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Review Article

Radiation detector deadtime and pile up: A review of the status of science

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ABSTRACT

Since the early forties, researchers from around the world have been studying the phenomenon of deadtime in radiation detectors. Many have attempted to develop models to represent this phenomenon. Two highly idealized models; paralyzable and non-paralyzable are commonly used by most individuals involved in radiation measurements. Most put little thought about the operating conditions and applicability of these ideal models for their experimental conditions. So far, there is no general agreement on the applicability of any given model for a specific detector under specific operating conditions, let alone a universal model for all detectors and all operating conditions. Further the related problem of pile-up is often confused with the deadtime phenomenon. Much work, is needed to devise a generalized and practical solution to these related problems. Many methods have been developed to measure and compensate for the detector deadtime count loss, and many researchers have addressed deadtime and pulse pile-up. The goal of this article is to summarize the state of science of deadtime; measurement and compensation techniques as proposed by some of the most significant work on these topics and to review the deadtime correction models applicable to present day radiation detection systems.

1. Introduction

Pulse counting in a random process and is unavoidably affected by losses. In nearly all detector systems a minimum amount of time must separate two events so that they can be recorded as two separate independent events. In some cases, the limiting time is determined by processes in the detector itself but in most cases the limit arises from the associated electronics. The minimum time of separation for proper detection is usually called the *deadtime* (or resolving time) of the counting system [1]. The total deadtime of a detection system is the aggregate of the intrinsic detector deadtime (e.g., the drift time in a gas detector), the analog front end losses (e.g., the shaping time of a spectroscopy amplifier etc.), and the data acquisition deadtime, for example, the conversion time of ADCs (analog-to-digital converter), or the readout and storage times. Thus, there is a need for correction at three different levels; first, for the internal losses inherent in the detector itself, second, for the losses generated by the system circuitry, and lastly, for the multichannel analyzer, i.e. the analog to digital conversion and storage deadtime. It is possible to correct for counting losses only if both the nature of the originating process and the effects of deadtime are clearly understood. A typical pulse counting system is shown in Fig. 1, which also gives an overview of the deadtime associated with various units. In most detectors, a small pulse lasting for only a fraction of a microsecond is generated which is not strong enough to be processed directly. To preserve the information carried by these individual pulses they are first processed by a preamplifier which adds a relatively long (tens of microsecond) tail to the original pulse. It is important to point out that all the information pertaining to the timing and the amplitude of the original pulse is contained in the leading edge of the tailed pulse, which is then carried to an amplifier where it is amplified and shaped. Charge collection time of the detector determines the rise time of the tailed pulse produced by the preamplifier. Amplifier's shaping of the pulse plays a critical role in preserving the spectroscopic and timing (or count rate) information. A compromise between preserving the rate and the pulse height information is generally needed for any high count rate application.

To avoid ballistic deficit, (ballistic deficit is the phenomenon when the slow component of the ions do not contribute to the pulse in the pulse shaping stage, hence pulse amplitude is reduced) the shaping time constant of the amplified pulse must be significantly

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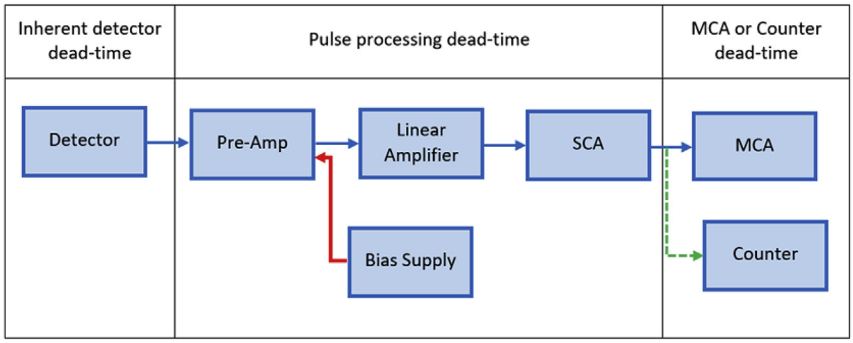

Fig. 1. Sources of deadtime in a typical detection system.

larger than the rise time of the tailed pulse, otherwise the amplitude information of the shaped pulse will be compromised. Ballistic deficit is not a major concern as long as the charge collection time (and consequently the preamplifier's pulse rise time) is constant for all pulses. However, in most cases the charge collection time depends on the location of the initial interaction of the radiation within the detector. This leads to variable ballistic deficit and energy resolution degradation. On the other hand, if the pulse shaping time is too long the amplified pulse will carry either a positive tail or a negative undershoot. Both of these will lead to pile-up and energy resolution degradation. The other situation where pile-up becomes an issue is when pulses with flat top arrive too close to each other producing a combined pulse of summed amplitude. This situation is referred as the peak pile-up (Fig. 2). The basic difference between the deadtime and the pile-up is the fact that, in pile-up a summed pulse is produced when two pulses combine leading to energy resolution degradation as well as count rate loss. In case of deadtime, the second pulse is lost without any energy degradation of the first pulse. In the literature both these problem are often not precisely presented leaving confusion for the readers.

In most high count rate situation both deadtime as well as pile-up problems are possible. As Evans [2] pointed out that every detection instrument used for counting exhibits a characteristic time constant resembling the recovery time. He noted that after recording one pulse, the counter is unresponsive for successive pulses until a time interval equal to or greater than its deadtime, τ, has elapsed. He found that if the interval between two true events is shorter than the resolving time τ, only the first event is recorded. Therefore, strictly speaking Evans was making reference to resolving time and τ in the discussion did not precisely represents deadtime. Thus the detection system causes a loss of counts and distorts the energy resolution. Evans very elegantly explains that the radiation counter systems do not actually count the nuclear events but the intervals between such events. This is a unique way of looking at the counting process in a detection system.

