OBJECTIVES

After completing this chapter, the reader should be able to:

- Compare directly ionizing and indirectly ionizing radiation and give examples of each.
- Define and state the relationships among linear energy transfer, specific ionization, the *W*-quantity, range, and energy.
- List the interactions that occur for electrons.
- Give examples of elastic and inelastic scattering by nuclei.
- Describe the interactions of neutrons.
- Write an equation for attenuation of photons in a given thickness of a material.
- List the interactions that occur for photons.
- Define atomic, electronic, mass, and linear attenuation coefficients.
- Discuss and compare energy absorption and energy transfer.
- List at least five types of electromagnetic radiation.

Directly and Indirectly Ionizing Radiation

Directly Ionizing Particles (Charged Particles)	Indirectly Ionizing Particles (Uncharged Particles)
Alpha (helium nuclei)	Photons
Any nuclei	Neutrons
Beta (electrons)	
Protons	

The term *interaction* may be used to describe the crash of two automobiles (an example in the macroscopic world) or the collision of an x ray with an atom (an example in the submicroscopic world). This chapter describes radiation interactions on a submicroscopic scale. Interactions in both macroscopic and microscopic scales follow fundamental principles of physics such as (a) the conservation of energy and (b) the conservation of momentum.

CHARACTERISTICS OF INTERACTIONS

In a radiation interaction, the radiation and the material with which it interacts may be considered as a single system. When the system is compared before and after the interaction, certain quantities will be found to be *invariant*. Invariant quantities are exactly the same before and after the interaction. Invariant quantities are said to be *conserved* in the interaction. One quantity that is always conserved in an interaction is the total energy of the system, with the understanding that mass is a form of energy. Other quantities that are conserved include momentum and electric charge.

Some quantities are not always conserved during an interaction. For example, the number of particles may not be conserved because particles may be fragmented, fused, "created" (energy converted to mass), or "destroyed" (mass converted to energy) during an interaction. Interactions may be classified as either *elastic* or *inelastic*. An interaction is elastic if the sum of the *kinetic energies* of the interacting entities is conserved during the interaction. If some energy is used to free an electron or nucleon from a bound state, kinetic energy is not conserved and the interaction is inelastic. Total energy is conserved in all interactions, but kinetic energy is conserved only in interactions designated as elastic.

DIRECTLY IONIZING RADIATION

When an electron is ejected from an atom, the atom is left in an *ionized* state. Hydrogen is the element with the smallest atomic number and requires the least energy (binding energy of 13.6 eV) to eject its K-shell electron. Radiation of energy less than 13.6 eV is termed *nonionizing radiation* because it cannot eject this most easily removed electron. Radiation with energy above 13.6 eV is referred to as *ionizing radiation*. If electrons are not ejected from atoms but merely raised to higher energy levels (outer shells), the process is termed *excitation*, and the atom is said to be "excited." Charged particles such as electrons, protons, and atomic nuclei are directly ionizing radiations because they can eject electrons from atoms through charged-particle interactions. Neutrons and photons (x and γ rays) can set charged particles into motion, but they do not produce significant ionization directly because they are uncharged. These radiations are said to be indirectly ionizing.

Energy transferred to an electron in excess of its binding energy appears as kinetic energy of the ejected electron. An ejected electron and the residual positive ion constitute an *ion pair*, abbreviated IP. An average energy of 33.85 eV, termed the W-quantity or W, is expended by charged particles per ion pair produced in air.[1] The average energy required to remove an electron from nitrogen or oxygen (the most common atoms in air) is much less than 33.85 eV. The W-quantity includes not only the electron's binding energy but also the average kinetic energy of the ejected electron and the average energy lost as incident particles excite atoms, interact with nuclei, and increase the rate of vibration of nearby molecules. On the average, 2.2 atoms are excited per ion pair produced in air.

