location of material.

For the authors-to-be among this book's readers: This book was begun in 1977 and completed in 1986. It started from classroom notes that were handed out to students to supplement other texts. These notes gradually evolved into chapters that were modified repeatedly, to keep what worked with the students, and change what didn't. This kind of project is not for anyone with a short attention span.

The original illustrations for this book were drawn by F. Orlando Canto. Kathryn A. McSherry and Colleen A. Schutz of the office staff were very helpful. I also thank the University of Wisconsin Department of Medical Physics for allowing me to use their copying equipment.

Finally, it is a pleasure to acknowledge that the preparation of this book could not have been accomplished without the dedicated partnership and enthusiasm of my wife Shirley. Not only did she do all the repetitious typing, during a time before a word processor was available, but she never complained about the seemingly endless hours I spent working on it.

HERB ATTIX

Madison, Wisconsin
August 1986

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CHAPTER 1

Ionizing Radiation

I. INTRODUCTION

Radiological physics is the science of ionizing radiation and its interaction with matter, with special interest in the energy thus absorbed. Radiation dosimetry has to do with the quantitative determination of that energy. It would be awkward to try to discuss these matters without providing at the outset some introduction to the necessary concepts and terminology.

Radiological physics began with the discovery of x-rays by Wilhelm Röntgen, of radioactivity by Henri Becquerel, and of radium by the Curies in the 1890s. Within a very short time both x-rays and radium became useful tools in the practice of medicine. In fact, the first x-ray photograph (of Mrs. Röntgen's hand) was made by Röntgen late in 1895, within about a month of his discovery, and physicians on both sides of the Atlantic were routinely using x-rays in diagnostic radiography within a year, thus setting some kind of record for the rapid adoption of a new technology in practical applications.

The historical development of the science of radiological physics since then is itself interesting, and aids one in understanding the quantities and units used in this field today. However, such an approach would be more confusing than helpful in an introductory course. Historical reviews have been provided by Etter (1965), Parker and Roesch (1962), and by Roesch and Attix (1968).

II. TYPES AND SOURCES OF IONIZING RADIATIONS

Ionizing radiations are generally characterized by their ability to excite and ionize atoms of matter with which they interact. Since the energy needed to cause a valence electron to escape an atom is of the order of 4–25 eV, radiations must carry kinetic or quantum energies in excess of this magnitude to be called "ionizing." As will be seen from Eq. (1.1), this criterion would seem to include electromagnetic radiation with wavelengths up to about 320 nm, which includes most of the ultraviolet (UV) radiation band (~10–400 nm). However, for practical purposes these marginally ionizing UV radiations are not usually considered in the context of radiological physics, since they are even less capable of penetrating through matter than is visible light, while other ionizing radiations are generally more penetrating.

The personnel hazards presented by optical lasers and by radiofrequency (RF) sources of electromagnetic radiation are often administratively included in the area of a health physicist's responsibilities, together with ionizing radiation hazards. Moreover, the determination of the energy deposition in matter by these radiations is often referred to as "dosimetry". However, the physics governing the interaction of such radiations with matter is totally different from that for *ionizing* radiations, and this book will not deal with them.

The important types of ionizing radiations to be considered are:

1. *γ-rays:* Electromagnetic radiation emitted from a nucleus or in annihilation reactions between matter and antimatter. The quantum energy of any electromagnetic photon is given in keV by

$$E_\gamma = h\nu = \frac{hc}{\lambda} = \frac{12.398 \text{ keV-Å}}{\lambda} = \frac{1.2398 \text{ keV-nm}}{\lambda} \tag{1.1}$$

where 1 Å (Angstrom) = 10^{-10} m, Planck's constant is

$$h = 6.626 \times 10^{-34} \text{ J s} = 4.136 \times 10^{-18} \text{ keV s}$$

(note that 1.6022×10^{-16} J = 1 keV), and the velocity of light *in vacuo* is

$$c = 2.998 \times 10^{8} \text{ m/s} = 2.998 \times 10^{18} \text{ Å/s} = 2.998 \times 10^{17} \text{ nm/s}$$

Evidently, by Eq. (1.1) the quantum energy of a photon of 0.1-nm wavelength is 12.4 keV, within one part in 6000.

The practical range of photon energies emitted by radioactive atoms extends from 2.6 keV (K_α characteristic x-rays from electron capture in $^{37}_{18}Ar$) to the 6.1- and 7.1-MeV γ-rays from $^{16}_{7}N$.