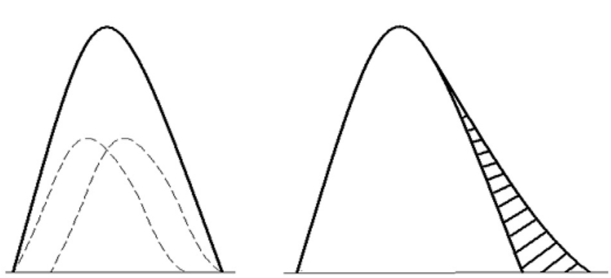

Fig. 2. Pulse pile-up leading to addition of high energy wings to the spectroscopy peak due to pulse superposition.

Fig. 1 shows a typical counting system where each unit can possibly add some deadtime and contribute towards the overall deadtime of the system leading to count loss. Identification of contribution from individual pulse processing unit to the overall deadtime helps in recognizing the bottleneck areas of the counting system and devising measures to correct the count losses accordingly. The relative contribution of each component can significantly vary depending on the component design and operating conditions.

The detector is first unit in the counting system. As discussed in Section 2, depending on the choice of detector, a wide variation of detector deadtime is observed. For Geiger-Müller (GM) counters, the detector deadtime contribution is perhaps the most significant within the entire counting system. Detector pulses are only a fraction of a microsecond wide. However, for extremely high count rates (exceeding million counts per second) it is possible that these pulses may ride on each other and may lead to the pile-up problem. In most cases however, deadtime is the primary concern arising from a detector. In some cases the detector is able to produce pulses at much faster rate than the subsequent instrumentation can process and in such cases the circuitry and pulse processing instrumentation determines the overall deadtime of the system.

The next unit in the counting system is the preamplifier, which is used to provide optimized coupling and electronic matching between the detector and amplifier. Its main purpose however, is to maximize the signal to noise ratio. The pulses from a preamplifier are long tail pulses with very short rise time and a fall time of tens of microsecond. In the shaping stage of the pulse processing; that is the amplifier, hence the problem of pile-up introduced in the preamplifier is removed. However, at very high count rates some piled-up pulses may reach the preamplifier saturation limit. This situation results in the degradation of energy resolution.

The amplifier, which is the next component in pulse processing, is perhaps the most important component in the counting system. Its primary function is to shape the tail pulse coming from the preamplifier and further amplify it, as required. The tail pulses are converted to linear amplified pulse within the expected range of the subsequent units in the counting system, usually between 0 and 10 V. As discussed earlier, the shape of the amplified pulse plays a critical role in minimizing pile-up and ballistic deficit to preserve the energy resolution as well as the count rate information. In addition to the pile-up, deadtime is also associated with the amplified pulse, which is of the same order as the width of the shaped pulse that is only a few microseconds. It is important to point out that invariably a compromise is to be made to preserve the energy resolution of the pulses and the count rate information under high count rate conditions.

The SCA (Single Channel Analyzer), when used, is not a major contributor to the deadtime problem of the counting system. A total of 1–2 μs deadtime is added because of their functioning. Modern counters are the other unit in counting chain, having even smaller deadtime associated with them. For example, ORTEC 994 [3] counter reports a deadtime for paired pulses of 10–40 ns. Hence the deadtime contribution from the counter is not at all significant.

MCA or Multi Channel Analyzer is the next major contributor to the deadtime in the counting system. Based on their design, MCA's can produce pile-up and/or deadtime problem. The main contributor in MCA deadtime is the ADC or Analog to Digital Converter. The deadtime of a Wilkinson type ADC is linearly dependent on the pulse height. In most modern MCAs, the system is capable of automatically correcting for the deadtime by counting for a longer duration of time (live time) than the clock time. It is however important to point out the auto correction at this level is only limited to the deadtime associated with the MCA. MCA electronics is not capable of de-convoluting two or more piled-up pulses or correcting for the deadtime initiated in the detector.

Muller [4] has complied a very comprehensive bibliography on radiation measurement system's deadtime covering almost all significant contributions to the area from 1913 till 1981. He has listed various articles in this area in chronological order of appearance and also according to the subject area. The present work differs in its approach, as the main goal of this paper is to gather some of the major findings on deadtime and pile-up behavior, which includes common modeling methods and measurement techniques for the interested user. This article is by no means an exhaustive bibliography of all contribution in area of detector deadtime and pile-up associated with measurement system. Rather, the authors have tried to present most prevalent and useful methods in this area.

In the next section, the physical phenomenon responsible for deadtime in various detectors is discussed, followed by major mathematical models for describing system deadtime in Section 3. Section 4 reviews the common methods for measuring the system's deadtime followed by a section devoted to deadtime and pile-up measurement of electronic instrumentation.

2. Physical phenomenon of deadtime

Detector design, geometry and material can significantly impact the phenomenon of deadtime and pulse pile-up. In addition to the operating conditions including the high voltage applied to a gas filled or semiconductor detector, operating temperature and pressure pay a significant role in detector deadtime [5,6]. This section discusses the physical nature of phenomenon of deadtime and pile-up in major radiation detector types. It is important for the end-users to understand the physics of the phenomenon to effectively reduce the effect of deadtime and correct for it.

