Before discussing the different types of radiation detectors individually, we will first outline some general properties which apply to all types. Included will be some basic definitions of detector properties, such as efficiency and energy resolution, together with some general modes of operation and methods of recording data which will be helpful in categorizing detector applications.

I. SIMPLIFIED DETECTOR MODEL

We begin with a hypothetical detector which is subject to some type of irradiation. Attention will first be focused on the interaction of a single particle or quantum of radiation in the detector which might, for example, be a single alpha particle or an individual gamma ray photon. In order for the detector to respond at all, the radiation must undergo interaction through one of the mechanisms discussed in the previous chapter. As indicated by Eq. 2-3, the interaction or stopping time is very small (typically a few nanoseconds in gases or a few picoseconds in solids). In most practical situations, these times are so short that the deposition of the radiation energy can be considered instantaneous.

The net result of the radiation interaction in a wide category of detectors is the appearance of a given amount of electric charge within the detector active volume.* Our simplified detector model will thus assume that a charge $Q$ appears within the detector at time $t = 0$ due to the interaction of a single particle or quantum of radiation. Next, this charge must be collected to form the basic electrical signal. Typically, collection of the charge is accomplished

*Strictly true only for detectors such as ion chambers, proportional tubes, G-M tubes, or semiconductor diode detectors. The discussion will also be useful for detector types in which the charge is formed indirectly, as from a photomultiplier tube used with a scintillation crystal.
through the imposition of an electric field within the detector which causes the positive and negative charges created by the radiation to flow in opposite directions. The time required to fully collect the charge varies greatly from one detector to another. For example, in ion chambers the collection time can be as long as a few milliseconds, whereas in semiconductor diode detectors the time is a few nanoseconds. These times reflect both the mobility of the charge carriers within the detector active volume and the average distance which must be traveled before arrival at the collection electrodes.

We therefore begin with a model of a prototypical detector whose response to a single particle or quantum of radiation will be a current which flows for a time equal to the charge collection time. The sketch below illustrates one example for the time dependence the detector current might assume, where $t_c$ represents the charge collection time.

![Current response sketch](image)

The time integral over the duration of the current must simply be equal to $Q$, the total amount of charge generated in that specific interaction.

In any real situation, many quanta of radiation will interact over a period of time. If the irradiation rate is high, situations can arise in which current is flowing in the detector from more than one interaction at a given time. For purposes of the present discussion, we will assume that the rate is low enough so that each individual interaction gives rise to a current which is distinguishable from all others. The magnitude and duration of each current pulse may vary depending on the type of interaction, and a sketch of the instantaneous current flowing in the detector might then appear as shown in the sketch below.

![Pulse response sketch](image)

II. CURRENT AND PULSE MODES OF OPERATION

We can now introduce a fundamental distinction between two general modes of operation of radiation detectors. The first is called current mode and represents the situation in which the average dc current produced by the detector is
measured. If we were to connect a simple ammeter across the terminals of the detector, it would record the time average of each individual burst of current caused by separate radiation interactions, as shown in the sketch below.

![Diagram showing current recording by an ammeter]

For a somewhat idealized ammeter with a fixed response time $T$, the time-dependent current registered by the ammeter will be given by

$$I(t) = \frac{1}{T} \int_{t-T}^{t} i(t') dt'$$  \hspace{1cm} (3-1)$$

Because the response time is typically a fraction of a second or greater, the result is to average out many of the fluctuations in the intervals between individual radiation interactions, and to record an average current that depends only on the product of the local rate and average charge per interaction.

Detectors which are applied to radiation dosimetry are often used in current mode for reasons that will be discussed in Chapter 5. Also, radiation detectors used for nuclear reactor power monitoring are most often operated in current mode. The vast majority of applications, however, are better served by using the detector in a different way. Instead of looking at the average current over many interactions, the output is recorded for each individual quantum of radiation which happens to interact in the detector. The detector is then operated in pulse mode.

The nature of the signal pulse produced from a single event depends on the input characteristics of the circuit to which the detector is connected (usually a preamplifier). The equivalent circuit can often be represented as shown below.

