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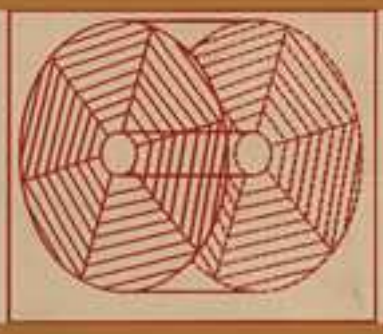
Techniques for Nuclear and Particle Physics Experiments

A How-to Approach

Second Revised Edition



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5. General Characteristics of Detectors

As an introduction to the following chapters on detectors, we will define and describe here some general characteristics common to detectors as a class of devices. For the reader without detector experience, these characteristics will probably take on more significance when examples of specific detectors are treated. He should not hesitate to continue on, therefore, and return at a later time if he has not fully understood the contents of this chapter.

While the history of nuclear and elementary particle physics has seen the development of many different types of detectors, all are based on the same fundamental principle: the transfer of part or all of the radiation energy to the detector mass where it is converted into some other form more accessible to human perception. As we have seen in Chap. 2, charged particles transfer their energy to matter through direct collisions with the atomic electrons, thus inducing excitation or ionization of the atoms. Neutral radiation, on the other hand, must first undergo some sort of reaction in the detector producing charged particles, which in turn ionize and excite the detector atoms. The form in which the converted energy appears depends on the detector and its design. The gaseous detectors discussed in the next chapter, for example, are designed to directly collect the ionization electrons to form an electric current signal, while in scintillators, both the excitation and ionization contribute to inducing molecular transitions which result in the emission of light. Similarly, in photographic emulsions, the ionization induces chemical reactions which allow a track image to be formed, and so on.

Modern detectors today are essentially electrical in nature, i.e., at some point along the way the information from the detector is transformed into electrical impulses which can be treated by electronic means. This, of course, takes advantage of the great progress that has been made in electronics and computers to provide for faster and more accurate treatment of the information. Indeed, most modern detectors cannot be exploited otherwise. When discussing "*detectors*", therefore, we will also take this to mean the electronics as well. This, of course, is not to say that only electrical detectors are used in modern experiments, and indeed there are many other types which are employed. However, if an electrical detector can be used, it is generally preferred for the reasons already mentioned. Our discussion in the following sections, therefore, will only be concerned with this type.

5.1 Sensitivity

The first consideration for a detector is its sensitivity, i.e., its capability of producing a usable signal for a given type of radiation and energy. No detector can be sensitive to all types of radiation at all energies. Instead, they are designed to be sensitive to certain types of radiation in a given energy range. Going outside this region usually results in an unusable signal or greatly decreased efficiency.

Detector sensitivity to a given type of radiation of a given energy depends on several factors:

1) the cross section for ionizing reactions in the detector
2) the detector mass
3) the inherent detector noise
4) the protective material surrounding the sensitive volume of the detector.

The cross-section and detector mass determine the probability that the incident radiation will convert part or all its energy in the detector into the form of ionization. (We assume here that the properties of the detector are such that the ionization created will be efficiently used.) As we saw in Chap. 2, charged particles are highly ionizing, so that most detectors even of low density and small volume will have some ionization produced in their sensitive volume. For neutral particles, this is much less the case, as they must first undergo an interaction which produces charged particles capable of ionizing the detector medium. These interaction cross sections are usually much smaller so that a higher mass density and volume are necessary to ensure a reasonable interaction rate, otherwise the detector becomes essentially transparent to the neutral radiation. The mass required, depends on the type of radiation and the energy range of interest. In the case of the neutrino, for example, detector masses on the order of tons are usually necessary!

Even if ionization is produced in the detector, however, a certain minimum amount is necessary in order for the signal to be usable. This lower limit is determined by the noise from the detector and the associated electronics. The noise appears as a fluctuating voltage or current at the detector output and is always present whether there is radiation or not. Obviously, the ionization signal must be larger than the average noise level in order to be usable. For a given radiation type in a given energy range, the total amount of ionization produced is determined by the sensitive volume.

