Radioactivity Measurement

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65.1 Radioactivity

Radioactivity is the phenomenon of emissions of neutral or charged particles, or electromagnetic radiations from unstable atomic nuclei. The more common types of radiations are listed in Table 65.1. Several naturally occurring (primordial) radionuclides and some produced by cosmic rays in the earth's atmosphere are given in Table 65.2. Methods of producing other unstable nuclei are discussed below. Radioactive isotopes from man-made sources and from naturally occurring nuclides are widely used in health sciences, industry, and academic research.

TABLE 65.1 Characteristics of Nuclear Radiations [8]

Type	Origin	Process	Charge	Mass [MeV]	Spectrum (energy)
α-particles	Nucleus	Nuclear decay or reaction	+2	3727.33	Discrete [MeV]
β^--rays (negatrons)	Nucleus	Nuclear decay	–1	0.511	Continuous [keV-MeV]
β^+-rays (positrons)	Nuclear	Nuclear decay	+1	0.511	Continuous [keV-MeV]
γ-rays	Nucleus	Nuclear deexcitation	0	0	Discrete [keV-MeV]
X-rays	Orbital electrons	Atomic deexcitation	0	0	Discrete [eV-keV]
Internal conversion electrons	Orbital electrons	Nuclear deexcitation	–1	0.511	Discrete [high keV]
Auger electrons	Orbital electrons	Atomic deexcitation	–1	0.511	Discrete [eV-keV]
Neutrons	Nucleus	Nuclear reaction	0	939.57	Continuous or discrete [keV-MeV]
Fission fragments	Nucleus	Fission	≅20	80–160	Continuous (bimodal) 30–150 MeV

Radioactivity was first discovered by Henri Becquerel in 1896. His student Marie Curie and her husband Pierre Curie were the first to chemically separate the radioactive elements polonium and radium. Becquerel and the Curies received the Nobel Prize in physics in 1903 for their pioneering work in nuclear and radiochemistry. The historical development of the field of radioactivity is covered in a number of

TABLE 65.2 Some Cosmogenic and Naturally Occurring Radionuclides

Radionuclide	Half Life
^{3}H	12.35 years
^{7}Be	53.3 days
^{14}C	5730 years
^{40}K	1.28×10^{9} years
^{232}Th	1.405×10^{10} years
^{235}U	7.04×10^{8} years
^{238}U	4.47×10^{9} years

standard texts, including *The Atomic Nucleus* [1] and *Radioactivity and Its Measurement* [2], and in *Radioactivity Measurements: Principles and Practice* [3]. Other excellent texts are available for students in nuclear medicine [4], in radiochemistry and nuclear chemistry [5, 6], in nuclear and particle physics [7, 8], and a popular general textbook *Radiation Detection and Measurement* by Knoll [9] for nuclear engineering and health physics.

Radioactivity is defined by the International Commission on Radiation Units and Measurements [10] in terms of the *activity*, *A*, of an amount of a radionuclide in a particular energy state at a given time. Mathematically, it is defined as the quotient of *dN* by *dt*, where *dN* is the number of spontaneous nuclear transformations from that energy state in the time interval *dt*, thus

$$A = \frac{dN}{dt} \tag{65.1}$$

The unit of activity in the International System (SI) of units is the becquerel (Bq), which is equal to the unit reciprocal second (s^{-1}). In many fields the older unit, the curie (Ci), is still in use, where 1 Ci = 3.7×10^{10} Bq (exactly).

The activity of an amount of radionuclide is given by the product of the decay constant, λ, and the number of nuclei present at time *t*, thus

$$A = \lambda N \tag{65.2}$$

The reciprocal of λ is the mean life of the nuclide. More commonly, one computes the time necessary for one half of the nuclei to decay, and since this is an exponential process, the half-life is given by

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.69315}{\lambda} \tag{65.3}$$

The activity at any time *t* can be computed using the initial activity A_0 and the decay time *t* according to

$$A = A_0 \exp\left(-0.69315 \frac{t}{T_{1/2}}\right) \tag{65.4}$$

The term *specific activity* is in use in several applied fields and one should be careful to look at the units in any particular application. It is normally defined in terms of the amount of activity per unit mass of the element. For example, the nominal activity of ^{14}C in modern carbon (that found in the biosphere) is 0.3 Bq g^{-1}. In nuclear medicine, however, specific activity is widely used to express the amount of activity per unit quantity of the radioactively labeled compound. For example, one might

produce ^{11}C in a cyclotron and oxidize it to carbon monoxide CO with a specific activity of 1 MBq ^{11}C μmol^{-1} (CO) (megabecquerel of activity per micromole of substance).

Stable nuclei are those nuclei in their ground state that have a proper number of neutrons and protons to balance the nuclear forces between constituents and thus do not decay spontaneously. Radioactive nuclei may be divided into three categories:

- those that have an excess of neutrons over protons,
- those that are neutron deficient, and
- those that are in excited nuclear states.

A schematic showing the most prominent simple transformations between elements of atomic number Z and neutron number N are given in Figure 65.1. The atomic number Z is the number of protons, and the isotopic mass number A is the total number of nucleons (protons plus neutrons). The notation for an isotope—for example, one of krypton—is ${}^{A}_{Z}Kr$. In this chapter, isotopes will be identified only by the mass number and the element symbol, e.g., ^{241}Am.

Particle Emission Radioactivity

Alpha particles are ^{4}He nuclei (2 protons plus 2 neutrons) and are usually emitted by heavy nuclei ($A > 150$). Alpha particles are monoenergetic and usually have energies between 4 and 6 MeV. Table 65.3 lists several alpha emitters, including some at lower and higher energies that can be used for the energy calibration of instruments. Alpha particles carry a +2 charge, and their detection with a variety of instruments is described in detail in Chapter 67, on charged-particle detectors. Alpha-particle pulse-height distributions for several radionuclides of interest in the nuclear fuel cycle are shown in Figure 65.2. The alpha-particle pulse-height distribution for an ^{241}Am source obtained with a high-resolution detector is given in Chapter 66 (Figure 66.16).

TABLE 65.3 Alpha-Particle-Emitting Radionuclides

Radionuclide	Half-Life	Energies (MeV)
^{148}Gd	90 years	3.183
^{241}Am	432.2 years	5.486, 5.443
^{210}Po	138 days	5.305
^{242}Cm	163 days	6.113, 6.070

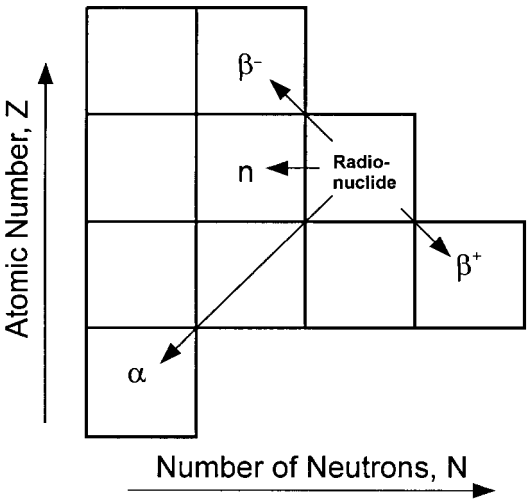

FIGURE 65.1 Characteristics of nuclear radiations [8].