The specific ionization (SI) is the number of primary and secondary ion pairs produced per unit length of path of the incident radiation. The specific ionization of α-particles in air varies from about 3–7 × 10^6 ion pairs per meter, and the specific ionization of protons and deuterons is slightly less. The linear energy transfer (LET) is the average loss in energy per unit length of path of the incident radiation. The LET is the product of the specific ionization and the W-quantity:

$$\text{LET} = (\text{SI})(W) \qquad \textbf{(4-1)}$$

Example 4-1

Assuming that the average specific ionization is 4 × 10^6 ion pairs per meter (IP/m), calculate the average LET of α-particles in air.

$$\begin{aligned} \text{LET} &= (\text{SI})(W) \\ &= 4 \times 10^6 \frac{\text{IP}}{\text{m}} \times 33.85 \frac{\text{eV}}{\text{IP}} \\ &= 1.35 \times 10^5 \frac{\text{keV}}{\text{m}} \end{aligned}$$

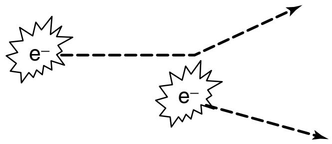
The range of ionizing particles in a particular medium is the straight-line distance traversed by the particles before they are completely stopped. For heavy particles with energy E that tend to follow straight-line paths, the range in a particular medium may be estimated from the average LET:

$$\text{Range} = \frac{E}{\text{LET}} \qquad \textbf{(4-2)}$$

Example 4-2

Calculate the range in air for 4-MeV α-particles with an average LET equal to that computed in Example 4-1.

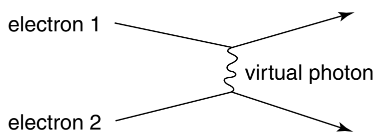
$$\begin{aligned} \text{Range} &= \frac{E}{\text{LET}} \\ &= \frac{4\text{MeV}(10^3\text{keV/ MeV})}{1.35 \times 10^5\text{keV/m}} \\ &= \text{approximately } 0.03 \text{ m} = 3 \text{ cm in air} \end{aligned}$$



MARGIN FIGURE 4-1
One electron is incident upon a target electron. As the incident electron nears the target electron, the electrostatic fields of the two negatively charged electrons interact, with the result that the stationary electron is set in motion by the repulsive force of the incident electron, and the direction of the incident electron is changed. This classical picture assumes the existence of electrostatic fields for the two electrons that exist simultaneously everywhere in space.

Classical Electrodynamics versus Quantum Electrodynamics (QED)
The classical diagram of particle interactions shows a picture of the interaction in space. The Feynman diagram of quantum electrodynamics (QED) shows the development of the interaction in time. The classical diagram of the interaction between two electrons assumes electrostatic fields for the electrons that exist everywhere in space simultaneously. The Feynman QED diagram of the interaction shows the brief exchange of a virtual photon between the two electrons.

In radiologic physics, we are primarily interested in determining which particles survive an interaction, where they go, and where they deposit their energy. For these purposes, the classical diagrams are adequate.



MARGIN FIGURE 4-2
The Feynman diagram of quantum electrodynamics (QED) showing the exchange of a virtual photon between two electrons. When electron 1 emits a virtual photon in a downward direction, conservation of momentum requires the electron to recoil upward. When electron 2 absorbs the virtual photon, it gains momentum and, therefore, must recoil downward. In the QED picture, the electrostatic force between two electrons is explained in terms of exchange of a virtual photon that can travel a specific distance in a specific time.

INTERACTIONS OF ELECTRONS

Interactions of negative and positive electrons may be divided into three categories:

1. Interactions with electrons
2. Elastic interactions with nuclei
3. Inelastic interactions with nuclei

Scattering by Electrons

Negative and positive electrons traversing an absorbing medium transfer energy to electrons of the medium. Impinging electrons lose energy and are deflected at some angle with respect to their original direction. An electron receiving energy may be raised to a shell farther from the nucleus or may be ejected from the atom. The kinetic energy E_k of an ejected electron equals the energy E received minus the binding energy E_B of the electron:

$$E_k = E - E_B \tag{4-3}$$

If the binding energy is negligible compared with the energy received, then the interaction may be considered an elastic collision between "free" particles. If the binding energy must be considered, then the interaction is inelastic.

Incident negatrons and positrons are scattered by electrons with a probability that increases with the atomic number of the absorber and decreases rapidly with increasing kinetic energy of the incident particles. Low-energy negatrons and positrons interact frequently with electrons of an absorber; the frequency of interaction diminishes rapidly as the kinetic energy of the incident particles increases.[2]

Ion pairs are produced by negatrons and positrons during both elastic and inelastic interactions. The specific ionization (ion pairs per meter [IP/m]) in air at STP (standard temperature = 0°C, standard pressure = 760 mm Hg) may be estimated with Eq. (4-4) for negatrons and positrons with kinetic energies between 0 and 10 MeV.

$$\mathrm{SI} = \frac{4500}{(v/c)^2} \tag{4-4}$$

In Eq. (4-4), v represents the velocity of an incident negatron or positron and c represents the speed of light *in vacuo* (3×10^8 m/sec).

