

Figure 2.17 Fraction η of normally incident electrons that are backscattered from thick slabs of various materials, as a function of incident energy E . (From Tabata et al.²⁷)

III. INTERACTION OF GAMMA RAYS

Although a large number of possible interaction mechanisms are known for gamma rays in matter, only three major types play an important role in radiation measurements: *photoelectric absorption*, *Compton scattering*, and *pair production*. All these processes lead to the partial or complete transfer of the gamma-ray photon energy to electron energy. They result in sudden and abrupt changes in the gamma-ray photon history, in that the photon either disappears entirely or is scattered through a significant angle. This behavior is in marked contrast to the charged particles discussed earlier in this chapter, which slow down gradually through continuous, simultaneous interactions with many absorber atoms. The fundamentals of the gamma-ray interaction mechanisms are introduced here but are again reviewed at the beginning of Chapter 10 in the context of their influence on the response of gamma-ray detectors.

A. Interaction Mechanisms

1. PHOTOELECTRIC ABSORPTION

In the photoelectric absorption process, a photon undergoes an interaction with an absorber atom in which the photon completely disappears. In its place, an energetic *photoelectron* is ejected by the atom from one of its bound shells. The interaction is with the atom as a whole and cannot take place with free electrons. For gamma rays of sufficient energy, the most probable origin of the photoelectron is the most tightly bound or *K* shell of the atom. The photoelectron appears with an energy given by

$$E_{e^-} = h\nu - E_b \quad (2.15)$$

where E_b represents the binding energy of the photoelectron in its original shell. For gamma-ray energies of more than a few hundred keV, the photoelectron carries off the majority of the original photon energy.

In addition to the photoelectron, the interaction also creates an ionized absorber atom with a vacancy in one of its bound shells. This vacancy is quickly filled through capture of a free electron from the medium and/or rearrangement of electrons from other shells of the atom. Therefore, one or more characteristic X-ray photons may also be generated. Although in most cases these X-rays are reabsorbed close to the original site through photoelectric absorption involving less tightly bound shells, their migration and possible escape from radiation detectors can influence their response (see Chapter 10). In some fraction of the cases, the emission of an Auger electron may substitute for the characteristic X-ray in carrying away the atomic excitation energy.

As an example of the complexity of these interactions, consider incident photons with energy above 30 keV that undergo photoelectric absorption in xenon. About 86% interact through *K*-shell absorptions in the xenon atom.²⁸ Of these, 87.5% result in *K*-shell characteristic (or “fluorescent”) X-rays (a mixture of *K*- α and *K*- β) and 12.5% de-excite through the emission of Auger electrons. The remaining 14% of the incident photons that do not undergo *K*-shell interactions are absorbed through photoelectric interaction with the *L* or *M* shells. These result in much lower energy characteristic X-rays or Auger electrons that are very short range and, to first approximation, are reabsorbed very near the site of the original interaction. Another example of such a “cascade sequence” is shown in Chapter 10 as Fig. 10.20.

The photoelectric process is the predominant mode of interaction for gamma rays (or X-rays) of relatively low energy. The process is also enhanced for absorber materials of high atomic number Z . No single analytic expression is valid for the probability of photoelectric absorption per atom over all ranges of E_γ and Z , but a rough approximation is

$$\tau \approx \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}} \quad (2.16)$$

where the exponent n varies between 4 and 5 over the gamma-ray energy region of interest.¹ This severe dependence of the photoelectric absorption probability on the atomic number of the absorber is a primary reason for the preponderance of high- Z materials (such as lead) in gamma-ray shields. As further detailed in Chapter 10, many detectors used for gamma-ray spectroscopy are chosen from high- Z constituents for the same reason.

A plot of the photoelectric absorption cross section for a popular gamma-ray detection material, sodium iodide, is shown in Fig. 2.18. In the low-energy region, discontinuities in the curve or “absorption edges” appear at gamma-ray energies that correspond to the binding energies of electrons in the various shells of the absorber atom. The edge lying highest in energy therefore corresponds to the binding energy of the *K*-shell electron. For gamma-ray energies slightly above the edge, the photon energy is just sufficient to undergo a photoelectric interaction in which a *K*-electron is ejected from the atom. For gamma-ray