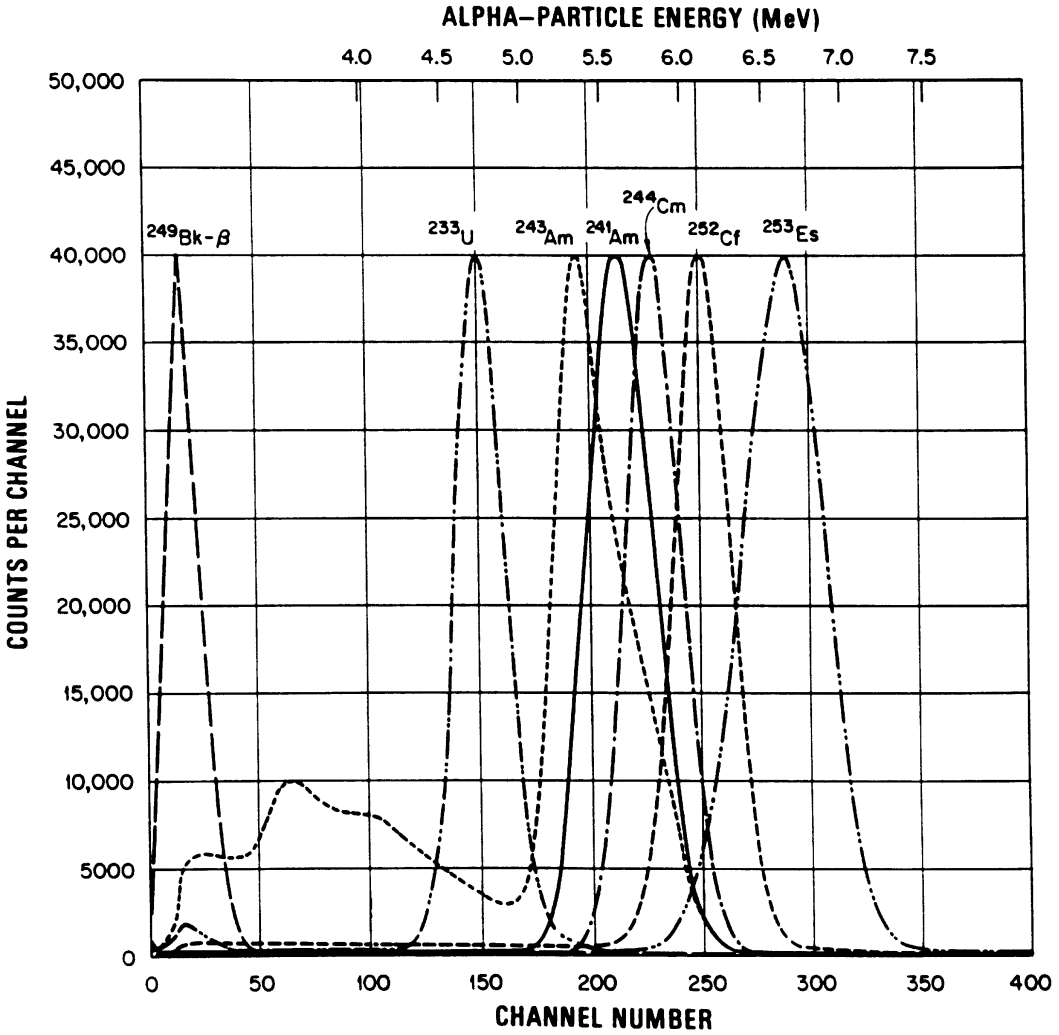

FIGURE 65.2 Liquid-scintillation spectra of selected actinides using a single-phototube detector with the peak channel counts for each major peak preset to 40,000 counts [11].

Beta particles are high-energy electrons emitted by the nucleus as a result of the "weak force" interactions in nuclei that contain too many or too few neutrons. For a system with excess neutrons, the neutron is transformed into a proton and in the process an electron and an antineutrino $\bar{\nu}$ are emitted

$$n \rightarrow p + e^{-} + \bar{\nu} \tag{65.5}$$

The proton remains behind in the nucleus. The antineutrino is required to maintain the conservation of momentum, energy, and "weak-interaction" quantum numbers with respect to the emitted electron [5]. The emitted negatively charged beta particles, usually denoted as β^{-}, have a continuum of energies from zero to a maximum energy denoted by $E_{\beta max}$. $E_{\beta max}$ is the total energy available for the kinetic energy of the electron. The antineutrino carries away that portion not transferred to the electron. An example of an emission spectrum for ^{32}P is given in Figure 65.3. The mode of decay for neutron deficient nuclei is quite similar, except that the proton is converted to a neutron with the emission of a positive electron or *positron* (β^{+}) and a neutrino, which may be written as

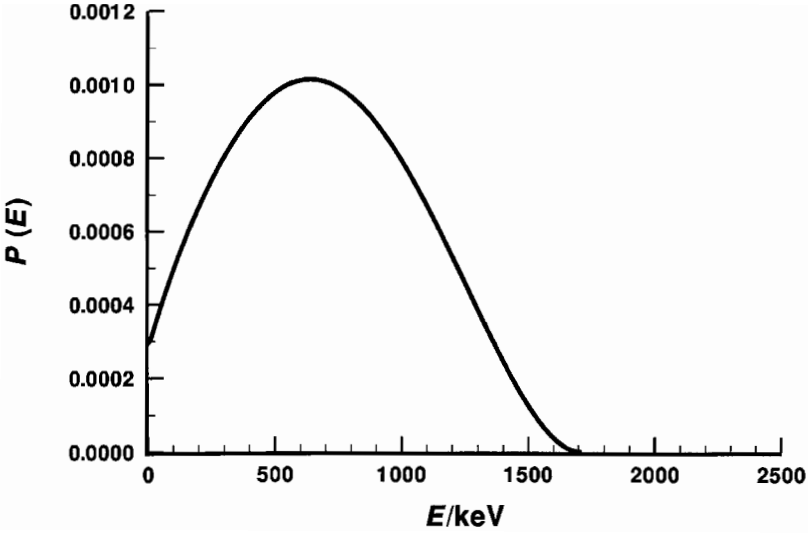

FIGURE 65.3 Theoretical distribution of beta particles as a function of energy for ^{32}P [12].

$$p \rightarrow n + e^{+} + \nu \tag{65.6}$$

Although it is unusual, some radioisotopes decay by both negatron β^- and positron β^+ emission. For example, in the decay of the 13-day half-life ^{126}I one has

$$^{126}I \rightarrow {}^{126}Te + e^{+} + \nu \tag{65.7}$$

$$^{126}I \rightarrow {}^{126}Xe + e^{-} + \overline{\nu} \tag{65.8}$$

Table 65.4 gives a short list of pure beta-particle emitters.