A second limiting factor is the material covering the entrance window to the sensitive volume of the detector. Because of absorption, only radiation with sufficient energy to penetrate this layer can be detected. The thickness of this material thus sets a lower limit on the energy which can be detected.

5.2 Detector Response

In addition to detecting the presence of radiation, most detectors are also capable of providing some information on the energy of the radiation. This follows since the amount of ionization produced by radiation in a detector is proportional to the energy it loses in the sensitive volume. If the detector is sufficiently large such that the radiation is completely absorbed, then this ionization gives a measure of the energy of the radiation. Depending on the design of the detector, this information may or may not be preserved as the signal is processed, however.

In general, the output signal of electrical detectors is in the form of a current pulse[1]. The amount of ionization is then reflected in the electrical charge contained in this

[1] Detectors may also be operated in a continuous mode in which the signal is a continuous current or voltage varying in time with the intensity of the radiation. This can be performed by electrically integrating the number of pules over a certain period of time.

signal, i.e., the integral of the pulse with respect to time. Assuming that the shape of the pulse does not change from one event to the other, however, this integral is directly proportional to the amplitude or *pulse height* of the signal, so that this characteristic may be used instead. The relation between the radiation energy and the total charge or pulse height of the output signal is referred to as the *response* of the detector.

Ideally, of course, one would like this relation to be linear although it is not absolutely necessary. It does, however, simplify matters greatly when transforming the measured pulse height to energy. For many detectors, the response is linear or approximately so over a certain range of energies. In general, however, the response is a function of the particle type and energy, and it does not automatically follow that a detector with a linear response for one type of radiation will be linear for another. A good example is organic scintillator. As will be seen later, the response is linear for electrons down to a very low energies but is nonlinear for heavier particles such as the proton, deuteron, etc. This is due to the different reaction mechanisms which are triggered in the medium by the different particles.

5.3 Energy Resolution. The Fano Factor

For detectors which are designed to measure the energy of the incident radiation, the most important factor is the energy resolution. This is the extent to which the detector can distinguish two close lying energies. In general, the resolution can be measured by sending a monoenergetic beam of radiation into the detector and observing the resulting spectrum. Ideally, of course, one would like to see a sharp delta-function peak. In reality, this is never the case and one observes a peak structure with a finite width, usually Gaussian in shape. This width arises because of fluctuations in the number of ionizations and excitations produced.

The resolution is usually given in terms of the *full width at half maximum* of the peak (FWHM). Energies which are closer than this interval are usually considered unresolvable. This is illustrated in Fig. 5.1. If we denote this width as ΔE, then the relative resolution at the energy E is

$$\text{Resolution} = \Delta E/E\,. \tag{5.1}$$

Equation (5.1) is usually expressed in percent. A NaI detector has about a 8% or 9% resolution for γ-rays of about 1 MeV, for example, while germanium detectors have resolutions on the order of 0.1%!

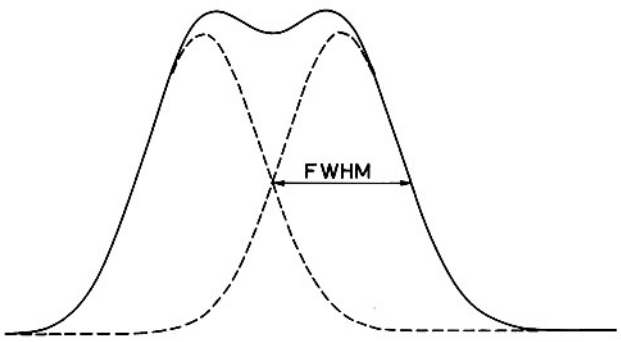

Fig. 5.1. Definition of energy resolution. Two peaks are generally considered to be resolved if they are separated by a distance greater than their full widths at half maximum (FWHM). The *solid line* shows the sum of two identical Gaussian peaks separated by just this amount

In general, the resolution is a function of the energy deposited in the detector, with the ratio (5.1) improving with higher energy. This is due to the Poisson or Poisson-like statistics of ionization and excitation. Indeed, it is found that the average energy required to produce an ionization is a fixed number, w, dependent only on the material. For a deposited energy E, therefore, one would expect on the average, $J = E/w$ ionizations. Thus as energy increases, the number of the ionization events also increases resulting in smaller relative fluctuations.

