
Gamma-Ray Interactions with Matter

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2.1 INTRODUCTION

A knowledge of gamma-ray interactions is important to the nondestructive assayist in order to understand gamma-ray detection and attenuation. A gamma ray must interact with a detector in order to be "seen." Although the major isotopes of uranium and plutonium emit gamma rays at fixed energies and rates, the gamma-ray intensity measured outside a sample is always attenuated because of gamma-ray interactions with the sample. This attenuation must be carefully considered when using gamma-ray NDA instruments.

This chapter discusses the exponential attenuation of gamma rays in bulk materials and describes the major gamma-ray interactions, gamma-ray shielding, filtering, and collimation. The treatment given here is necessarily brief. For a more detailed discussion, see Refs. 1 and 2.

2.2 EXPONENTIAL ATTENUATION

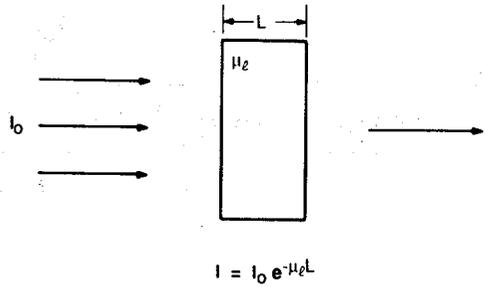
Gamma rays were first identified in 1900 by Becquerel and Villard as a component of the radiation from uranium and radium that had much higher penetrability than alpha and beta particles. In 1909, Soddy and Russell found that gamma-ray attenuation followed an exponential law and that the ratio of the attenuation coefficient to the density of the attenuating material was nearly constant for all materials.

2.2.1 The Fundamental Law of Gamma-Ray Attenuation

Figure 2.1 illustrates a simple attenuation experiment. When gamma radiation of intensity I_0 is incident on an absorber of thickness L , the emerging intensity (I) transmitted by the absorber is given by the exponential expression

$$I = I_0 e^{-\mu \rho L} \quad (2-1)$$

Fig. 2.1 The fundamental law of gamma-ray attenuation. The transmitted gamma-ray intensity I is a function of gamma-ray energy, absorber composition, and absorber thickness.



where μ_e is the attenuation coefficient (expressed in cm^{-1}). The ratio I/I_0 is called the gamma-ray transmission. Figure 2.2 illustrates exponential attenuation for three different gamma-ray energies and shows that the transmission increases with increasing gamma-ray energy and decreases with increasing absorber thickness. Measurements with different sources and absorbers show that the attenuation coefficient μ_e depends on the gamma-ray energy and the atomic number (Z) and density (ρ) of the absorber. For example, lead has a high density and atomic number and transmits

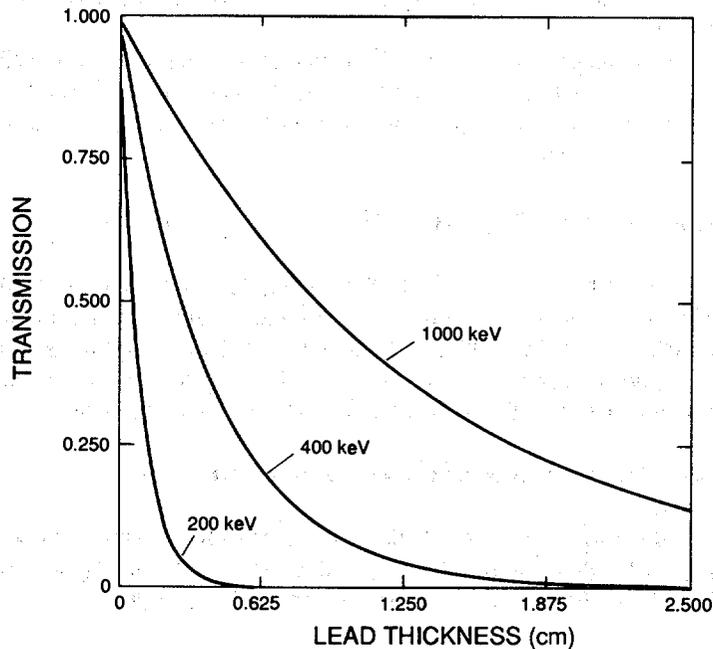


Fig. 2.2 Transmission of gamma rays through lead absorbers.

a much lower fraction of incident gamma radiation than does a similar thickness of aluminum or steel. The attenuation coefficient in Equation 2-1 is called the linear attenuation coefficient. Figure 2.3 shows the linear attenuation of solid sodium iodide, a common material used in gamma-ray detectors.