2. *X-rays:* Electromagnetic radiation emitted by charged particles (usually electrons) in changing atomic energy levels (called *characteristic* or *fluorescence* x-rays) or in slowing down in a Coulomb force field (*continuous* or *bremsstrahlung* x-rays). Note that an x-ray and a γ-ray photon of a given quantum energy have identical properties, differing only in mode of origin. Older texts sometimes referred to all lower-energy photons as x-rays and higher energy photons as γ-rays, but this basis for the distinction is now obsolete. Most commonly, the energy ranges of x-rays are now referred to as follows, in terms of the generating voltage:

0.1–20 kV	Low-energy or "soft" x-rays, or "Grenz rays"
20–120 kV	Diagnostic-range x-rays
120–300 kV	Orthovoltage x-rays
300 kV–1 MV	Intermediate-energy x-rays
1 MV upward	Megavoltage x-rays

3. *Fast Electrons:* If positive in charge, they are called positrons. If they are emitted from a nucleus they are usually referred to as β-rays (positive or negative). If they result from a charged-particle collision they are referred to as "δ-rays". Intense continuous beams of electrons up to 12 MeV are available from Van de Graaff generators, and pulsed electron beams of much higher energies are available from linear accelerators ("linacs"), betatrons, and microtrons. Descriptions of such accelerators, as encountered in medical applications, have been given by Johns and Cunningham (1974) and Hendee (1970).

4. *Heavy Charged Particles:* Usually obtained from acceleration by a Coulomb force field in a Van de Graaff, cyclotron, or heavy-particle linear accelerator. Alpha particles are also emitted by some radioactive nuclei. Types include:

- Proton—the hydrogen nucleus.
- Deuteron—the deuterium nucleus, consisting of a proton and neutron bound together by nuclear force.
- Triton—a proton and two neutrons similarly bound.
- Alpha particle—the helium nucleus, i.e., two protons and two neutrons. ^{3}He particles have one less neutron.
- Other heavy charged particles consisting of the nuclei of heavier atoms, either fully stripped of electrons or in any case having a different number of electrons than necessary to produce a neutral atom.
- Pions—negative π-mesons produced by interaction of fast electrons or protons with target nuclei.

5. *Neutrons:* Neutral particles obtained from nuclear reactions [e.g., (p, n) or fission], since they cannot themselves be accelerated electrostatically.

The range of kinetic or photon energies most frequently encountered in applications of ionizing radiations extends from 10 keV to 10 MeV, and relevant tabulations of data on their interactions with matter tend to emphasize that energy range. Likewise the bulk of the literature dealing with radiological physics focuses its attention primarily on that limited but useful band of energies. Recently, however, clinical radiotherapy has been extended (to obtain better spatial distribution, and/or more direct cell-killing action with less dependence on oxygen) to electrons and x-rays up to about 50 MeV; and neutrons to 70 MeV, pions to 100 MeV, protons to 200 MeV, α-particles to 10^3 MeV, and even heavier charged particles up to 10 GeV are being investigated in this connection. Electrons and photons down to about 1 keV are also proving to be of experimental interest in the context of radiological physics.

The ICRU (International Commision on Radiation Units and Measurements, 1971) has recommended certain terminology in referring to ionizing radiations which emphasizes the gross differences between the interactions of charged and uncharged radiations with matter:

1. *Directly Ionizing Radiation.* Fast charged particles, which deliver their energy to matter directly, through many small Coulomb-force interactions along the particle's track.
2. *Indirectly Ionizing Radiation.* X- or γ-ray photons or neutrons (i.e., uncharged particles), which first transfer their energy to charged particles in the matter through which they pass in a relatively few large interactions. The resulting fast charged particles then in turn deliver the energy to the matter as above.

It will be seen that the deposition of energy in matter by indirectly ionizing radiation is thus a *two-step process*. In developing the concepts of radiological physics the importance of this fact will become evident.

The reason why so much attention is paid to ionizing radiation, and that an extensive science dealing with these radiations and their interactions with matter has evolved, stems from the unique effects that such interactions have upon the irradiated material. Biological systems (e.g., humans) are particularly susceptible to damage by ionizing radiation, so that the expenditure of a relatively trivial amount of energy (~ 4 J/kg) throughout the body is likely to cause death, even though that amount of energy can only raise the gross temperature by about 0.001°C. Clearly the ability of ionizing radiations to impart their energy to individual atoms, molecules, and biological cells has a profound effect on the outcome. The resulting high local concentrations of absorbed energy can kill a cell either directly or through the formation of highly reactive chemical species such as free radicals* in the water medium that constitutes the bulk of the biological material. Ionizing radiations can also produce gross changes, either desirable or deleterious, in organic compounds by breaking molecular bonds, or in crystalline materials by causing defects in the lattice structure.

*A free radical is an atom or compound in which there is an unpaired electron, such as H or CH_3.