![Equivalent circuit diagram for a detector]
Here $R$ represents the input resistance of the circuit, and $C$ represents the equivalent capacitance of both the detector itself and the measuring circuit. If, for example, a preamplifier is attached to the detector, then $R$ is its input resistance and $C$ is the summed capacitance of the detector, the cable used to connect the detector to the preamplifier, and the input capacitance of the preamplifier itself. In most cases the time-dependent voltage $V(t)$ across the load resistance is the fundamental signal voltage upon which pulse mode operation is based. Two separate extremes of operation can be identified which depend on the relative value of the time constant of the measuring circuit. From simple circuit analysis, this time constant is given by the product of $R$ and $C$, or $\tau = RC$.

**Case I Small $RC(\tau \ll t_c)$**

In this extreme the time constant of the external circuit is kept small compared with the charge collection time, so that the current flowing through the load resistance $R$ is essentially equal to the instantaneous value of the current flowing in the detector. The signal voltage $V(t)$ produced under these conditions has a shape nearly identical to the time

![Diagram](image)

**FIGURE 3-1.** (a) The assumed current output from a hypothetical detector. (b) The signal voltage $V(t)$ for the case of small time constant load circuit. (c) The signal voltage $V(t)$ for the case of a large time constant load circuit.
dependence of the current produced within the detector, as illustrated in Fig. 3-1b. Radiation detectors are sometimes operated under these conditions, especially when timing information is at a premium.

**Case II Large RC(τ ≫ t_c)**

It is far more common to operate detectors in the opposite extreme in which the time constant of the external circuit is much larger than the detector charge collection time. In this case, very little current will flow in the load resistance during the charge collection time and the detector current is momentarily integrated on the capacitance. Assuming the time between pulses is sufficiently large, the capacitance will then discharge through the resistance, returning the voltage across the load resistance to zero. The corresponding signal voltage \( V(t) \) is illustrated in Fig. 3-1c.

Because the latter case is by far the most common means of pulse-type operation of detectors, it is important to draw some general conclusions. First, the time required for the signal pulse to reach its maximum value is determined by the charge collection time within the detector itself. No properties of the external or load circuit influence the rise time of the pulses. On the other hand, the decay time of the pulses, or the time required to restore the signal voltage to zero, is determined only by the time constant of the load circuit. The conclusion that the leading edge is detector-dependent and the trailing edge circuit-dependent is a generality that will hold for a wide variety of radiation detectors operated under conditions in which \( RC > t_c \). A second major conclusion to note is that the amplitude of the signal pulse shown as \( V_{\text{max}} \) on Fig. 3-1c is determined simply by the ratio of the total charge \( Q \) created within the detector during one radiation interaction divided by the capacitance \( C \) of the equivalent load circuit. Because this capacitance is normally fixed, the amplitude of the signal pulse is directly proportional to the corresponding charge generated within the detector and is given by the simple expression:

\[
V_{\text{max}} = \frac{Q}{C}
\]  

(3-2)

Thus, the output of a detector operated in pulse mode normally consists of a string of individual signal pulses, each representing the results of the interaction of a single quantum of radiation within the detector. A measurement of the rate at which such pulses occur will give the corresponding rate of radiation interactions within the detector. Furthermore, the amplitude of each individual pulse reflects the amount of charge generated due to each individual interaction. We shall see that a very common analytical method will be to record the distribution of these amplitudes from which some information can often be inferred about the incident radiation. An example is that set of conditions in which the charge \( Q \) is directly proportional to the energy of the incident quantum of radiation.
Then, a recorded distribution of pulse amplitudes will reflect the corresponding distribution in energy of the incident radiation.

As shown by Eq. 3-2, the proportionality between $V_{\text{max}}$ and $Q$ holds only if the capacitance $C$ remains constant. In most detectors, the inherent capacitance is set by its size and shape, and the assumption of constancy is fully warranted. In other types (notably the semiconductor diode detector), the capacitance may change with variations in normal operating parameters. In such cases, voltage pulses of different amplitude may result from events with the same $Q$. In order to preserve the basic information carried by the magnitude of $Q$, a type of preamplifier circuit known as a charge sensitive configuration has come into widespread use. As described in Chapter 17, this type of circuit uses feedback to largely eliminate the dependence of the output amplitude on the value of $C$, and restores proportionality to the charge $Q$ even in cases in which $C$ may change.