2.1. Gas filled detectors (Geiger Muller and proportional counters)

In a gas filled detector, when an electron-ion pair is produced (say in a G-M tube) by radiation, the electrons are accelerated toward the anode creating a cascade of secondary ionization leading to what is called as Townsend avalanches [1]. In G-M counter this avalanche propagates along the anode wire at the rate of approximately 2–4 cm/μs [7] and eventually envelopes the entire anode. Collection of all the negative charge results in the formation of the initial pulse, which lasts for a few microseconds. However, the exact duration of the pulse will depend on the geometric dimensions of the counter, location of the initial ionization, as well as the operating voltage, temperature and gas pressure [5]. Obviously one would also expect the inherent nature of the fill gas (work function) impacting the charge collection time. G-M counter does not provide any spectroscopic information therefore one is not concerned about pile-up, that is another event taking place during the charge collection time resulting in pulse height resolution degradation. In theory, all pulses from G-M counter are of the same amplitude irrespective of the energy of radiation initiating them.

Although electrons are collected at the anode rather quickly, positive ions tend to wander longer around the anode due to their low mobility before being collected at the cathode. Presence of positive charge results in severe distortion of the electric field. Any subsequent event during the time when the electric field is distorted will either produce no pulse at all or produce a pulse with reduced amplitude, which may or may not be detected by the subsequent counting system. Therefore G-M counters are prone to deadtime count losses. Duration of deadtime will again depend on the detector geometry, fill gas properties and operating condition of pressure, temperature and most importantly the applied voltage [5].

Fig. 3 illustrates the deadtime, resolving time and recovery time of a G-M tube. These three terms are unfortunately used interchangeably causing some confusion for the readers. As discussed earlier, the positive ions slowly drift toward the cathode; consequently the space charge becomes dilute. There is a minimum electric field necessary to collect the negative charge and produce any pulse in the tube. By strict definition, deadtime is the time required for the electric field to recover to a level such that a second pulse of any size can be produced. Just after the deadtime, the electric field gradually recovers during this time the amplitude of the second pulse is hampered by the presence of the lingering positive charge. Therefore immediately after the deadtime, if a second pulse is produced its amplitude will be reduced.

There is minimum amplitude needed for the second pulse for it to pass through the discrimination threshold and be recorded. The time needed between the two pulses to produce this minimum amplitude recordable second pulse is called the resolving time of the detection system. Since the true deadtime is impossible to measure, resolving time is often referred to as deadtime of the G-M counter. Finally, after complete recombination of the gas in the Geiger tube a full amplitude pulse can be produced. The minimum time required to produce a full amplitude pulse is called as the recovery time of the detection system. Typically, the deadtime for a GM detector is on the order of hundreds of microseconds [1].

In proportional counters the avalanche is local, i.e. not engulfing the entire anode wire. The production of initial ion pair and its subsequent multiplication is proportional to the initial energy deposited in the fill gas. Therefore the energy spectroscopy information of the interaction is preserved. However, if a second event takes place within the charge collection time of the first interaction, the second pulse will be piled-up with the first pulse, producing a summed pulse degrading the energy resolution. Likewise, if the second event takes place before all positive ions are neutralized, the amplitude of the second pulse will be reduced, again leading to a degradation of the energy resolution. If the time gap is too small between the two pulses, the second pulse would be totally lost. Therefore for proportional counter it is more of a pile-up problem than that of deadtime. But depending on the time gap between the two events both pile-up and deadtime loss is possible.

2.2. Scintillation detectors

There are two major categories of scintillators; inorganic and organic scintillators. In the case of inorganic scintillator, the energy state of the crystal lattice structure is perturbed by radiation and elevates an electron from its valence band into the conduction band or activator sites when impurity is added (which is mostly the case) to the crystal by design. Subsequent return of electron from excited state to valence band produces light/photon emission (Fig. 4).

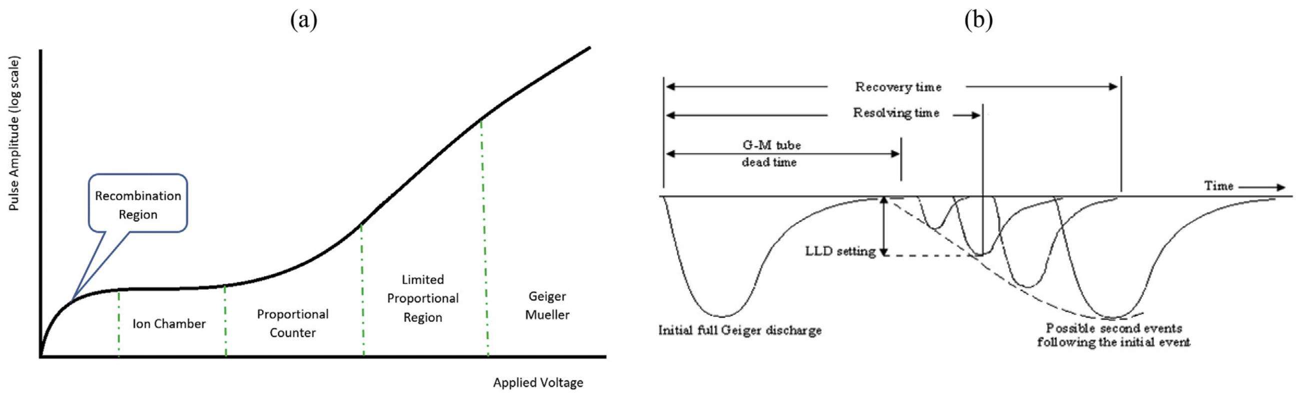

Fig. 3. (a) Typical gas-filled detector behavior with distinct regions of operation (b) Deadtime representation of a Geiger Mueller Counter.

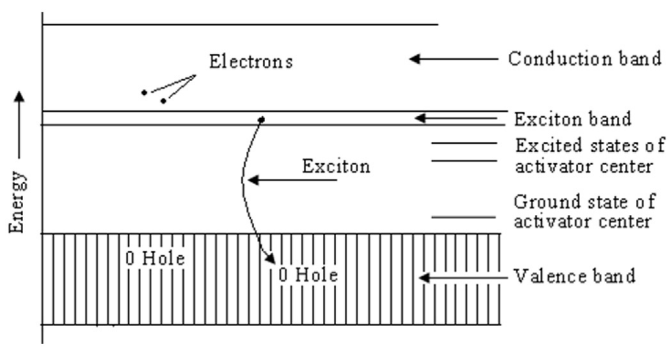

Fig. 4. Energy band structure for Scintillator crystal.