TABLE 65.4 Pure Beta-Particle-Emitting Radionuclides

Radionuclide	Half-Life	Maximum Energy (keV)	Average Energy (keV)
Negatron (β^-) Emitters			
^{3}H	12.35 years	18.6	5.69
^{14}C	5730.0 years	156.5	49.5
^{32}P	14.29 days	1710	695
^{33}P	25.34 days	249	77
^{35}S	87.44 days	167	49
^{89}Sr	50.5 days	1492	583
^{90}Sr	28.5 years	546	196
^{90}Y	64.0 hours	2283	934
Positron (β^+) Emitters[a]			
^{11}C	20.38 min.	960	386
^{18}F	109.71 min.	633	250
^{22}Na	2.602 years	545	216

a.These nuclides exhibit a small amount of electron-capture (EC) decay.

Neutrons are constituents of the nucleus that have a mass number of unity and carry no charge. In normal radioactive decay processes, neutrons are not emitted from the nucleus. With energies exceeding

a few million electron volts (MeVs), however, one can add sufficient energy to cause a neutron to be ejected from the nucleus. These energies can be attained by bombardment with alpha particles from radioactive decay, which is the basis for the common neutron source americium-beryllium (AmBe) in which the alpha particles from the ^{241}Am induce neutron emission from the ^{9}Be nucleus:

$$^{241}\text{Am} \rightarrow {}^{237}\text{Np} + \alpha \tag{65.9}$$

$$\alpha + {}^{9}\text{Be} \rightarrow {}^{13}\text{C}^* \text{ (excited state)} \tag{65.10}$$

$$^{13}\text{C}^* \rightarrow \begin{cases} {}^{12}\text{C}^* + n \\ {}^{8}\text{Be} + \alpha + n \\ 3\alpha + n \end{cases} \tag{65.11}$$

In this case, the ^{13}C nucleus is formed in a highly unstable excited state and rapidly disintegrates by several processes, all of which lead to neutron emission. The neutron spectrum from a ^{241}AmBe source is shown in Figure 65.4. It is very difficult to measure neutron spectra directly, because it is necessary to deconvolve a complicated detector response. Figure 65.4 is the "standard" spectral shape recommended in recent national and international standards [13, 14]. The units on the *y*-axis are explained in Reference 13.

Neutrons are also readily produced in high-energy particle accelerators. Various combinations of accelerated particles and target materials are used to produce neutron beams with selected energies (e.g., 2 and 14 MeV). Neutrons from isotopic sources, accelerators and nuclear reactors can then be used in such applications as boron neutron capture therapy to treat cancer, or in metal fatigue analysis. The neutrons can also be used to produce radionuclides for other applications.

Protons with unit positive charge and unit mass number are simply ^{1}H nuclei stripped of the single orbital electron. Spontaneous emission of protons by nuclei is an exotic decay mode that has been

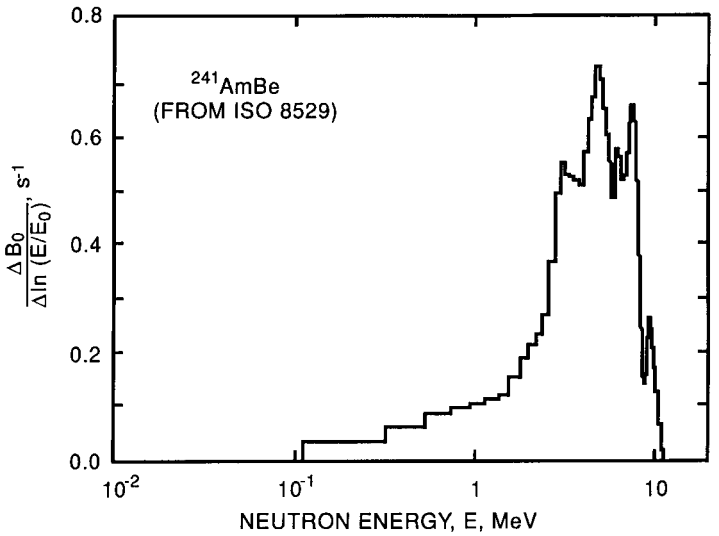

FIGURE 65.4 Neutron spectrum of an ^{241}AmBe radioisotopic source as given in the American National Standard [13] and the International Standard [14]. The units used on the *y*-axis are explained in Reference 13.

observed in only a few cases involving extremely neutron-deficient nuclei [15]. However, beams of protons can be made in positive-ion, charged-particle accelerators by injecting high-purity hydrogen gas, stripping the electrons, and then accelerating the protons to high energies. When these protons are incident on stable target nuclei, a variety of nuclear reactions are possible. The product nuclides are normally radioactive and neutron deficient.

Fission fragments are the large-mass debris formed when a high-Z nuclide such as ^{235}U spontaneously (or by absorption of a slow neutron) breaks up into two or more smaller nuclides in a process known as nuclear fission. The best known fissionable nuclei ^{235}U and ^{239}Pu fission as a result of capturing a neutron. For a given nucleus, the fission fragments are distributed according to a mass distribution which has two maxima. For ^{235}U fission, the maxima occur at A = 90 and A = 130, resulting in fission-product radionuclides such as ^{90}Sr, ^{95}Zr, ^{131}I and ^{137}Cs. A small number of high-Z radionuclides decay by spontaneous fission (e.g. ^{248}Cm). This decay process usually competes with alpha-particle decay and is mostly limited to high-Z nuclides.

Electromagnetic Emission Radioactivity

Gamma rays are photons emitted during nuclear deexcitation processes. These gamma-ray transitions may be from a metastable excited state, or between levels in a daughter nucleus. Two examples are shown in Figure 65.5 for the 6-hour half-life ^{99m}Tc and the 2-day ^{111}In. The large majority of gamma rays from fission products and man-made radionuclides have energies between 20 keV and 2 MeV. A list of gamma-ray emitters used for instrument calibrations are given in Table 65.5. The probability of gamma-ray emission in a particular radionuclide decay (P_γ) is also given in the table. The rate of gamma-ray emission is given by the product $P_\gamma A_0$.

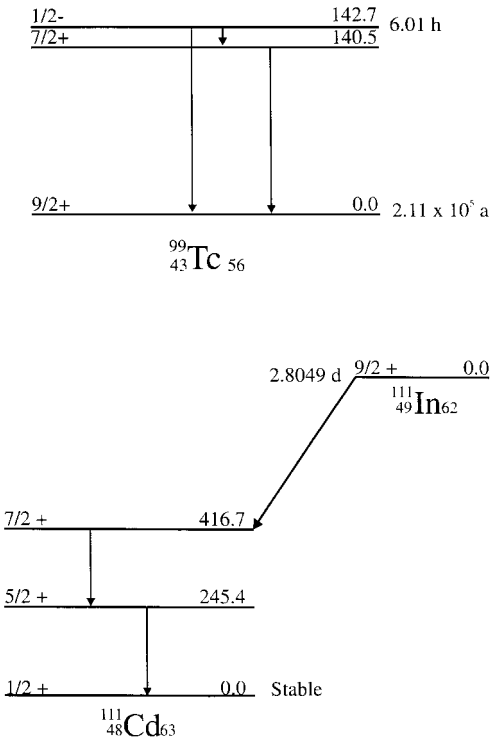

FIGURE 65.5 Simplified nuclear decay schemes for the radionuclides ^{99m}Tc and ^{111}In. The vertical arrows indicate transitions between nuclear excited states. Gamma-ray emission competes with internal conversion processes for each transition [8].