To calculate the fluctuations it is necessary to consider two cases. For a detector in which the radiation energy is not totally absorbed, for example, a thin transmission detector which just measures the dE/dx loss of a passing particle, the number of signal-producing reactions is given by a Poisson distribution. The variance is then given by

$$\sigma^2 = J\,, \tag{5.2}$$

where J is the mean number of events produced. The energy dependence of the resolution can then be seen to be

$$R = 2.35\frac{\sqrt{J}}{J} = 2.35\sqrt{\frac{w}{E}}\,, \tag{5.3}$$

where the factor 2.35 relates the standard deviation of a Gaussian to its FWHM. Thus the resolution varies inversely as the square root of the energy.

If the full energy of the radiation is absorbed as is the case for detectors used in spectroscopy experiments, the naive assumption of Poisson statistics is incorrect. And indeed, it is observed that the resolution of many such detectors is actually smaller than that calculated from Poisson statistics. The difference here is that the total energy deposited is a fixed, constant value, while in the previous case, the energy deposited can fluctuate. The total number of ionizations which can occur and the energy lost in each ionization are thus constrained by this value. Statistically, this means that the ionization events are not all independent so that Poisson statistics is not applicable. *Fano* [5.1] was the first to calculate the variance under this condition and found

$$\sigma^2 = FJ\,, \tag{5.4}$$

where J is the mean ionization produced and F is a number known as the Fano factor.

The factor F is a function of all the various fundamental processes which can lead to an energy transfer in the detector. This includes all reactions which do not lead to ionization as well, for example, phonon excitations, etc. It is thus an intrinsic constant of the detecting medium. Theoretically, F is very difficult to calculate accurately as it requires a detailed knowledge of all the reactions which can take place in the detector. From (5.4), the resolution is then given by

$$R = 2.35\frac{\sqrt{FJ}}{J} = 2.35\sqrt{\frac{Fw}{E}}\,. \tag{5.5}$$

If $F = 1$, the variance is the same as that for a Poisson distribution and (5.5) reduces to (5.3). This seems to be the case for scintillators, however, for many detectors such as semiconductors or gases, $F<1$. This, of course, greatly increases the resolution of these types of detectors.

In addition to the fluctuations in ionization, a number of external factors can affect the overall resolution of a detector. This includes effects from the associated electronics such as noise, drifts, etc. Assuming all these sources are independent and distributed as Gaussians, the total resolution E is then given by (4.64), i.e.,

$$(\Delta E)^2 = (\Delta E_{\text{det}})^2 + (\Delta E_{\text{elect}})^2 + \dots . \tag{5.6}$$

5.4 The Response Function

For the measurement of energy spectra, an important factor which must be considered is the *response function* of the detector for the type of radiation being detected. This is the spectrum of pulse heights observed from the detector when it is bombarded by a monoenergetic beam of the given radiation. Up to now, we have assumed that this response spectrum is a Gaussian peak. If we ignore the finite width for a moment, this essentially corresponds to a Dirac delta function, i.e., for a fixed incident energy the output signal has a single, fixed amplitude. Then, if the response is linear, the spectrum of pulse heights measured from the detector corresponds directly to the energy spectrum of the incident radiation. This is the ideal case. Unfortunately, a Gaussian peak response is not always realized particularly in the case of neutral radiation.