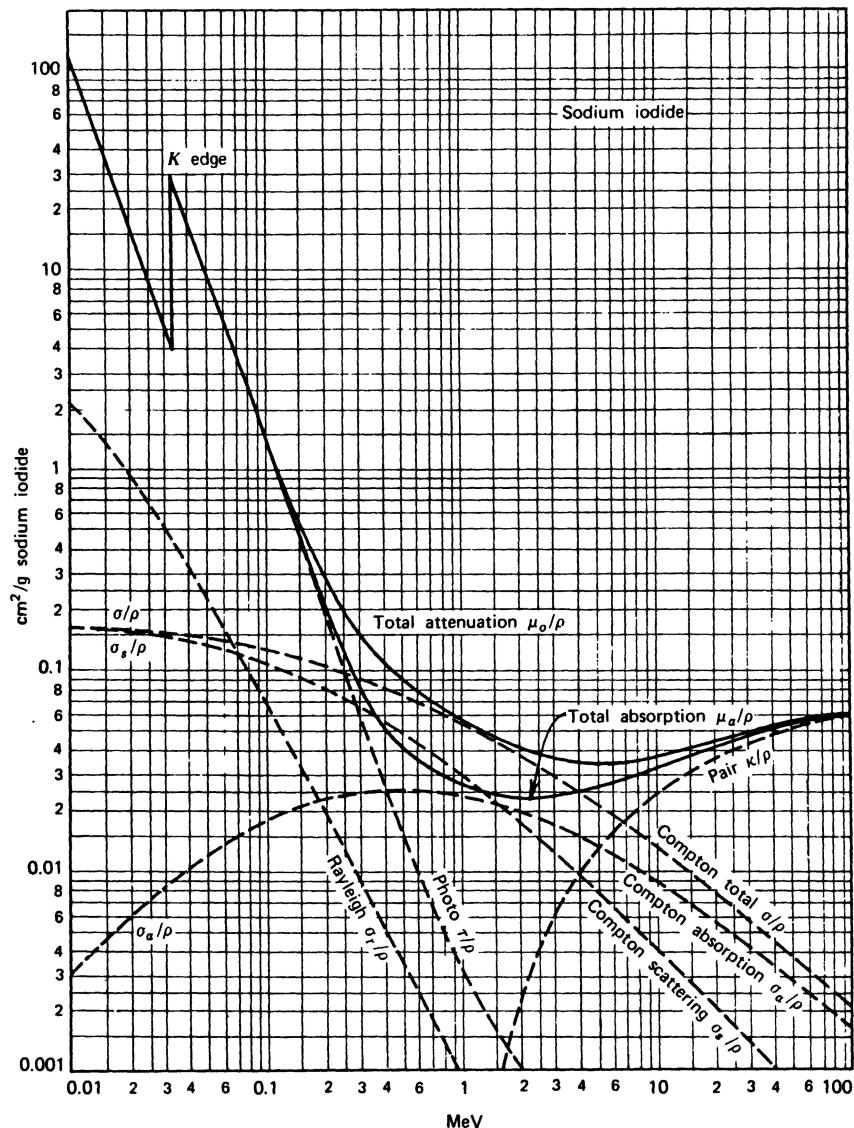


Figure 2.18 Energy dependence of the various gamma-ray interaction processes in sodium iodide. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)

energies slightly below the edge, this process is no longer energetically possible and therefore the interaction probability drops abruptly. Similar absorption edges occur at lower energies for the L, M, \dots electron shells of the atom.

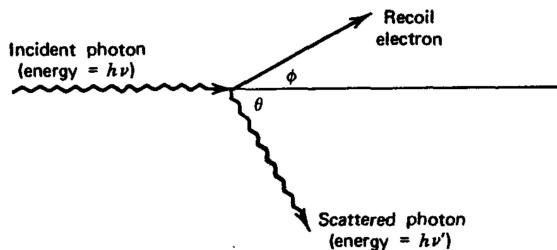
2. COMPTON SCATTERING

The interaction process of Compton scattering takes place between the incident gamma-ray photon and an electron in the absorbing material. It is most often the predominant interaction mechanism for gamma-ray energies typical of radioisotope sources.

In Compton scattering, the incoming gamma-ray photon is deflected through an angle θ with respect to its original direction. The photon transfers a portion of its energy to the electron (assumed to be initially at rest), which is then known as a *recoil electron*. Because

all angles of scattering are possible, the energy transferred to the electron can vary from zero to a large fraction of the gamma-ray energy.