TABLE 65.5 Gamma-Ray-Emitting Radionuclides Used for Detector Efficiency Calibrations

Radionuclide	Half-Life (days)	Energy (keV)	Gamma Rays per Decay, P_γ
^{109}Cd	462.6	88	0.0363 ± 0.0002
^{57}Co	271.79	122	0.8593 ± 0.0027
^{139}Ce	137.64	166	0.7987 ± 0.0006
^{203}Hg	46.595	279	0.8148 ± 0.0008
^{113}Sn	115.09	392	0.6489 ± 0.0013
^{85}Sr	64.849	514	0.984 ± 0.004
^{137}Cs	1.102×10^4	662	0.851 ± 0.002
^{88}Y	106.63	898	0.940 ± 0.003
^{60}Co	1925.5	1173	0.9990 ± 0.0002
^{60}Co	1925.5	1332	0.99983 ± 0.00001
^{88}Y	106.63	1836	0.9936 ± 0.0003

Characteristic **X-rays** are photons emitted during atomic relaxation processes. X-rays are emitted from radionuclides when electrons are involved in the high-energy processes in the nucleus. In the *electron capture* process, for example, the nucleus captures an electron (usually a *K*-shell electron, since it is closest to the nucleus), and a proton and electron form a neutron. This process leaves a *K*-shell vacancy, and a characteristic X-ray from the daughter nucleus can be emitted as orbital electrons from higher shells fill the vacancy. An example is the decay of the 2.6-year half life ^{55}Fe

$$^{55}\text{Fe} + e^- \rightarrow {}^{55}\text{Mn} + X \tag{65.12}$$

The rate of Mn *K* X-ray emission from an ^{55}Fe source of activity A_0 is

$$N_K = P_{KX} A_0 \tag{65.13}$$

where P_{KX} = probability of K X-ray emission.

Conversion electrons are monoenergetic electrons emitted from the nucleus in isomeric transitions between nuclear levels. Conversion-electron emission competes with gamma-ray emission as a mode of nuclear deexcitation.

Interactions with Matter

Before examining in detail the manner in which ionizing radiations can interact, consider two sources of photon radiations, annihilation radiation and bremsstrahlung, which are associated with radioactive decay but depend on the material in which the decay process occurs.

Annihilation radiation is a form of photon radiation associated with a class of radioactive decays. Positrons, since they are the antiparticles of ordinary electrons, cannot survive long in normal matter. Thus, positrons emitted during radioactive decay will slow down in matter until they reach thermal equilibrium. (Depending on the material, they may exist for some microseconds in a state of matter known as positronium.) Ultimately, they combine with an electron in an annihilation event in which their combined mass (1.022 MeV) is converted to energy. This takes the form of two annihilation quanta of 0.511 MeV each which are oppositely directed (to ensure the conservation of momentum). Depending on the positron energy and the density and thickness of the stopping material, there is a slight but calculable probability of *annihilation in flight* [1]. These decays do not result in characteristic 0.511-keV quanta.

Bremsstrahlung is the photon radiation emitted by the deceleration of an electron in the Coulomb field of an atom. Thus, bremsstrahlung radiation is present during all beta decay processes as the emitted β particles (both negatrons and positrons) slow down in matter; it has a continuum of photon energies extending up to the maximum beta-particle energy. The shape of this continuum depends on the nature of the stopping material, as is described in the following section. Bremsstrahlung radiation represents a

particular safety hazard for high-energy pure-beta particle emitters such as ^{32}P (14.4 day, 1.710 MeV β^- max). At higher energies, bremsstrahlung production is almost linear in electron energy and proportional to Z^2 of the stopping material. Thus, to minimize bremsstrahlung, one uses low-Z shielding materials such as plastic.

Now, consider the more general ways in which ionizing radiations from radioactive decay interact with matter. They interact by collisions with the electrons and nuclei along their path. The nature of these interactions is characterized by the charge, mass, and energy of the incident ionizing photon or particle, as well as the charge and mass of the traversed matter. In the energy region of interest, electromagnetic radiation (gamma-ray and X-ray photons) interact with matter principally by three processes: photoelectric absorption, Compton scattering, and pair production. In the photoelectric process, which dominates at lower energies, the photon transfers its energy to an atomic electron, which is then ejected from the atom with an energy equal to that of the incident photon minus the electron's binding energy. In Compton scattering (incoherent scattering), the photon loses a fraction of its energy to an atomic electron, and the scattered photon emerges generally in a direction different from that of the incident photon. Higher-energy photons will undergo multiple Compton scatter events until the process is finally terminated by a photoelectric absorption. For photons with energies exceeding 1.022 MeV, the process of pair production can occur whereby an electron-positron pair is formed. The positron produced will ultimately annihilate with the production of two 0.511-MeV photons (or in flight). The three interaction processes compete as a function of photon energy, electron density, and nuclear charge of the stopping material. Above 2.044 MeV, triplet production can occur [16], but this is a low-probability process, and few radionuclides emit gamma rays above 2 MeV.

Quantitative measures of the photon interactions in matter are attenuation coefficients based on cross sections for specific interactions [8,9]. The total narrow-beam attenuation coefficient μ is given by the sum

$$\mu = \mu_{\text{photoelectric}} + \mu_{\text{Compton}} + \mu_{\text{pair production}}$$

The attenuation process for a beam of photons traversing a slab of matter is an exponential function of the form

$$I = I_0 \exp(-\mu l) \tag{65.14}$$

where I and I_0 = intensities of the transmitted beam and the incident beam, respectively, l = distance traveled in matter, and μ = the linear attenuation coefficient. A useful procedure is to express distances in terms of the mass thickness—the product of density ρ and thickness l. The beam transmission equation can then be rewritten as

$$I = I_0 \exp\left[\frac{-\mu}{\rho}\right](\rho l) \tag{65.15}$$

where μ/ρ is the *mass attenuation coefficient*. The mass attenuation coefficient, in contrast to the linear attenuation coefficient, does not depend on the density of the absorber, but only on its composition. The mass attenuation coefficient as a function of energy for water and lead are shown in Figures 65.6 and 65.7. This discussion of photon interactions has been limited to narrow-beam (or ideal) geometries. In practice, most radioactive sources emit a broad beam of radiation such that the detector registers not only events from the incident beam but also those scattered through large angles, and these effects must be included in computing detector response [9].