The response function of a detector at a given energy is determined by the different interactions which the radiation can undergo in the detector and its design and geometry. To take an example, consider monoenergetic charged particles, say electrons, incident on a detector thick enough to stop the particles. Assuming all the electrons lose their energy by atomic collisions, it is clear that the spectrum of pulse heights will be a Gaussian peak. In reality, however, some of the electrons will scatter out of the detector before fully depositing their energy. This produces a low energy tail. Similarly some electrons will emit bremsstrahlung photons which may escape from the detector. This again gives rise to events at a lower energy than the peak. The response function thus consists of a Gaussian peak with a low energy tail determined by the amount of scattering and bremsstrahlung energy loss. If the tail is small, however, this can still be a reasonable approximation to the ideal Gaussian response depending on the precision desired. Moreover, the response function can be improved by changing the design and geometry of the detector. A material of lower atomic number Z can be chosen, for example, to minimize backscattering and bremsstrahlung. Similarly if the detector is made to surround the source, backscattering electrons will be captured thus decreasing the escape of these particles, etc.

To see how the response function can change with radiation type, consider the same detector with gamma rays instead. As we have already mentioned, gamma rays must first convert into charged particles in order to be detected. The principal mechanisms for this are the photoelectric effect, Compton scattering and pair production. In the photoelectric effect, the gamma ray energy is transferred to the photoelectron which is then stopped in the detector. Since the energy of all the photoelectrons is the same, this results in a sharp peak in the pulse height spectrum, which is the desired Gaussian response. However, some gamma rays will also suffer Compton scatterings. As given by (2.113), the Compton electrons are distributed continuously in energy so that a distribution, similar to Fig. 2.24, also appears in the response function. This, of course,

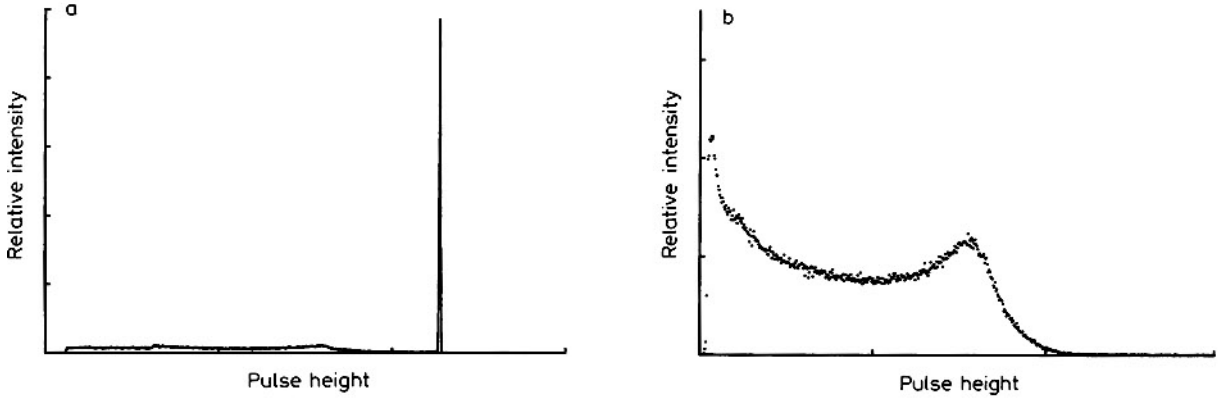

Fig. 5.2a, b. The response functions of two different detectors for 661 keV gamma rays. **(a)** shows the response of a germanium detector which has a large photoelectric cross section relative to the Compton scattering cross section at this energy. A large photopeak with a relatively small continuous Compton distribution is thus observed. **(b)** is the response of an organic scintillator detector. Since this material has a low atomic number Z, Compton scattering is predominant and only this distribution is seen in the response function

immediately destroys the ideal delta-function response. In a similar manner, those events interacting via the pair production mechanism will also contribute a structure to the function. One such total response function is sketched in Fig. 5.2. The observed pulse height spectrum, therefore, simply reflects the different interactions which occur in the detector volume. Since the relative intensity of each structure in the spectrum is determined by the relative cross sections for each interaction mechanism, the response function will also be different at different energies and for different detector media.