The expression that relates the energy transfer and the scattering angle for any given interaction can simply be derived by writing simultaneous equations for the conservation of energy and momentum. Using the symbols defined in the sketch below



we can show¹ that

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2} (1 - \cos \theta)} \quad (2.17)$$

where $m_0 c^2$ is the rest-mass energy of the electron (0.511 MeV). For small scattering angles θ , very little energy is transferred. Some of the original energy is always retained by the incident photon, even in the extreme of $\theta = \pi$. Equations (10.3) through (10.6) describe some properties of the energy transfer for limiting cases. A plot of the scattered photon energy predicted from Eq. (2.17) is also shown in Fig. 10.7.[†]

The probability of Compton scattering per atom of the absorber depends on the number of electrons available as scattering targets and therefore increases linearly with Z . The dependence on gamma-ray energy is illustrated in Fig. 2.18 for the case of sodium iodide and generally falls off gradually with increasing energy.

The angular distribution of scattered gamma rays is predicted by the *Klein-Nishina formula* for the differential scattering cross section $d\sigma/d\Omega$:

$$\frac{d\sigma}{d\Omega} = Zr_0^2 \left(\frac{1}{1 + \alpha(1 - \cos \theta)} \right)^2 \left(\frac{1 + \cos^2 \theta}{2} \right) \left(1 + \frac{\alpha^2(1 - \cos \theta)^2}{(1 + \cos^2 \theta)[1 + \alpha(1 - \cos \theta)]} \right) \quad (2.18)$$

where $\alpha = h\nu/m_0 c^2$ and r_0 is the classical electron radius. The distribution is shown graphically in Fig. 2.19 and illustrates the strong tendency for forward scattering at high values of the gamma-ray energy.

3. PAIR PRODUCTION

If the gamma-ray energy exceeds twice the rest-mass energy of an electron (1.02 MeV), the process of pair production is energetically possible. As a practical matter, the probability of this interaction remains very low until the gamma-ray energy approaches several MeV and therefore pair production is predominantly confined to high-energy gamma rays. In the interaction (which must take place in the coulomb field of a nucleus), the gamma-ray photon disappears and is replaced by an electron-positron pair. All the excess energy carried in by the photon above the 1.02 MeV required to create the pair goes into kinetic energy shared by the positron and the electron. Because the positron will subsequently annihilate

[†]The simple analysis here neglects the atomic binding of the electron and assumes that the gamma-ray photon interacts with a free electron. If the small binding energy is taken into account, the unique energy of the scattered photon at a fixed angle predicted by Eq. 2.17 is spread into a narrow distribution centered about that energy (see Fig. 13.9).

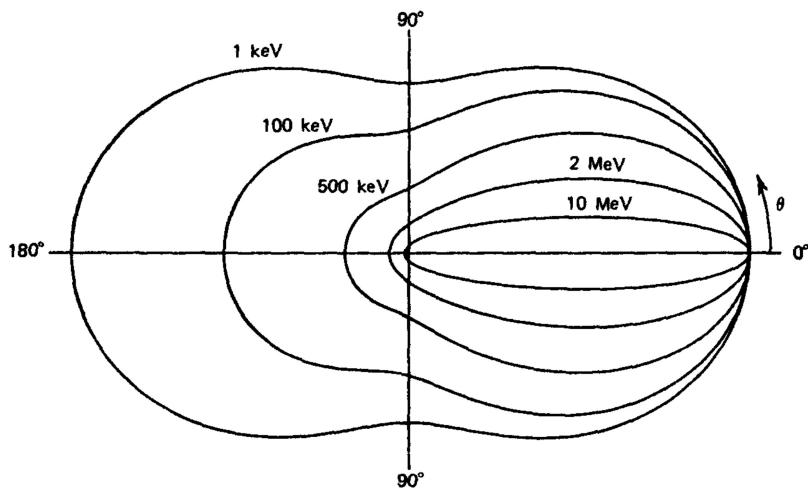


Figure 2.19 A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle θ . The curves are shown for the indicated initial energies.

after slowing down in the absorbing medium, two annihilation photons are normally produced as secondary products of the interaction. The subsequent fate of this annihilation radiation has an important effect on the response of gamma-ray detectors, as described in Chapter 10.

No simple expression exists for the probability of pair production per nucleus, but its magnitude varies approximately as the square of the absorber atomic number.¹ The importance of pair production rises sharply with energy, as indicated in Fig. 2.18.

The relative importance of the three processes described above for different absorber materials and gamma-ray energies is conveniently illustrated in Fig. 2.20. The line at the left represents the energy at which photoelectric absorption and Compton scattering are equally probable as a function of the absorber atomic number. The line at the right represents the energy at which Compton scattering and pair production are equally probable. Three areas are thus defined on the plot within which photoelectric absorption, Compton scattering, and pair production each predominate.