Detailed discussion of scintillation process is beyond the scope of this review but interested readers are referred to the literature [8,9].

There is a finite time associated with excitation and de-excitation of the perturbed sites and in many cases the decay time is composed of more than one component. There is also a wide range of decay times. For example, NaI(Tl), the most commonly used scintillator material, has a decay time of approximately 230ns whereas some fast inorganic material such as BaF_2 with a decay time of less than a nanosecond are also available. Presence of secondary de-excitation path (e.g., phosphorescence) can further complicate the phenomenon, producing light yield at much longer decay time. Researchers [10,11] have reported large variability in the performance of inorganic scintillators. In case of scintillators, if the second interaction is within the decay of the first interaction, the light emission from the second interaction will add to light emission of the first event and can potentially produce a summed peak. Therefore, the problem lands in the realm of pulse pile-up. However, due to comparatively small decay times this becomes a problem only at significantly high count rates. In the case of organic scintillators the excitation is that of a single molecule (for noble gas scintillators like, Xe and Kr as a single atom) and the electron is promoted to higher energy level. De-excitation of these electrons produces the scintillation photons which are responsible for the pulse formation. Most organic scintillators have even smaller decay constant in the range of nano-seconds (e.g. Anthracene solvent has a decay time constant of only 3.68ns [12]) and are well suited for high intensity measurements. For scintillators, in general, the problem of deadtime/pile-up is not as important as compared to the G-M counters. For scintillator detectors, material characteristics play the most critical role in the detector performance. Minute amount of impurities can drastically alter detector performance including pile-up. One must bear in mind that presence of activators or waveshifter can drastically alter the deadtime behavior of any scintillation detector. Furthermore, additional deadtime or pile-up considerations are warranted in matching an appropriate photomultiplier tube or photo diodes. Light-to-pulse conversion process (by PMT or photo diodes) can also add a few nano-seconds of deadtime [13]. Proper choices of photomultiplier tube (PMT) electronics and operation conditions are required to optimize the system for high count rate applications.

2.3. Semiconductor detectors

Semiconductor detector operation is based on collection of charge carried by electron and holes, which are produced due to radiation interaction. A major advantage of semiconductor is its superior energy resolution because only a few eVs of deposited radiation energy is required to produce a pair of charge carrier (electron and holes) as compared to approximately 30 eV of radiation energy deposition to produce an ion pair in gas filled detector. High charge carrier production coupled with more than thousand times higher density as compared to gas filled detector results in favorable characteristics of semiconductor detectors. Unlike gas filled detectors where only electrons contribute to the signal, in semiconductor detectors the mobility of holes is comparable to that of electrons, and hence both charge carriers contribute to the pulse formation. The mobility of the electrons and holes depends on: material characteristics, strength of the electric field applied and operating conditions (temperature). For most cases the charge carrier mobility is on the order of 10^3–10^4 cm^2/V-sec [14,15]. Therefore for a typical semiconductor detector the charge collection time is just a fraction of a microsecond [1].

If a second event takes place before all the charge from the first event is collected, the charge carriers produced by the second event will be added to the pulse produced by the initial event, hence leading to the problem of pile-up. Since both the charge carriers are contributing to the formation of pulses there is no deadtime in the strict sense, and only pile-up is observed.

The shape of the pulse is dependent on the location of the initial interaction where electron-hole formation takes place, and the mobility of each charge carrier in the material at the operating voltage. Charge carrier mobility is also a strong function of detector temperature. Voltage applied to the p-n junction causes the depletion layer to grow and hence increases the active volume of the detector (Fig. 5). Therefore, detector geometry, operating voltage, and temperature all play important roles in pile-up time for a semiconductor detector.

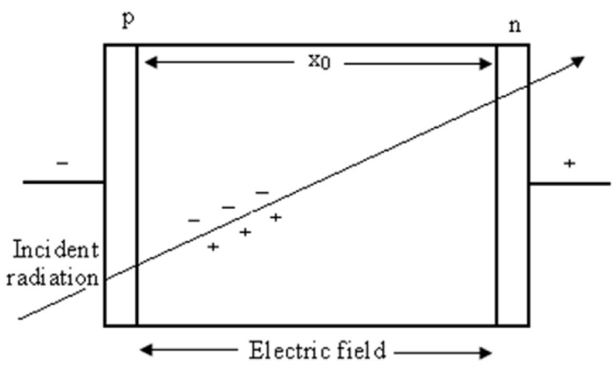

Fig. 5. A p-n junction with reverse bias as a semiconductor detector.

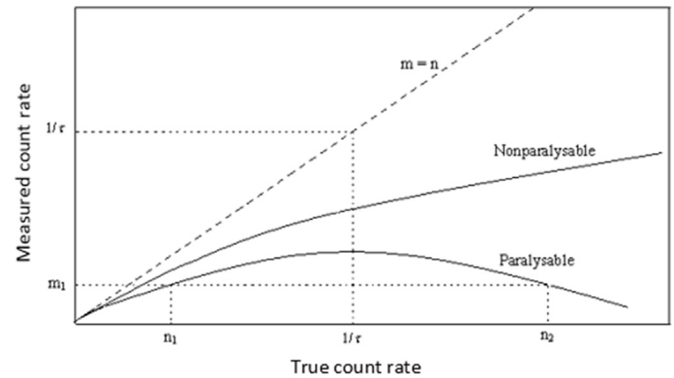

Fig. 6. Paralyzable and nonparalyzable models of deadtime.

