Bureau
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The Detection Estimation of Spurious Pulses

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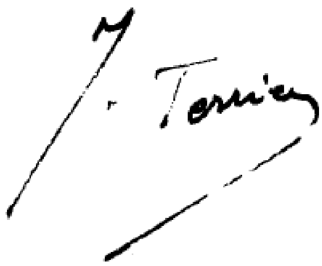
Foreword

This monograph is one of several to be published by the Bureau International des Poids et Mesures (BIPM) on behalf of the Comité Consultatif pour les Etalons de Mesure des Rayonnements lonisants (CCEMRI). The aim of this series of publications is to review various topics which are of importance for the measurement of ionizing radiation and radioactivity, in particular those techniques normally used by participants in international comparisons. It is hoped that these publications will prove to be useful reference volumes both for those who are already engaged in this field and for those who are approaching such measurements for the first time.

This volume is concerned with the problem of establishing an acceptably low upper limit to the presence of spurious pulses in radiation detectors used for the metrology of radionuclides; it was prepared for publication by P.J. Campion.



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The Detection and Estimation of Spurious Pulses

Contents

1. Introduction

This monograph is concerned with the methods available for the detection and quantitative estimation of spurious pulses, the relevance of which to the metrology of radionuclides need hardly be stressed. Spurious pulses are regarded in this context as those resulting from the operation of the detector itself in the process of recording a genuine event, the latter being defined as the passage of an ionizing particle through the sensitive volume of the detector. Such an event may give rise to a genuine pulse at the output of the amplifier. All pulses which are not genuine in this sense are spurious, but in the present paper only those spurious pulses which occur as a result of a genuine event are considered. Thus pulses due to breakdown across insulators, malfunctioning of ancillary electronic equipment or the pick-up of extraneous signals are not considered here; they are also present if there are no ionizing particles and can usually be avoided by proper arrangement of the electronic circuits or, if reproducible, be subtracted as background.

In the metrology of radionuclides two closely related situations concerning spurious pulses are often encountered. Thus an attempt is made in this monograph to distinguish between, on the one hand, the **detection** of the point of onset of spurious pulses as a function of some parameter, for example counter voltage, and, on the other hand, the **estimation**, that is the quantitative measurement of a non-negligible component of spurious pulses in a given pulse train. Since the techniques used for the two situations are basically similar, and indeed may be identical, it is not always possible to rigidly maintain such a semantic distinction. The techniques to be described are, in general, applicable to all pulse detectors but, since proportional and scintillation counters are the most commonly used instruments in 4π and 4π-coincidence counting at the present time, the techniques are illustrated by reference to these detectors. The cause of spurious pulses is, in some cases, not well understood and is a field of investigation in its own right. For this reason there is little discussion of the possible mechanisms for the production of such pulses except where the mechanism seems to be well established; a review of the time-interval distributions of spurious pulses observed in proportional counters has been recently published [1], while those obtained in scintillation detectors have been discussed by Williams and Smith [2].

The total probability for the production of a spurious pulse, or pulses, per genuine pulse is usually denoted by θ and, as so defined, is independent of the time-interval distribution of spurious pulses. However, only those spurious pulses which can be detected are of any practical significance, i.e. only those which occur beyond the end of the dead time {which is assumed to be non-extendable} and which trigger the discriminator of the recording system; thus the measurement of the spurious pulses in any practical situation yields a probability θ' which depends on the dead time {and hence on the shape of the time-interval distribution} and the discrimination level. In this monograph θ' will be tacitly equated with θ, but the difference should be noted when comparing measurements of spurious pulses using different amplifier-discriminator systems.

2. Techniques

A simple way to detect the presence of spurious pulses is the method of plotting the count rate obtained from a detector as a function of the discriminator bias at a fixed counter voltage or, more usually, as the voltage is varied for a fixed bias. The length and slope of the resultant “plateau” are frequently taken to be indicative of satisfactory operation of detectors, particularly of proportional counters. The length of a plateau of such a counter is often expressed in terms of the difference in the voltage applied to the counter at the end and at the beginning of the plateau, while the slope is described as the percentage rise per unit voltage difference. These are poor indices of merit since the length expressed in this way depends on the counter dimensions and particularly on the anode diameter. A plateau can be readily “lengthened” by increasing the anode diameter and thus reducing the change in gas gain per unit increase of counter voltage. A more satisfactory way of expressing the quality of a plateau is in terms of the ratio of the gas gain at the end of the plateau to that at the beginning. Yet, in whatever way it is characterized, the “end” of the plateau is normally taken to indicate the onset of spurious pulses. This may be a rather naive view since the slope of a plateau could also be due to spurious pulses as has been demonstrated in the case of Geiger counters. On the other hand, the slope could result from a genuine increase in efficiency of the detector. Another elementary method is the visual observation of an oscilloscope screen but, unless the spurious pulses are produced with near-constant time intervals relative to the initiating pulse, it is difficult to detect their presence when θ is less than about 0.1.

With the possible exceptions of pulses occurring in Geiger counters and some pulses in photomultipliers, spurious events in radiation detectors give rise to very small pulses compared with those due to the majority of genuine counts from radioactive sources. This, together with the fact that genuine events normally have a continuous distribution of pulse heights, makes pulse-height analysis by itself a rather unsatisfactory technique for the detection and estimation of spurious pulses, especially when one is attempting to establish the presence or the absence of a very small number of spurious events. However, there is a notable exception to this generalization.

In the case of 2π and 4π-proportional counters it has been shown [3] that the observed pulse-height spectrum due to β-particles usually consists of a broad peak having a high-energy tail and a valley on the low-energy side as shown in Figure 1. This valley arises from, on the one hand, the natural fall off in the distribution of the number of events with event size and, on the other hand, the incidence of spurious pulses(1). This fact is the basis of a technique for detecting spurious pulses which is applicable both to 4π-proportional counters and to NaI(Tl) scintillation detectors used to assay β-emitters [4]. The count rate from a single-channel pulse-height analyser, with a window set just above the threshold of the integral discriminator normally used to obtain a conventional plateau, is observed as the voltage across the counter is raised. A typical result, obtained for a ^{60}Co source in a proportional counter, is shown in Figure 2 and is compared with a conventional plateau. The minimum of this pulse-height analyser curve corresponds to the position of the valley shown in Figure 1; at this point a few spurious pulses are being detected as indicated in Figure 3. This technique is basically more suited to the detection rather than the estimation of spurious pulses, since any quantitative measurement of the ratio of spurious to genuine pulses at a given discriminator setting must be made by extrapolating the component curves, as has been done in Figure 3, and integrating over the appropriate areas; hence the uncertainties of extrapolation are introduced into the estimation.

(1) It should be noted that the dead time of the pulse-height analyser may distort the number of spurious pulses in the observed spectrum relative to that of genuine pulses (see Appendix 1, *see* p. 26).

Besides pulse height two other closely related properties of spurious pulses may be invoked in order to detect them. The first is their time relationship with genuine pulses while the second, in its simplest form, is based on the fact that most correlated events occur in pairs, i.e. a genuine pulse is followed by a spurious pulse. It is convenient to subdivide the methods based on the first property, i.e. the time relationship, into direct techniques, in which the time-interval distributions are actually recorded, and gating techniques in which the presence of spurious pulses is inferred from an analysis of the count rates in suitable intervals of time determined by electronic gating circuits. Because of the (normally) large difference in pulse heights between genuine and spurious events, the spurious-to-genuine sensitivity in most of the techniques described below can be considerably improved by using appropriate pulse-height selection, but the penalty incurred by doing so is that it is difficult to make quantitative measurements of θ. However, if it is merely desired to detect the point of onset of spurious pulses, as a function of detector voltage for example, the combination of pulse-height analysis with time analysis can be used with advantage.