Alpha and beta particles have a well-defined range or stopping distance; however, as Figure 2.2 shows, gamma rays do not have a unique range. The reciprocal of the attenuation coefficient $1/\mu_\ell$ has units of length and is often called the mean free path. The mean free path is the average distance a gamma ray travels in the absorber before interacting; it is also the absorber thickness that produces a transmission of $1/e$, or 0.37.

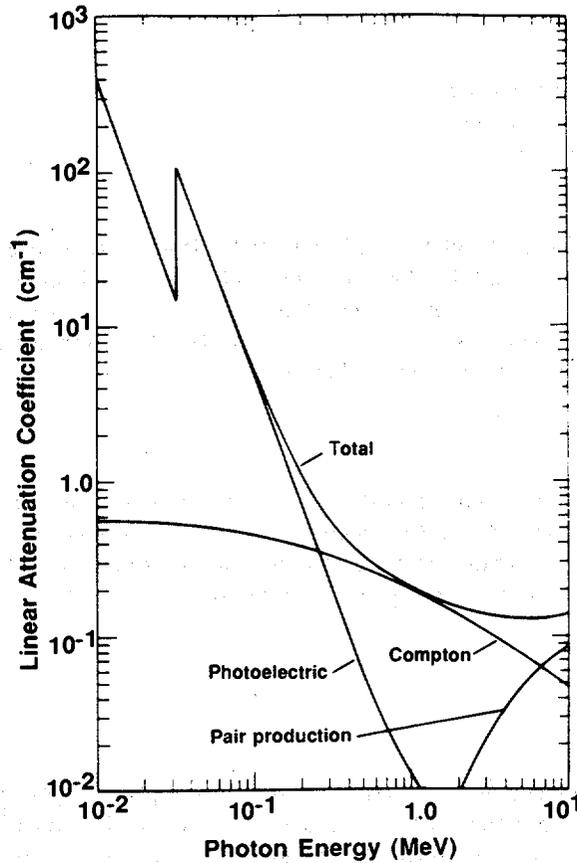


Fig. 2.3 Linear attenuation coefficient of NaI showing contributions from photoelectric absorption, Compton scattering, and pair production.

2.2.2 Mass Attenuation Coefficient

The linear attenuation coefficient is the simplest absorption coefficient to measure experimentally, but it is not usually tabulated because of its dependence on the density of the absorbing material. For example, at a given energy, the linear attenuation coefficients of water, ice, and steam are all different, even though the same material is involved.

Gamma rays interact primarily with atomic electrons; therefore, the attenuation coefficient must be proportional to the electron density P , which is proportional to the bulk density of the absorbing material. However, for a given material the ratio of the electron density to the bulk density is a constant, Z/A , independent of bulk density. The ratio Z/A is nearly constant for all except the heaviest elements and hydrogen.

$$P = Z \rho / A \quad (2-2)$$

where P = electron density
 Z = atomic number
 ρ = mass density
 A = atomic mass.

The ratio of the linear attenuation coefficient to the density (μ/ρ) is called the mass attenuation coefficient μ and has the dimensions of area per unit mass (cm^2/g). The units of this coefficient hint that one may think of it as the effective cross-sectional area of electrons per unit mass of absorber. The mass attenuation coefficient can be written in terms of a reaction cross section, $\sigma(\text{cm}^2)$:

$$\mu = \frac{N_0 \sigma}{A} \quad (2-3)$$

where N_0 is Avagadro's number (6.02×10^{23}) and A is the atomic weight of the absorber. The cross section is the probability of a gamma ray interacting with a single atom. Chapter 12 gives a more complete definition of the cross-section concept. Using the mass attenuation coefficient, Equation 2-1 can be rewritten as

$$I = I_0 e^{-\mu \rho L} = I_0 e^{-\mu x} \quad (2-4)$$

where $x = \rho L$.

The mass attenuation coefficient is independent of density; for the example mentioned above, water, ice, and steam all have the same value of μ . This coefficient is more commonly tabulated than the linear attenuation coefficient because it quantifies the gamma-ray interaction probability of an individual element. References 3 and 4 are widely used tabulations of the mass attenuation coefficients of the elements. Equation 2-5 is used to calculate the mass attenuation coefficient for compound materials:

$$\mu = \sum \mu_i w_i \quad (2-5)$$

where μ_i = mass attenuation coefficient of i^{th} element
 w_i = weight fraction of i^{th} element.