Of the many interesting individuals who helped shape our modern view of quantum mechanics, Richard Feynman is remembered as one of the most colorful. Recognized as a math and physics prodigy in college, he came to the attention of the physics community for his work on the Manhattan Project in Los Alamos, New Mexico. In addition to his many contributions to atomic physics and computer science during the project, he was known for playing pranks on military security guards by picking locks on file cabinets, opening safes, and leaving suspicious notes. His late-night bongo sessions in the desert of New Mexico outside the lab were also upsetting to security personnel. After the war, he spent most of his career at Cal Tech, where his lectures were legendary, standing-room-only sessions attended by faculty as well as students.

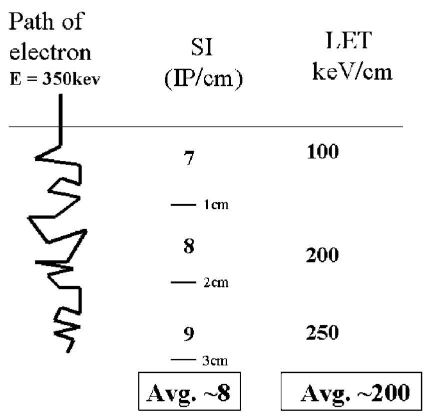
Example 4-3

Calculate the specific ionization (SI) and linear energy transfer (LET) of 0.1 MeV electrons in air ($v/c = 0.548$). The LET may be computed from the SI or Eq. (4-1) by using an average W-quantity for electrons of 33.85 eV/IP:

$$\begin{aligned} \mathrm{SI} &= \frac{4500}{(v/c)^2} \\ &= \frac{4500}{(0.548)^2} \\ &= 15{,}000\ \mathrm{IP/m} \end{aligned}$$

$$\begin{aligned} \mathrm{LET} &= (\mathrm{SI})\,(W) \\ &= (15{,}000\ \mathrm{IP/m})\,(33.85\ \mathrm{eV/IP})\,(10^{-3}\ \mathrm{keV/eV}) \\ &= 508\ \mathrm{keV/m} \end{aligned}$$

After expending its kinetic energy, a positron combines with an electron in the absorbing medium. The particles annihilate each other, and their mass appears as electromagnetic radiation, usually two 0.51-MeV photons moving in opposite directions. These photons are termed *annihilation radiation*, and the interaction is referred to as *pair annihilation*.



MARGIN FIGURE 4-3
An electron having energy $E = 350$ keV interacts in a tissue-like material. Its actual path is torturous, changing direction a number of times, as the electron interacts with atoms of the material via excitations and ionizations. As interactions reduce the energy of the electron through excitation and ionization, the elctron's energy is transferred to the material. The interactions that take place along the path of the particle may be summarized as specific ionization (SI, ion pairs/cm) or as linear energy transfer (LET, keV/cm) along the straight line continuation of the particle's trajectory beyond its point of entry.

Elastic Scattering by Nuclei

Electrons are deflected with reduced energy during elastic interactions with nuclei of an absorbing medium. The probability of elastic interactions with nuclei varies with Z^2 of the absorber and approximately with $1/E_k^2$, where E_k represents the kinetic energy of the incident electrons. The probability for elastic scattering by nuclei is slightly less for positrons than for negatrons with the same kinetic energy. Backscattering of negatrons and positrons in radioactive samples is primarily due to elastic scattering by nuclei.

Probabilities for elastic scattering of electrons by electrons and nuclei of an absorbing medium are about equal if the medium is hydrogen ($Z = 1$). In absorbers with higher atomic number, elastic scattering by nuclei occurs more frequently than electron scattering by electrons because the nuclear scattering cross section varies with Z^2, whereas the cross section for scattering by electrons varies with Z.

Inelastic Scattering by Nuclei

A negative or positive electron passing near a nucleus may be deflected with reduced velocity. The interaction is inelastic if energy is released as electromagnetic radiation during the encounter. The radiated energy is known as bremsstrahlung (braking radiation). A bremsstrahlung photon may possess any energy up to the entire kinetic energy of the incident particle. For low-energy electrons, bremsstrahlung photons are radiated predominantly at right angles to the motion of the particles. The angle narrows as the kinetic energy of the electrons increases (see Margin Figure 4-6).