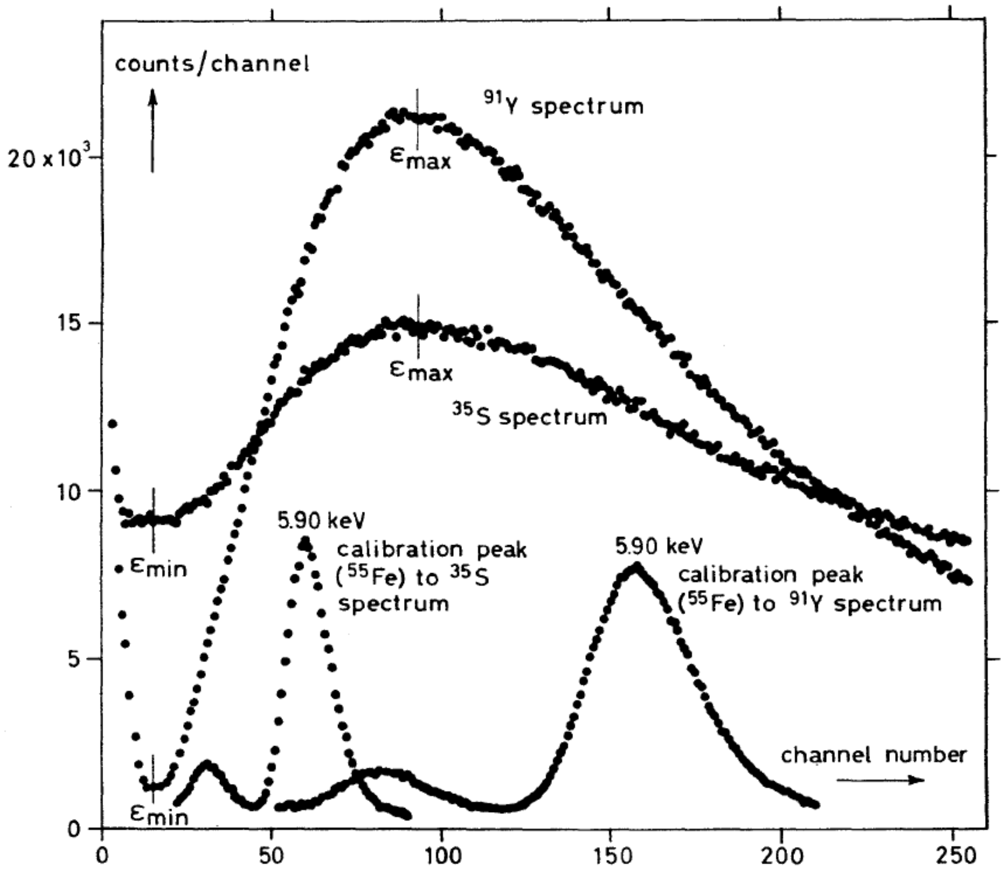


Figure 1 — Pulse height spectra for ^{91}Y and ^{35}S in a 2π proportional counter using argon plus 2% methane. (Note: the external amplification was different for the two spectra) (from [3], courtesy IAEA, Vienna).

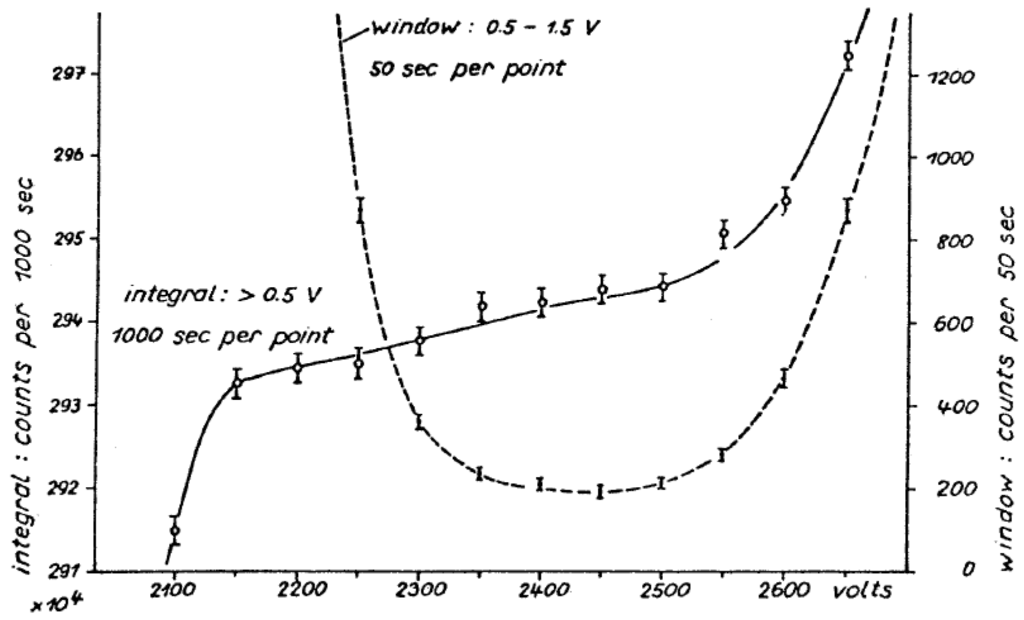


Figure 2 — A plateau plot (left-hand ordinate) together with the output from a single-channel analyser with a fixed window (right-hand ordinate) for a ^{60}Co source in a methane filled proportional counter (from [4], courtesy IAEA, Vienna).

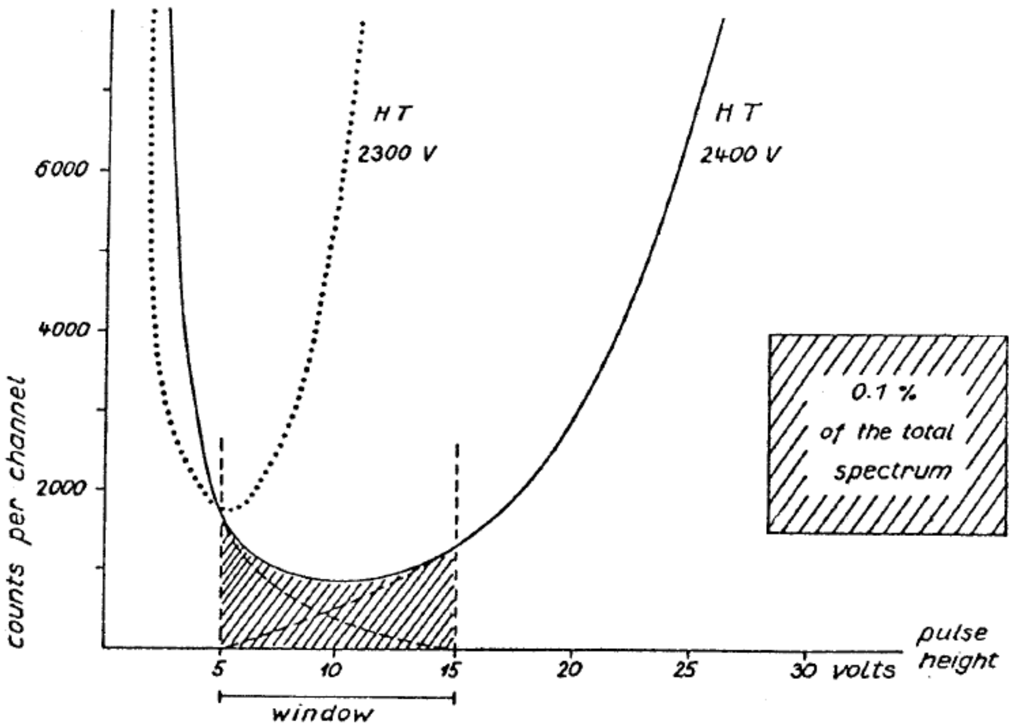


Figure 3 — First part of the pulse-height spectrum of a ^{137}Cs source in a 4π proportional counter (from [4], courtesy IAEA, Vienna).

2.1. Direct techniques

In the original method of delayed coincidences [5] one input of a coincidence circuit is connected directly to a pulse train from a single detector-amplifier system while the other input is connected to the same pulse train through a variable de lay. This requires very simple electronic equipment but is time consuming in operation and hence the statistical precision that can be achieved is limited. The method can be made more rapid by the use of a multichannel analyser in the time mode [6], [7]. In this technique a suitable pulse from the amplifier-discriminator system is used to start the {internal} clock of the multichannel analyser and all subsequent pulses are recorded in channels whose addresses are proportional to the time e lapsed from the start pulse. Thus θ is given by the number of correlated pulses divided by the number of start pulses. The first number is obtained from the total number of pulses recorded in the relevant channels less the number of genuine pulses which may be estimated from the (statistically) flat distribution beyond the end of the time-interval distribution of spurious pulses. A correction to this procedure may be necessary, depending on circumstances, to allow for the time interval between adjacent channels, the so-called "switching time". Some multichannel analysers are completely insensitive during this time while others allow one, and only one, pulse to be stored in this period; it is then recorded in the next channel. It is thus necessary to know the switching time interval and how the analyser functions. Another correction may be necessary to the second number (i.e. thd number of start pulses) to take account of those time sweeps started by spurious pulses (see Appendix 1, see p. 26).