3. Deadtime models

Over the last sixty years many researchers have proposed models to correct for deadtime. These models rest on the assumption that a Poisson distribution exists at the input of a detector. In one of the earliest papers on this topic, Levert and Sheen [16], demonstrated that the frequency distribution of discharges counted by a Geiger-Muller counter is not necessarily a Poisson distribution. Rather it depends on the resolving time, which may be comparable to the observation interval.

3.1. Idealized deadtime model

Feller [17] and Evans [2] have developed the two basic types of idealized models for deadtime, i.e., type I or (*nonparalyzable model*) *and* type II (*paralyzable model*), respectively. The paralyzable detection system is unable to provide a second output pulse unless there is a time interval equal to at least the resolving time τ between the two successive true events. If a second event occurs before this time, then the resolving time extends by τ. Thus, the system experiences continued paralysis until an interval of at least τ lapses without a radiation event. This interval permits relaxation of the apparatus. Based on the interval distribution of radiation events, the fraction of those events which are longer than τ is given as $e^{-n\tau}$, where n is the average number of true events per unit time. Product of this fraction with the true count rate provides the observed count rate:

$$m = ne^{-n\tau}. \quad (1)$$

The nonparalyzable or the type I detector system is non-extending and is not affected by events which occur during its recovery time (deadtime), τ. Thus the apparatus is dead for a fixed time τ after each recorded event. If the observed counting rate is 'm', then the fraction of time during which the apparatus is dead is $m\tau$. And the fraction of time during which the apparatus is sensitive is $1 - m\tau$. Thus, the fraction of true number of events that can be recorded is given as,

$$\frac{m}{n} = 1 - m\tau \quad (2)$$

or

$$n = \frac{m}{1 - m\tau}. \quad (3)$$

For low count rates, both these models give virtually the same result, but their behavior is very different at higher rates (Fig. 6). The count loss in a paralyzable model is predicted to be much higher than in nonparalyzable model. As one can see, at extremely high count rates the paralyzable systems do not even record any counts, the deadtime just keeps extending.

Feller [17] while proposing the idealized deadtime models pointed out that the actual counter behavior is somewhere between the two idealized cases. This can easily be shown by Taylor expansion of the paralyzing expression and by truncating after the first terms results in nonparalyzable expression. By retaining higher order terms, the result approaches that of a paralyzable model, as shown in Fig. 7. The first attempt to develop a generalized deadtime model was reported by Albert and Nelson [18]. Albert and Nelson's generalized approach is based on associating a probability 'θ' for detector getting paralyzed. The value of 'θ' can vary from 0 to 1. Thus, for a generalized deadtime model, only a fraction 'θ' of all incoming events are capable of triggering an extension of the deadtime. For the extreme case, $\theta = 1$, the model approaches Type II (paralyzable). For the other extreme, $\theta = 0$, the model becomes type I (nonparalyzable).

3.2. Hybrid deadtime model

The major contribution in generalized approach for deadtime came from Takacs's [19] who was the first one to obtain Laplace transform of the interval density for generalized deadtime. Muller in a series of reports and publications [20,21] further simplified the generalized model given by Takacs. The output (observed) count rate (m) for generalized deadtime can be expressed as:

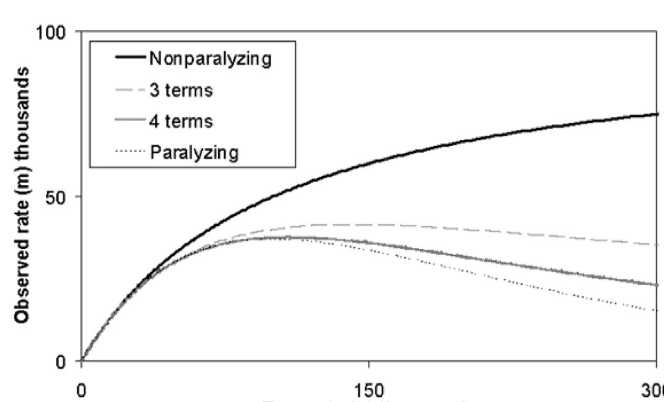

Fig. 7. Plot to show Taylor expansion of Paralyzable model.

$$m = \frac{n\theta}{e^{\theta n\tau} + \theta - 1} \tag{4}$$

where τ is the generalized deadtime and θ is the probability of paralysis. Another representation of this development is presented by Lee and Gardner [22] who made use of two independent deadtimes. The hybrid model proposed by them:

$$m = \frac{n\exp(-n\tau_P)}{1 + n\tau_N} \tag{5}$$

makes use of the paralyzable deadtime τ_P and the nonparalyzable deadtime τ_N. Using least square fitting of the data obtained from a decaying of Mn56 source, they obtained the two required deadtimes for a GM counter. While in their discussion the order of the two deadtimes was alluded, but not identified precisely. It appears that for G-M counter they placed a nonparalyzable deadtime before the paralyzable deadtime. They did not offer any justification for this order of the two deadtimes. Obviously, one would expect a significant change in the deadtime behavior if the order of the two deadtimes were reversed. The hybrid model is a good application of the generalization originally proposed by Albert and Nelson [18]. Lee and Gardner did not offer any practical method to determine the two deadtimes. Most recently Hou and Gardner proposed an improved version of the original two deadtimes model by further dividing paralyzing and non-paralyzing each into three components [23]. The approach seems to be producing improved results but it does add to the empirical nature of the solution. With the new proposed solution (their case 2) the user would need to know four deadtimes; τ_P, τ_{N0}, τ_{N1} and τ_{N2}. This approach is similar to including additional terms from the Taylor expansion of the expression.