The probability of bremsstrahlung production varies with Z^2 of the absorbing medium. A typical bremsstrahlung spectrum is illustrated in Margin Figure 4-4. The relative shape of the spectrum is independent of the atomic number of the absorber.

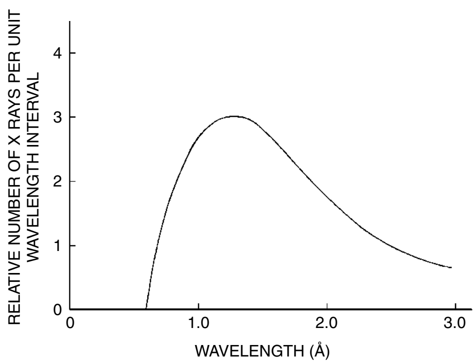
The ratio of radiation energy loss (the result of inelastic interactions with nuclei) to the energy lost by excitation and ionization (the result of interactions with electrons) is approximately

$$\frac{\text{Radiation energy loss}}{\text{Ionization energy loss}} = \frac{E_k Z}{820} \tag{4-5}$$

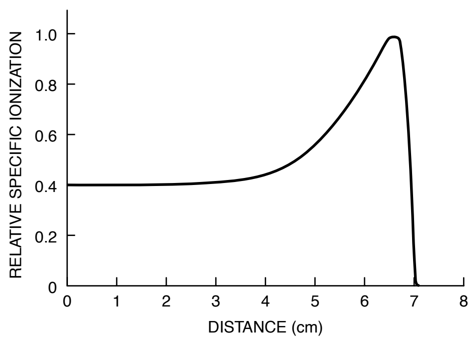
where E_k represents the kinetic energy of the incident electrons in MeV and Z is the atomic number of the absorbing medium. For example, excitation-ionization and bremsstrahlung contribute about equally to the energy lost by 10-MeV electrons traversing lead ($Z = 82$). The ratio of energy lost by the production of bremsstrahlung to that lost by ionization and excitation of atoms is important to the design of x-ray tubes in the diagnostic energy range (below 0.1 MeV) where the ratio is much smaller and therefore x ray production is less efficient.

The speed of light in a vacuum (3×10^8 m/sec) is the greatest velocity known to be possible. Particles cannot exceed a velocity of 3×10^8 m/sec under any circumstances. However, light travels through many materials at speeds slower than its speed in a vacuum. In a material, it is possible for the velocity of a particle to exceed the speed of light in the material. When this occurs, visible light known as Cerenkov radiation is emitted. Cerenkov radiation is the cause of the blue glow that emanates from the core of a "swimming pool"-type nuclear reactor. Only a small fraction of the kinetic energy of high-energy electrons is lost through production of Cerenkov radiation.

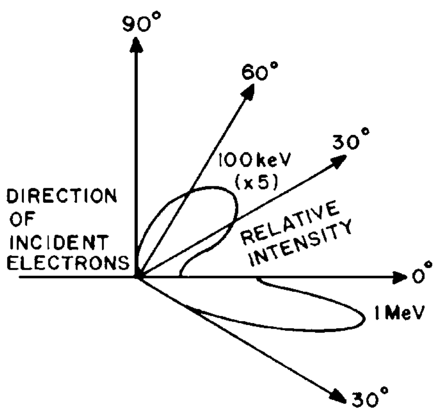
A cross section is an expression of probability that an interaction will occur between particles. The bigger the cross section, the higher the probability an interaction will occur. This is the same principle as the observation that "the bigger the target, the easier it is to hit." The unit in which atomic cross sections are expressed is the barn, where one barn equals 10^{-28} m^2. Its origin is in the American colloquialism, "as big as a barn" or "such a bad shot, he couldn't hit the broad side of a barn." The unit name was first used by American scientists during the Manhattan Project, the project in which the atomic bomb was developed during World War II. In 1950, the Joint Commission on Standards, Units, and Constants of Radioactivity recommended international acceptance because of its common usage in the United States (Evans, R. D. *The Atomic Nucleus*. Malabar, FL, Krieger Publishing, 1955, p. 9.)



MARGIN FIGURE 4-4
Bremsstrahlung spectrum for a molybdenum target bombarded by electrons accelerated through 20 kV plotted as a function of wavelength in angstroms (Å) = 10^{-10} m. (From Wehr, M., and Richards, J. *Physics of the Atom*. Reading, MA, Addison-Wesley, 1960, p. 159. Used with permission.)