The chief disadvantage of the time-mode analyser technique is that most commercially available multichannel analysers have a channel dwell time plus switching time of the order of 10µs or more, and hence the method is unsatisfactory for investigating time intervals of less than a few tens of microseconds. For such situations a time-to-amplitude converter (TAC) may be used together with a multichannel analyser in the pulse-height mode. In order to observe time-interval distributions of pulses from a single detector, it is necessary to feed the same pulse train to both the "start" and "stop" inputs of the TAC. Hence, in order to avoid the unit starting and stopping on the **same** pulse, the start pulse must be delayed; the necessary delay can be found by experiment and is normally less than a microsecond. Alternatively, a suitable gating system can be arranged. It must be noted that the TAC system is inherently different from the previous technique in that random pulses produce an exponential time-interval distribution because only the first pulse (after a start pulse) is registered, while the time-mode analyser technique yields a statistically uniform distribution, neglecting dead-time effects [8]. However, for a sufficiently low count rate, the corresponding exponential function can be regarded as flat over a limited time range. A correction to allow for the distortion of the observed time-interval distribution of both Poisson and correlated events, when a time-to-amplitude converter is used at high rates of data collection, has been described by Coates [9], [10]. An extension of this technique in which, by means of a second measurement involving a pulse generator, the corrected time-interval distribution of the correlated pulses only may be obtained, has been proposed by Houtermans [11]. The theory, of this technique, as outlined by Houtermans and modified by Smith [12], is given in Appendix 2. However, it should be noted that if two or more spurious pulses arise from a single event then, neglecting genuine pulses, the TAC system will record only the first spurious pulse and no information can be obtained about the time-interval distribution of the subsequent spurious pulses without further experimentation; this is true even for the situation where the overall value of θ is considerably less than unity.

Direct techniques can be used for both detection and estimation but, as mentioned above, the sensitivity for the former operation can be enhanced under certain circumstances by the use of pulse-height selection. For example, by making use of the fact that spurious pulses in proportional counters are normally much smaller than most pulses due to genuine events, a pulse-height selector in the "stop" channel will considerably improve the spurious-to-genuine sensitivity. Alternatively, or additionally, a pulse-height selector in the start channel will enable time-interval distributions of spurious pulses following genuine pulses of different heights to be compared.

2.2. Gating techniques

Gating techniques give no direct information regarding the shape of the time-interval distribution but serve to quantify the presence or the absence of spurious pulses from detectors for which the distribution has been assumed or established by the direct techniques described above. There are at least three variants of this general method which, for convenience, will be referred to as gating techniques 1 to 3 in what follows.

2.2.1. Subtraction technique

A simple gating technique [13] consists of counting only those pulses which occur in an interval of time following a genuine pulse, the electronic circuits being so arranged that the genuine pulse is not counted within the gate. The number of counts in such gating intervals may· be measured as a function of the voltage across the detector. Since at the centres of most plateaux of proportional counters, for example, the probability of spurious counts occurring is very small (but see below), the gated count taken on a plateau will be due to the random events from the radioactive source, but as soon as the counter voltage is increased to the point where spurious counts occur, the gated count will increase. A typical example of the use of this method as applied to a proportional counter is given in Figure 4 where the gated count is compared with a conventional plateau plot, using a gating interval of 25µs. A simple calculation shows that the method can be several orders of magnitude more sensitive in detecting the point of onset of spurious pulses compared with the normal plateau plot. It will be seen that this method is the time analogue of the pulse-height technique of Houtermans et al. [4] described above. A combination of the two methods, in which only those pulses that fall into both the time interval and the pulse-height interval are recorded, would undoubtedly make a powerful technique for the detection of spurious pulses.

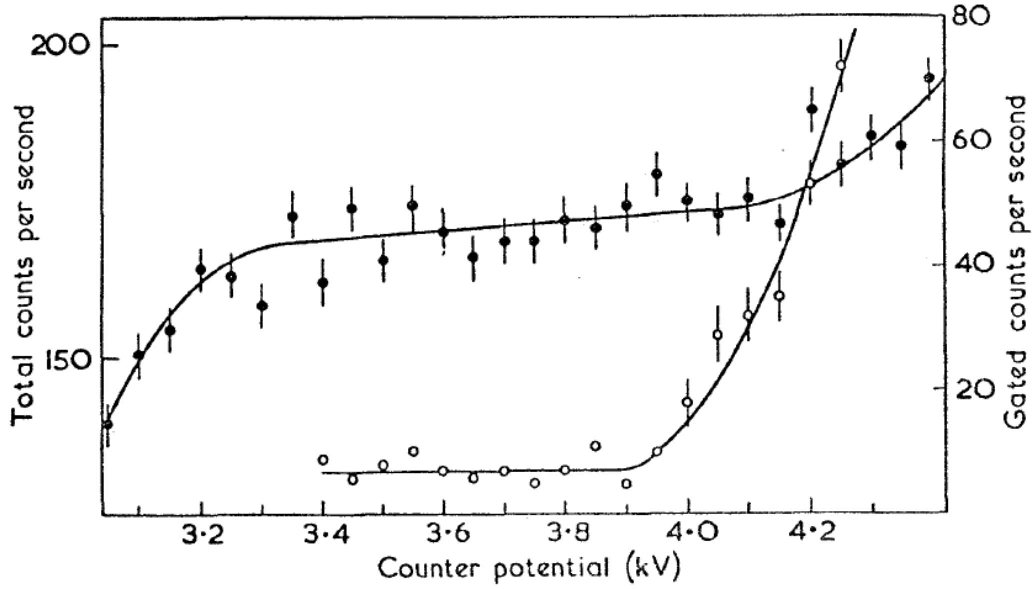


Figure 4 — A plateau plot {solid circles, left-hand ordinate} and the gated counts as described in the text (open circles, right-hand ordinate) (from [13], courtesy Institute of Physics, London).

As described above the method compares the number of counts in a gating interval obtained when the detector voltage is set just beyond the plateau with the number obtained when the voltage is set just on the plateau and hence is particularly useful for establishing the "end" of a plateau in a proportional counter. It is not necessary to know the exact length of the gating interval, the only requirement being that it should remain constant. However, instead of observing the increase in gated counts as the voltage is raised, the component of the gated counts due to genuine pulses can be calculated and subtracted from the observed gated counts to yield the spurious events. Thus

$$\theta = (n_g - \langle n_g \rangle)/n_o,$$

where n_g is the total number of gated counts recorded in a counting interval T, using a gate of length τ (which must be longer than the maximum time interval τ_s between a genuine pulse and its associated spurious pulse(s)). The expected number of counts due to random events is $\langle n_g \rangle$ and n_o is the total number of times the gate opens in the time interval T. Further, let n be the total number of genuine counts in this interval. If τ_D is the minimum time between pulses which can actuate the gate, then, assuming that all such pulses are due to genuine events,

$$\langle n_g \rangle = n_o^2 \tau / [T(1 - n_o \tau_D / T)].$$

For the case that $\tau_D = \tau$,

$$\langle n_g \rangle = n_o^2 \tau / [T(1 - n_o \tau / T)];$$

but for the latter situation

$$n_g + n_o = n(1 + \theta)$$

and

$$\langle n_g \rangle = n_o n \tau / T = n_o (n_g + n_o) \tau / [T(1 + \theta)].$$

Equating these two estimates for $\langle n_g \rangle$ gives

$$\theta = n_g/n_o - \tau(n_g + n_o)/T.$$

The assumption that n_o includes only genuine events is discussed in Appendix 1 and is valid if $n\tau_s\theta/T$ is small compared with unity. Thus the method can be used for the quantitative estimation of θ whether or not the detector gives rise to a plateau. For both techniques it is essential that the gate width is sufficient to include all the spurious pulses, although for **detection** a better spurious-to-genuine sensitivity may sometimes be obtained by selecting a gating interval which excludes some spurious pulses. In certain circumstances (e. g. for some proportional counters filled with argon-methane, where most spurious pulses fall in a peak several hundred microseconds after the initiating pulse) it is advantageous to use a delayed gating interval.