The use of Equation 2-5 is illustrated below for solid uranium hexafluoride (UF₆) at 200 keV:

$$\mu_u = \text{mass attenuation coefficient of U at 200 keV} = 1.23 \text{ cm}^2/\text{g}$$

$$\mu_f = \text{mass attenuation coefficient of F at 200 keV} = 0.123 \text{ cm}^2/\text{g}$$

$$w_u = \text{weight fraction of U in UF}_6 = 0.68$$

$$w_f = \text{weight fraction of F in UF}_6 = 0.32$$

$$\rho = \text{density of solid UF}_6 = 5.1 \text{ g/cm}^3$$

$$\mu = \mu_u w_u + \mu_f w_f = 1.23 \times 0.68 + 0.123 \times 0.32 = 0.88 \text{ cm}^2/\text{g}$$

$$\mu_\ell = \mu \rho = 0.88 \times 5.1 = 4.5 \text{ cm}^{-1}.$$

2.3 INTERACTION PROCESSES

The gamma rays of interest to NDA applications fall in the range 10 to 2000 keV and interact with detectors and absorbers by three major processes: photoelectric absorption, Compton scattering, and pair production. In the photoelectric absorption process, the gamma ray loses all of its energy in one interaction. The probability for this process depends very strongly on gamma-ray energy E_γ and atomic number Z . In Compton scattering, the gamma ray loses only part of its energy in one interaction. The probability for this process is weakly dependent on E and Z . The gamma ray can lose all of its energy in one pair-production interaction. However, this process is relatively unimportant for fissile material assay since it has a threshold above 1 MeV. Reference 3 is recommended for more detailed physical descriptions of the interaction processes.

2.3.1 Photoelectric Absorption

A gamma ray may interact with a bound atomic electron in such a way that it loses all of its energy and ceases to exist as a gamma ray (see Figure 2.4). Some of the gamma-ray energy is used to overcome the electron binding energy, and most of the remainder is transferred to the freed electron as kinetic energy. A very small amount of recoil energy remains with the atom to conserve momentum. This is called photoelectric absorption because it is the gamma-ray analog of the process discovered by Hertz in 1887 whereby photons of visible light liberate electrons from a metal surface. Photoelectric absorption is important for gamma-ray detection because the gamma ray gives up all its energy, and the resulting pulse falls in the full-energy peak.

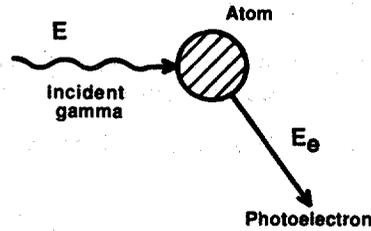


Fig. 2.4 A schematic representation of the photoelectric absorption process.

The probability of photoelectric absorption depends on the gamma-ray energy, the electron binding energy, and the atomic number of the atom. The probability is greater the more tightly bound the electron; therefore, K electrons are most affected (over 80% of the interactions involve K electrons), provided the gamma-ray energy exceeds the K-electron binding energy. The probability is given approximately by Equation 2-6, which shows that the interaction is more important for heavy atoms like lead and uranium and low-energy gamma rays:

$$\tau \propto Z^4/E^3 \quad (2-6)$$

where τ = photoelectric mass attenuation coefficient.

This proportionality is only approximate because the exponent of Z varies in the range 4.0 to 4.8. As the gamma-ray energy decreases, the probability of photoelectric absorption increases rapidly (see Figure 2.3). Photoelectric absorption is the predominant interaction for low-energy gamma rays, x rays, and bremsstrahlung.

The energy of the photoelectron E_e released by the interaction is the difference between the gamma-ray energy E_γ and the electron binding energy E_b :

$$E_e = E_\gamma - E_b \quad (2-7)$$

In most detectors, the photoelectron is stopped quickly in the active volume of the detector, which emits a small output pulse whose amplitude is proportional to the energy deposited by the photoelectron. The electron binding energy is not lost but appears as characteristic x rays emitted in coincidence with the photoelectron. In most cases, these x rays are absorbed in the detector in coincidence with the photoelectron and the resulting output pulse is proportional to the total energy of the incident gamma ray. For low-energy gamma rays in very small detectors, a sufficient number of K x rays can escape from the detector to cause escape peaks in the observed spectrum; the peaks appear below the full-energy peak by an amount equal to the energy of the x ray.

Figure 2.5 shows the photoelectric mass attenuation coefficient of lead. The interaction probability increases rapidly as energy decreases, but then becomes much

smaller at a gamma-ray energy just below the binding energy of the K electron. This discontinuity is called the K edge; below this energy the gamma ray does not have sufficient energy to dislodge a K electron. Below the K edge the interaction probability increases again until the energy drops below the binding energies of the L electrons; these discontinuities are called the L_I , L_{II} , and L_{III} edges. The presence of these absorption edges is important for densitometry and x-ray fluorescence measurements (see Chapters 9 and 10).