Pulse mode operation is the more common choice for most radiation detector applications because of several inherent advantages over current mode. First, the sensitivity that is achievable is often many factors greater than when using current mode because each individual quantum of radiation can be detected as a distinct pulse. Lower limits of detectability are then normally set by background radiation levels. In current mode, the minimum detectable dc current may represent an average interaction rate in the detector which is many times greater. The second and more important advantage is that each pulse amplitude carries some information which is often a useful or even necessary part of a particular application. In current mode operation, this information on individual pulse amplitudes is lost and all interactions, regardless of amplitude, contribute to the average measured current. Because of these inherent advantages of pulse mode, the emphasis in nuclear instrumentation is largely in pulse circuits and pulse processing techniques.

III. PULSE HEIGHT SPECTRA

When operating a radiation detector in pulse mode, each individual pulse amplitude carries important information regarding the charge generated by that particular radiation interaction in the detector. If we examine a large number of such pulses, their amplitudes will not all be the same. Variations may be due either to differences in the radiation energy or to fluctuations in the inherent response of the detector to monoenergetic radiation. The pulse amplitude distribution is a fundamental property of the detector output which is routinely used to deduce information about the incident radiation or the operation of the detector itself.

The most common way of displaying pulse amplitude information is through the differential pulse height distribution. Figure 3-2a gives a hypothetical distribution for purposes of example. The abscissa is a linear pulse amplitude scale.
which runs from zero to a value larger than the amplitude of any pulse observed from the source. The ordinate is the differential number \( dN \) of pulses observed with an amplitude within the differential amplitude increment \( dH \), divided by that increment, or \( dN/dH \). The horizontal scale then has units of pulse amplitude (volts), whereas the vertical scale has units of inverse amplitude (volts\(^{-1}\)). The number of pulses whose amplitude lies between two specific values, \( H_1 \) and \( H_2 \), can be obtained by integrating the area under the distribution between those two limits, as shown by the cross-hatched area in Fig. 3-2.

Number of pulses with amplitude between \( H_1 \) and \( H_2 \) = \( \int_{H_1}^{H_2} \frac{dN}{dH} dH \) (3-3)

The total number of pulses \( N_0 \) represented by the distribution can be obtained by integrating the area under the entire spectrum

\[ N_0 = \int_{0}^{\infty} \frac{dN}{dH} dH \] (3-4)

Most users of radiation instrumentation are accustomed to looking at the shape of the differential pulse height distribution to display significant features about the source of the pulses. The maximum pulse height observed \( (H_3) \) is simply the point along the abscissa at which the distribution goes to zero. Peaks in the distribution, such as at \( H_4 \), indicate pulse amplitudes about which a large number of pulses may be found. On the other hand, valleys or low points in the spectrum, such as at pulse height \( H_3 \), indicate values of the pulse amplitude around which relatively few pulses, occur. The physical interpretation of differential pulse height spectra always involves areas under the spectrum between two given limits of pulse height. The value of the ordinate itself \( (dN/dH) \) has no physical significance until multiplied by an increment of the abscissa \( H \).

A less common way of displaying the same information about the distribution of pulse amplitudes is through the integral pulse height distribution. Figure 3-2b shows the integral distribution for the same pulse source displayed as a differential spectrum in Fig. 3-2a. The abscissa in the integral case is the same pulse height scale shown for the differential distribution. The ordinate now represents the number of pulses whose amplitude exceeds that of a given value of the abscissa \( H \). The ordinate \( N \) must always be a monotonically decreasing function of \( H \) because fewer and fewer pulses will lie above an amplitude \( H \) which is allowed to increase from zero. Because all pulses have some finite amplitude, the value of the integral spectrum at \( H = 0 \) must be the total number of pulses observed \( N_0 \). The value of the integral distribution must decrease to zero at the maximum observed pulse height \( (H_3) \).

The differential and integral distributions convey exactly the same information and one can be derived from the other. The amplitude of the differential
distribution at any pulse height $H$ is given by the absolute value of the slope of the integral distribution at the same value. Where peaks appear in the differential distribution, such as $H_4$, local maxima will occur in the slope of the integral distribution. On the other hand, where minima appear in the differential spectrum, such as $H_3$, regions of minimum slope are observed in the integral distribution. Because it is easier to display subtle differences by using the differential distribution, it has become the predominant means of displaying pulse height distribution information.