A variation of this method is to record the pulses from a detector-amplifier- discriminator system in two scalers, one of which has an appreciably longer dead time than that in the other channel. Thus, for low count rates, the difference in the accumulated counts in the two scalers will be the number of counts that would have been recorded in a gating interval of length equal to the difference in the two dead times.

2.2.2. Correlation technique

A further gating technique involves the principle of correlation counting [14] in which any departure from a strictly Poisson distribution of events, due to the presence of time-correlated spurious counts, can be detected by a statistical analysis of the counts recorded in gating intervals taken at random with respect to the pulse train. If measurements are made for a large number n_o of counting intervals each of length τ, and if p_i genuine pulses and d_i spurious pulses occur in the ith interval, then the mean number of observed counts per interval will be

$$m = \frac{n_g}{n_o} = \frac{1}{n_o}\sum_{i=1}^{n_o}\left(p_i + d_i\right) = \overline{p} + \overline{d} = \overline{p}\,(1+\theta).$$

Separating those genuine pulses which do not have associated pulses in the same interval from those which do, gives

$$p_i = x_i + c_i,$$

$$d_i = y_i + c_i,$$

where x_i and y_i are uncorrelated pulses, and c_i is the number of correlated pairs of pulses[(1)]. Hence the number of pulses in this interval can be written as $x_i + y_i + 2c_i$. The expectation value of the variance v on the number of counts per interval, for n_o large, is

[(1)] The numbers x_i and y_i are only strictly uncorrelated in the absence of dead times.

$$E[v] = v = E\left[\left(x_i + y_i + 2c_i\right)^2\right] - \left\{E\left[x_i + y_i + 2c_i\right]\right\}^2$$

$$= E\left[\left(x_i + y_i\right)^2\right] - \left\{E\left[x_i + y_i\right]\right\}^2 + 4E\left[c_i^2\right] - 4\left\{E\left[c_i\right]\right\}^2$$

$$= m + 2\overline{c},$$

if x_i, x_i and c_i are Poisson distributed.

Here $\overline{c}$ represents the mean number of genuine events producing spurious pulses in the same interval, and it may be expressed

$$\overline{c} = \overline{p}\theta f(\lambda, \tau),$$

where λ is some characteristic time constant. As $\lambda\tau$ becomes very large, $f(\lambda, \tau)$ tends to unity and

$$\bar{c} = \frac{1}{2}(v - m) = \bar{p}\theta = m\theta/(1+\theta);$$

thus

$$\theta = \frac{v-m}{3m-v}.$$

Although the method requires rather sophisticated electronics, it has applications outside the investigation of spurious pulses (for example, in the activity measurement of parent-daughter radionuclides) and hence, for laboratories concerned with radionuclide metrology, the equipment may be available. However, the method is sensitive to dead-time effects and to any extraneous fluctuations in the count rate which affect the observed variance and, further, its practical application is limited to those situations in which no more than one spurious pulse is associated with a genuine pulse [14].

2.2.3. Pulsed source technique

A powerful variant of the general gating technique is to use a pulsed source of radiation instead of a radioactive source to actuate the detector. The radiation pulse can be provided by a suitable accelerator, but a much simpler method is to actuate the detector by means of a discharge lamp. A small spark discharge in air will produce sufficient ultra-violet radiation to extract up to several hundred photoelectrons from the cathode of a proportional counter provided that an appropriately transparent window can be furnished. The spark is, of course, more than sufficient to actuate the phototube of a scintillation detector. However, although most spurious pulses appear to be generated in the phototube, a pulsed accelerator would test both scintillator and phototube. In its simplest form the method would involve the recording of the number of pulses produced by the accelerator or discharge lamp and comparing this with the number of recorded events from the detector suitably corrected for background due to cosmic rays, etc. Any excess of the latter number over the former would represent spurious pulses which were generated in the detector. While pulsed discharge lamps have been used to examine the shapes of time-interval distributions of spurious pulses (principally in phototubes), the application of this technique on a quantitative basis has not been reported, as far as we know. In the case of the discharge lamp the difficulty lies in demonstrating that a spark has no inherent spurious radiation at the single-photon level. However, in principle, the method is by far the most sensitive technique for detecting the presence of spurious pulses (see below) and, moreover, the sensitivity is less dependent on the time scale on which spurious pulses are produced than in the other methods. Solid state gallium arsenide emitters are reputedly free from inherent after-pulses and are suitable for testing phototube systems, but it is doubtful whether the wavelength of the radiation emitted from such devices is sufficiently short to extract electrons from a proportional counter cathode unless the latter were to be specially sensitized.

2.3. Modulo counting technique

A recent technique for the detection of spurious pulses is based on the fact that most correlated events occur in pairs, i.e. a genuine pulse is followed by a spurious pulse [15], [16]. Therefore, the total number n of events observed in a given counting interval τ can always be decomposed into pairs and single pulses; thus

$$n = 2n_{\text{pair}} + n_{\text{sing}}.$$

As the quality of n being even or odd depends exclusively on n_{sing}, any measuring method based on "modulo two" counting will only "see" the unpaired events, permitting the statistical separation of them from the pulses arriving in pairs. Both n_{pair} and n_{sing} always form Poisson processes (with mean rates N_{pair} and N_{sing}, respectively), provided this was the case for the series of original (parent) events. In general, the count rates depend on the distribution of the parent-daughter time intervals. If this is assumed to be exponential with mean λ^{-1}, it is found that

$$N_{\text{pair}} = N\varepsilon_p\varepsilon_d\theta\left[1 - \frac{1}{\lambda\tau}\ (1 - e^{-\lambda\tau})\right]$$

and

$$N_{\text{sing}} = N\left\{\varepsilon_p + \varepsilon_d\theta - 2\varepsilon_p\varepsilon_d\theta\left[1 - \frac{1}{\lambda\tau}\ (1 - e^{-\lambda\tau})\right]\right\}.$$

Here ε_p (ε_d) is the detection efficiency for a parent (daughter) pulse, and θ denotes the probability of a spurious pulse being generated.

However, if $\lambda\tau > > 1$, i.e. for sufficiently long counting intervals, the exact form of the parent-daughter time-interval distribution is irrelevant since the rates then approach the limiting values

$$N_{\text{pair}} = N\varepsilon_p\varepsilon_d\theta$$

and

$$N_{\text{sing}} = N\left(\varepsilon_p + \varepsilon_d\theta - 2\varepsilon_p\varepsilon_d\theta\right).$$

A convenient way for determining experimentally the probability for n being even or odd as a function of τ consists in using a correlator of the type first applied by Landaud and Mabboux [17] for measuring life-times. As the parity of n does not depend on the number of pairs, such a measurement yields directly N_{sing}, and for a Poisson distribution:

$$\text{Prob}\left(n\ \text{even}\right) = \frac{1}{2}\left[1 + \exp\left(-2N_{\text{sing}}\tau\right)\right].$$

On the other hand, a simple direct counting of the total pulse train gives

$$N_{\text{tot}} = N\left(\varepsilon_p + \varepsilon_d\theta\right) = N_{\text{sing}} + 2N_{\text{pair}}.$$

Therefore, any significant difference between N_{tot} and N_{sing} as deduced from the correlation measurement allows one to determine N_{pair}, i.e. the spurious pulse count rate.