If the detector is now used to measure a spectrum of gamma rays, the observed pulse height distribution will be a convolution of the gamma ray spectrum and the detector response, i.e.,

$$PH(E) = \int S(E')R(E, E')\,dE' , \tag{5.7}$$

where $R(E, E')$ is the response function at the incident energy E' and $S(E')$ is the spectrum of gamma ray energies. To determine the gamma ray spectrum $S(E')$, from the measured pulse height distribution then requires knowing $R(E, E')$ in order to invert (5.7). Here, of course, we see the utility of having $R(E, E') = \delta(E' - E)$!

5.5 Response Time

A very important characteristic of a detector is its response time. This is the time which the detector takes to form the signal after the arrival of the radiation. This is crucial to the timing properties of the detector. For good timing, it is necessary for the signal to be quickly formed into a sharp pulse with a rising flank as close to vertical as possible. In this way a more precise moment in time is *marked* by the signal.

The duration of the signal is also of importance. During this period, a second event cannot be accepted either because the detector is insensitive or because the second signal will *pile up* on the first. This contributes to the *dead* time of the detector and limits the count rate at which it can be operated. The effect of dead time is discussed in Sect. 5.7.

5.6 Detector Efficiency

Two types of efficiency are generally referred to when discussing radiation detection: *absolute* efficiency and *intrinsic* detection efficiency. The absolute or total efficiency of a detector is defined as that fraction of events emitted by the source which is actually registered by the detector, i.e.,

$$\mathscr{E}_{\text{tot}} = \frac{\text{events registered}}{\text{events emitted by source}} . \tag{5.8}$$

This is a function of the detector geometry and the probability of an interaction in the detector. As an example, consider a cylindrical detector with a point source at a distance d on the detector axis as shown in Fig. 5.3. If the source emits isotropically, then, the probability of the particle being emitted at an angle θ is

$$P(\theta)\,d\Omega = d\Omega/4\pi . \tag{5.9}$$

The probability that a particle hitting the detector will have an interaction in the detector is given by (2.7). Combining the two then yields

$$d\mathscr{E}_{\text{tot}} = \left[1 - \exp\left(\frac{-x}{\lambda}\right)\right]\frac{d\Omega}{4\pi} , \tag{5.10}$$

where x is the path length in the detector and λ is the mean free path for an interaction. The total efficiency is then found by integrating (5.10) over the volume of the detector.

In many cases, however, the value of x does not vary too much over the detector or the value of λ is so small that the exponential can be considered as zero. The absolute efficiency can then be factored into two parts: the *intrinsic* efficiency, $\mathscr{E}_{\text{int}}$, and the *geometrical* efficiency or *acceptance*, $\mathscr{E}_{\text{geom}}$. The total or absolute efficiency of the detector is then given by the product

$$\mathscr{E}_{\text{tot}} \simeq \mathscr{E}_{\text{int}}\,\mathscr{E}_{\text{geom}} . \tag{5.11}$$

The intrinsic efficiency is that fraction of events actually hitting the detector which is registered, i.e.,

$$\mathscr{E}_{\text{int}} = \frac{\text{events registered}}{\text{events impinging on detector}} . \tag{5.12}$$

This probability depends on the interaction cross sections of the incident radiation on the detector medium. The intrinsic efficiency is thus a function of the type of radiation,

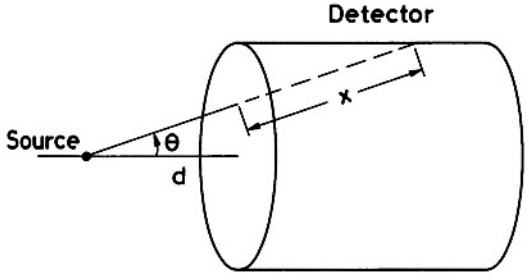

Fig. 5.3. Calculating the detection efficiency of a cylindrical detector for a point source

its energy and the detector material. For charged particles, the intrinsic efficiency is generally good for most detectors, since it is rare for a charged particle *not* to produce some sort of ionization. For heavier particles, though, quenching effects may be present in some materials which drain the ionization produced. The problem of efficiency is generally more important for neutral particles as they must first interact to create secondary charged particles. These interactions are much rarer in general, so that capturing a good fraction of the incident neutral radiation is not always assured. The dimensions of the detector become important as sufficient mass must be present in order to provide a good probability of interaction.