FIGURE 3-2. Examples of differential and integral pulse height spectra for an assumed source of pulses.
IV. COUNTING CURVES AND PLATEAUS

When radiation detectors are operated in pulse mode, a common situation often arises in which the pulses from the detector are fed to a counting device with a fixed discrimination level. Signal pulses must exceed a given level $H_d$ in order to be registered by the counting circuit. Sometimes it is possible to vary the level $H_d$ during the course of the measurement to provide information about the amplitude distribution of the pulses. Assuming that $H_d$ can be varied between 0 and $H_5$ in Fig. 3-2, a series of measurements can be carried out in which the number of pulses $N$ per unit time is measured as $H_d$ is changed through a sequence of values between 0 and $H_5$. This series of measurements is just an experimental determination of the integral pulse height distribution, and the measured counts should lie directly on the curve shown in Fig. 3-2b.

In setting up a nuclear counting measurement, it is often desirable to establish an operating point which will provide maximum stability over long periods of time. For example, small drifts in the value of $H_d$ could be expected in any real application, and one would like to establish conditions under which these drifts would have minimal influence on the measured counts. One such stable operating point can be achieved at a discrimination point set at the level $H_3$ in Fig. 3-2. Because the slope of the integral distribution is a minimum at that point, small changes in the discrimination level will have minimum impact on the total number of pulses recorded. In general, regions of minimum slope on the integral distribution are called *counting plateaus* and represent areas of operation in which minimum sensitivity to drifts in discrimination level are achieved. It should be noted that plateaus in the integral spectrum correspond to valleys in the differential distribution.

Plateaus in counting data can also be observed in a somewhat reverse process. For a particular radiation detector it is often possible to vary the gain or amplification provided for the charge produced in radiation interactions. This variation could be accomplished by varying the amplification factor of a linear amplifier between the detector and counting circuit, or in many cases more directly by changing the applied bias voltage to the detector itself. Figure 3-3 shows the differential pulse height distribution corresponding to three different values of voltage gain applied to the same source of pulses. Here the value of gain can be defined as the ratio of the voltage amplitude for a given event in the detector to the same amplitude before some parameter (such as amplification or detector bias) was changed. The highest voltage gain will result in the largest maximum pulse height, but in all cases the area under the differential distribution will be a constant. In the example shown in Fig. 3-3, no counts will be recorded for a gain $G = 1$ because under those conditions all pulses will be smaller than $H_d$. Pulses will begin to be recorded somewhere between a gain $G = 1$ and $G = 2$. An experiment can be carried out in which the number of pulses recorded is measured as a function of the gain applied, sometimes called the “counting curve.” Such a plot is shown also in Fig. 3-3 and in many ways
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resembles an integral pulse height distribution. We now have a mirror image of the integral distribution, however, because small values of gain will record no pulses, whereas large values will result in counting nearly all the pulses. Again, plateaus can be anticipated in this counting curve for values of the gain in which the effective discrimination pulse height $H_d$ passes through minima in the differential pulse height distribution. In the example shown in Fig. 3-3, the minimum slope in the counting curve should correspond to a gain of about three, in which case the discrimination point is near the minimum of the valley in the differential pulse height distribution.

In some types of radiation detectors, such as Geiger-Mueller tubes or scintillation counters, the gain can be conveniently varied by changing the applied bias voltage to the detector. Although the gain may not change linearly with bias

FIGURE 3-3. Example of a "counting curve" generated by varying gain under constant source conditions. The three plots at the top give the corresponding differential pulse height spectra.
voltage, the qualitative features of the counting curve can be traced by a simple measurement of the detector counting rate as a function of voltage. In order to select an operating point of maximum stability, plateaus are again sought in the counting curve that results, and the bias voltage is often selected to lie at a point of minimum slope on this counting curve. We will discuss these plateau measurements more specifically in Chapters 6 and 7 in connection with proportional counters and Geiger-Mueller detectors.