The feasibility of this new method has been shown by various checks with artificial pulse trains [8]. It can be seen from Figure 5 how the presence of spurious pulses modifies the logarithmic plot of the correlation function $R(\tau)$, which is here defined as

$$R(\tau) = \text{Prob}\,(n\ \text{even}) - \text{Prob}\,(n\ \text{odd}),$$

giving

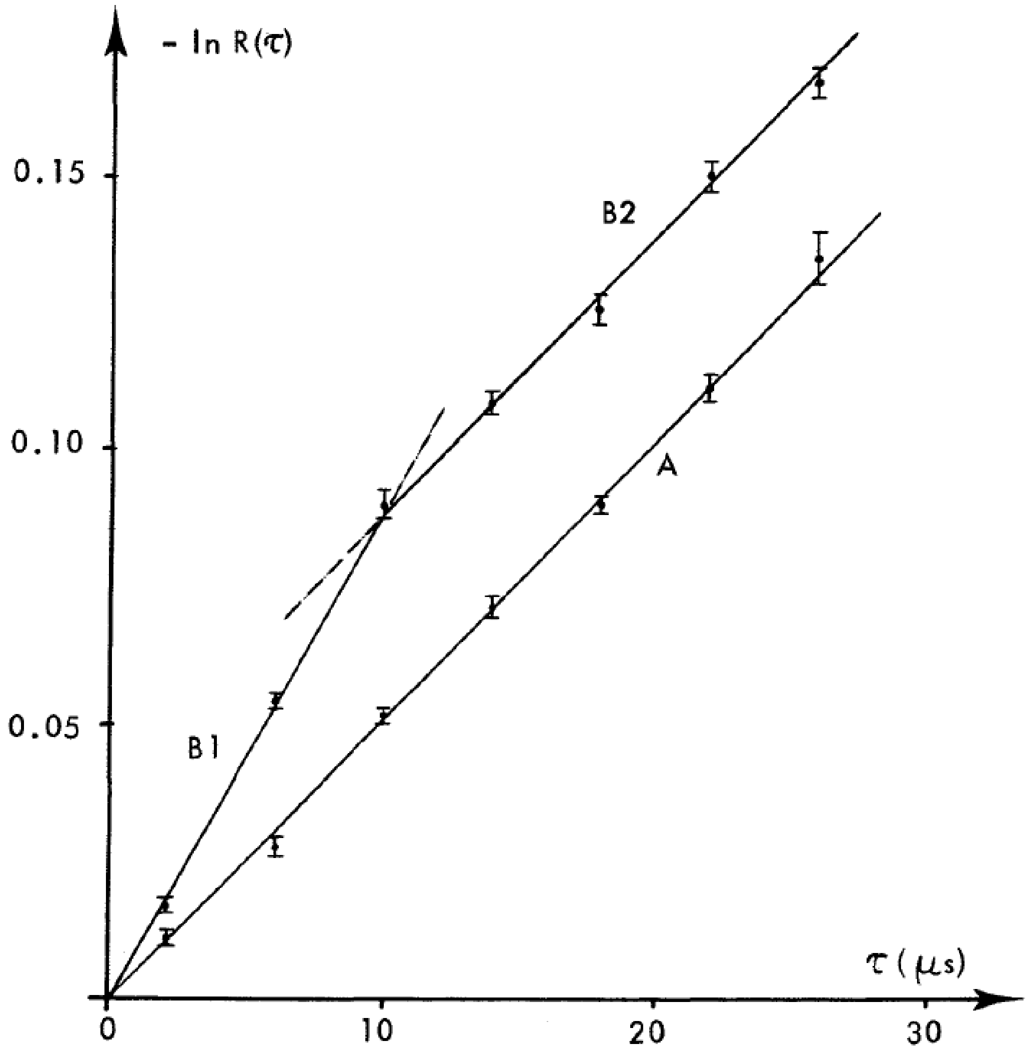
$$R(\tau) = \begin{cases} \exp\left[-2N_{\text{tot}}\tau\right] & \text{for } \tau < < \lambda^{-1} \\ \exp\left[-2\left(N_{\text{tot}} - 2N_{\text{pair}}\tau\right)\right] & ''\ \tau > > \lambda^{-1}. \end{cases}$$

In particular, for a fixed delay between parent and daughter pulses, this change in the exponent occurs suddenly at $\tau = \lambda^{-1}$. The experiments suggest that even for a ratio $N_{\mathrm{pair}}/N_{\mathrm{tot}}$ as low as 0.005 the presence of spurious pulses can still be readily established.

It is also possible to generalize this approach to multiple spurious pulses [18], but for this and for all further details the references indicated should be consulted.

2.4. Comparison of techniques

In order to compare the sensitivities of the gating methods 1, 2 and 3 and the modulo counting technique outlined above, the variance on the estimate of θ for each technique is given in Table 1 for a counting time T and a genuine pulse rate N. These variances are all to some extent approximate since implicit in their calculation is the assumption that spurious pulses obey Poisson statistics. Nevertheless, they give a useful guide for comparison purposes. In Table 1 two further approximations are given for the variance depending on whether θ is large or small compared to $N\tau$, or its equivalent in the case of method 3. The variance estimate for the modulo counting technique is taken from [16]. The requirement which is often encountered in radionuclide metrology is to establish the presence or absence of a very small θ, i.e. $\theta << N\tau$.



The theoretical curves given for comparison are
A - without pairs:
$-\ln R = 2N_{\text{sing}}\tau$
B - with pairs:
$-\ln R = \begin{cases} 2N_{\text{tot}}\tau \\ 2N_{\text{tot}}\tau - 4N_{\text{pair}}\,(\tau - \tau_o \end{cases}$
(from [8], *see* p. 29).

Figure 5 — Measurement of the correlation function $R(\tau)$, for the approximate parameters $N_{\text{sing}} = 2500\text{s}^{-1}$, $N_{\text{pair}} = 0$ or 900s^{-1} and $\lambda^{-1} \equiv \tau_o = 10\mu\text{s}$.

For method 1 two expressions are given for the variance on θ corresponding to the two techniques for handling the data. In calculating the variance for the first technique (which, as pointed out above, is perhaps more useful for determining the "end" of a plateau rather than measuring θ quantitatively) it is assumed that the counting time is divided between two readings as opposed to one reading for the second technique. In practice, of course, a number of points would be taken along the plateau as shown in Figure 4.

Table 1. A comparison of methods for measuring θ, the probability for producing a spurious pulse

Method	Variance on θ	Variance on θ for $\theta << N\tau$ or equivalent	Variance on θ for $\theta >> N\tau$ or equivalent	Comments
Direct technique	$2\,(2N\tau + \theta)/NT$	$4\tau/T$	$2\theta/NT$	Minimum of two readings required. Calculation assumes total time is T [a].

(Plateau technique)				
Gating techniques				
1. Subtraction technique	$(N\tau+\theta)/NT$	τ/T	θ/NT	τ must be known. Calculation assumes $\tau_D=\tau$ [(a)].
2. Correlation technique	$(N\tau+2\theta)/NT$	τ/T	$2\theta/NT$	Unnecessary to know τ, but it must be constant. Application to multiple spurious pulses requires knowledge of number distribution.
3. Pulsed source technique	$\frac{\left[N_b^{1/2}+(N_s\theta+N_b)^{1/2}\right]^2}{N_s^2T}$	$4N_b/N_s^2T$ $(\theta<<N_b/N_s)$	θ/N_sT $(\theta<<N_b/N_s)$	N_s is accelerator/spark rate and N_b background rate. Calculation assumes optimum division of total time T between background and source plus background measurements.
Modulo counting technique		$2/NT$		Calculation assumes absence of multiple spurious pulses. $N\tau$ should be in the range 0.1 to 1.0; therefore the method is not applicable to the case $\theta>>N\tau$. For details see [16].

(a) Valid for multiple spurious pulses

For small θ values, method 3 (pulsed source technique) is the most sensitive since the effect of the random nature of the pulses used in the other methods has been removed. However, considering methods 1 (subtraction technique) and 2 {correlation technique} alone, it is seen that the variances are comparable, there being no difference for the case that $\theta<<N\tau$, while for $\theta>>N\tau$ the variance of method 1 is a factor of 2 smaller. The variance of both the subtraction and correlation techniques is somewhat smaller than that of the modulo counting technique because of the restriction on the value $N\tau$ in the latter method [16].

3. Results

3.1. Proportional counters

Since the subject of time-interval distributions obtained in proportional counters has been reviewed recently [1], only a very brief summary will be given here. The review has drawn attention to the fact that there is a wide variation in the shapes of the time-interval distributions as between one counting gas and another, and, for a given gas, as a function of pressure and also, in some cases, anode diameter. Further, only two features of these distributions can be related with any certainty to physical phenomena known to create free electrons. The first of these is the cathode photoelectric process; it is of little practical significance since the electronically imposed dead time is normally sufficient to mask any spurious pulses due to this effect. However, such pulses may be encountered in situations where the electron transit time is considerable as, for example, in large high-pressure proportional counters. The second phenomenon is the ion-cathode effect; again this is not observed very often, due, in this case, to the fact that there is, apparently, a relatively low probability associated with this phenomenon. Thus the majority of spurious pulses are produced by as yet unidentified processes.

