Physics in Nuclear Medicine

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PREFACE

Physics and instrumentation impact all of the subspecialty areas of nuclear medicine. Because of their fundamental importance, they usually are taught as a separate course in nuclear medicine training programs. The authors have taught such courses to physicians, technologists, and scientists for a number of years. In our experience there is a need for an introductory text covering the physics and instrumentation of nuclear medicine in sufficient depth to be of permanent value to the trainee or student, but not at such depth as to be of interest only to the physics or instrumentation specialist. This textbook has been prepared with the hope of meeting this need.

The text is designed to be used in training programs for physicians, technologists, and other scientists who desire to become specialists in nuclear medicine. We have assumed that the student or trainee will have had introductory courses in basic physics and mathematics, including an introduction to basic algebra. Knowledge of calculus is not required, although a few examples employing the methods of calculus are presented for the interest of those having a knowledge of this subject.

Nuclear medicine physics and instrumentation are complex subjects, especially when presented to students or trainees who are not specialists in these areas. Therefore, we have at all times tried to make our presentations as clear and understandable as possible. On the other hand, we also have attempted to be thorough and accurate in our discussions of important basic principles, believing this approach to be of more permanent value than a superficial or oversimplified one designed to make these complex topics more "palatable" to the student or trainee.

The organization of this text proceeds from basic principles to more practical aspects. We begin with a review of atomic and nuclear physics (Chapter 1) and basic principles of radioactivity and radioactive decay (Chapters 2 and 3). Basic principles of radiation detectors (Chapter 4), radiation counting electronics (Chapter 5), and nuclear counting statistics (Chapter 6) are treated next. These topics appear relatively early in the text to permit the introduction of laboratory exercises involving simple nuclear counting experiments in those training programs incorporating laboratory sections.

Radionuclide production methods are discussed in Chapter 7, followed by radiation interactions in Chapters 8 and 9. Radiation dosimetry, which is closely related to radiation interactions, is treated in Chapter 10.

Pulse-height spectrometry, which plays an important role in many nuclear medicine procedures is described in Chapter 11, followed by general problems in nuclear radiation counting in Chapter 12. The next two chapters are devoted to specific types of nuclear radiation counting instruments, for both in vivo and in vitro measurements. Chapter 13 deals exclusively with systems incorporating NaI(Tl) detectors, and Chapter 14 with systems employing other types of detectors: chiefly, semiconductor, liquid scintillation, and gas filled.

Chapters 15 through 18 discuss topics in radionuclide imaging, beginning with a description of the principles and performance characteristics of the Anger camera (Chapters 15 and 16), then other imaging instruments and techniques (scanners, multicrystal cameras, and radionuclide computed tomography) (Chapter 17), and finally general problems in radionuclide imaging (Chapter 18). The purpose of this last chapter is to tie together and relate the many interacting factors affecting the quality of radionuclide images obtained with virtually any radionuclide imaging instrument. Our discussion of imaging instruments is limited to those which now enjoy or appear to have the potential for achieving clinical acceptance. Instruments that seem to be of research interest only are not described.

The text concludes with an introduction to the problems of radiation safety and health physics (Chapter 19). We did not deal with more general problems in radiation biology, believing this topic of sufficient importance to warrant its own special treatment, as has been done already in several excellent books on the subject.

Additional reading for more detailed information is suggested at the end of each chapter. We also have included sample problems with solutions to illustrate certain quantitative relationships and to demonstrate standard calculations that are required in the practice of nuclear medicine. As much as possible, we have used metric units. Exceptions are those instances where dimensions of standard-sized detectors, etc., are commonly given in inches. SI (Systeme Internationale) units are introduced and defined to familiarize the student with them. Because they do not yet enjoy widespread popularity, however, they are not used as the standard for this text.

As is usually the case, the authors received much valuable assistance in preparing this textbook. We are expecially indebted to Drs. Gerry Hine and Bill

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1
Basic Atomic and Nuclear Physics

Radioactivity is a process involving events in individual atoms and nuclei. Before discussing radioactivity, therefore, it is worthwhile to review some of the basic concepts of atomic and nuclear physics.

A. MASS AND ENERGY UNITS

Events occurring on the atomic scale, such as radioactive decay, involve masses and energies much smaller than those encountered in the events of our everyday experiences. Therefore they are described in terms of mass and energy units more appropriate to the atomic scale.

The basic unit of mass is the *universal mass unit,* abbreviated u. One u is defined as being equal to exactly $\frac{1}{12}$ the mass of a ^{12}C atom.† A slightly different unit, commonly used in chemistry, is the *atomic mass unit* (amu), based on the average weight of oxygen isotopes in their natural abundance. In this text, except where indicated, masses will be expressed in universal mass units, u.

The basic unit of energy is the *electron volt,* abbreviated eV. One eV is defined as the amount of energy acquired by an electron when it is accelerated through an electrical potential of one volt. Basic multiples are the keV (*k*ilo *e*lectron *v*olt; 1 keV = 1000 eV) and the MeV (*M*ega *e*lectron *v*olt; 1 MeV = 1000 keV = 1,000,000 eV).

Mass m and energy E are related to each other by Einstein's equation $E = mc^2$, where c is the velocity of light. According to this equation, 1 u of mass is equivalent to 931.5 MeV of energy.

†Atomic notation is discussed in Section D.2 of this chapter.

Table 1–1
Mass and Energy Units

Multiply → To Obtain	By	To Obtain ← Divide
u	1.66043×10^{-24}	g
u	4.86×10^{-26}	oz
u	1.00083	amu
eV	1.6021×10^{-12}	ergs
eV	3.83×10^{-20}	g·cal
u	931.478	MeV

Relationships between various units of mass and energy are summarized in Table 1–1. Universal mass units and electron volts are very small, yet, as we shall see, they are quite appropriate to the atomic scale.

B. ELECTROMAGNETIC RADIATION (PHOTONS)

Atomic and nuclear processes often result in the emission of electromagnetic radiation, such as x rays (Section C.3), and γ rays (gamma rays, Section D.5). Electromagnetic radiation consists of oscillating electrical and magnetic fields traveling through space with the velocity of light, c (approximately 3×10^8 meters/sec in vacuum). The wavelength λ and frequency ν of these oscillating fields are related by

$$\lambda \nu = c \tag{1–1}$$

In some cases, e.g., when interacting with atoms, electromagnetic radiations behave as discrete "packets" of energy, called *photons* (also called *quanta*). A photon is a packet of electromagnetic energy having no mass or electrical charge that also travels through space at the velocity of light. The energy of a photon, E, and the wavelength λ of its associated electromagnetic field are related by

$$E(\text{keV}) = 12.4/\lambda(\text{Å}) \tag{1–2}$$

$$\lambda(\text{Å}) = 12.4/E(\text{keV}) \tag{1–3}$$

Table 1–2 lists approximate photon energies and wavelengths for different parts of the electromagnetic spectrum. Note that x and γ rays occupy the highest-energy, shortest-wavelength end of the spectrum; x- and γ-ray photons have energies in the keV–MeV range, whereas visible light photons, for example, have energies of only a few eV. As a consequence of their short wavelength