Patil and Usman [24] presented a graphical technique to obtain the two parameters for a generalized deadtime model using data from a fast decaying source. They offered a simple modification to the hybrid model [22] simplifying it back to a form to similar the original Takacs equation (equation (4)):

$$m = \frac{n\exp(-n\tau f)}{1 + n\tau(1-f)}. \tag{6}$$

In their paper, Patil and Usman [24], referred to the probability of paralyzing as the paralysis factor (f). Measurements were made to obtain the paralysis factor and the deadtime for an HPGe detector. Using the graphical technique they found the deadtime of 5–10 μs and the paralysis factor approaching unity. Yousaf and co-workers compared the behavior of the traditional dead-time models with recently proposed hybrid deadtime models [25]. They clearly demonstrated the inherent difference between the paralysis factor based models and the two deadtimes model. They concluded that use of a single deadtime model for a given detector under all operating conditions is not advisable let alone using one model for all detectors for all operating conditions. Therefore, one must carefully examine the applicability of deadtime model for the given operating condition. Their conclusion highlighted the need for additional work in the area of deadtime modeling and count rate correction. Hasegawa and co-workers [26] proposed a technique of measuring higher count rates based on the system clock. Realizing that in some parts of the data acquisition system processing is performed on fixed system clock. Latching or buffering system is used to retain system information temporally to synchronize output event with the system clock. This latching capability allows the system to measure more counts than the standard nonparalyzable model. Their system has the ability to record one event per system cycle irrespective of the timing of the arrival of the true events. Unless there are no true events, one event is recorded per system cycle. In this manner, the system is able to record more events than the nonparalyzable system. Based on Poisson distribution of the input count rate the *on clock nonparalyzable count loss model's* observed count rate is expressed by,

$$m = \frac{1 - \exp(-\tau_{clock}\cdot n)}{\tau_{clock}}. \tag{7}$$

For a fast system clock there can be significant improvement in the counting efficiency by relying on the system clock.

4. Detector system deadtime measurement and correction methods

One of the simplest methods of estimating the overall deadtime of a counting system is the two-source method originally developed by Moon [27] and later incorporated in the work of other researchers [28]. Two-source method is based on observing the counting rate from two sources individually and in combination. Because the counting losses are nonlinear, the observed rate of the combined sources will be less than the sum of rates when the two sources observed individually and the deadtime can be calculated from the difference.

The advantage of the two-source method is that it uses observed data to predict the deadtime. Because the two-source method is essentially based on observation of the difference between two nearly equal, large numbers, careful measurements are required to get reliable values for the deadtime.

Repeating well-defined geometry is necessary to measure deadtime using two-source method which might be difficult in some situations. A dummy source is often used to replicate the exact geometry when counting the sources individually. Likewise if the background is not negligible the algebraic expression for the deadtime is little more involved. It is also important to point out that in order to achieve good measurements counting statistics must also be incorporated in the experiment. In some cases scattering from surroundings may also influence the measurements.

The decaying source is another commonly used method for measuring overall deadtime of detection system [1]. This technique, which requires a short lived radioisotope, is based on the known behavior of a decaying source where the true count rate varies as:

$$n = n_0 e^{-\lambda t} + n_b \tag{8}$$

where n_b is the background count rate, n_0 is the true rate at the beginning of the measurement and λ is the decay constant of the particular isotope. Assuming negligible background and substituting (8) in the expression for the non-paralyzable model, one obtains:

$$me^{\lambda t} = -n_0\tau m + n_0. \tag{9}$$

If m is plotted as the abscissa and $me^{\lambda t}$ as the ordinate the slope of the straight line so obtained would be $-n_0\tau$. The initial true rate n_0 (often unknown) can be obtained by finding the intercept of the straight line with the y-axis (Fig. 8). Finally the deadtime is calculated by taking the ratio of the slope ($n_0\tau$) with the intercept (n_0). Similar procedure can be carried out for the paralyzable model, where the abscissa is taken to be $e^{-\lambda t}$ and the ordinate is taken to be $\lambda t + \ln m$. In this case, the slope again is be $-n_0\tau$ and the intercept is n_0. One can use the information to estimate the deadtime.

The decaying source method has the advantage of not only measuring the value of deadtime, but also testing the validity of the idealized assumption of paralyzable and nonparalyzable models.

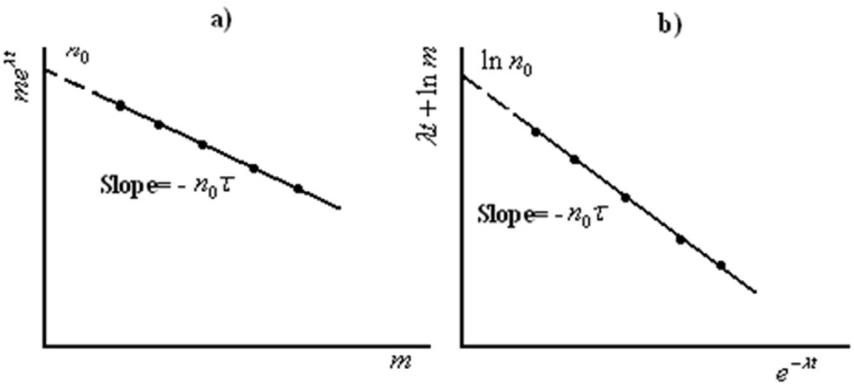

Fig. 8. Decaying source method for (a) nonparalyzable and (b) paralyzable model.

However, care must be taken in selecting a suitable isotope. The isotope used for this technique must be pure with a single half-life, which is not too long or too short such that the entire counting rate range can be measured in a reasonable time. Moreover, the half-life of the decaying isotope must be known with good accurately. A disadvantage of decaying source method is that it takes a long time for deadtime determination. Yi and coworkers recently applied the decaying source method for calibrating dose rate meters [29] and reported good success.

