# Chapter 10

# Radiation Spectroscopy with Scintillators

The widespread availability in the early 1950s of thallium-activated sodium iodide scintillation detectors allowed the spectroscopy of gamma rays to be carried out for the first time with small, portable instruments. With this development, a practical detector was available that could provide a high efficiency for the detection of gamma rays and, at the same time, was capable of sufficiently good energy resolution to be useful in separating the contributions of polyenergetic gamma-ray sources. Gamma-ray spectroscopy using scintillators has since developed into a mature science with applications in an impressive array of technical fields.

Despite the fact that it was virtually the first practical solid detection medium used for gamma-ray spectroscopy, NaI(Tl) remains the most popular scintillation material for this application. This extraordinary success stems from its extremely good light yield, excellent linearity, and the high atomic number of its iodine constituent. Other scintillators mentioned in Chapter 8, notably cesium iodide and some of the newer inorganic scintillators, have also achieved some success in gamma-ray spectroscopy, but the combined use of all other materials extends to only a small fraction of the cases in which sodium iodide is found. In the sections that follow, we concentrate on NaI(Tl), with the understanding that most of the discussion and general conclusions can be extended to other scintillation materials by taking into account the differences in their gamma-ray interaction probabilities and scintillation properties.

Useful textbook reviews of scintillation spectroscopy of gamma radiation have been published by Birks,[1] Shafroth,[2] and Siegbahn.[3]

## GENERAL CONSIDERATIONS IN GAMMA-RAY SPECTROSCOPY

An X-ray or gamma-ray photon is uncharged and creates no direct ionization or excitation of the material through which it passes. The detection of gamma rays is therefore critically dependent on causing the gamma-ray photon to undergo an interaction that transfers all or part of the photon energy to an electron in the absorbing material. These interaction processes are detailed in Chapter 2 and represent sudden and major alterations of the photon properties, as opposed to the continuous slowing down of heavy charged particles or electrons through many simultaneous interactions.

Because the primary gamma-ray photons are "invisible" to the detector, it is only the fast electrons created in gamma-ray interactions that provide any clue to the nature of the incident gamma rays. These electrons have a maximum energy equal to the energy of the

incident gamma-ray photon and will slow down and lose their energy in the same manne as any other fast electron, such as a beta particle. Energy loss is therefore through ioniza tion and excitation of atoms within the absorber material and through bremsstrahlun emission (see Chapter 2).

In order for a detector to serve as a gamma-ray spectrometer, it must carry out two di tinct functions. First, it must act as a conversion medium in which incident gamma rays hav a reasonable probability of interacting to yield one or more fast electrons; second, it mu function as a conventional detector for these secondary electrons. In the discussion that fo lows, we first assume that the detector is sufficiently large so that the escape of secondar electrons (and any bremsstrahlung created along their track) is not significant. For incider gamma rays of a few MeV, the most penetrating secondary electrons will also be created wit a few MeV kinetic energy. The corresponding range in typical solid detector media is a fe millimeters (most bremsstrahlung photons generated along the electron track will be co siderably less penetrating). The assumption of complete electron absorption therefo implies a detector whose minimum dimension is at least about a centimeter. Then only small fraction of the secondary electrons, which are created more or less randomly throug out the volume of the detector, lie within one range value of the surface and could possib escape. Later in this chapter we discuss the complicating effects of electron ar bremsstrahlung escape in small detectors as a perturbation on the simpler model that follow

The following discussions are kept relatively general so that they apply not only other scintillation materials but also to other solid or liquid detection media used gamma-ray spectroscopy. Chapters 12 and 13 discuss semiconductor detectors, which al have been widely applied to gamma-ray spectroscopy. The following section serves as general introduction to these chapters as well, because the basic modes of gamma-r interactions are identical for all detector types.

Because of the low stopping power of gases, the requirement of full energy absorptic for the secondary electrons generally rules out gas-filled detectors for the spectroscopy gamma rays. Exceptions to this statement are possible only if the gas is at very high pre sure (see the discussion of high pressure xenon chambers in Chapter 19) or if the incide photon has very low energy. The penetration distance of a 1 MeV electron in STP gases several meters, so normal gas-filled detectors of practical size can never come close absorbing all the secondary electron energy. To complicate the situation further, mc gamma-ray-induced pulses from a gas-filled counter arise from gamma-ray interactio taking place in the solid counter wall, following which the secondary electron finds its w to the gas. Under these conditions, the electron loses a variable and indeterminate amou of energy in the wall, which does not contribute to the detector output pulse, and virtual all hope of relating the electron to incident gamma-ray energy is lost.

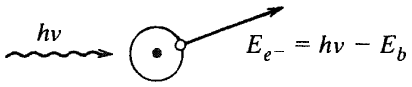
## II. GAMMA-RAY INTERACTIONS

Of the various ways gamma rays can interact in matter, only three interaction mechanis have any real significance in gamma-ray spectroscopy: photoelectric absorption, Compt scattering, and pair production. As detailed in Chapter 2, photoelectric absorption pr dominates for low-energy gamma rays (up to several hundred keV), pair production pr dominates for high-energy gamma rays (above 5–10 MeV), and Compton scattering is t most probable process over the range of energies between these extremes. The atom number of the interaction medium has a strong influence on the relative probabilities these three interactions, as can be seen from the formulas and plots given in Chapter 2. T most striking of these variations involves the cross section for photoelectric absorptio which varies approximately as $Z^{4.5}$. As we shall see from the following discussion, becau photoelectric absorption is the preferred mode of interaction, there is a premium on choc

ing detectors for gamma-ray spectroscopy from materials that incorporate elements with high atomic number.

## Photoelectric Absorption

Photoelectric absorption is an interaction in which the incident gamma-ray photon disappears. In its place, a photoelectron is produced from one of the electron shells of the absorber atom with a kinetic energy given by the incident photon energy $h\nu$ minus the binding energy of the electron in its original shell ($E_b$). This process is shown in the diagram below. For typical gamma-ray energies, the photoelectron is most likely to emerge from the $K$ shell, for which typical binding energies range from a few keV for low-$Z$ materials to tens of keV for materials with higher atomic number. Conservation of momentum requires that the atom recoils in this process, but its recoil energy is very small and usually can be neglected.