Charged particles interact with matter in many different ways. These include:

1. inelastic collisions involving ionization and excitation of atomic electrons of the material
2. inelastic collisions involving bremsstrahlung production in the field of the atom
3. elastic scattering in the field of the atom

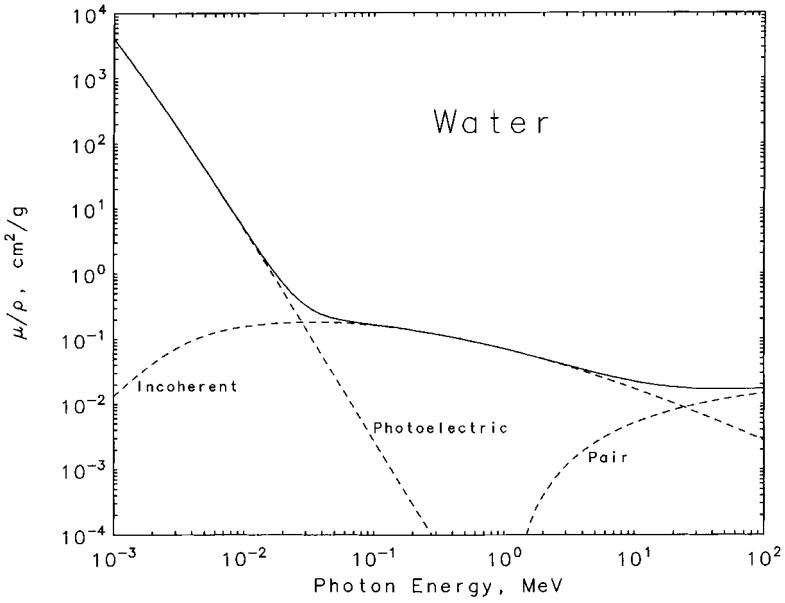

FIGURE 65.6 Narrow-beam mass attenuation coefficients for water as a function of photon energy [17].

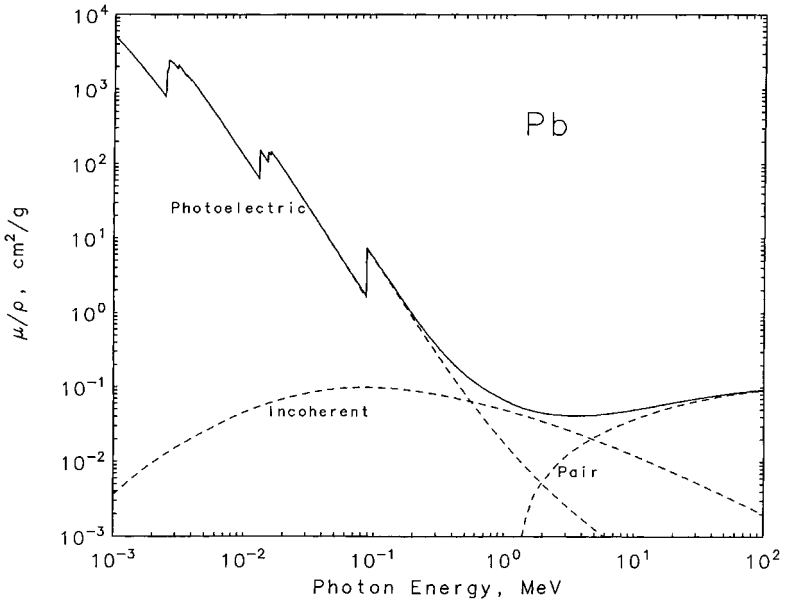

FIGURE 65.7 Narrow-beam mass attenuation coefficients for lead as a function of photon energy [17].

4. nuclear reactions
5. emission of Cerenkov radiation (photons in the visible and ultraviolet regions)

Electrons and positrons, due to their much smaller mass, behave differently from protons, alpha particles, and low-Z charged particles. Two quantitative parameters used to describe inelastic interactions of charged particles as they slow down in matter are *stopping power* and *range.* The total mass stopping power, S/ρ, is defined by the ICRU [10] as the quotient of dE by ρdl, where dE is the energy lost by a charged particle in traversing a distance dl in the material of density ρ. For energies for which the nuclear

interactions can be neglected, the total mass stopping power can be represented as the sum of an electronic (ionization and excitation) term and a radiative (bremsstrahlung) term as follows:

$$\frac{S}{\rho} = \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{\text{elec}} + \frac{1}{\rho}\left(\frac{dE}{dl}\right)_{\text{rad}} \tag{65.16}$$

Figure 65.8 illustrates the contributions of the electronic term and the radiative term to the total mass stopping power for electrons in lead and water over the energy range from 10^{-2} MeV to 10^{3} MeV. For alpha particles, the radiative term can be neglected, but the nuclear interactions cannot. The nuclear interactions are pronounced at lower energies, while at higher energies the inelastic collision process dominates. This is illustrated in Figure 65.9 for alpha-particle interactions in lead and water.

The range of a charged particle of a given energy in a material is an important parameter in designing detectors and shielding materials. In general, a charged particle does not travel in a straight line as it slows down. However, the total rectified path length traveled by the charged particle, called the mean range, is given by

$$r_0 = \int_0^E \frac{\rho}{S} dE \tag{65.17}$$

where E = incident electron energy. The range as given in Equation 65.17 has units of g cm^{-2}. Range in water and lead as a function of incident particle energy for electrons and for alpha particles is given in Figures 65.10 and 65.11, respectively.

Neutron Interactions

Since neutrons are uncharged, they can travel some distance in matter before they interact. This interaction is normally a "nuclear reaction" in which the neutron is absorbed, scattered, or produces a nuclear reaction. The probability of each of these interactions occurring is described by the capture, scatter, and nuclear reaction cross sections. Secondary particles produced by neutrons are usually high-energy charged

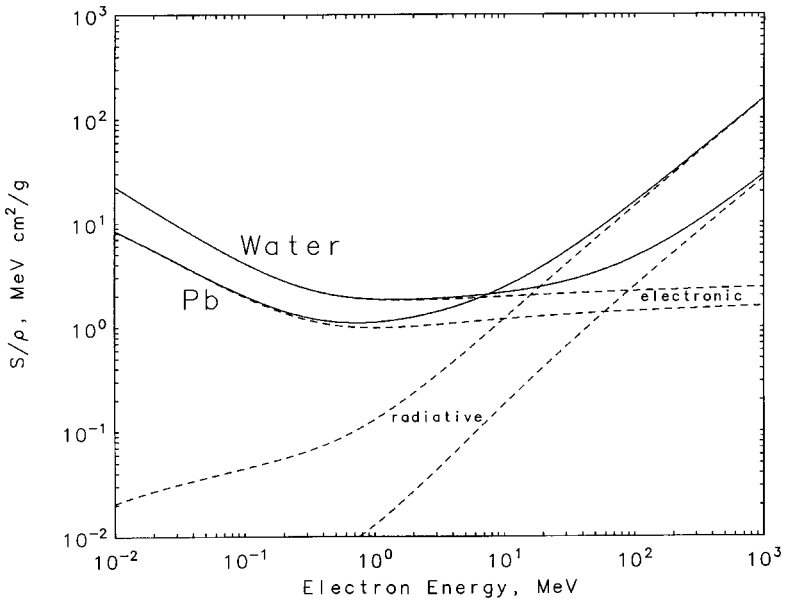

FIGURE 65.8 Stopping power for electrons in water and lead as a function of electron energy [18].