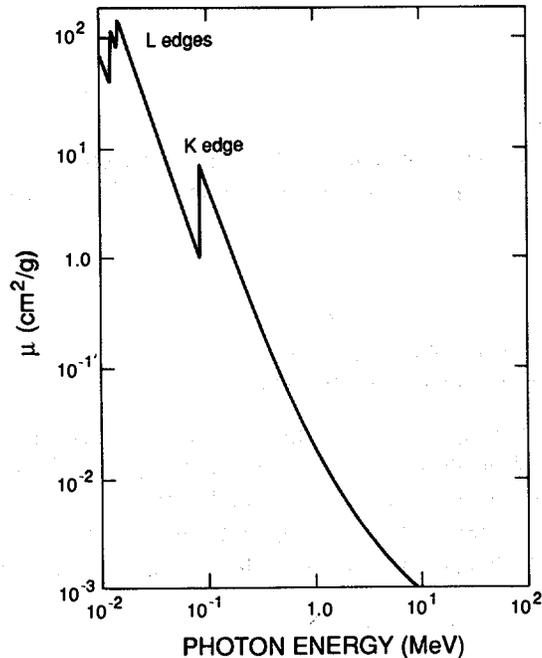


Fig. 2.5 Photoelectric mass attenuation coefficient of lead.

2.3.2 Compton Scattering

Compton scattering is the process whereby a gamma ray interacts with a free or weakly bound electron ($E_\gamma \gg E_b$) and transfers part of its energy to the electron (see Figure 2.6). Conservation of energy and momentum allows only a partial energy transfer when the electron is not bound tightly enough for the atom to absorb recoil energy. This interaction involves the outer, least tightly bound electrons in the scattering atom. The electron becomes a free electron with kinetic energy equal to the difference of the energy lost by the gamma ray and the electron binding energy. Because the electron

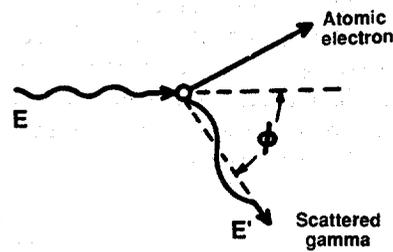


Fig. 2.6 A schematic representation of Compton scattering.

binding energy is very small compared to the gamma-ray energy, the kinetic energy of the electron is very nearly equal to the energy lost by the gamma ray:

$$E_e = E_\gamma - E' \quad (2-8)$$

where E_e = energy of scattered electron

E_γ = energy of incident gamma ray

E' = energy of scattered gamma ray.

Two particles leave the interaction site: the freed electron and the scattered gamma ray. The directions of the electron and the scattered gamma ray depend on the amount of energy transferred to the electron during the interaction. Equation 2-9 gives the energy of the scattered gamma ray, and Figure 2.7 shows the energy of the scattered electron as a function of scattering angle and incident gamma-ray energy.

$$E' = m_0c^2 / (1 - \cos \phi + m_0c^2/E) \quad (2-9)$$

where m_0c^2 = rest energy of electron = 511 keV

ϕ = angle between incident and scattered gamma rays (see Figure 2.6).

This energy is minimum for a head-on collision where the gamma ray is scattered 180° and the electron moves forward in the direction of the incident gamma ray. For this case the energy of the scattered gamma ray is given by Equation 2-10 and the energy of the scattered electron is given by Equation 2-11:

$$\begin{aligned} E'(\min) &= m_0c^2 / (2 + m_0c^2/E) \\ &\simeq m_0c^2/2 = 256 \text{ keV}; \text{ if } E \gg m_0c^2/2. \end{aligned} \quad (2-10)$$

$$\begin{aligned} E_e(\max) &= E/[1 + m_0c^2/(2E)] \\ &\simeq E - m_0c^2/2 = E - 256 \text{ keV}; \text{ if } E \gg m_0c^2/2. \end{aligned} \quad (2-11)$$