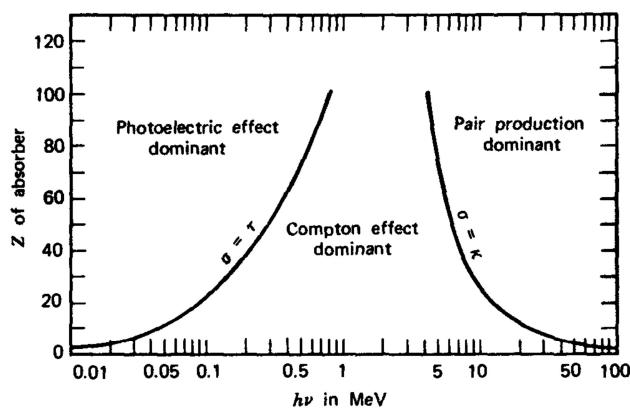


Figure 2.20 The relative importance of the three major types of gamma-ray interaction. The lines show the values of Z and $h\nu$ for which the two neighboring effects are just equal. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)

4. COHERENT SCATTERING

In addition to Compton scattering, another type of scattering can occur in which the gamma-ray photon interacts coherently with all the electrons of an absorber atom. This *coherent scattering* or *Rayleigh scattering* process¹ neither excites nor ionizes the atom, and the gamma-ray photon retains its original energy after the scattering event. Because virtually no energy is transferred, this process is often neglected in basic discussions of gamma-ray interactions, and we will also ignore it in the discussions that follow. However, the direction of the photon is changed in coherent scattering, and complete models of gamma-ray transport must take it into account. The probability of coherent scattering is significant only for low photon energies (typically below a few hundred keV for common materials) and is most prominent in high- Z absorbers. The average deflection angle decreases with increasing energy, further restricting the practical importance of coherent scattering to low energies.

B. Gamma-Ray Attenuation

1. ATTENUATION COEFFICIENTS

If we again picture a transmission experiment as in Fig. 2.21, where monoenergetic gamma rays are collimated into a narrow beam and allowed to strike a detector after passing through an absorber of variable thickness, the result should be simple exponential attenuation of the gamma rays as also shown in Fig. 2.21. Each of the interaction processes removes the gamma-ray photon from the beam either by absorption or by scattering away from the detector direction and can be characterized by a fixed probability of occurrence per unit path length in the absorber. The sum of these probabilities is simply the probability per unit path length that the gamma-ray photon is removed from the beam:

$$\mu = \tau(\text{photoelectric}) + \sigma(\text{Compton}) + \kappa(\text{pair}) \quad (2.19)$$

and is called the *linear attenuation coefficient*. The number of transmitted photons I is then given in terms of the number without an absorber I_0 as

$$\frac{I}{I_0} = e^{-\mu t} \quad (2.20)$$

The gamma-ray photons can also be characterized by their *mean free path* λ , defined as the average distance traveled in the absorber before an interaction takes place. Its value can be obtained from

$$\lambda = \frac{\int_0^\infty xe^{-\mu x} dx}{\int_0^\infty e^{-\mu x} dx} = \frac{1}{\mu} \quad (2.21)$$

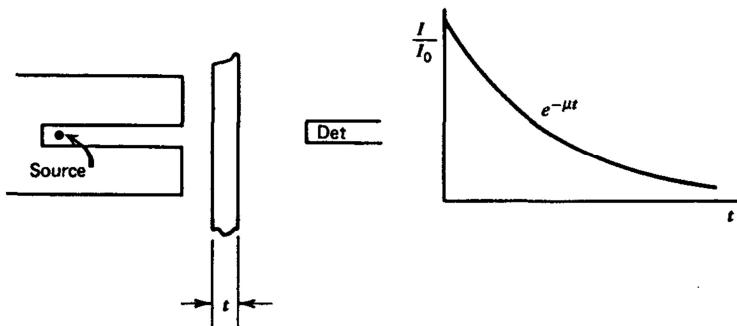


Figure 2.21 The exponential transmission curve for gamma rays measured under “good geometry” conditions.

and is simply the reciprocal of the linear attenuation coefficient. Typical values of λ range from a few mm to tens of cm in solids for common gamma-ray energies.

Use of the linear attenuation coefficient is limited by the fact that it varies with the density of the absorber, even though the absorber material is the same. Therefore, the *mass attenuation coefficient* is much more widely used and is defined as

$$\text{mass attenuation coefficient} = \frac{\mu}{\rho} \quad (2.22)$$

where ρ represents the density of the medium. For a given gamma-ray energy, the mass attenuation coefficient does not change with the physical state of a given absorber. For example, it is the same for water whether present in liquid or vapor form. The mass attenuation coefficient of a compound or mixture of elements can be calculated from

$$\left(\frac{\mu}{\rho}\right)_c = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad (2.23)$$

where the w_i factors represent the weight fraction of element i in the compound or mixture.