The vacancy that is created in the electron shell as a result of the photoelectron emission is quickly filled by electron rearrangement. In the process, the binding energy is liberated either in the form of a characteristic X-ray or Auger electron. In iodine, a characteristic X-ray is emitted in about 88% of the cases.[4] The Auger electrons have extremely short range because of their low energy. The characteristic X-rays may travel some distance (typically a millimeter or less) before being reabsorbed through photoelectric interactions with less tightly bound electron shells of the absorber atoms. Although escape of these X-rays can at times be significant, for now we assume that they are also fully absorbed in keeping with our simplified model.

Thus, the effect of photoelectric absorption is the liberation of a photoelectron, which carries off most of the gamma-ray energy, together with one or more low-energy electrons corresponding to absorption of the original binding energy of the photoelectron. If nothing escapes from the detector, then the sum of the kinetic energies of the electrons that are created must equal the original energy of the gamma-ray photon.

Photoelectric absorption is therefore an ideal process if one is interested in measuring the energy of the original gamma ray. The total electron kinetic energy equals the incident gamma-ray energy and will always be the same if monoenergetic gamma rays are involved. Under these conditions, the differential distribution of electron kinetic energy for a series of photoelectric absorption events would be a simple delta function as shown below. The single peak appears at a total electron energy corresponding to the energy of the incident gamma rays.

## B. Compton Scattering

The result of a Compton scattering interaction is the creation of a recoil electron and scattered gamma-ray photon, with the division of energy between the two dependent on the scattering angle. A sketch of the interaction is given below.


Before After

The energy of the scattered gamma ray $h\nu'$ in terms of its scattering angle $\theta$ is given by

$$h\nu' = \frac{h\nu}{1 + (h\nu/m_0c^2)(1 - \cos\theta)} \tag{10.1}$$

where $m_0c^2$ is the rest mass energy of the electron (0.511 MeV). The kinetic energy of the recoil electron is therefore

$$E_{e^-} = h\nu - h\nu' = h\nu\left(\frac{(h\nu/m_0c^2)(1 - \cos\theta)}{1 + (h\nu/m_0c^2)(1 - \cos\theta)}\right) \tag{10.2}$$

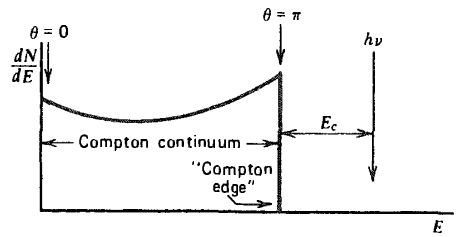
Two extreme cases can be identified:

1. A grazing angle scattering, or one in which $\theta \cong 0$. In this case, Eqs. (10.1) and (10.2) predict that $h\nu' \cong h\nu$ and $E_{e^-} \cong 0$. In this extreme, the recoil Compton electron has very little energy and the scattered gamma ray has nearly the same energy as the incident gamma ray.
2. A head-on collision in which $\theta = \pi$. In this extreme, the incident gamma ray is backscattered toward its direction of origin, whereas the electron recoils along the direction of incidence. This extreme represents the maximum energy that can be transferred to an electron in a single Compton interaction. Equations (10.1) and (10.2) yield for this case

$$h\nu'\Big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2} \tag{10.3}$$

$$E_{e^-}\Big|_{\theta=\pi} = h\nu\left(\frac{2h\nu/m_0c^2}{1 + 2h\nu/m_0c^2}\right) \tag{10.4}$$

In normal circumstances, all scattering angles will occur in the detector. Therefore, a continuum of energies can be transferred to the electron, ranging from zero up to the maximum predicted by Eq. (10.4). Figure 10.1 shows the shape of the distribution of Compton recoil electrons predicted by the Klein–Nishina cross section (Chapter 2) for several different values of the incident gamma-ray energy. For any one specific gamma-ray energy the electron energy distribution has the general shape shown in the sketch below.



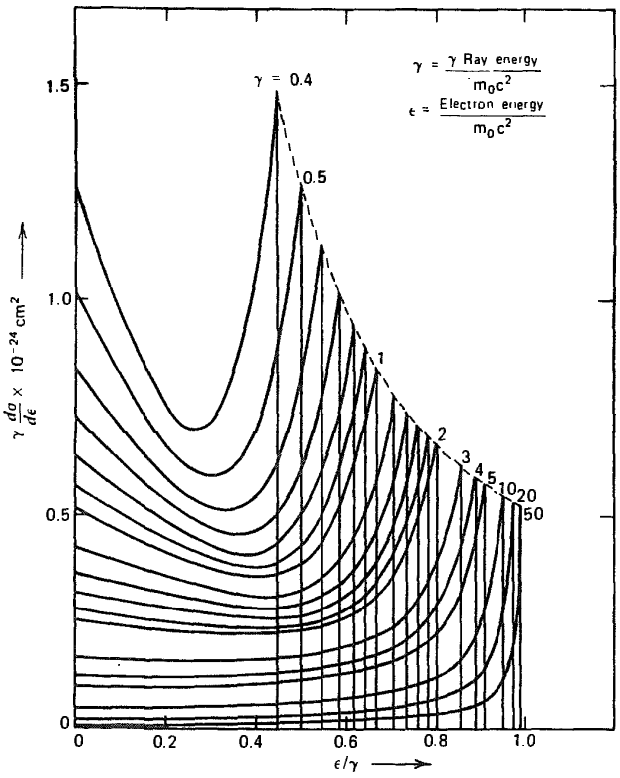



**Figure 10.1** Shape of the Compton continuum for various gamma-ray energies. (From S. M. Shafroth (ed.), *Scintillation Spectroscopy of Gamma Radiation.* Copyright 1964 by Gordon & Breach, Inc. By permission of the publisher.)