Another variation of the decaying source method could be when a constant source is measured at various distances from the detector. However the distance between the source and the detector must be measured accurately because of the $1/r^2$ dependence of the observed count rate and inaccuracies in the distance measurement will be squared. For low intensity measurements the distances is usually not very long consequently the geometric variability (assumption of point source-point detector is no longer valid) may also contribute to the overall quality of the results. Scattering from the surroundings or even the air between the source and the detector can also complicate the measurements. This is particularly true for high energy sources where the scattering interactions could be complex.

Patil and Usman [24] contributed to the effort by proposing a modified decaying source method to measure the two detector parameters i.e., the deadtime and the paralysis factor of the detector system. The detection system consisted of the radiation detector, preamplifier, amplifier and multichannel scaler. HPGe detector was tested using a short lived isotope (Mn^{56} and V^{52}). A multi-channel scaler with zero dead-time was used to collect the decay statistics. The plot below (Fig. 9) shows the characteristic rise and fall behavior as the source decays away.

The two variables in equation (6) were introduced: the total deadtime of detection system τ and the paralysis factor f, which is a property of a detector system and represents the amount of paralysis. The paralysis factor for a detection system is the ratio of paralyzable to total deadtime.

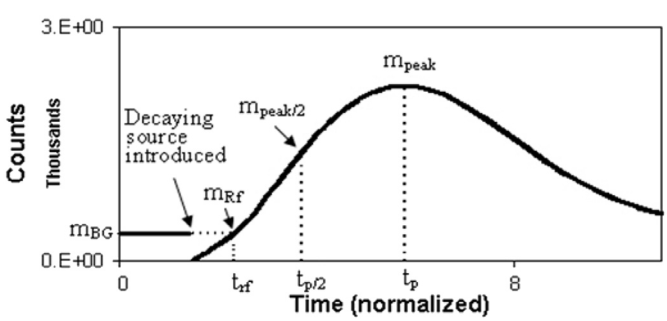

Fig. 9. Characteristic decay of V^{56} with HPGe counting system.

The paralysis factor is calculated from the rise time of the isotope decay curve. The dead-time is interpolated from the maximum peaking count curve which is a property of a detector. This hybrid method has advantage over other methods (standard decay source method) in that, the calculation of deadtime does not require any assumption about the nature of paralysis. Further, this technique, which can be used at high counting rates, calculates the overall deadtime for the detection system which includes the radiation detector.

Pomme [30–32] has contributed significantly to the study of pile-up and deadtime. His work addresses the count loss issues in counter systems when pile-up losses and deadtime occur in combinations as a series arrangement of deadtime. A counter is injected with artificial deadtime (paralyzable and nonparalyzable) for every counted event to calculate the count losses and errors arising due to both the pile-up and deadtime. Based on the assumption that the arrival time of events in the spectrometer is stochastically distributed based on an exponential distribution, and the assumption of the stationary process with a stable input rate n, Pomme modeled each electronic pulse with a finite width, τ_W The count loss mechanism competes with the fixed deadtime imposed (paralyzable or nonparalyzable) on every counted event and combination of pile-up and deadtime can be seen as equivalent to a series arrangement. Further, the model calculates the average output rates for a cascade of pile-up with nonparalyzable deadtime:

$$m = \frac{n}{e^{n\tau_w} + n\max(0, \tau_N - \tau_W)} \tag{10}$$

and for pile-up with paralyzable deadtime:

$$m = ne^{-n\tau_w}(1 - P_{loss}) \tag{11}$$

where,

$$P_{loss} = -\sum_{j=1}^{J} \frac{[-n(\tau_P - j\tau_W)]^j}{j!} \tag{12}$$

In addition, Pomme calculated the error caused by the cascade effect on the loss-corrected count rate. This calculation can be done in either of two ways; measurement can be made in 'live time mode' while relying on the obtained real-time-to-live-time correction factor, or, they can be made by working in 'real-time mode' and explicitly using the inverse throughput formula. However, Pomme makes paralyzing deadtime and nonparalyzing deadtime assumptions to calculate the system dead-time while these are the two extreme cases for deadtime determination. How to deal with a more realistic deadtime model for this analysis is not yet clear.

The method proposed by Galushka, and reviewed by J.W. Muller [33], can be applied for online correction of counts lost due to deadtime. The deadtime losses are restored based on the assumptions that the incoming pulses from the detector are purely Poisonion, and that the deadtime remains constant and is of the nonparalyzable type. Fig. 10 shows the arrangement of incoming arrivals with fixed deadtime τ.

If one removes the observed sequence T_1, T_2, …of arrival times along with the corresponding paralysis duration, a new sequence (b) of arrivals:

$$t_k = \sum_{j=1}^{K} \delta_j \tag{13}$$

is obtained, such that t_k itself is a Poisson process. The losses in this method can be estimated based on a logical circuit that fits the new series t_k (for K occurrences) into the fixed deadtime as lost events in the original Poisson process. Based on this correction, additional pulses can be electronically added to the counting circuit to compensate for the lost pulses.

However, if the artificially added pulses are a significant fraction of the total corrected count rate, then the new averages are no longer independent events. Thus the accuracy of the output becomes doubtful. Moreover, there may be issues with averaging the count rates, i.e., imprecise correction factors. Care must be taken to use appropriate observation intervals to determine average arrival interval. Further, Galushka's method is not applicable to fast varying sources (e.g., fast build up or decaying isotopes) with sharp rise and fall behavior. Since the correction pulses are generated based on the observation of the previous averaging time, therefore the correction circuit may under-correct or over-correct around the peaking point and thus introducing additional errors in the final corrected count rates. This shortcoming can be corrected by additional level of checks for the count loss correction data. After the actual logical circuit proposed by Galushka, one can introduce additional circuit to compare the original count with the corrected count rate to make adjustment for any over/under compensation for fast varying source.