2. ABSORBER MASS THICKNESS

In terms of the mass attenuation coefficient, the attenuation law for gamma rays now takes the form

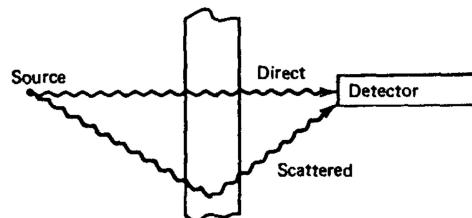
$$\frac{I}{I_0} = e^{-(\mu/\rho)\rho t} \quad (2.24)$$

The product ρt , known as the *mass thickness* of the absorber, is now the significant parameter that determines its degree of attenuation. Units of mass thickness have historically been mg/cm², and this convention is retained in this text. The thickness of absorbers used in radiation measurements is therefore often measured in mass thickness rather than physical thickness, because it is a more fundamental physical quantity.

The mass thickness is also a useful concept when discussing the energy loss of charged particles and fast electrons. For absorber materials with similar neutron/proton ratios, a particle will encounter about the same number of electrons passing through absorbers of equal mass thickness. Therefore, the stopping power and range, when expressed in units of ρt , are roughly the same for materials that do not differ greatly in Z .

3. BUILDUP

The gamma-ray attenuation experiment of Fig. 2.21, in which the gamma rays are collimated to a narrow beam before striking the absorber, is sometimes characterized as a “narrow beam” or “good geometry” measurement. The essential characteristic is that only gamma rays from the source that escape interaction in the absorber can be counted by the detector. Real measurements are often carried out under different circumstances (as sketched below) in which the severe collimation of the gamma rays is absent.



Now the detector can respond either to gamma rays directly from the source, to gamma rays that reach the detector after having scattered in the absorber, or to other types of secondary photon radiation. Many types of detectors will be unable to distinguish between these possibilities, so that the measured detector signal will be larger than that recorded under equivalent “good geometry” conditions. The conditions that lead to the simple exponential attenuation of Eq. (2.20) are therefore violated in this “broad beam” or “bad geometry” measurement because of the additional contribution of the secondary gamma rays. This situation is usually handled by replacing Eq. (2.20) by the following:

$$\frac{I}{I_0} = B(t, E_\gamma) e^{-\mu t} \quad (2.25)$$

where the factor $B(t, E_\gamma)$ is called the *buildup factor*. The exponential term is retained to describe the major variation of the gamma-ray counting rate with absorber thickness, and the buildup factor is introduced as a simple multiplicative correction. The magnitude of the buildup factor depends on the type of gamma-ray detector used, because this will affect the relative weight given to the direct and secondary gamma rays. (With a detector that responds only to the direct gamma rays, the buildup factor is unity.) The buildup also depends on the specific geometry of the experiment. As a rough rule of thumb, the buildup factor for thick slab absorbers tends to be about equal to the thickness of the absorber measured in units of mean free path of the incident gamma rays, provided the detector responds to a broad range of gamma-ray energies.

IV. INTERACTION OF NEUTRONS

A. General Properties

In common with gamma rays, neutrons carry no charge and therefore cannot interact in matter by means of the coulomb force, which dominates the energy loss mechanisms for charged particles and electrons. Neutrons can also travel through many centimeters of matter without any type of interaction and thus can be totally invisible to a detector of common size. When a neutron does undergo interaction, it is with a nucleus of the absorbing material. As a result of the interaction, the neutron may either totally disappear and be replaced by one or more secondary radiations, or else the energy or direction of the neutron is changed significantly.

In contrast to gamma rays, the secondary radiations resulting from neutron interactions are almost always heavy charged particles. These particles may be produced either as a result of neutron-induced nuclear reactions or they may be the nuclei of the absorbing material itself, which have gained energy as a result of neutron collisions. Most neutron detectors utilize some type of conversion of the incident neutron into secondary charged particles, which can then be detected directly. Specific examples of the most useful conversion processes are detailed in Chapters 14 and 15.

The relative probabilities of the various types of neutron interactions change dramatically with neutron energy. In somewhat of an oversimplification, we will divide neutrons into two categories on the basis of their energy, either “fast neutrons” or “slow neutrons,” and discuss their interaction properties separately. The dividing line will be at about 0.5 eV, or about the energy of the abrupt drop in absorption cross section in cadmium (the *cadmium cutoff* energy).