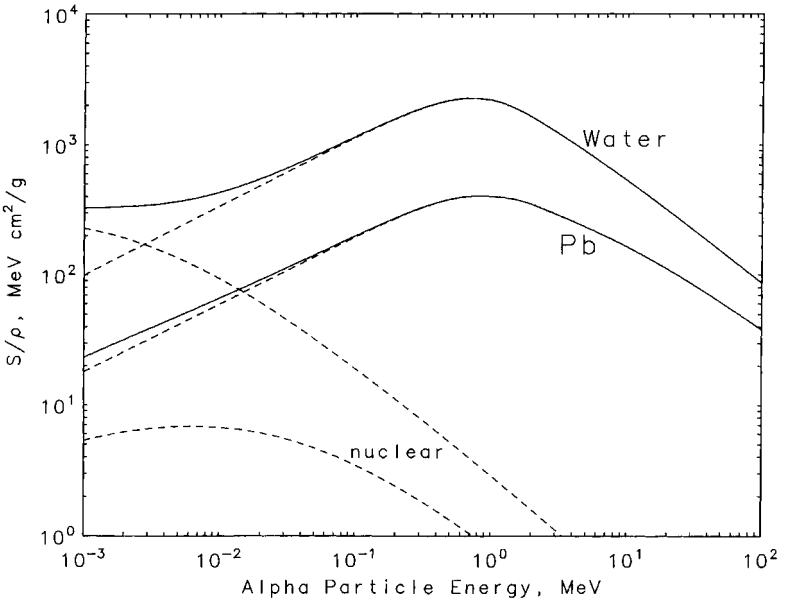

FIGURE 65.9 Stopping power for alpha particles in water and lead as a function of alpha-particle energy [19]

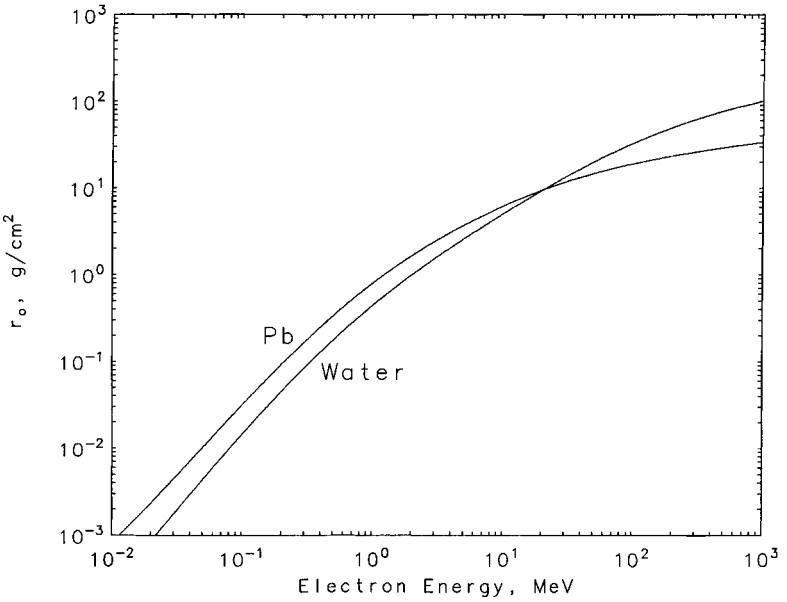

FIGURE 65.10 Range-energy curves for electrons in water and lead [18].

particles that are stopped in short distances in the stopping material. Neutrons from nuclear reactions normally start with energies of a few MeV. They are moderated by collisions with atomic nuclei until they experience a capture process. Capture cross sections for a given elemental stopping material exhibit resonances characteristic of specific nuclear excited states. The total neutron cross section of carbon as a function of neutron energy is shown in Figure 65.12 [20]. The structure in the cross section is the result of resonances in the compound nucleus formed by neutron interaction with ^{12}C. The intensity of a neutron beam in an absorber will decrease exponentially (analogous to a photon beam) with absorber thickness. The attenuation coefficient will include the scatter and capture components.

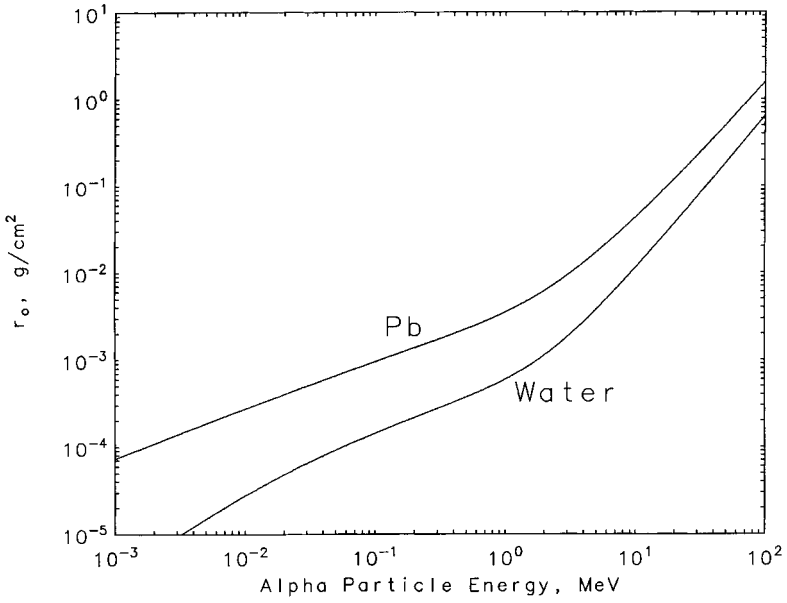

FIGURE 65.11 Range-energy curve for alpha particles in water and lead [19].

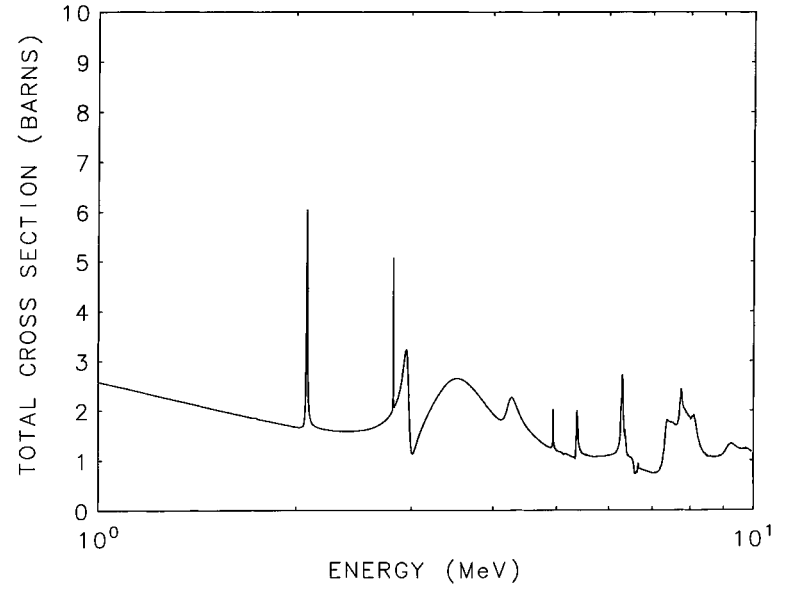

FIGURE 65.12 Total neutron cross section for carbon as a function of neutron energy [20]. The *barn* is the traditional unit of area used to describe neutron cross sections (1 *barn* = 10^{-28} m^2).