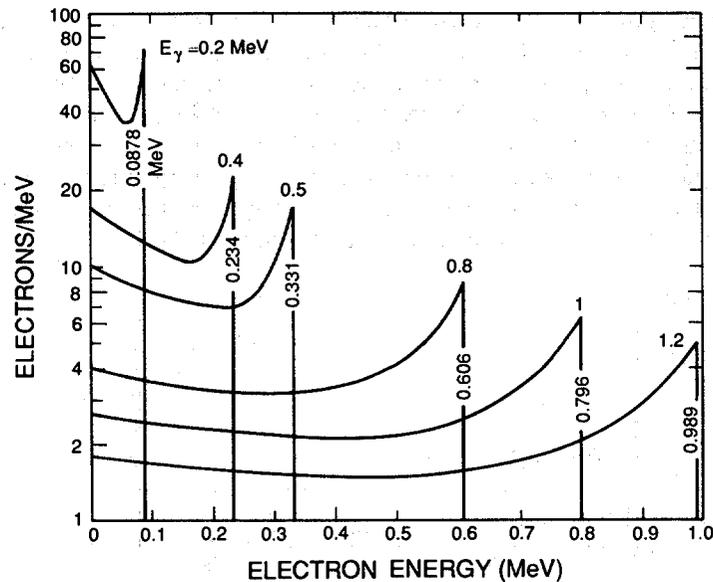


Fig. 2.7 Energy of Compton-scattered electrons as a function of scattering angle and incident gamma-ray energy (E_γ). The sharp discontinuity corresponds to the maximum energy that can be transferred in a single scattering.

For very small angle scatterings ($\phi \simeq 0^\circ$), the energy of the scattered gamma ray is only slightly less than the energy of the incident gamma ray and the scattered electron takes very little energy away from the interaction. The energy given to the scattered electron ranges from near zero to the maximum given by Equation 2-11.

When a Compton scattering occurs in a detector, the scattered electron is usually stopped in the detection medium and the detector produces an output pulse that is proportional to the energy lost by the incident gamma ray. Compton scattering in a detector produces a spectrum of output pulses from zero up to the maximum energy given by Equation 2-11. It is difficult to relate the Compton-scattering spectrum to the energy of the incident gamma ray. Figure 2.8 shows the measured gamma-ray spectrum from a monoenergetic gamma-ray source (^{137}Cs). The full-energy peak at 662 keV is formed by interactions where the gamma ray loses all of its energy in the detector either by a single photoelectric absorption or by a series of Compton scatterings followed by photoelectric absorption. The spectrum of events below the full-energy peak is formed by Compton scatterings where the gamma ray loses only part of its energy in the detector. The step near 470 keV corresponds to the maximum energy that can be transferred to an electron by a 662-keV gamma ray in a single Compton scattering. This step is called a Compton edge; the energy of the Compton edge is given by Equation 2-11 and plotted in Figure 2.9. The small peak at 188 keV in Figure 2.8 is called a backscatter peak. The backscatter peak is formed when the

gamma ray undergoes a large-angle scattering ($\approx 180^\circ$) in the material surrounding the detector and then is absorbed in the detector. The energy of the backscatter peak is given by Equation 2-10, which shows that the maximum energy is 256 keV. The sum of the energy of the backscatter peak and the Compton edge equals the energy of the incident gamma ray. Both features are the result of large-angle Compton scattering of the incident gamma ray. The event contributes to the backscatter peak when only the scattered gamma ray deposits its energy in the detector; it contributes to the Compton edge when only the scattered electron deposits its energy in the detector.

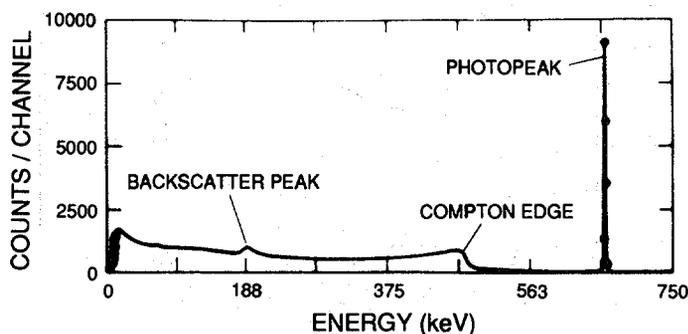


Fig. 2.8 High-resolution spectrum of ^{137}Cs showing full-energy photopeak, Compton edge, and backscatter peak from the 662-keV gamma ray. Events below the photopeak are caused by Compton scattering in the detector and surrounding materials.

Because Compton scattering involves the least tightly bound electrons, the nucleus has only a minor influence and the probability for interaction is nearly independent of atomic number. The interaction probability depends on the electron density, which is proportional to Z/A and nearly constant for all materials. The Compton-scattering probability is a slowly varying function of gamma-ray energy (see Figure 2.3).

2.3.3 Pair Production

A gamma ray with an energy of at least 1.022 MeV can create an electron-positron pair when it is under the influence of the strong electromagnetic field in the vicinity of a nucleus (see Figure 2.10). In this interaction the nucleus receives a very small amount of recoil energy to conserve momentum, but the nucleus is otherwise unchanged and the gamma ray disappears. This interaction has a threshold of 1.022 MeV because that is the minimum energy required to create the electron and positron. If the gamma-ray energy exceeds 1.022 MeV, the excess energy is shared between the electron and positron as kinetic energy. This interaction process is relatively unimportant for nuclear material assay because most important gamma-ray signatures are below 1.022 MeV.