The geometric efficiency, in contrast, is that fraction of the source radiation which is geometrically intercepted by the detector. This, of course, depends entirely on the geometrical configuration of the detector and source. The angular distribution of the incident radiation must also be taken into account. For the cylindrical detector in Fig. 5.3, $\mathscr{E}_{\text{geom}}$ is simply the average solid angle fraction. For multidetector systems, where coincidence requirements are imposed, however, the calculations can be somewhat complicated and recourse to numerical simulation with Monte Carlo methods must be made.

5.7 Dead Time

Related to the efficiency is the *dead time* of the detector. This is the finite time required by the detector to process an event which is usually related to the duration of the pulse signal. Depending on the type, a detector may or may not remain sensitive to other events during this period. If the detector is insensitive, any further events arriving during this period are lost. If the detector retains its sensitivity, then, these events may *pile-up* on the first resulting in a distortion of the signal and subsequent loss of information from both events. These losses affect the observed count rates and distort the time distribution between the arrival of events. In particular, events from a random source will no longer have the Poissonian time distribution given by (4.60). To avoid large dead time effects, the counting rate of the detector must be kept sufficiently low such that the probability of a second event occurring during a dead time period is small. The remaining effect can then be corrected.

When calculating the effects of dead time, the entire detection system must be taken into account. Each element of a detector system has it own dead time and, indeed, it is often the electronics which account for the larger part of the effect. Moreover, when several elements have comparable dead times, combining the effects is also a difficult task and a general method does not exist for solving such problems.

As an illustration let us analyze the effect on count rate due to the dead time of a simple element in the system. Suppose the element has a dead time τ and that τ is constant for all events. Two fundamental cases are usually distinguished: *extendable* or *non-extendable* dead times. These are also referred to as the *paralyzable* or *non-paralyzable* models. In the extendable case, the arrival of a second event during a dead time period extends this period by adding on its dead time τ starting from the moment of its arrival. This is illustrated in Fig. 5.4. This occurs in elements which remain sensitive during the dead time. In principle if the event rate is sufficiently high, events can arrive such that their respective dead time periods all overlap. This produces a prolonged period during which no event is accepted. The element is thus *paralyzed*. The non-

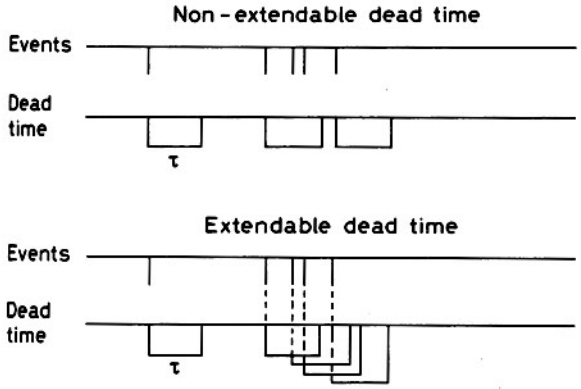

Fig. 5.4. Extendable (paralyzable) and non-extendable (non-paralyzable) dead time models

extendable case, in contrast, corresponds to a element which is insensitive during the dead time period. The arrival of a second event during this period simply goes unnoticed and after a time τ the element becomes active again.