V. ENERGY RESOLUTION

In many applications of radiation detectors, the object is to measure the energy distribution of the incident radiation. These efforts are classified under the general term radiation spectroscopy, and later chapters give examples of the use of specific detectors for spectroscopy involving alpha particles, gamma rays, and other types of nuclear radiation. At this point we will discuss some general properties of detectors when applied to radiation spectroscopy and introduce some definitions that will be useful in these discussions.

One important property of a detector in radiation spectroscopy can be examined by noting its response to a monoenergetic source of that radiation. Figure 3-4 illustrates the differential pulse height distribution which might be produced by a detector under these conditions. This distribution is called the response function of the detector for the energy used in the determination. The curve labeled “good resolution” illustrates one possible distribution around an average pulse height $H_0$. The second curve, labeled “poor resolution,” illustrates the response of a detector with inferior performance. Although both distributions are centered at the same average value $H_0$, the width of the distribution in the poor resolution case is much greater. This width reflects the fact that a large amount of fluctuation was recorded from pulse to pulse even though the same energy was deposited in the detector for each event. If the amount of these fluctuations is made smaller, the width of the corresponding distribution will also become smaller and the peak will approach a sharp spike or a mathematical delta function. The ability of a given measurement to resolve fine detail in the incident energy of the radiation is obviously improved as the width of the response function (illustrated in Fig. 3-4) becomes smaller and smaller.

A formal definition of detector energy resolution is shown in Fig. 3-5. The differential pulse height distribution for a hypothetical detector is shown under the same assumption that only radiation of a single energy is being recorded. The full width at half maximum (FWHM) is illustrated on the figure and is defined as the width of the distribution at a level which is just half the maximum ordinate of the peak. The energy resolution of the detector is conventionally defined as the FWHM divided by the location of the peak centroid $H_0$. The energy resolution $R$ is thus a dimensionless fraction conventionally expressed as a percentage. Semiconductor diode detectors used in alpha spectroscopy can have an energy resolution less than 1 percent, whereas scintillation detectors
used in gamma ray spectroscopy normally show an energy resolution in the range of 5-10 percent. It should be clear that the smaller the figure for the energy resolution, the better the detector will be able to distinguish between two radiations whose energies lie near each other. An approximate rule of thumb is that one should be able to resolve two energies which are separated by more than one value of the detector FWHM.

There are a number of potential sources of fluctuation in the response of a given detector which result in imperfect energy resolution. These include any drift of the operating characteristics of the detector during the course of the measurements, sources of random noise within the detector and instrumentation system, and statistical noise arising from the discrete nature of the measured signal itself. The third source is in some sense the most important because it...
represents an irreducible minimum amount of fluctuation that will always be present in the detector signal no matter how perfect the remainder of the system is made. In a wide category of detector applications, the statistical noise represents the dominant source of fluctuation in the signal and thus sets an important limit on detector performance.

The statistical noise arises from the fact that the charge $Q$ generated within the detector by a quantum of radiation is not a continuous variable but instead represents a discrete number of charge carriers. For example, in an ion chamber the charge carriers are the ion pairs produced by the passage of the charged particle through the chamber, whereas in a scintillation counter they are the number of electrons collected from the photocathode of the photomultiplier tube. In all cases the number of carriers is discrete and subject to random fluctuation from event to event even though exactly the same amount of energy is deposited in the detector.

An estimate can be made of the amount of inherent fluctuation by assuming that the formation of each charge carrier is a Poisson process. Under this assumption, if a total number $N$ of charge carriers is generated on the average, one would expect a standard deviation of $\sqrt{N}$ to characterize the inherent statistical fluctuations in that number (see Section II of Chapter 4). If this were the only source of fluctuation in the signal, the response function, as shown in Fig. 3-5, should have a Gaussian shape, because $N$ is typically a large number. The response of many detectors is approximately linear, so that the average pulse amplitude $H_0 = KN$, where $K$ is a proportionality constant. The standard deviation $\sigma$ of the peak in the pulse height spectrum is then $\sigma = K\sqrt{N}$ and its FWHM (equal to $2.35\sigma$ for a Gaussian-shaped peak) is $2.35K\sqrt{N}$. We then would calculate a limiting resolution $R$ due only to statistical fluctuations in the number of charge carriers as

$$\frac{\text{FWHM}}{H_0} = \frac{2.35K\sqrt{N}}{KN} = \frac{2.35}{}\sqrt{N}$$

Note that this limiting value of $R$ depends only on the number of charge carriers $N$, and the resolution improves ($R$ will decrease) as $N$ is increased. From Eq. 3-5 we see that in order to achieve an energy resolution better than 1 percent, one must have $N$ greater than 55,000. An ideal detector would have as many charge carriers generated per event as possible, so that this limiting resolution be as small a percentage as possible. The great popularity of semiconductor, diode detectors stems from the fact that a very large number of charge carriers are generated in these devices per unit energy lost by the incident radiation.