Radioactivity Measurements

Measurements of electromagnetic radiations and charged particles are discussed in Chapters 66 through 69. However, there are certain classes of instruments that are widely used for the measurement of radioactivity. Three examples will be dealt with here: alpha- and beta-particle liquid-scintillation spectrometers, high-purity germanium (HPGe) gamma-ray spectrometers, and gamma-ray dose calibrators.

Most liquid-scintillation spectrometers operate with two phototubes that view a cylindrical vial containing the radionuclide intimately mixed with an organic liquid scintillator [21, 22]. The radiations emitted during radioactive decay interact in the scintillator to produce light pulses that strike the photocathodes of the phototubes. The magnitude of the light pulse depends on the energy deposited by the radiation and on chemical and optical quenching processes [21]. The scintillation yield for high energy electrons (low dE/dx) for the best organic scintillators does not exceed 5 percent. That is, 5 percent of the deposited energy is emitted as photons in the near ultraviolet (~400 nm wavelength) and the remaining 95 percent is lost to radiationless transitions in the organic molecules. In real samples, this photon yield is reduced further through chemical processes (electron scavengers), and optical losses (colored samples, mismatches at vial interfaces, etc.). The counting efficiency for the two phototubes in coincidence is defined as the ratio of the counting rate to the activity. The counting efficiency approaches unity for beta particles with energies exceeding 20 keV [23]. For alpha particles, the efficiency is essentially unity (although the magnitude of the light pulse for alpha particles is less than that for beta particles due to the nature of the interactions of the particles with the organic scintillator). The counting systems are calibrated using standard solutions of known activity [22]. Since the pulse height is largely proportional to the energy of the incident particle, the signal from the counting system can be sorted according to pulse height in a multichannel analyzer (MCA). The pulse height spectra for a mixture of alpha-particle emitters is shown in Figure 65.13 [24]. In practice one obtains the area under the peak for a given radionuclide and divides by time to get the counting rate N_α. The activity A_0 is given by N_α/ε_c, where ε_c is the coincidence counting efficiency.

The activity of mixtures of gamma-ray emitters is needed at many stages in the nuclear fuel cycle. For example, in measurements of environmental radioactivity, a gamma-ray spectrometer allows rapid determination of many fission and activation product nuclides in the presence of naturally occurring radioactivity. Both NaI(Tl) scintillation detectors and HPGe semiconductors are used for this purpose, and their design and operation are covered in Chapter 66. Gamma-ray spectra for a mixture of radionuclides with a semiconductor detector are shown in Figure 65.14 [22]. The detectors are calibrated using radioactivity standard sources prepared by the National Institute of Standards and Technology or one of the commercial secondary standards suppliers. A photopeak efficiency curve for a HPGe detector is shown in Figure 65.15.

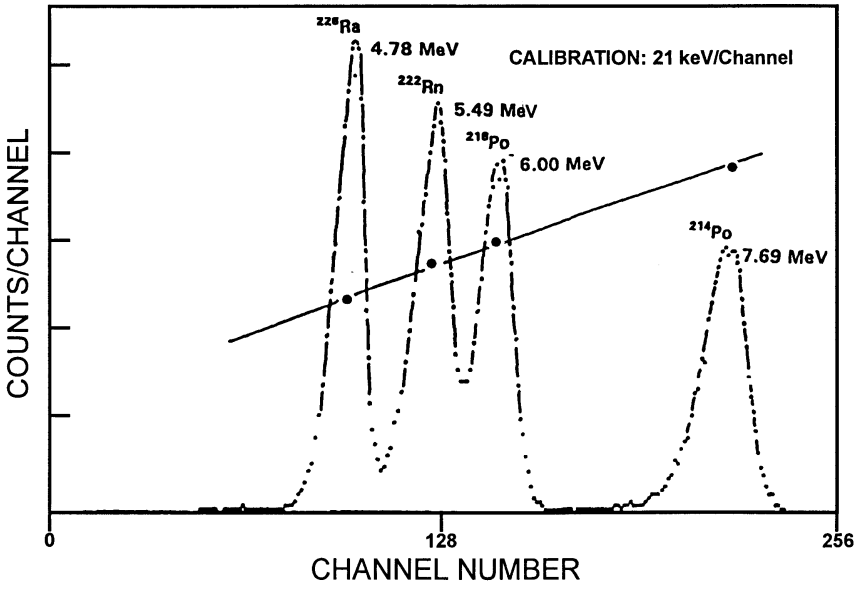

FIGURE 65.13 Liquid scintillation spectrum of mixture of alpha-particle-emitting radionuclides [24].

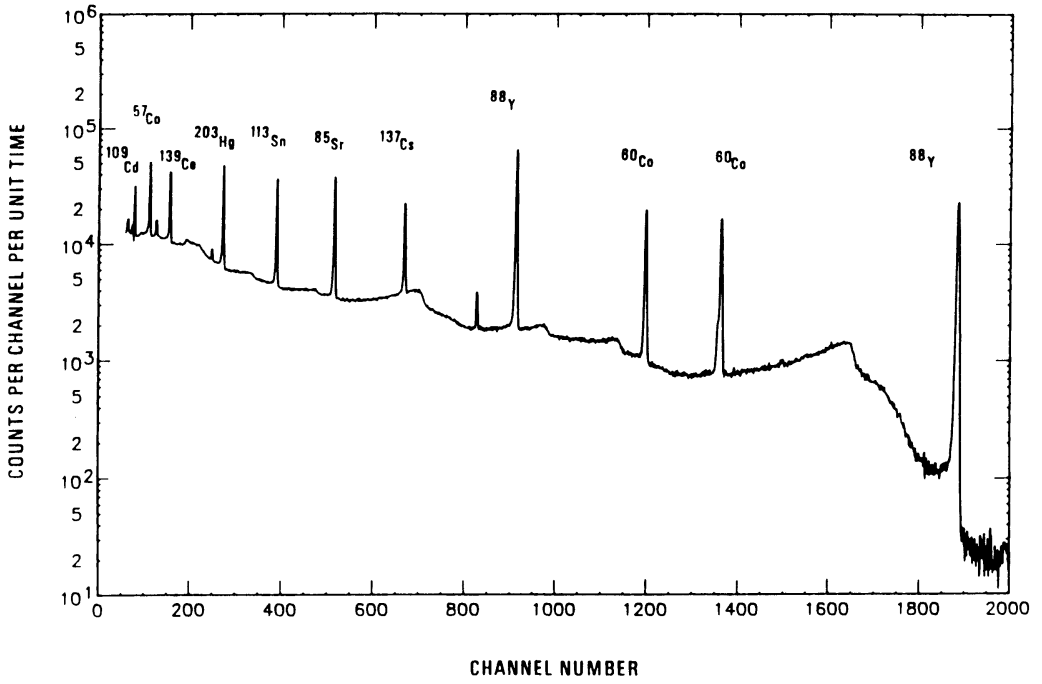

FIGURE 65.14 Gamma-ray spectrum for a solution standard of mixed radionuclides obtained with a Ge(Li) semiconductor detector [22].