Let us consider the non-extendable case first. Suppose m is the true count rate and the detector registers k counts in a time T. Since each detected count n engenders a dead time τ, a total dead time $k\tau$ is accumulated during the counting period T. During this dead period, a total of $mk\tau$ counts is lost. The true number of counts is therefore

$$mT = k + mk\tau . \tag{5.13}$$

Solving for m in terms of k, we find

$$m = \frac{k/T}{1-(k/T)\tau} . \tag{5.14}$$

Thus (5.14) provides us with a formula for finding the true rate m from the observed rate k/T.

The extendable case is somewhat more difficult. Here, one realizes that only those counts which arrive at time intervals greater than τ are recorded. As given by (4.60), the distribution of time intervals between events decaying at a rate m, is

$$P(t) = m\exp(-mt) . \tag{5.15}$$

The probability that $t>\tau$ is then

$$P(t>\tau) = m\int_{r}^{\infty} \exp(-mt)dt = \exp(-m\tau) . \tag{5.16}$$

The number of counts observed in a time T, therefore, is just that fraction of the mT true events whose arrival times satisfy this condition,

$$k = mT\exp(-m\tau) . \tag{5.17}$$

To find the true value, m, (5.17) must be solved numerically. Figure 5.5 shows the behavior of (5.17). Note that the function first increases, goes through a maximum at $m = 1/\tau$ and then decreases once again. This means that for a given observed rate, k/T, there are two corresponding solutions for m. Care should be taken, therefore, to distinguish between the two.

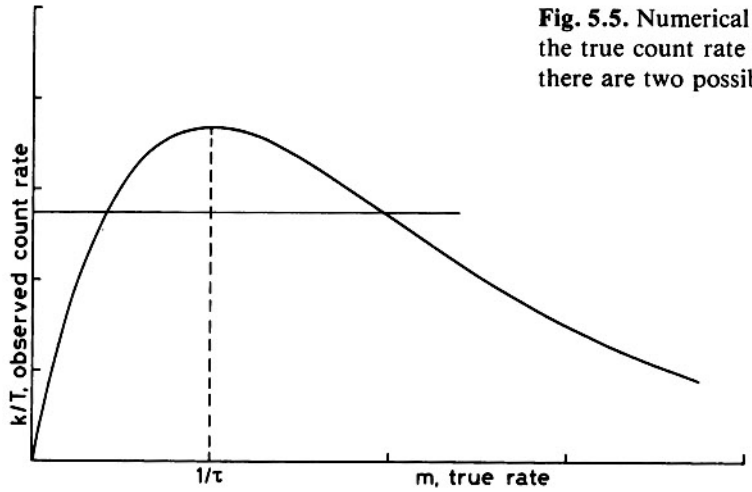

Fig. 5.5. Numerical solution of equation (5.17) to determine the true count rate in the extended dead time model. Note there are two possible solutions

The above results are generally adequate for most practical problems, however, they are only first order approximations. More rigorous treatments are given by *Foglio Parra* and *Mandelli Bettoni* [5.2] and a general discussion of dead time problems by *Muller* [5.3]. The case of a variable dead time is also treated by *Libert* [5.4].

Given the above results, the problem which often arises is to determine which class, extendable or non-extendable, is applicable. Indeed, many detectors systems are combinations of both, having some elements which are extendable and others which are not. And some may not be in either class. Moreover the dead time of the elements could be variable depending on the count rate, the pulse shapes, etc. A solution often used is to deliberately add in a blocking circuit element with a dead time larger than all other elements into the system such that the detector system can be treated by one of the fundamental models. This, of course, slows down the system but removes the uncertainty in the dead-time model. This should be done quite early in the system, however, in order to avoid pile-up problems later. See for example the *Inhibit* in Chap. 16.