The gap between the maximum Compton recoil electron energy and the incident gamma-ray energy is given by

$$E_C \equiv h\nu - E_{e^-}\Big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2} \tag{10.5}$$

In the limit that the incident gamma-ray energy is large, or $h\nu \gg m_0c^2/2$, this energy difference tends toward a constant value given by

$$E_C \cong \frac{m_0c^2}{2} \; (= 0.256 \text{ MeV}) \tag{10.6}$$

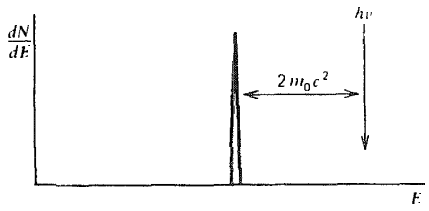
The preceding analysis is based on the assumption that Compton scattering involves electrons that are initially free or unbound. In actual detector materials, the binding energy of the electron prior to the scattering process can have a measurable effect on the shape of the Compton continuum. These effects will be particularly noticeable for low incident gamma-ray energy. They involve a rounding-off of the rise in the continuum near its upper extreme and the introduction of a finite slope to the abrupt drop of the Compton edge. These effects are often masked by the finite energy resolution of the detector but can be evident in the spectra from detectors with high inherent resolution (see Fig. 13.9). The finite momentum of orbital electrons also causes gamma-ray photons that are scattered at a fixed angle from a monoenergetic source to have a narrow distribution in their energy (the "Doppler spread"), as contrasted with a single energy predicted by Eq. (10.1).

### C. Pair Production

The third significant gamma-ray interaction is pair production. The process occurs in the intense electric field near the protons in the nuclei of the absorbing material and corresponds to the creation of an electron–positron pair at the point of complete disappearance of the incident gamma-ray photon. Because an energy of $2m_0c^2$ is required to create the electron–positron pair, a minimum gamma-ray energy of 1.02 MeV is required to make the process energetically possible. If the incident gamma-ray energy exceeds this value, the excess energy appears in the form of kinetic energy shared by the electron–positron pair. Therefore, the process consists of converting the incident gamma-ray photon into electron and positron kinetic energies, which total

$$E_{e^-} + E_{e^+} = h\nu - 2m_0c^2 \tag{10.7}$$

For typical energies, both the electron and positron travel a few millimeters at most before losing all their kinetic energy to the absorbing medium. A plot of the total (electron + positron) charged particle kinetic energy created by the incident gamma ray is again a simple delta function, but it is now located $2m_0c^2$ below the incident gamma-ray energy, as illustrated in the sketch below. In our simple model, this amount of energy will be deposited each time a pair production interaction occurs within the detector. As introduced in the next section, this energy corresponds to the position of the *double escape peak* in actual gamma-ray pulse height spectra.




The pair production process is complicated by the fact that the positron is not a stable particle. Once its kinetic energy becomes very low (comparable to the thermal energy of normal electrons in the absorbing material), the positron will annihilate or combine with a normal electron in the absorbing medium. At this point both disappear, and they are replaced by two annihilation photons of energy $m_0c^2$ (0.511 MeV) each. The time required for the positron to slow down and annihilate is small, so that the annihilation radiation appears in virtual coincidence with the original pair production interaction.

## III. PREDICTED RESPONSE FUNCTIONS

### A. "Small" Detectors

As an example of one extreme in gamma-ray detector behavior, we first examine the expected response of detectors whose size is small compared with the mean free path of the *secondary gamma radiations* produced in interactions of the original gamma rays. These secondary radiations consist of Compton scattered gamma rays, together with annihilation photons formed at the end of the tracks of positrons created in pair production. Because the mean free path of the secondary gamma rays is typically of the order of several centimeters, the condition of "smallness" is met if the detector dimensions do not exceed 1 or 2 cm. At the same time, we retain our original simplifying assumption that all charged particle energy (photoelectron, Compton electron, pair electron, and positron) is completely absorbed within the detector volume.

The predicted electron energy deposition spectra under these conditions are illustrated in Fig. 10.2. If the incident gamma-ray energy is below the value at which pair production is significant, the spectrum results only from the combined effect of Compton scattering

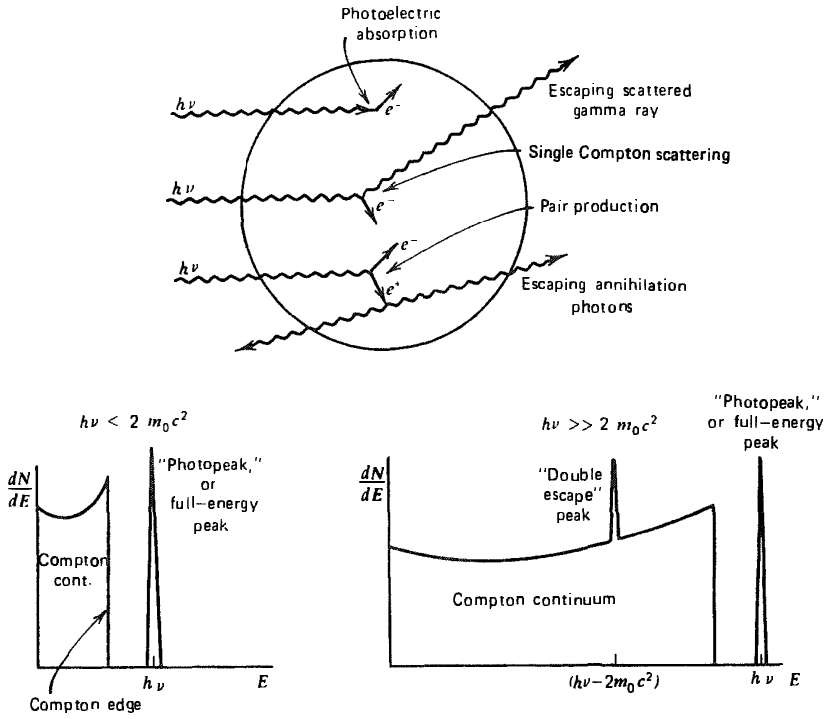



**Figure 10.2** The "small detector" extreme in gamma-ray spectroscopy. The processes of photoelectric absorption and single Compton scattering give rise to the low-energy spectrum at the left. At higher energies, the pair production process adds a double escape peak shown in the spectrum at the right.

and photoelectric absorption. The continuum of energies corresponding to Compton scattered electrons is called the *Compton continuum*, whereas the narrow peak corresponding to photoelectrons is designated as the *photopeak*. For the "small" detector, only single interactions take place, and the ratio of the area under the photopeak to the area under the Compton continuum is the same as the ratio of the photoelectric cross section to the Compton cross section in the detector material.

If the incident gamma-ray energy is sufficiently high (several MeV), the results of pair production are also evident in the electron energy spectrum. For a small detector, only the electron and positron kinetic energies are deposited, and the annihilation radiation escapes. The net effect is to add a *double escape peak* to the spectrum located at an energy of $2m_0c^2$ (~1.02 MeV) below the photopeak. The term *double escape* refers to the fact that both annihilation photons escape from the detector without further interaction.