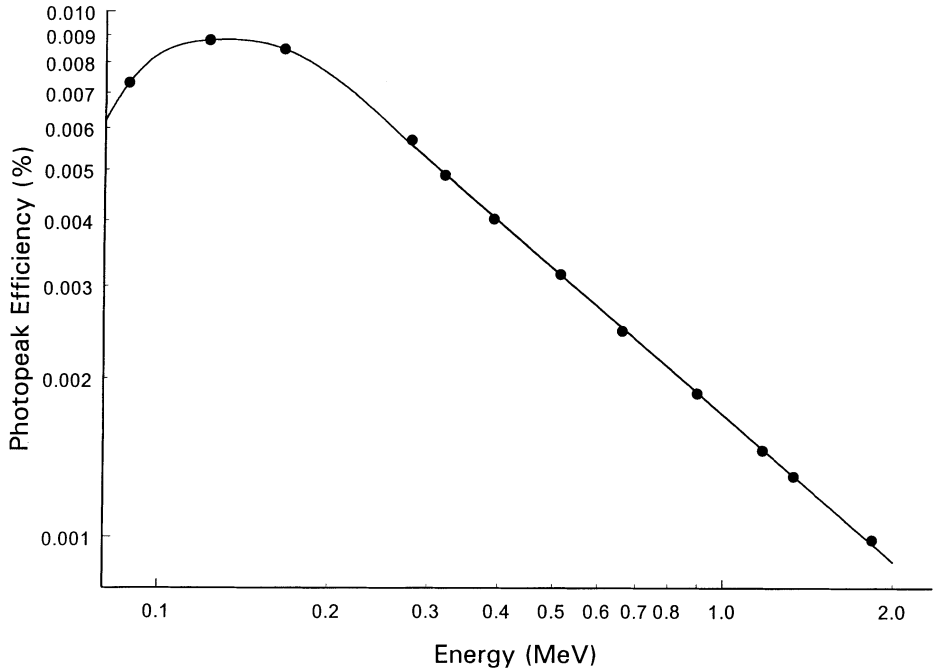

FIGURE 65.15 Photopeak efficiency as a function of energy for a 90 cm^3 HPGe detector for a mixed radionuclide gamma-ray standard of the type listed in Table 65.5. A 5 mL solution source was positioned at 10 cm from the side of a p-type semiconductor [25].

FIGURE 65.16 A well-type ionization chamber used for the assay of single radionuclides in nuclear medicine [26].

Single radionuclides are widely used in many applications in health sciences. In nuclear medicine most samples are assayed in reentrant dose calibrators, which are essentially ionization chambers. In this counting geometry the sample is placed inside a well detector which is normally a sealed, pressurized argon gas, ionization chamber (See, for example, Figure 65.16). The photons emitted from the sample traverse the inner wall of the chamber and cause ionization events in the counting gas. The chambers typically operate at a few atmospheres pressure at a bias voltage of 600 to 1000 V. The charge created is subsequently collected at the anode. These chambers are designed to assay large amounts of activity such that the current from the device in picoamperes is proportional to the activity in megabecquerels. For a given radionuclide, the manufacturer can establish calibration factors for specific radionuclides in order to convert the current response of the chamber to a unit activity (pA MBq^{-1}). A dose calibrator response curve for gamma-ray emitters is shown in Figure 65.17 [26].

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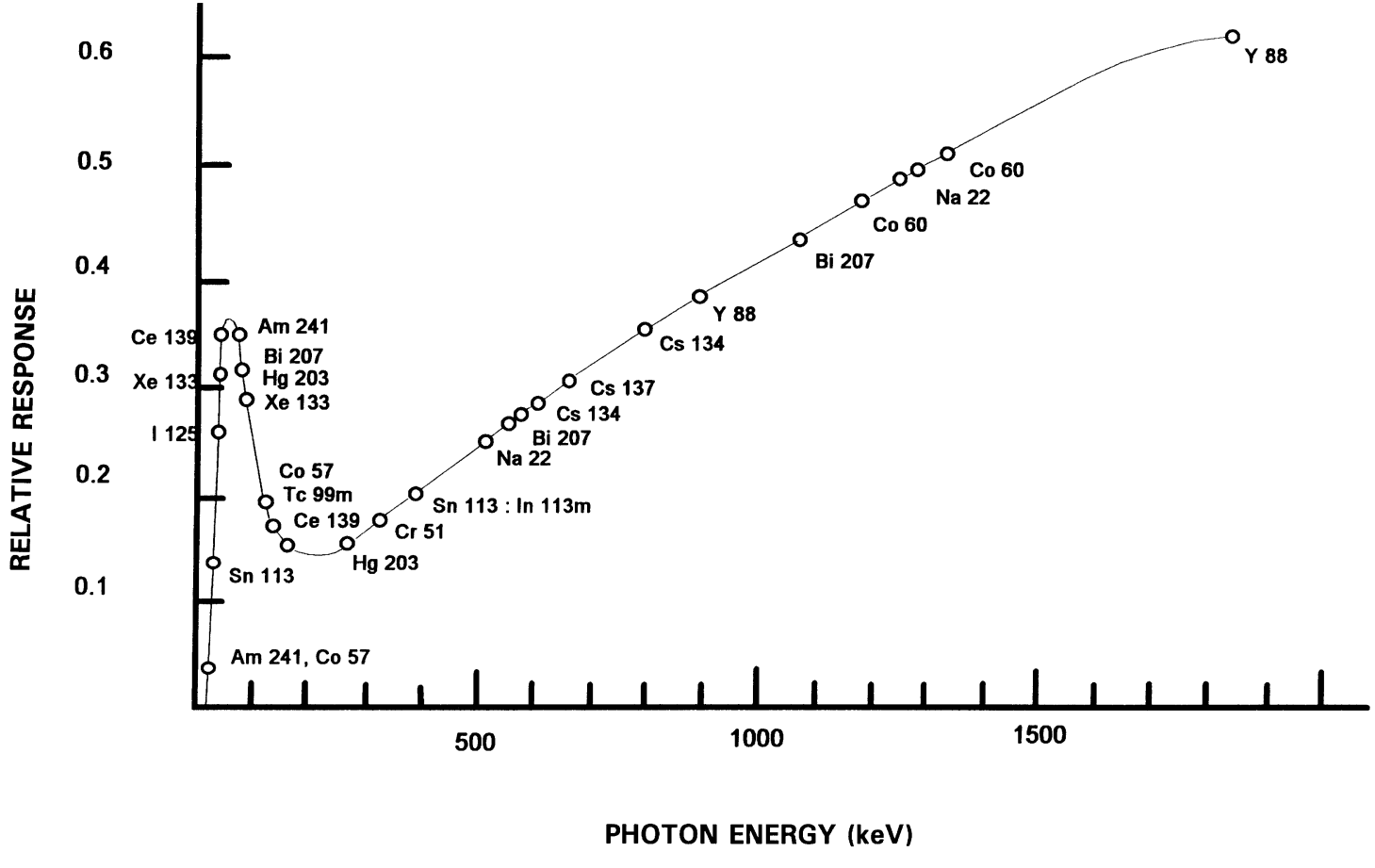

FIGURE 65.17 Photon response as a function of energy for a pressurized reentrant ionization chamber [26].

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