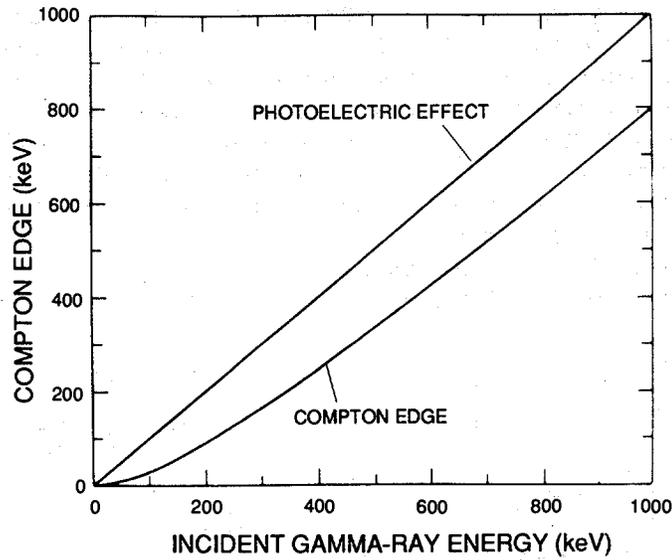


Fig. 2.9 Energy of the Compton edge versus the energy of the incident gamma ray.

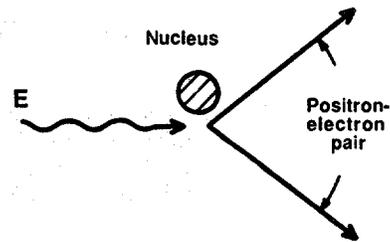


Fig. 2.10 A schematic representation of pair production.

The electron and positron from pair production are rapidly slowed down in the absorber. After losing its kinetic energy, the positron combines with an electron in an annihilation process, which releases two gamma rays with energies of 0.511 MeV. These lower energy gamma rays may interact further with the absorbing material or may escape. In a gamma-ray detector, this interaction often gives three peaks for a high-energy gamma ray (see Figure 2.11). The kinetic energy of the electron and positron is absorbed in the detector. One or both of the annihilation gamma rays may escape from the detector or they may both be absorbed. If both annihilation gamma rays are absorbed in the detector, the interaction contributes to the full-energy peak in the measured spectrum; if one of the annihilation gamma rays escapes from

the detector, the interaction contributes to the single-escape peak located 0.511 MeV below the full-energy peak; if both gamma rays escape, the interaction contributes to the double-escape peak located 1.022 MeV below the full-energy peak. The relative heights of the three peaks depend on the energy of the incident gamma ray and the size of the detector. These escape peaks may arise when samples of irradiated fuel, thorium, and ^{232}U are measured because these materials have important gamma rays above the pair-production threshold. Irradiated fuel is sometimes measured using the 2186-keV gamma ray from the fission-product ^{144}Pr . The gamma-ray spectrum of ^{144}Pr in Figure 2.11 shows the single- and double-escape peaks that arise from pair-production interactions of the 2186-keV gamma ray in a germanium detector.

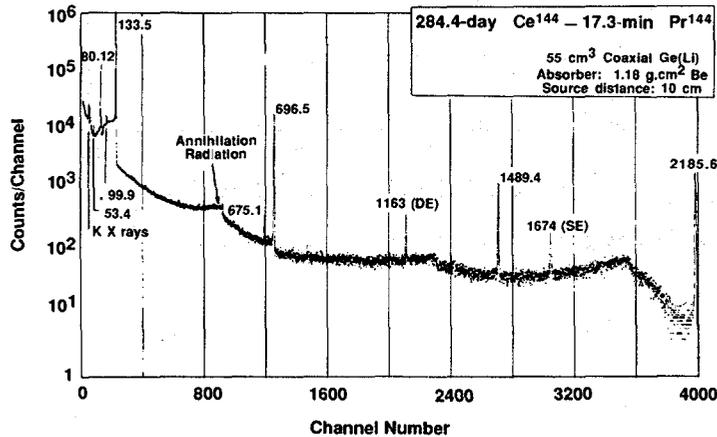


Fig. 2.11 Gamma-ray spectrum of the fission-product ^{144}Pr showing single-escape (SE) and double-escape (DE) peaks (1674 and 1163) that arise from pair-production interactions of 2186-keV gamma rays in a germanium detector.