MARGIN FIGURE 4-5
The relative specific ionization of 7.7-MeV α-particles from the decay of ^{214}Po is plotted as a function of the distance traversed in air.



MARGIN FIGURE 4-6
Relative intensity of bremsstrahlung radiated at various angles for electrons with kinetic energies of 100 keV and 1 MeV. (Data from Scherzer, O. *Ann Phys* 1932; **13**:137; and Andrews, H. *Radiation Physics*. Englewood Cliffs, NJ, Prentice-Hall International, 1961.)

INTERACTIONS OF HEAVY, CHARGED PARTICLES

Protons, deuterons, α-particles, and other heavy, charged particles lose kinetic energy rapidly as they penetrate matter. Most of the energy is lost as the particles interact inelastically with electrons of the absorbing medium. The transfer of energy is accomplished by interacting electrical fields, and physical contact is not required between the incident particles and absorber electrons. From Examples 4-1 and 4-2, it is apparent that α-particles produce dense patterns of interaction but have limited range. Deuterons, protons, and other heavy, charged particles also exhibit high specific ionization and a relatively short range. The density of soft tissue (1 g/cm^3) is much greater than the density of air (1.29×10^{-3} g/cm^3). Hence, α-particles of a few MeV or less from radioactive nuclei penetrate soft tissue to depths of only a few microns ($1\ \mu\text{m} = 10^{-6}$m). For example, α-particles from a radioactive source near or on the body penetrate only the most superficial layers of the skin.

The specific ionization (SI) and LET are not constant along the entire path of monoenergetic charged particles traversing a homogeneous medium. The SI of 7.7-MeV α-particles from ^{214}Po is plotted in Margin Figure 4-5 as a function of the distance traversed in air. The increase of SI near the end of the path of the particles reflects the decreased velocity of the α-particles. As the particles slow down, the SI increases because nearby atoms are influenced for a longer period of time. The region of increased SI is termed the Bragg peak. The rapid decrease in SI beyond the peak is due primarily to the capture of electrons by slowly moving α-particles. Captured electrons reduce the charge of the α-particles and decrease their ability to produce ionization.

INDIRECTLY IONIZING RADIATION

Uncharged particles such as neutrons and photons are said to be indirectly ionizing. Neutrons have no widespread application at the present time in medical imaging. They are discussed here briefly to complete the coverage of the "fundamental" particles that make up the atom.

INTERACTIONS OF NEUTRONS

Neutrons may be produced by a number of sources. The distribution of energies available depends on the method by which the "free" neutrons are produced. Slow, intermediate, and fast neutrons (Table 4-1) are present within the core of a nuclear reactor. Neutrons with various kinetic energies are emitted by ^{252}Cf, a nuclide that fissions spontaneously. This nuclide has been encapsulated into needles and used experimentally for implant therapy. Neutron beams are available from cyclotrons and other accelerators in which low-Z nuclei (e.g., ^{3}H or ^{9}Be) are bombarded by positively charged particles (e.g., nuclei of ^{1}H, ^{2}H, ^{3}H) moving at high velocities. Neutrons are released as a product of this bombardment. The energy distribution of neutrons from these devices depends on the target material and on the type and energy of the bombarding particle.

Neutrons are uncharged particles that interact primarily by "billiard ball" or "knock-on" collisions with absorber nuclei. A knock-on collision is elastic if the kinetic energy of the particles is conserved. The collision is inelastic if part of the kinetic energy is used to excite the nucleus. During an elastic knock-on collision, the energy transferred from a neutron to the nucleus is maximum if the mass of the nucleus equals the neutron mass. If the absorbing medium is tissue, then the energy transferred per collision is greatest for collisions of neutrons with nuclei of hydrogen, because the mass of the hydrogen nucleus (i.e., a proton) is close to the mass of a neutron. Most nuclei in tissue are hydrogen, and the cross section for elastic collision is greater for hydrogen than for other constituents of tissue. For these reasons, elastic collisions with hydrogen nuclei account for most of the energy deposited in tissue by neutrons with kinetic energies less than 10 MeV.

For neutrons with kinetic energy greater than 10 MeV, inelastic scattering also contributes to the energy lost in tissue. Most inelastic interactions occur with nuclei other than hydrogen. Energetic charged particles (e.g., protons or α-particles) are often ejected from nuclei excited by inelastic interactions with neutrons.