5.7.1 Measuring Dead Time

The classical method of measuring dead time is the so-called *two-source* technique. In this procedure, the count rates of two different sources are measured separately and together. To illustrate the principle of the method, let us suppose n_1 and n_2 are the true count rates of the two sources and R_1, R_2 and R_{12} are the rates observed for the separate and combined sources. For simplicity also, let us assume that there is no background. In the non-extended case, we then have the relations

$$n_1 = \frac{R_1}{1-R_1\tau}, \quad n_2 = \frac{R_2}{1-R_2\tau} \quad \text{and}$$
$$n_1+n_2 = \frac{R_{12}}{1-R_{12}\tau}. \tag{5.18}$$

Eliminating the n's, we have

$$\frac{R_{12}}{1-R_{12}\tau} = \frac{R_1}{1-R_1\tau} + \frac{R_2}{1-R_2\tau} \tag{5.19}$$

which yields the solution

$$\tau = \frac{R_1 R_2 - [R_1 R_2 (R_{12} - R_1)(R_{12} - R_2)]^{1/2}}{R_1 R_2 R_{12}} . \tag{5.20}$$

While conceptually the double source method is quite simple, it is in practice, a cumbersome and time consuming method which yields results to no better than 5 – 10% [5.3]. This can be seen already in (5.20) which shows τ to be given by a difference between two numbers. From the point of view of statistical errors (see Sect. 4.6.1), of course, this is disadvantageous. Experimentally, care must also be taken to ensure the same positioning for the sources when they are measured separately and together. Even then, however, there may be scattering effects of one source on the other which may modify the combined rates, etc.

A number of other methods have been proposed, however. One technique is to replace one of the sources with a pulse generator [5.5] of frequency $f < (3\tau)^{-1}$. If R_s is the observed rate of the source alone and R_c is the observed combined rate of the source and generator, then it can be shown that the dead time in the non-extended case is

$$\tau \simeq \frac{1 - [(R_c - R_s)/f]^{1/2}}{R_s} . \tag{5.21}$$

Equation (5.21) is only approximate, but it should give results to better than 1% as long as the oscillator frequency condition stated above is met [5.3]. This method, of course, avoids the problem of maintaining a fixed source geometry but it does require an estimate of the dead time and a fast pulser to ensure the frequency condition above. A more general formula valid at all frequencies has been worked out by *Muller* [5.6] requiring, however, a long numerical calculation of a correction factor.

For an extended dead time, it can also be shown [5.3] that

$$(m + f - mf\tau) \exp(-m\tau) = R_c \tag{5.22}$$

where m is the true rate of the source. If (5.17) for the case of source alone is used, the relation

$$\frac{R_c - R_s}{f} = (1 - m\tau) \exp(-m\tau) \tag{5.23}$$

is found which can be solved for $m\tau$. If m is known then, of course, τ follows.

A very quick and accurate method which can be used for measuring the dead time of the electronics system alone is to inject pulses from two oscillators [5.3] of frequency f_1 and f_2 and to measure the mean frequency of the combined pulses, f_c. For the non-extended model, it can be shown then,

$$f_c = \begin{cases} f_1 + f_2 - 2f_1 f_2 \tau & \text{for } 0 < \tau < T/2 \\ 1/T & \text{for } T/2 < \tau < T \end{cases} \tag{5.24}$$

where T is the period of the faster oscillator, i.e., the smaller of $1/f_1$ and $1/f_2$. For the extended model, we have similarly

$$f_c = \begin{cases} f_1 + f_2 - 2f_1 f_2 \tau & \text{for } 0 < \tau < T \\ 0 & \text{for } \tau > T . \end{cases} \tag{5.25}$$

The expressions are thus identical if the frequency of the faster oscillator is chosen such that $f<(2\tau)^{-1}$; the dead time, *irrespective* of the model, is then given by

$$\tau = \frac{t_m}{2} \frac{R_1+R_2-R_c}{R_1 R_2} \tag{5.26}$$

where R_1, R_2 and R_c are the total measured counts for the two oscillators separately and combined in a measurement period t_m. If f is chosen greater then $(2\tau)^{-1}$, then a determination of the model type can be made by comparing the results to the predictions in (5.24) and (5.25).

When using this method, of course, it is important to assure that the form of the pulses are close to those of true detector signals and that the frequencies of the oscillators are stable. In such cases, the two-oscillator method can yield quick and accurate results to a precision better than 10^{-3}.