## Very Large Detectors

As an opposite extreme case, imagine that gamma rays could be introduced near the center of a very large detector, perhaps in an arrangement resembling that of Fig. 10.3. The detector dimensions are now assumed to be sufficiently large so that all secondary radiations, including Compton scattered gamma rays and annihilation photons, also interact within the detector active volume and none escape from the surface. For typical gamma-ray energies, this condition would translate into requiring detector dimensions on the order of many tens of centimeters, unrealistically large for most practical cases.

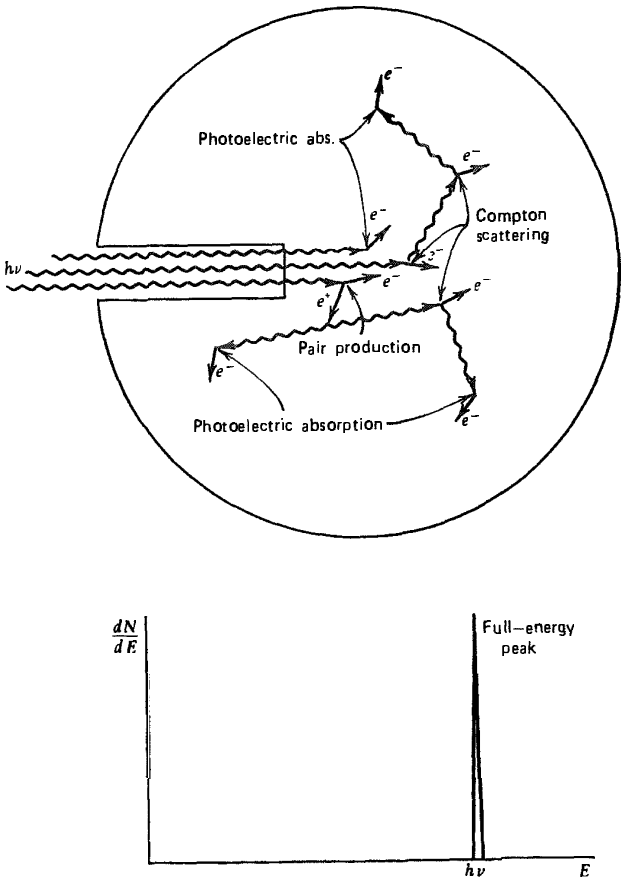



**Figure 10.3** The "large detector" extreme in gamma-ray spectroscopy. All gamma-ray photons, no matter how complex their mode of interaction, ultimately deposit all their energy in the detector. Some representative histories are shown at the top.

Nonetheless, it is helpful to see how increasing the detector size greatly simplifies it response function. Some typical histories, obtained by following a particular source gamm ray and all subsequent secondary radiation, are sketched in Fig. 10.3. If the initial interactio is a Compton scattering event, the scattered gamma ray will subsequently interact at som other location within the detector. This second interaction may also be a Compton scatte ing event, in which case a scattered photon of still lower energy is produced. Eventually, photoelectric absorption will occur and the history is terminated at that point.

It is important to appreciate the small amount of time required for the entire history t take place. The primary and secondary gamma rays travel at the speed of light. If the averag migration distance of the secondary gamma rays is of the order of 10 cm, the total elapse time from start to finish of the history will be less than a nanosecond. This time is substan tially less than the inherent response time of virtually all practical detectors used in gamma ray spectroscopy. Therefore, the net effect is to create the Compton electrons at each scat tering point and the final photoelectron in time coincidence. The pulse produced by th detector will therefore be the sum of the responses due to each individual electron. If th detector responds linearly to electron energy, then a pulse is produced which is proportiona to the *total* energy of all the electrons produced along the history. Because nothing escape

from the detector, this total electron energy must simply be the original energy of the gamma-ray photon, no matter how complex any specific history may be. *The detector response is the same as if the original gamma-ray photon had undergone a simple photoelectric absorption in a single step.*

The same type of argument can be used if the history involves a pair production event. The annihilation photons formed when the positron is stopped are now assumed to interact through Compton scattering or photoelectric absorption elsewhere in the detector. Again, if the detector is large enough to prevent any secondary radiation from escaping, the sum of the kinetic energies of the electron–positron pair and subsequent Compton and photoelectrons produced by interaction of the annihilation radiation must equal the original gamma-ray photon energy. Therefore, the detector response is again simply proportional to the original gamma-ray energy.

The conclusion to be reached is therefore very simple: If the detector is sufficiently large and its response linearly dependent on electron kinetic energy, then the signal pulse is identical for all gamma-ray photons of the same energy, regardless of the details of each individual history. This circumstance is very fortunate because the detector response function now consists of the single peak shown in Fig. 10.3 rather than the more complex function shown in Fig. 10.2. The ability to interpret complex gamma-ray spectra involving many different energies is obviously enhanced when the response function consists of a single peak.

By common usage, the corresponding peak in the response function is often called the *photopeak*, just as in the case of the small detector. It should be realized, however, that in addition to simple photoelectric events, much more complex histories involving multiple Compton scattering or pair production also contribute pulses that fall within this peak. A better name is the *full-energy peak* because it represents all histories in which all of the original gamma-ray energy is fully converted to electron kinetic energy.

## Intermediate Size Detectors

Real detectors of the sizes in common use for gamma-ray spectroscopy are neither small nor large by the standards given above. For usual geometries in which the gamma rays are incident externally on the surface of the detector, even large-volume detectors appear finite because some interactions will take place near the entrance surface. Normal detector response functions therefore combine some of the properties discussed for the two previous cases, as well as additional features related to *partial* recovery of the secondary gamma-ray energy. Some representative histories that illustrate these added possibilities are shown in Fig. 10.4, together with corresponding features in the response function.

The spectrum for low to medium gamma-ray energies (where pair production is not significant) again consists of a Compton continuum and photopeak. Now, however, the ratio of the area under the photopeak to that under the Compton continuum is significantly enhanced over that for the very small detector due to the added contribution of multiple events to the photopeak. The lower the incident gamma-ray energy, the lower will be the average energy of a Compton scattered photon and the corresponding average distance of migration. Thus, even detectors of moderate size will appear to be large, and the relative area under the photopeak increases with decreasing incident photon energy. At very low energies (say, $< 100$ keV) the Compton continuum may effectively disappear.