Pair production is impossible for gamma rays with energy less than 1.022 MeV. Above this threshold, the probability of the interaction increases rapidly with energy (see Figure 2.3). The probability of pair production varies approximately as the square of the atomic number Z and is significant in high- Z elements such as lead or uranium. In lead, approximately 20% of the interactions of 1.5-MeV gamma rays are through the pair-production process, and the fraction increases to 50% at 2.0 MeV. For carbon, the corresponding interaction fractions are 2% and 4%.

2.3.4 Total Mass Attenuation Coefficient

The three interaction processes described above all contribute to the total mass attenuation coefficient. The relative importance of the three interactions depends on

gamma-ray energy and the atomic number of the absorber. Figure 2.12 shows a composite of mass attenuation curves covering a wide range of energy and atomic number. It shows dramatically the interplay of the three processes. All elements except hydrogen show a sharp, low-energy rise that indicates where photoelectric absorption is the dominant interaction. The position of the rise is very dependent on atomic number. Above the low-energy rise, the value of the mass attenuation coefficient decreases gradually, indicating the region where Compton scattering is the dominant interaction. The mass attenuation coefficients for all elements with atomic number less than 25 (iron) are nearly identical in the energy range 200 to 2000 keV. The attenuation curves converge for all elements in the range 1 to 2 MeV. The shape of the mass attenuation curve of hydrogen shows that it interacts with gamma rays with energy greater than 10 keV almost exclusively by Compton scattering. Above

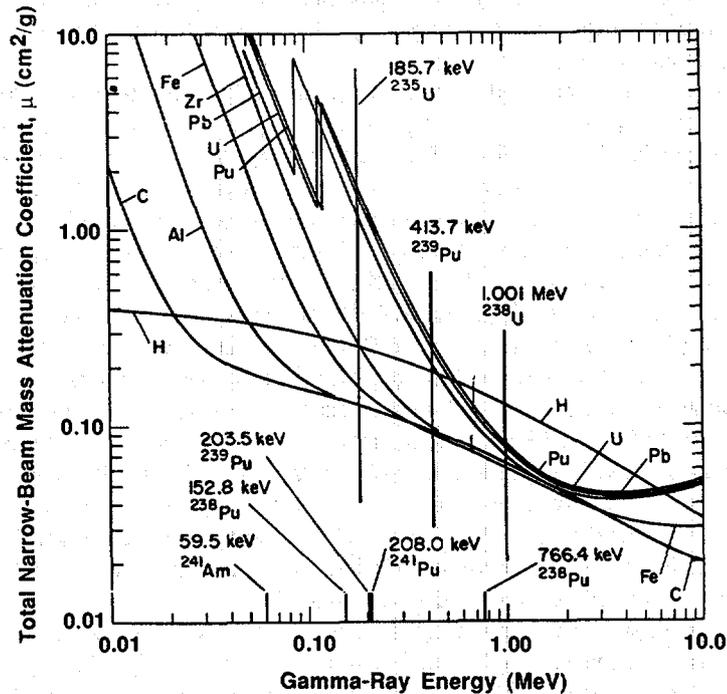


Fig. 2.12 Mass attenuation coefficients of selected elements. Also indicated are gamma-ray energies commonly encountered in NDA of uranium and plutonium.

2 MeV, the pair-production interaction becomes important for high-Z elements and the mass attenuation coefficient begins to rise again. An understanding of the major features of Figure 2.12 is very helpful to the understanding of NDA techniques.

2.4 FILTERS

In many assay applications, the gamma rays of interest can be measured more easily if lower energy gamma rays can be absorbed before they reach the detector. The lower energy gamma rays can cause significant count-rate-related losses in the detector and spectral distortion if they are not removed. The removal process is often called filtering. A perfect filter material would have a transmission of zero below the energy of interest and a transmission of unity above that energy, but as Figure 2.12 shows, such a material does not exist. However, useful filters can be obtained by selecting absorbers of appropriate atomic number such that the sharp rise in photoelectric cross section is near the energy of the gamma rays that must be attenuated but well below the energy of the assay gamma rays.

Filtering is usually employed in the measurement of plutonium gamma-ray spectra. Except immediately after chemical separation of americium, all plutonium samples have significant levels of ^{241}Am , which emits a very intense gamma ray at 60 keV. In most samples, this gamma ray is the most intense gamma ray in the spectrum and must be attenuated so that the plutonium gamma rays can be accurately measured. A thin sheet of cadmium is commonly used to attenuate the ^{241}Am activity. Table 2-1 shows the effect of a cadmium filter on the spectrum from a 2-g disk of plutonium metal. In the absence of the filter, the 60-keV gamma ray dominates the spectrum and may even paralyze the detector. A 1- to 2-mm cadmium filter drastically attenuates the 60-keV activity but only slightly attenuates the higher energy plutonium lines. The plutonium spectrum below 250 keV is usually measured with a cadmium filter. When only the ^{239}Pu 414-keV gamma ray is of interest, lead may be used as the filter material because it will attenuate gamma rays in the 100- to 200-keV region and will stop most of the 60-keV gamma rays. It is interesting to note that at 60 keV the mass attenuation coefficients of lead and cadmium are essentially equal, in spite of the higher Z of lead (82) relative to cadmium (48). This is because the K edge of lead appears at 88 keV, as discussed in Section 2.3.1.