Apart from the photoelectric effect in cylindrical counters, the pulse heights of spurious pulses correspond to those of single electrons and become apparent towards the end of a plateau when the latter is obtained for a typical β-emitter. Hence the few measurements that have been made at the centres of plateau show no evidence for spurious pulses. However, the generalization of this statement to all plateaux should be made with a certain amount of caution for the following reasons. Firstly, the “centre” of a plateau is not a well defined point. Secondly, the length of a plateau region is dependent to some extent on the energy of the β-radiation. Starting with the count-rate characteristic due to a single electron, the “plateau” will lengthen as the number of primary electrons increases, i.e. as the energy of the incident ~-particles increases, until their energy is such that most tracks cross the counter. Any further increase in the β-particle energy will have little effect on the length of the plateau. Thus it will depend on how close the “centre” of the plateau is to the point at which single electrons can be detected as to whether significant numbers of spurious pulses will be recorded. In this respect the response of the proportional counter to single electrons should be considered. The pulse-height spectrum for single electrons varies between an exponential for low gas gains and a distribution having a more or less pronounced peak for high gas gains. The shape of single-electron spectra varies considerably with experimental conditions (see, for example, the recent review by Genz [19] and Figure 6 compares the exponential distribution

$$f_e(E) = \frac{1}{m} e^{-E/m}$$

with a strongly peaked Pólya-type distribution

$$f_p(E) = \frac{4E}{m^2} e^{-2E/m},$$

where m is the mean of the distribution in both cases. In practice most single-electron spectra will lie somewhere between these two distributions.

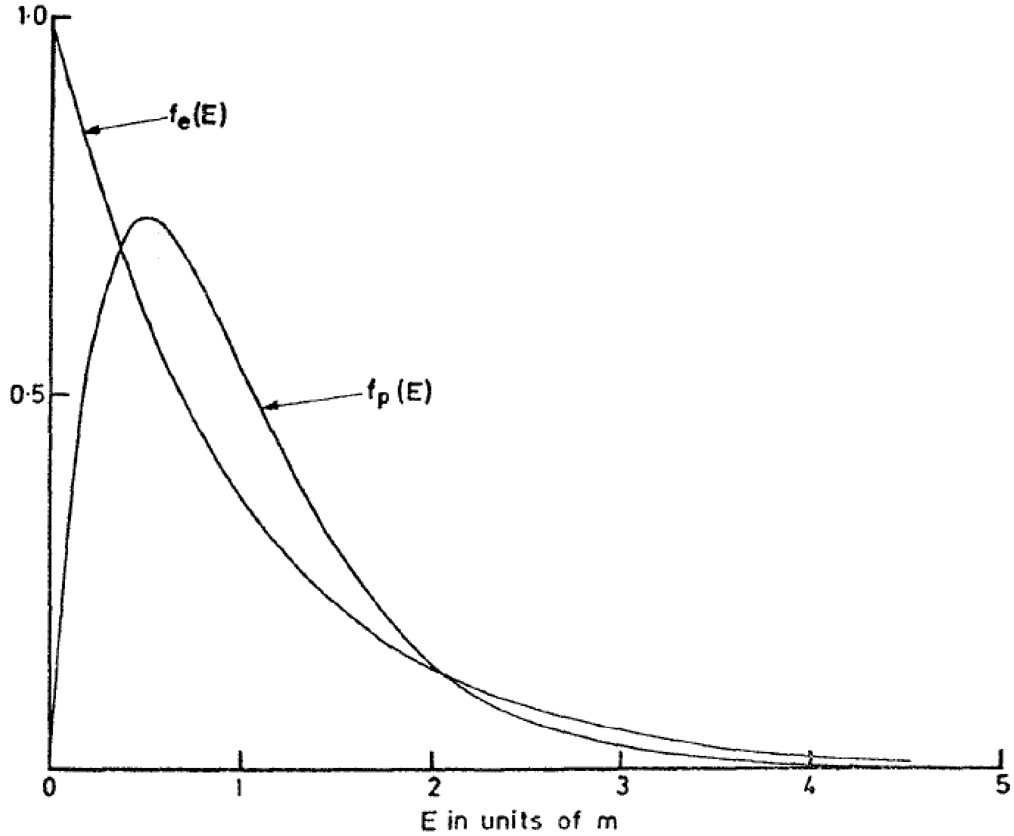


Figure 6 — Theoretical single-electron pulse-height distributions. The mean of both distributions is *m*.

Figure 6 shows that, for a discriminator set at a level corresponding to about two or more electrons, fewer single electrons, and hence fewer spurious pulses, will be recorded if the second rather than the first distribution is applicable. Some recent work [20] has indicated that for many counting gases it may not be possible to detect single electrons without incurring some spurious pulses, the number varying considerably with the gas and, further, that there is a significant probability that some events produce more than one spurious pulse even although the mean θ may be considerably less than unity.

3.2. Scintillation counters

A review of spurious pulses in scintillation counters has been given by Williams and Smith [2]. In such detectors, spurious pulses may arise either in the phototube and its envelope or in the scintillator and its container; the relative importance of these two sources evidently varies between detector systems [2], [21].

The time-interval distribution of spurious pulses generated in the phototube depends to a certain extent on the design of the tube. Two examples of observed distributions are shown in Figure 7 and Figure 8. The structure at short time intervals in these distributions is due to ions of residual gas molecules striking the photocathode [22]. These ions are created in the space between the cathode and first dynode and, owing to the nature of the electric field in this region, the transit time is almost independent of the point of origin of the ions. Ions may be created in other parts of the phototube [23] but these have considerably less chance of reaching the photocathode and, if the interaction of such ions with a dynode surface should produce an electron, the effect is progressively less significant the further down the dynode chain the interaction takes place. Some ions, notably H_2^+ and He^+, may cause the simultaneous release of up to 20 electrons per incident ion on the photocathode. Thus spurious pulses due to this effect may be larger than the genuine pulse which caused them.

Other spurious pulses may be due to light generated within the phototube [24] and have a pulse height equivalent to a single photoelectron pulse. Effects which cause such spurious pulses include

1. electrode glow and
2. faceplate phosphorescence initiated either by Cerenkov radiation or direct excitation by ionizing radiations.

Effect 1) occurs when the phototube is operated at high gain ($\geq 10^9$ say) when light emitted from the anode and last few dynodes is scattered back to the photocathode. This gives rise to a spurious pulse at one electron transit time through the phototube, i.e. in less than about 50 ns. It is more usual to operate phototubes at much lower gains when the effect is absent,

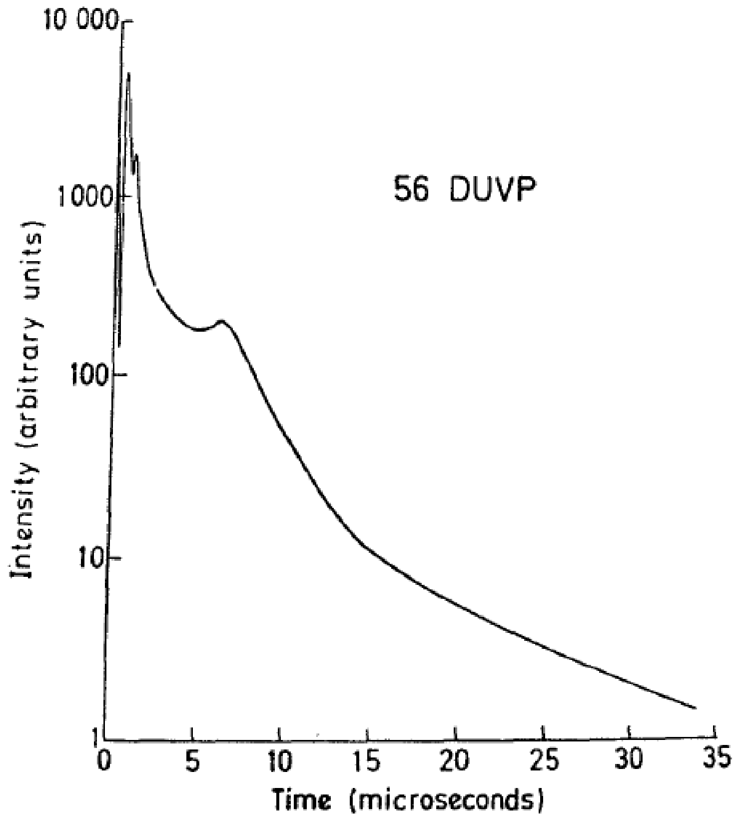


Figure 7 — Time-interval distribution of spurious pulses in a phototube type 56 DUVP (from [12], see p. 29).