At medium energies, the possibility of multiple Compton scattering followed by escape of the final scattered photon can lead to a total energy deposition that is greater than the maximum predicted by Eq. (10.4) for single scattering. These multiple events can thus partially fill in the gap between the Compton edge and the photopeak, as well as distort the shape of the continuum predicted for single scattering.

If the gamma-ray energy is high enough to make pair production significant, a more complicated situation prevails. The annihilation photons now may either escape or under-

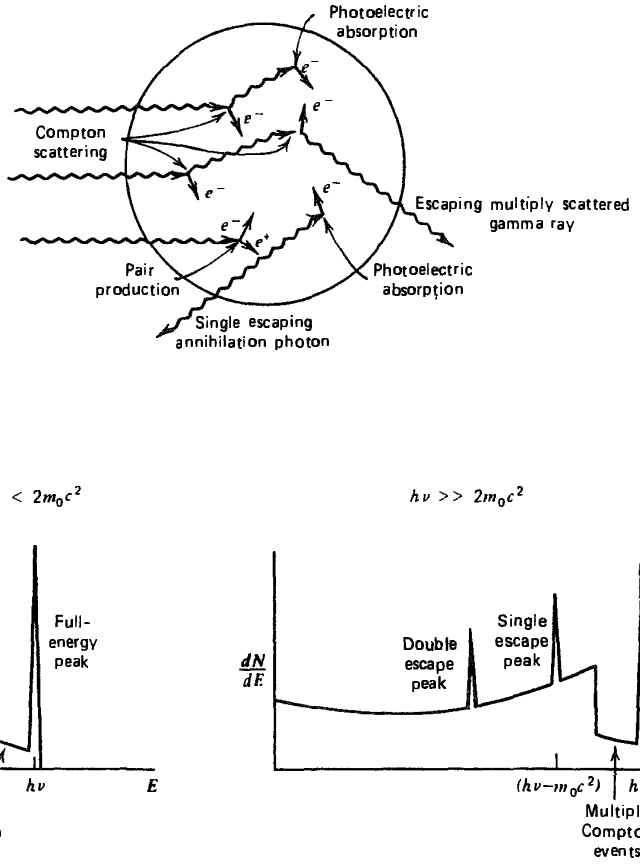



**Figure 10.4** The case of intermediate detector size in gamma-ray spectroscopy. In addition to the continuum from single Compton scattering and the full-energy peak, the spectrum at the left shows the influence of multiple Compton events followed by photon escape. The full-energy peak also contains some histories that began with Compton scattering. At the right, the single escape peak corresponds to initial pair production interactions in which only one annihilation photon leaves the detector without further interaction. A double escape peak as illustrated in Fig. 10.2 will also be present due to those pair production events in which both annihilation photons escape.

go further interaction within the detector. These additional interactions may lead to eith partial or full-energy absorption of either one or both of the annihilation photons.

If both annihilation photons escape without interaction, events occur that contribute the double escape peak discussed previously. Another relatively frequent occurrence is history in which one annihilation photon escapes but the other is totally absorbed. The events contribute to a *single escape peak*, which now appears in the spectrum at an ener of $m_0c^2$ (0.511 MeV) below the photopeak. A continuous range of other possibilities exis in which one or both of the annihilation photons are partially converted to electron ener through Compton scattering and subsequent escape of the scattered photon. Such even accumulate in a broad continuum in the pulse height spectrum lying between the doub escape peak and the photopeak.

The response function to be expected for a real gamma-ray detector will depend on the size, shape, and composition of the detector, and also the geometric details of the irradiation conditions. For example, the response function will change somewhat if a point gamma-ray source is moved from a position close to the detector to one that is far away. The variation is related to the differences in the spatial distribution of the primary interactions that occur within the detector as the source geometry is changed. In general, the response function is too complicated to predict in detail other than through the use of Monte Carlo calculations, which simulate the histories actually taking place in a detector of the same size and composition.

Some properties of the response function are of general interest in gamma-ray spectroscopy. The *photofraction* is defined as the ratio of the area under the photopeak (or full-energy peak) to that under the entire response function. It is a direct measure of the probability that a gamma ray that undergoes interaction of any kind within the detector ultimately deposits its full energy. Large values of the photofraction are obviously desirable to minimize the complicating effects of Compton continua and escape peaks in the spectrum.

At high gamma-ray energies, the single and double escape peaks are quite prominent parts of the response function and can, under some circumstances, become larger than the photopeak. The ratio of the area under the single or double escape peak to the area under the photopeak is also a widely quoted property of the response function that can help in the interpretation of complex spectra.

## Complications in the Response Function

### *1. SECONDARY ELECTRON ESCAPE*

If the detector is not large compared with typical secondary electron ranges, a significant fraction of the electrons may leak from the detector surface and their energy will not be fully collected. This effect is enhanced for high gamma-ray energies for which the average secondary electron energy is also high. Electron leakage will tend to distort the response function by moving some events to a lower amplitude from that which would be observed if the entire electron energy were collected. The shape of the Compton continuum will therefore be altered somewhat to favor lower amplitudes. Because some events will be lost from the photopeak, the photofraction will be reduced as compared with the situation in which electron leakage is not important.

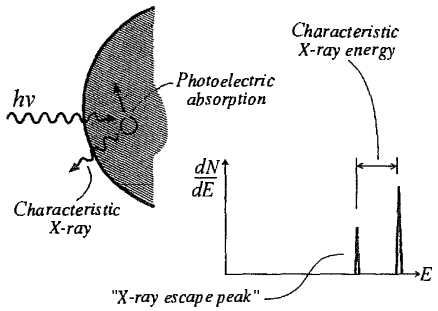
### *2. BREMSSTRAHLUNG ESCAPE*

One of the mechanisms by which secondary electrons lose energy is by the radiation of bremsstrahlung photons. The fraction lost by this process increases sharply with electron energy and becomes the dominant process for electrons with energy over a few MeV. Bremsstrahlung production scales approximately as $Z^2$ of the absorber [see Eq. (2.11)] so its importance is greatest in detectors with high atomic number. Even though the electron itself may be fully stopped within the detector, there is a possibility that some fraction of the bremsstrahlung photons may escape without being reabsorbed. The effects on the response function are similar to those described in the previous paragraph for electron escape and are again most important when the incident gamma-ray energy is large. For both secondary electron or bremsstrahlung escape, the effects are to change the shape of the response function somewhat, but additional peaks or sharp features are not introduced.