A cadmium filter is often used when measuring ^{235}U because it attenuates gamma rays and x rays in the 90- to 120-keV region and does not significantly affect the 186-keV gamma ray from ^{235}U . Filters may also be used for certain irradiated fuel measurements. The 2186-keV gamma ray from the fission products ^{144}Ce - ^{144}Pr is measured in some applications as an indicator of the residual fuel material in leached hulls produced at a reprocessing plant (see Chapter 18). The major fission-product gamma-ray activity is in the 500- to 900-keV region and can be selectively reduced relative to the 2186-keV gamma ray using a 10- to 15-cm-thick lead filter.

Table 2-1. Effect of cadmium filter on plutonium spectrum

Absorber (cm)	Plutonium Signal (counts/s) ^a			
	60 keV	129 keV	208 keV	414 keV
0	3.57×10^6	1.29×10^4	8.50×10^4	2.02×10^4
0.1	2.40×10^4	0.67×10^4	6.76×10^4	1.85×10^4
0.2	1.86×10^2	0.34×10^4	5.37×10^4	1.69×10^4

^a $^{241}\text{Am} = 0.135\%$; $^{239}\text{Pu} = 81.9\%$; $^{241}\text{Pu} = 1.3\%$. Signal from 2-g disk of plutonium metal, 1 cm diam \times 0.13 cm thick.

Graded filters with two or more materials are sometimes used to attenuate the characteristic x rays from the primary filter material before they interact in the detector. When gamma rays are absorbed in the primary filter material, the interaction produces copious amounts of x rays. For example, when the 60-keV gamma rays from ^{241}Am are absorbed in a thin cadmium filter, a significant flux of 23-keV x rays can be produced. If these x rays create a problem in the detector, they can be easily attenuated with a very thin sheet of copper. Because the K x rays of copper at 8 keV are usually of sufficiently low energy, they do not interfere with the measurement. If the primary filter material is lead, cadmium is used to absorb the characteristic K x rays of lead at 73 and 75 keV, and copper is used to absorb the characteristic K x rays of cadmium at 23 keV. In graded filters, the lowest Z material is always placed next to the detector.

2.5 SHIELDING

In NDA instruments, shields and collimators are required to limit the detector response to background gamma rays and to shield the operator and detector from transmission and activation sources. Gamma-ray shielding materials should be of high density and high atomic number so that they have a high total linear attenuation coefficient and a high photoelectric absorption probability. The most common shielding material is lead because it is readily available, has a density of 11.35 g/cm^3 and an atomic number of 82, and is relatively inexpensive. Lead can be molded into many shapes; however, because of its high ductility it cannot be machined easily or hold a given shape unless supported by a rigid material.

In some applications, an alloy of tungsten (atomic number 74) is used in place of lead because it has significantly higher density (17 g/cm^3), can be machined easily, and holds a shape well. Table 2-2 shows some of the attenuation properties of the two materials. The tungsten is alloyed with nickel and copper to improve its machinability.

Table 2-2 shows that at energies above 500 keV the tungsten alloy has a significantly higher linear attenuation coefficient than lead because of its higher density. Thus, the same shielding effect can be achieved with a thinner shield. At energies below 500 keV, the difference between the attenuation properties of the two materials is less significant; the higher density of the tungsten alloy is offset by the lower atomic number. The tungsten alloy is used where space is severely limited or where machinability and mechanical strength are important. However, the tungsten material is over thirty times more expensive than lead; therefore, it is used sparingly and is almost never used for massive shields. The alloy is often used to hold intense gamma-ray transmission sources or to collimate gamma-ray detectors.

Table 2-2. Attenuation properties of lead and tungsten

Energy (keV)	Attenuation Coefficient (cm ⁻¹) ^a		Thickness (cm) ^a	
	Lead	Tungsten ^b	Lead	Tungsten ^b
1000	0.77	1.08	2.98	2.14
500	1.70	2.14	1.35	1.08
200	10.6	11.5	0.22	0.20
100	60.4	64.8	0.038	0.036

^aThickness of absorber with 10% transmission.

^bAlloy: 90% tungsten, 6% nickel, 4% copper.

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