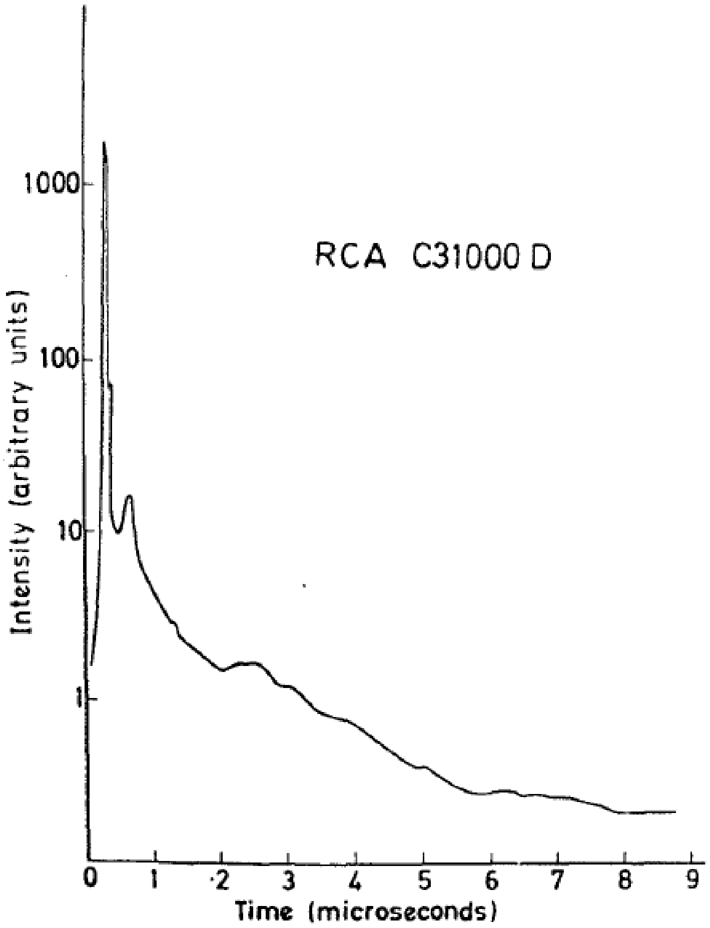


Figure 8 — Time-interval distribution of spurious pulses in a phototube type RCA C31000 D (from [2], courtesy North-Holland Publishing Company, Amsterdam).

and, in any case, modern phototubes are well baffled so that light from this source does not reach the photocathode. The second effect may be due to Cerenkov radiation emitted by relativistic particles (e.g. Compton scattered electrons from high energy γ-rays) traversing the glass envelope. The Cerenkov radiation can then interact with the photocathode to produce a pulse. If the phototube is part of a scintillation detector, this pulse will be coincident with, and add to, the main pulse due to light from the scintillator itself. However, it has been shown that such pulses can be accompanied by several smaller pulses occurring up to several tens of microseconds afterwards. An explanation put forward [25] is that the blue light of the Cerenkov radiation excites phosphorescence in the glass faceplate which, as the excited states subsequently decay, emits visible radiation. However, another investigation, while confirming the effect, has cast doubt on this explanation and an alternative mechanism in which the effect is due to direct excitation of the electrons in the solid has been put forward [26]. An extensive study of three phototubes having a gallium arsenide first dynode has confirmed the existence of spurious pulses due to ions and to the interaction of energetic radiation with the face plate in this type of phototube [23], [27].

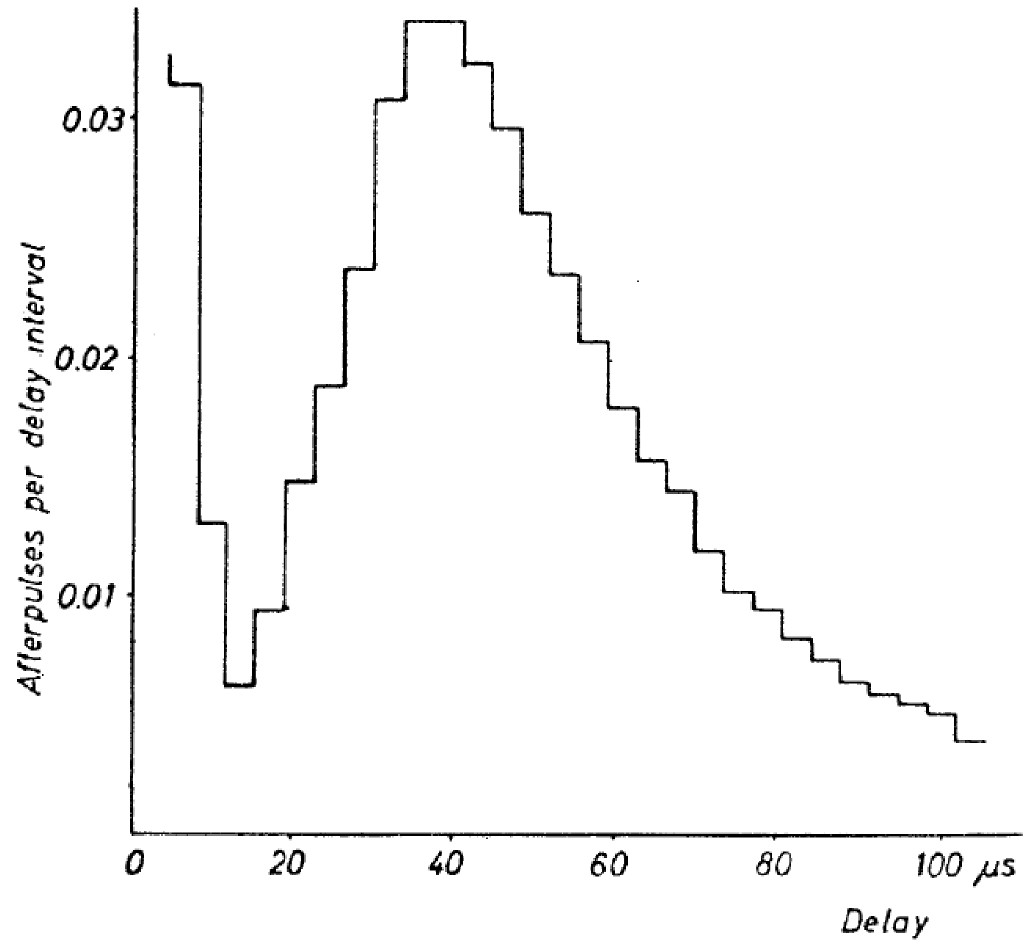


Figure 9 — Time-interval distribution of spurious pulses for ^{147}Pm dissolved in a liquid scintillator. Start pulses correspond to an energy loss of 30 to 90keV (from [21], courtesy North-Holland Publishing Company, Amsterdam).

Spurious pulses caused by the decay of excited states in the faceplates are probably single-electron events. However, it is an oversimplification to assume that all spurious pulses in the tails of the time-interval distributions in Figure 7 and Figure 8 are single photoelectron pulses; there is in fact a distribution of event size. The explanation is probably that "ion pulses" are produced as a result of spurious single-electron events.

Liquid and plastic scintillators together with most glasses phosphoresce after exposure to strong light and hence it is advisable to keep such materials in darkness or red light for several hours before using them. Because of these phosphorescent properties there is always the possibility that spurious pulses, due to phosphorescence induced by the light generated by a genuine pulse or due to direct excitation, may occur. Houtermans [21] has published a time-interval distribution (reproduced in Figure 9 obtained with a complete scintillation detector and concludes that, since a significant difference was found between the shapes obtained using liquid and plastic scintillators, some spurious pulses originate in the scintillator itself. However, in general, this aspect has received rather little attention to date.