### *3. CHARACTERISTIC X-RAY ESCAPE*

In the photoelectric absorption process, a characteristic X-ray often is emitted by the absorber atom. In the majority of cases this X-ray energy is reabsorbed near the original

interaction site. If the photoelectric absorption occurs near a surface of the detector, however, the X-ray photon may escape as shown in the sketch below.




In this event, the energy deposited in the detector is decreased by an amount equal to the X-ray photon energy. Without the X-ray escape, the original gamma ray would have been fully absorbed and the resulting pulse would have contributed to the photopeak. With escape, a new category of events is created in which an amount of energy equal to the original gamma-ray energy minus the characteristic X-ray energy is repeatedly deposited in the detector. Therefore, a new peak will appear in the response function and will be located at a distance equal to the energy of the characteristic X-ray below the photopeak. These peaks are generally labeled "X-ray escape peaks" and tend to be most prominent at low incident gamma-ray energies and for detectors whose surface-to-volume ratio is large. Examples are shown in the spectra of Figs. 10.10 and 13.7.

For gamma rays whose energies are above the *K*-shell binding energy of the absorber, most photoelectric absorptions involve these most tightly-bound electrons in the atom. The main characteristic X-ray escape peak is therefore located below the full-energy peak by an amount given by the *K*-shell binding energy. More subtle effects are also present in principle because of interactions in and transitions to the more weakly-bound electron shells, but corresponding escape peaks are usually difficult to resolve from the full-energy peak because of the much lower X-ray energies that are involved.

### *4. SECONDARY RADIATIONS CREATED NEAR THE SOURCE*

#### *a. Annihilation Radiation*

If the gamma-ray source consists of an isotope that decays by positron emission, an additional peak in the spectrum at 0.511 MeV is to be expected from the annihilation photons created when the positron is stopped. Most standard gamma-ray sources are encapsulated in a covering sufficiently thick to fully stop all the positrons, and thus they undergo annihilation in the region immediately surrounding the source. This region therefore acts as a source of 0.511 MeV annihilation radiation, which is superimposed on the gamma-ray spectrum expected from decay of the source itself. For detector geometries in which it is possible to detect both annihilation photons from a single decay simultaneously (as in a well counter), then a peak at 1.022 MeV may also be observed in the recorded spectrum.

#### *b. Bremsstrahlung*

Most commonly-available gamma-ray sources decay by beta-minus emission, and the source encapsulation is usually also thick enough to stop these beta particles. In other cases, an external absorber may be used to prevent the beta particles from reaching the detector where their energy deposition would needlessly complicate the gamma-ray spectrum. In the absorption process, however, some secondary radiation in the form of bremsstrahlung will be generated and may reach the detector and contribute to the measured spectrum. In principle, the bremsstrahlung spectrum may extend to an energy equal to the maximum beta particle energy, but significant yields are confined to energies that are

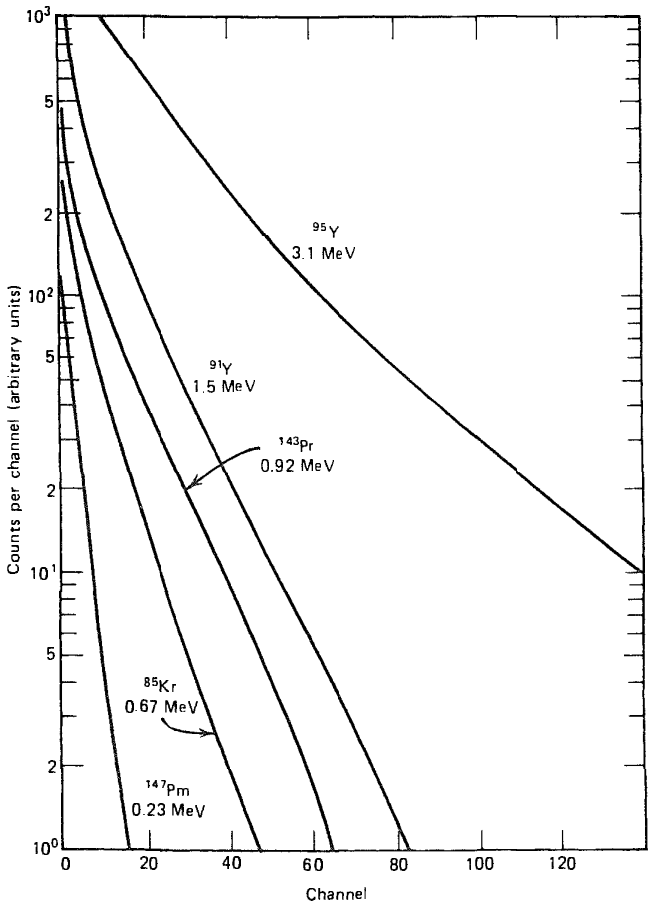



**Figure 10.5** Shape of the bremsstrahlung spectra produced by beta particles with the indicated endpoint energies. (From Heath.[5])

much lower than this value. Some examples of bremsstrahlung energy spectra are given in Fig. 10.5, which illustrates the shape of the spectrum favoring low-energy bremsstrahlung photon emission. Because these spectra are continua, they do not lead to peaks in the recorded spectra but rather can add a significant continuum on which all other features of the gamma-ray spectra are superimposed. Because the bremsstrahlung contribution cannot simply be subtracted as a background, its inclusion can lead to errors in quantitative measurements of areas under peaks in the gamma-ray spectrum. To minimize the generation of bremsstrahlung, the use of beta absorbers made from low atomic number materials, such as beryllium, is often preferred.