Even structural steel will be damaged by large enough numbers of fast neutrons, suffering embrittlement and possible fracture under mechanical stress.

Discussing the details of such radiation effects lies beyond the scope of this book, however. Here we will concentrate on the basic physics of the interactions, and methods for measuring and describing the energy absorbed in terms that are useful in the various applications of ionizing radiation.

III. DESCRIPTION OF IONIZING RADIATION FIELDS

A. Consequences of the Random Nature of Radiation

Suppose we consider a point P in a field of ionizing radiation, and ask: "How many *rays* (i.e., photons or particles) will strike P per unit time?" The answer is of course zero, since a point has no cross-sectional area with which the rays can collide. Therefore, the first step in describing the field at P is to associate some nonzero volume with the point. The simplest such volume would be a sphere centered at P, as shown in Fig. 1.1, which has the advantage of presenting the same cross-sectional target area to rays incident from all directions. The next question is how large this imaginary sphere should be. That depends on whether the physical quantities we wish to define with respect to the radiation field are *stochastic* or *nonstochastic*.

A stochastic quantity has the following characteristics:*

a. Its values occur randomly and hence cannot be predicted. However, the probability of any particular value is determined by a probability distribution.

b. It is defined for finite (i.e. noninfinitesimal) domains only. Its values vary discontinuously in space and time, and it is meaningless to speak of its gradient or rate of change.

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

d. The *expectation value* N_e of a stochastic quantity is the mean $\overline{N}$ of its measured values N as the number n of observations approaches ∞. That is, $\overline{N} \rightarrow N_e$ as $n \rightarrow \infty$.

A nonstochastic quantity, on the other hand, has these characterstics:

a. For given conditions its value can, in principle, be predicted by calculation.

b. It is, in general, a "point function" defined for infinitesimal volumes; hence it is a continuous and differentiable function of space and time, and one may speak of its spatial gradient and time rate of change. In accordance with common usage in physics, the argument of a legitimate differential quotient may always be assumed to be a nonstochastic quantity.

*Further discussion of stochastic vs. nonstochastic physical quantities will be found in ICRU (1971) and ICRU (1980).

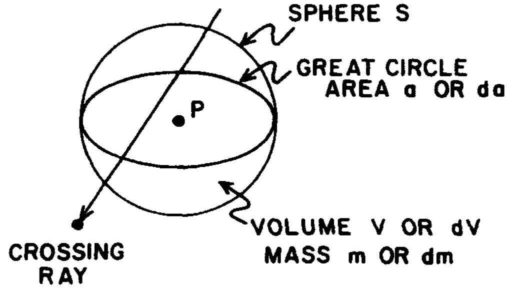

FIGURE 1.1. Characterizing the radiation field at a point *P* in terms of the radiation traversing the spherical surface *S*.

c. Its value is equal to, or based upon, the *expectation value* of a related stochastic quantity, if one exists. Although nonstochastic quantities in general need not be related to stochastic quantities, they are so related in the context of ionizing radiation.

It can be seen from these considerations that the volume of the imaginary sphere surrounding point P in Fig. 1.1 may be small but must be *finite* if we are dealing with stochastic quantities. It may be infinitesimal (dV) in reference to nonstochastic quantities. Likewise the great-circle area (da) and contained mass (dm) for the sphere, as well as the irradiation time (dt), may be expressed as infinitesimals in dealing with nonstochastic quantities. Since the most common and useful quantities for describing ionizing radiation fields and their interactions with matter are all nonstochastic, we will defer further discussion of stochastic quantities (except when leading to nonstochastic quantities) until a later chapter (16) dealing with *microdosimetry*, that is, the determination of energy spent in small but finite volumes. Microdosimetry is of particular interest in relation to biological-cell damage.

In general one can assume that a "constant" radiation field is strictly random with respect to how many rays arrive at a given point per unit area and time interval. It can be shown (e.g., see Beers, 1953) that the number of rays observed in repetitions of the measurement (assuming a fixed detection efficiency and time interval, and no systematic change of the field vs. time) will follow a Poisson distribution. For large numbers of events this may be approximated by the normal (Gaussian) distribution. If N_e is the expectation value of the number of rays detected per measurement, the standard deviation of a single random measurement N relative to N_e is equal to

$$\sigma = \sqrt{N_e} \cong \sqrt{N} \tag{1.2a}$$

and the corresponding percentage standard deviation is

$$S = \frac{100\sigma}{N_e} = \frac{100}{\sqrt{N_e}} \cong \frac{100}{\sqrt{N}} \tag{1.2b}$$

That is, a single measurement would have a 68.3% chance of lying within $\pm\sigma$