Careful measurements of the energy resolution of some types of radiation detectors have shown that the achievable values for $R$ can be lower by a factor as large as 3 or 4 than the minimum predicted by the statistical arguments given.
above. These results would indicate that the processes that give rise to the formation of each individual charge carrier are not independent, and therefore the total number of charge carriers cannot be described by simple Poisson statistics. The Fano factor has been introduced in an attempt to quantify the departure of the observed statistical fluctuations in the number of charge carriers from pure Poisson statistics, and is defined as

\[ F \equiv \frac{\text{observed variance in } N}{\text{Poisson predicted variance (}= N)\} \]  

(3-6)

Because the variance is given by \( \sigma^2 \), the equivalent expression to Eq. 3-5 is now

\[ R_{\text{Statistical limit}} = \frac{2.35K\sqrt{N}}{K\sqrt{F}} = 2.35\sqrt{\frac{F}{N}} \]  

(3-7)

Although the Fano factor is substantially less than unity for semiconductor diode detectors and proportional counters, other types such as scintillation detectors appear to show a limiting resolution consistent with Poisson statistics and the Fano factor would, in these cases, be unity.

Any other source of fluctuations in the signal chain will combine with the inherent statistical fluctuations from the detector to give the overall energy resolution of the measuring system. It is sometimes possible to measure the contribution to the overall FWHM due to a single component alone. For example, if the detector is replaced by a stable pulse generator, the measured response of the remainder of the system will show a fluctuation due primarily to electronic noise. If each source of fluctuation is independent, then the overall FWHM will be the quadrature sum of the FWHM values for each individual source:

\[(\text{FWHM})_{\text{overall}}^2 = (\text{FWHM})_{\text{statistical}}^2 + (\text{FWHM})_{\text{noise}}^2 + (\text{FWHM})_{\text{drift}}^2 + \cdots\]

Each term on the right-hand side is the square of the FWHM which would be observed if all other sources of fluctuation were zero.

VI. DETECTION EFFICIENCY

All radiation detectors will, in principle, give rise to an output pulse for each quantum of radiation which interacts within its active volume. For primary charged radiation such as alpha or beta particles, interaction in the form of ionization or excitation will take place immediately upon entry of the particle into the active volume. The particle only must travel a sufficient distance so that the resulting pulse is large enough to be seen above sources of noise in order for the event to be recorded. Thus, it is often easy to arrange a situation in which a detector will see every alpha or beta particle which enters its active volume.
GENERAL PROPERTIES OF RADIATION DETECTORS

Under these conditions the detector is said to have a counting efficiency of 100 percent.

On the other hand, uncharged radiations such as gamma rays or neutrons must first undergo a significant interaction in the detector before detection is possible. Because these radiations can travel large distances between interactions, detectors are often less than 100 percent efficient. It then becomes necessary to have a precise figure for the detector efficiency in order to relate the number of pulses counted to the number of neutrons or photons incident on the detector.

It is convenient to subdivide counting efficiencies into two classes: absolute and intrinsic. Absolute efficiencies are defined as

\[ \varepsilon_{\text{abs}} = \frac{\text{no. of pulses recorded}}{\text{no. of radiation quanta emitted by source}} \]  

and are dependent not only on detector properties but also on the details of the counting geometry (primarily the distance from the source to the detector). The intrinsic efficiency is defined as:

\[ \varepsilon_{\text{int}} = \frac{\text{no. of pulses recorded}}{\text{no. of quanta incident on detector}} \]

and no longer includes the solid angle subtended by the detector as an implicit factor. The two efficiencies are simply related for isotropic sources by \( \varepsilon_{\text{int}} = \varepsilon_{\text{abs}} \times \frac{4\pi}{\Omega} \), where \( \Omega \) is the solid angle of the detector seen from the actual source position. It is much more convenient to tabulate values of intrinsic rather than absolute efficiencies because the geometric dependence is much milder for the former. The intrinsic efficiency of a detector usually depends primarily on the detector material, the radiation energy, and the physical thickness of the detector in the direction of the incident radiation. A slight dependence on distance between the source and the detector does remain, however, because the average path length of the radiation through the detector will change somewhat with this spacing.