### *5. EFFECTS OF SURROUNDING MATERIALS*

In any practical application, a detector used for gamma-ray spectroscopy is surrounded by other materials that can have a measurable influence on its response. At a very minimum, the detector is encapsulated to provide a barrier against moisture and light or is mounted within a vacuum enclosure. To reduce natural background, most gamma-ray detectors are also operated within a shielded enclosure. The gamma-ray source itself is often part of a larger sample of material or is contained within some type of encapsulation. All these

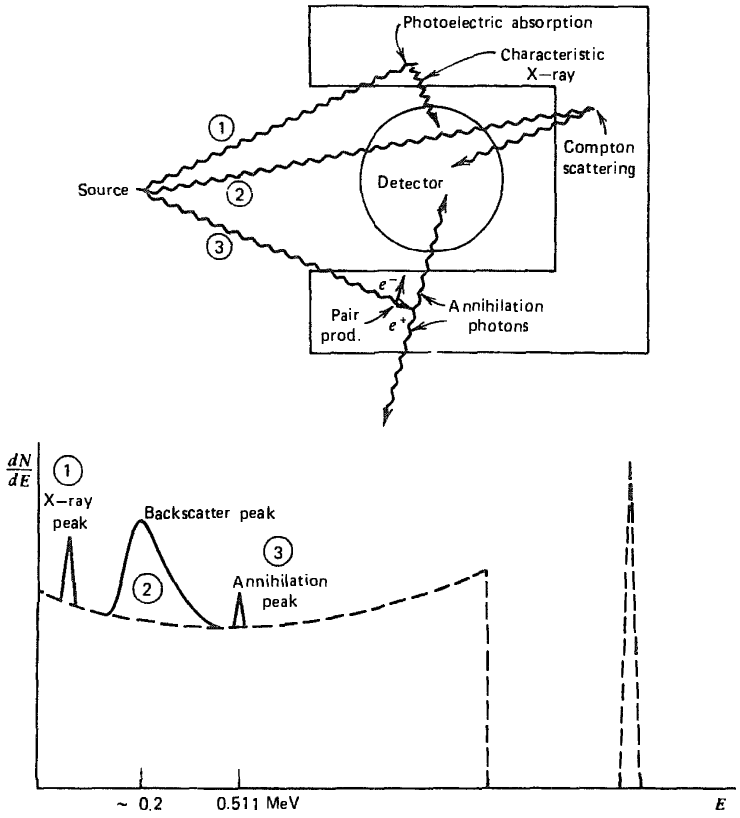



**Figure 10.6** Influence of surrounding materials on detector response. In addition to the expected spectrum (shown as a dashed line), the representative histories shown at the top lead to the indicated corresponding features in the response function.

materials are potential sources of secondary radiations that can be produced by interac tions of the primary gamma rays emitted by the source. If the secondary radiations reac the detector, they can influence the shape of the recorded spectrum to a noticeable exten Some possibilities are illustrated in Fig. 10.6.

***a. Backscattered Gamma Rays***

Pulse height spectra from gamma-ray detectors often show a peak in the vicinity c 0.2–0.25 MeV, called the *backscatter peak*. The peak is caused by gamma rays from th source that have first interacted by Compton scattering in one of the materials surround ing the detector. Figure 10.7 shows the energy dependence of these scattered gamma ray as a function of the scattering angle. From the shape of these curves, it can be seen that an scattering angle greater than about 110–120° results in scattered photons of nearly identi cal energy. Therefore, a monoenergetic source will give rise to many scattered gamma ray whose energy is near this minimum value, and a peak will appear in the recorded spectrum The energy of the backscatter peak will correspond to Eq. (10.3):

$$h\nu'\big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2}$$

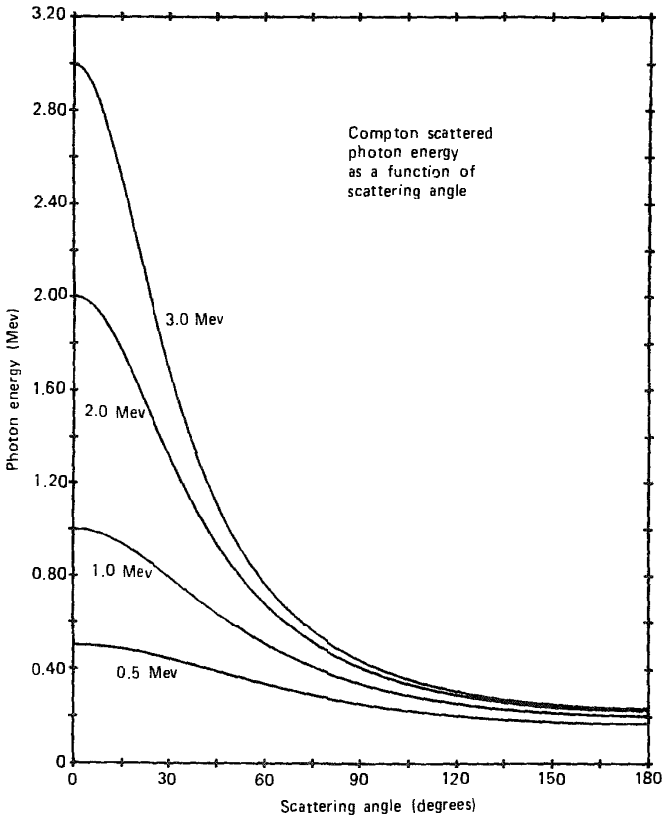



**Figure 10.7** Variation of scattered gamma-ray energy with scattering angle.

In the limit that the primary gamma-ray energy is large ($h\nu \gg m_0c^2/2$), this expression reduces to

$$h\nu'\big|_{\theta=\pi} \cong \frac{m_0c^2}{2} \tag{10.8}$$

Thus, the backscatter peak always occurs at an energy of 0.25 MeV or less.

***b. Other Secondary Radiations***

In addition to Compton scattering, other interactions of the primary gamma rays in the surrounding materials can give noticeable peaks in the recorded spectrum. For example, photoelectric absorption in the materials immediately surrounding the detector can lead to generation of a characteristic X-ray that may reach the detector. If the atomic number of the material is high, the X-ray photon will be relatively energetic and can penetrate significant thicknesses of intervening material. Therefore, high-$Z$ materials should be avoided in the immediate vicinity of the detector. On the other hand, the most effective shielding materials are those with high atomic numbers such as lead. A *graded shield* is one in which the bulk of the shield is made from high-$Z$ materials, but the inner surface is lined with a material with lower atomic number. This inner lining serves to absorb the characteristic X-ray emitted by the bulk of the shield, at the same time emitting only low-energy or weakly penetrating X-rays of its own.