4. Conclusion

It is clear that an experimenter should be aware of the possibility of spurious pulses in any counting system, but it is also evident that spurious pulses are not likely to be a serious source of error in most well-designed counting experiments for the measurement of β-emitters, except possibly those involving liquid scintillation counters. With one or two provisos the usual practice of operating a proportional counter near the centre of the plateau is probably sound. It is however advisable to check, using one of the methods described above, for the existence of spurious pulses from time to time and especially when any new or unusual measurement is undertaken. One such situation may be the use of large high-pressure proportional counters.

In scintillation counting the situation is satisfactory for NaI(Tl) systems unless one is working at extremely low γ-ray energies. But perhaps the most critical situation is in the use of liquid scintillation counting for absolute measurements of low energy β-emitters. Here the light output is small and therefore the pulse heights of spurious events are more comparable with those of genuine pulses. Thus there is a significant possibility of spurious pulses and the use of liquid scintillators as 4πβ-detectors at the present time is limited largely by this phenomenon [28]. The use of two phototubes in coincidence will substantially reduce the number of spurious pulses detected but the overall efficiency is also reduced.

Appendix 1. The influence of an imposed dead time on the detection of subsequent spurious pulses

Many of the methods described in the text for the estimation of θ involve the recording of the number of times a detecting circuit is actuated. This circuit may be, for example, a gate, a time-to-amplitude converter or an analyser in either the pulse-height or time mode. In such methods it is assumed that the circuit is actuated by genuine pulses only; this assumption is usually justified by the fact that the value of θ is very much less than unity. Here the validity of this assumption will be examined.

The problem may be stated in the following way: given a pulse train, composed of both genuine and spurious pulses, which is detected by a circuit, the overall dead time of which is longer than the maximum time interval between a genuine pulse and its associated spurious pulse{s), what is the probability that the circuit will be actuated by a spurious pulse?

Let $f(\tau)$ be the density for the time interval between a genuine and a spurious pulse and τ_s the maximum value of this interval (Figure 1.1, see p. 26).

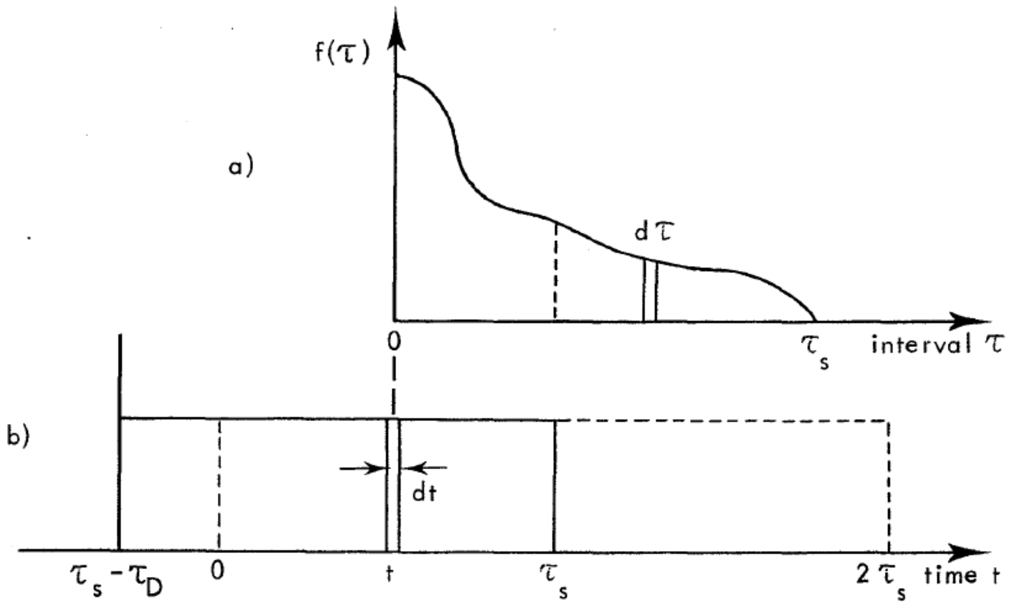


Figure 1.1 — a) A hypothetical interval density $f(\tau)$ of spurious pulses as a function of time interval τ. b) A sketch illustrating the relationship of the density $f(\tau)$ with respect to events in real time t.

The circuit, of dead time τ_D, is actuated at time $t = \tau_s - \tau_D$ and it is immaterial whether the actuating pulse is genuine or spurious. Time $t = 0$ is taken at a point τ_s before the end of the dead time since, neglecting second order spurious pulses, only genuine pulses in the interval $t = 0$ to τ_s can produce a spurious pulse, which must fall in the interval $t = \tau_s$ to $2\tau_s$. The next pulse after the end of the dead time up to $t = 2\tau_s$ may be spurious or genuine, or there may be no pulse. However, in the last case, the next pulse to arrive must be genuine. Hence, if the count rate of genuine pulses is N, then the probability P_s that the next pulse after the end of the dead time is spurious is

$$P_s = \int_0^{\tau_s} N\theta \mathrm{d}t \int_{\tau_s - \tau}^{\tau_s} f(\tau) e^{-N(\tau - \tau_s + t)} \mathrm{d}\tau.$$

The evaluation of this requires a knowledge of the shape of the time-interval density $f(\tau)$, and, as noted in the text, this may vary considerably from one case to another. However, by way of an example, assume that $f(\tau)$ is constant for $\tau \leq \tau_s$ and equal to $1/\tau_s$. Then

$$P_s = \theta[1 - (1 - e^{-N\tau_s})/N\tau_s].$$

As $N\tau_s$ increases to large values, P_s tends to θ, while for small values of $N\tau_s$ for this particular case, P_s tends to $N\tau_s\theta/2$. In general $P_s = a\theta$, where a is some function of N and τ_s while the probability P_g that the next pulse is genuine is $P_g = 1 - a\theta$.

Thus the assumption that all actuating counts are genuine is only incorrect by a factor $(1 - a\theta)$; by using a sufficiently low count rate the departure of this factor from unity may be made insignificant, **independently** of the value of θ. Thus for most situations, especially where θ is also small, the assumption is a valid one.

Appendix 2. The elimination of genuine pulses from time-interval distributions obtained by the time-to-amplitude converter technique

The time-to-amplitude converter (TAC) system can usually be arranged such that every start pulse gives rise to one recorded stop pulse. In the event that the next pulse after a start pulse occurs at a time greater than the range of the TAC system, the pulse may be recorded in an "overflow" channel. Let n_s be the total number of start pulses and $n(t)$ the recorded time-interval distribution. Then the probability $S(t)$ that no stop pulse arrives earlier than t is given by

$$S(t)=\frac{1}{n_s}\int_t^{\infty} n\,(t)\mathrm{d}t=1-\frac{1}{n_s}\int_0^{t} n\,(t)\mathrm{d}t,$$

since

$$n_s=\int_0^{\infty} n\,(t)\mathrm{d}t;$$

thus

$$n(t)\mathrm{d}t=-n_s\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{S}(t)\mathrm{d}t.$$

The stop pulses may be genuine, or spurious and time correlated to the start pulse, or spurious but arising from a genuine pulse occurring before the start pulse (i.e. not correlated with the start pulse). The three types will be indicated by the subscripts r, c and a, respectively. Thus, neglecting the influence of dead times,

$$S(t)=S_r\,(t)\cdot S_c\,(t)\cdot S_a\,(t).$$

However, the probability differential $C(t)\ \mathrm{d}t$ for the spurious pulses, which would be observed in the absence of all genuine events (except for the start), would be $-\mathrm{d}S_c\,(t)$, i.e.

$$C(t)=-\frac{\mathrm{d}}{\mathrm{d}t}S_c\,(t)=-\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{S(t)}{S_r\,(t)\cdot S_a\,(t)}\right],$$

and hence

$$\theta=-\int_0^{\infty}\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{S(t)}{S_r\,(t)\cdot S_a\,(t)}\right]\mathrm{d}t.$$

The probability $S(t)$ can be readily determined from the observed time-interval distribution and $S_r\,(t)$. In a similar manner, $S_a\,(t)$ can be obtained from a subsidiary experiment in which a pulse generator is used to start the TAC system.

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