Counting efficiencies are also categorized by the nature of the event recorded. If we accept all pulses from the detector, then it is appropriate to use total efficiencies. In this case all interactions, no matter how low in energy, are assumed to be counted. In terms of a hypothetical differential pulse height distribution shown in Fig. 3-6, the entire area under the spectrum is a measure of the number of all pulses recorded regardless of amplitude, and would be counted in defining the total efficiency. The peak efficiency, however, assumes that only those interactions which deposit the full energy of the incident radiation are counted. In a differential pulse height distribution, these full energy events are normally evidenced by a peak which appears at the highest
end of the spectrum. Events which deposit only part of the incident radiation energy then will appear farther to the left in the spectrum. The number of full energy events can be obtained by simply integrating the total area under the peak, which is shown as the cross-hatched area in Fig. 3-6. The total and peak efficiencies are related by the “peak-to-total” ratio \( r \)

\[
 r = \frac{\varepsilon_{\text{peak}}}{\varepsilon_{\text{total}}}
\]  

(3-10)

which is sometimes tabulated separately. It is often preferable from an experimental standpoint to use only peak efficiencies, because the number of full energy events is not sensitive to some perturbing effects such as scattering from surrounding objects or spurious noise. Therefore, values for the peak efficiency can be compiled and universally applied to a wide variety of laboratory conditions, whereas total efficiency values may be influenced by variable conditions.

To be complete, a detector efficiency should be specified according to both of the above criteria. For example, the most common type of efficiency tabulated for gamma ray detectors is the “intrinsic peak efficiency.”

A detector with known efficiency can be used to measure the absolute activity of a radioactive source. In the following discussion, we will assume that a detector with an intrinsic peak efficiency \( \varepsilon_{\text{ip}} \) has been used to record \( N \) events under the full energy peak in the detector spectrum. For simplicity, we will also assume that the source emits radiation isotropically, and that no attenuation takes place between the source and detector. From the definition of intrinsic peak efficiency, the number of radiation quanta \( S \) emitted by the source over the

![FIGURE 3-6. Example of the “full-energy peak” in a differential pulse height spectrum.](image)
measurement period is then given by

\[ S = N \frac{4\pi}{c_{ip} \Omega} \]  

(3-11)

where \( \Omega \) represent the solid angle (in steradians) subtended by the detector at the source position. The solid angle is defined by an integral over the detector surface which faces the source, of the form

\[ \Omega = \int \frac{\cos \alpha}{r^2} dA \]  

(3-11a)

where \( r \) represents the distance between the source and a surface element \( dA \), and \( \alpha \) is the angle between its normal and the source direction. If the volume of the source is not negligible, then a second integration must be carried out over all volume elements of the source. For the common case of a point source located along the axis of a right circular cylindrical detector, \( \Omega \) is given by:

\[ \Omega = 2\pi \left( 1 - \frac{d}{\sqrt{d^2 + a^2}} \right) \]  

(3-11b)

where the source-detector distance \( d \) and detector radius \( a \) are shown in the sketch below:

For \( d \gg a \), the solid angle reduces to the ratio of the detector plane frontal area \( A \) visible at the source to the square of the distance

\[ \Omega \approx \frac{A}{d^2} = \frac{\pi a^2}{d^2} \]  

(3-11c)

Published values for \( \Omega \) can sometimes be found for more complicated geometric arrangements involving off-axis or volumetric sources, or detectors with more complex shapes. Some specific examples of data or descriptions of algorithms useful in solid angle computations are given in References 1-8.

**VII. DEAD TIME**

In nearly all detector systems, there will be a minimum amount of time which must separate two events in order that they be recorded as two separate pulses. In some cases the limiting time may be set by processes in the detector itself,