If the energy of the primary gamma rays is high, pair production within high-$Z$ surrounding materials can give a significant yield of annihilation radiation. A peak can therefore appear at 0.511 MeV in the spectrum from the detection of these secondary photons. There is a danger of confusing this peak with that expected from annihilation radiation produced by radioactive sources that are positron emitters, and care must therefore be exercised in identifying the source of these annihilation photons.

## E. Summation Effects

Additional peaks caused by the coincident detection of two (or more) gamma-ray photons may also appear in the recorded pulse height spectrum. The most common situation occurs in applications involving an isotope that emits multiple cascade gamma rays in its decay, as illustrated in Fig. 10.8. If we assume that no isomeric states are involved, the lifetime of the intermediate state is generally so short that the two gamma rays are, in effect, emitted in coincidence. It is then quite possible for both gamma-ray photons from a single decay to interact and deposit all their energy within a time that is short compared with the response time of the detector or the resolving time of the following electronics. If enough of these events occur, a *sum coincidence peak* will be observable in the spectrum that occurs at a pulse height that corresponds to the sum of the two individual gamma-ray energies. A continuum of sum events will also occur at lower amplitudes due to the summation of partial energy loss interactions.

The relative number of events expected in the sum peak depends on the branching ratio of the two gamma rays, the angular correlation that may exist between them, and the solid angle subtended by the detector. A complete analysis is often quite complex, but the following simplified derivation illustrates the general approach that can be applied.

Let $\epsilon_1$ be the intrinsic peak efficiency of the detector for gamma ray ①, and let $\Omega$ be the fractional solid angle (steradians/$4\pi$) subtended by the detector. Then the full-energy peak area for gamma ray ① in the absence of summing effects is

$$N_1 = \epsilon_1 \Omega S y_1 \tag{10.9}$$

where $S$ is the number of source decays over the observation period and $y_1$ is the yield of gamma ray ① per disintegration. Applying the same definitions to gamma ray ②, we obtain

$$N_2 = \epsilon_2 \Omega S y_2 \tag{10.10}$$

The probability of simultaneous detection of both gamma rays is the product of both individual detection probabilities, multiplied by a factor $W(0°)$ to account for any angular correlation between the gamma-ray photons. $W(0°)$ is defined as the relative yield of $\gamma_2$ per

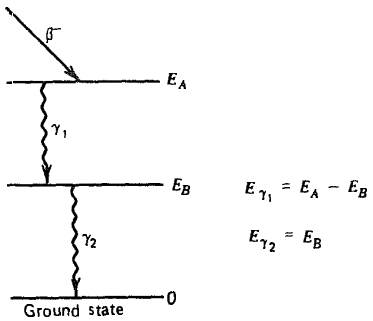



**Figure 10.8** Simplified nuclear decay scheme which can lead to summation effects in gamma spectra. Provided the intermediate state (at $E_B$) is short-lived, $\gamma_1$ and $\gamma_2$ are emitted in virtual coincidence.

unit solid angle about the 0° direction defined by the detector position, given that $\gamma_1$ is emitted in the same direction. Then the sum peak area should be

$$\begin{aligned} N_{12} &= S\,(\epsilon_1 \Omega y_1)(\epsilon_2 \Omega y_2) W(0°) \\ &= S\epsilon_1 \epsilon_2 y_1 y_2 \Omega^2 W(0°) \end{aligned} \tag{10.11}$$

The summation process not only creates the sum peak but also removes events that would otherwise fall within individual gamma-ray full-energy peaks. The remaining number of full-energy events for $\gamma_1$ is [from Eqs. (10.9) and (10.11)]

$$\begin{aligned} N_1\Big|_{\substack{\text{with} \\ \text{summation}}} &= N_1 - N_{12} \\ &= \epsilon_1 \Omega S y_1 [1 - \epsilon_2 \Omega y_2 W(0°)] \end{aligned} \tag{10.12}$$

Because a coincident event of any kind from $\gamma_2$ (not just a photopeak event) will remove a count from $N_1$, the detection efficiency $\epsilon_2$ should now be interpreted as the intrinsic *total* efficiency. For these losses to remain small, the fractional solid angle $\Omega$ is often restricted to small values to keep the second term in the above equation much smaller than the first. If the solid angle is too large, quantitative measurements based on determination of the area under full-energy peaks can be in error unless an accounting of the second term is provided.[6]

The summation process described above involves multiple radiations from the same nuclear decay event and therefore is classified as a *true coincidence* by the definitions given in Chapter 17. Another process can also lead to summed pulses due to the accidental combination of two separate events from independent decays that occur closely spaced in time. Because the time intervals separating adjacent events are randomly distributed, some will be less than the inherent resolving time of the detector or pulse-processing system. These *chance coincidences* increase rapidly with increasing counting rate and will occur even in the absence of true coincidences. A corresponding sum peak can therefore appear in spectra from isotopes that emit only a single radiation per decay. For both true coincidence and chance summing, there will also be many cases in which a second interaction involves partial rather than full energy absorption in the detector. For this category of events, the first event (assumed here to be a full-energy absorption) still is lost from the peak where it normally would be expected in the absence of summing. Now, however, the summed pulse is stored into a continuum that lies above the expected peak and it does not contribute to a sum peak in the spectrum.

Chance coincidences will occur if a second pulse arrives within the resolving time $t_r$ following a typical signal pulse. For a random pulse rate of $r_s$ and $r_s t_r \ll 1$, the rate at which coincidences occur should be the fraction of all time that lies within $t_r$ of a preceding pulse (given by $r_s t_r$) multiplied by the rate of pulse arrival ($r_s$), or

$$r_{ch} = r_s^2 t_r \tag{10.13}$$

Therefore, the accidental sum peak will have an intensity that is proportional to the square of the counting rate, whereas both the true sum peak or normal photopeaks will be linearly related to the counting rate. When multiple radiations are involved, accidental sum peaks may potentially occur at all possible combinations of any two single energies. At normal rates and typical detector solid angles, however, sum peaks are usually lost in fluctuations in the continua and background present from other energies, except at the upper energy extremes of the spectrum where such backgrounds are low.

As a practical matter, the resolving time $t_r$ is normally set by the shaping time constants of the linear amplifier used in the pulse-processing chain from the detector. The chance coincidences therefore take the form of *pulse pile-up* in the amplifier, which is further detailed in the discussions of Chapter 17.