Galushka's method has not so far been given the attention that it deserves. Muller suggested that Galushka's method cannot be applied to paralyzable deadtime. This limitation may not be a true limitation, however further work is needed to investigate the feasibility of extending Galushka's method for paralyzing deadtime. Incorporating a known expression of extendable deadtime, which could depend on count rate and using the extendable deadtime for all corrections may be a plausible solution to the limitation. Likewise, as Muller [33] pointed out, Galushka's method compromises on accuracy, however additional research can possibly overcome some of these deficiencies. Exact accuracy compromise will depend on two factors; fraction of the artificially added pulses and the decaying nature of source.

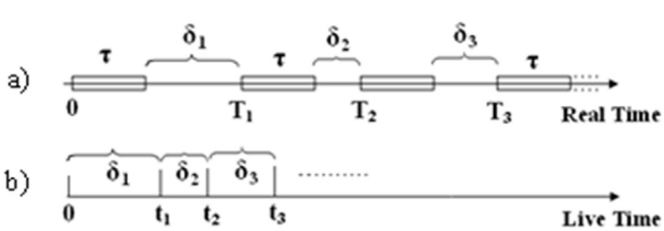

Fig. 10. (a) The observed arrival times T_j followed by a deadtime, τ (b) the corresponding Poisson process t_j.

5. Methods and techniques for measuring instrumentation deadtime

In the previous section some important methods and techniques were discussed which are used to measure the overall deadtime of the entire measurement system. Deadtime of the entire measurement includes not only the deadtime introduced in the detector while generating these random pulses but also the additional deadtime introduced in the electronic pulse processing. This last section will focus on the techniques and methods developed to determine the deadtime of the electronics. One can interpret this as the post detector deadtime. The two-source method discussed in previous section was modified by Baerg [34] with the use of a source-pulser combination. Muller [35] later developed a technique with the use of two pulse generators for better deadtime characterizations. Another variation of the two-source method was proposed by Schonfeld and Janssen [36], in which electronic switches were used to keep the source geometry fixed, to achieve ideal measurement conditions. Vinagre and Conde [37] developed a method for instrumentation deadtime measurements based on introducing variable delays between the true pulses from a detector and generated ones from a pulser, to measure the output count rate and corresponding deadtimes. Another pulser based technique was introduced by Strauss and co-workers [38], who developed a solid-state pulse generator along with electronic circuitry to count logic pulses for true and observed radiation events. It is important to note that the deadtime calculated with all the methods described below is only for the instrumentation deadtime and one is required to add the detector deadtime to obtain the overall deadtime of the counting system.

Baerg [34] proposed the modified source-generator method (MSGM), which is one of the earlier methods of instrumentation deadtime measurement using a variation of the two-source method. His technique replaces one of the sources with a periodic pulse generator which is connected to the amplifier along with the signal from the detector. As a result of using one artificial pulse, the combined probability of counting is determined by the random pulse interval distribution which is originating from the lone source. By counting the random pulse alone and then in combination with the periodic pulses gives two simultaneous equations which can then be solved for deadtime. If the periodic pulse rate is m_p^0 and random source rate is m_r, and the total counting rate is m_{rp}, then the deadtime can be expressed as;

$$\tau = \frac{1}{m_r}\left[1 - \left(\frac{m_{rp} - m_r}{m_p^0}\right)^{\frac{1}{2}}\right]. \tag{14}$$

The two-source method was derived only for nonparalyzing deadtime, however, with proper modifications the MSGM can be extended for paralyzable deadtimes. In addition, this method has two advantages; first, it requires no special sources and, second, since only one source is required and because it remains fixed during the course of measurement, no uncertainty arises from its positioning. It is however important to note that the pulse repetition rate of the pulse generator must be stable and the pulses generated must be of identical in shape and size to the detector pulses.

In a similar approach, called the Source-Pulser method [39,40] the input pulse train, which is the superposition of pulses from a source and from an oscillator is fed into the preamplifier test input.

The numerical value of the deadtime for paralyzable and non-paralyzable systems can be calculated by this technique. It is observed that the superposition of regularly spaced pulses with the ones from the source, gives rise to some complicated interval densities. Other researchers [41,42], have treated the problem rigorously and derived the corrections applicable for the non-paralyzable case.

The two-oscillator method proposed by Muller [43,44] mixes the periodic pulses of two entirely independent quartz oscillators and feeds the combined pulse to the deadtime unit. The frequencies need to be as high as possible while being smaller than one half of the reciprocal of the deadtime ($\upsilon < 1/(2\tau)$). In addition, the difference between the frequencies of the two oscillators should be small. The simplified expression for deadtime for this case is given by;

$$\tau \frac{(m_1 + m_2 - m_s)t}{2m_1 m_2} \tag{15}$$

where, m_1, m_2, and m_s are the count rates in the singles and sum channel for time interval t. The main advantages of this approach are its simplicity and accuracy. The fact that no radiation detector is involved here, the impact of background or noise is avoided, because of which the final expression is much simplified unlike the two source method with background term contributing to uncertainty. This method can also be a used as a check for extendable deadtime, by using variable frequencies and measuring the deadtime.

Schonfeld and Janssen [36] have modified the two-source method, calling it the modified two-source method (MTSM). This method uses two detectors with two fixed sources, and switches S_1 and S_2 for singles and sum counting. Measurements are taken with three different switch combinations yielding seven count rates. Based on the ratios of obtained count rates the simplified expression for deadtime is given as;

$$\tau = \frac{1}{m_s}\left\{1 - \left[1 - \frac{m_s}{m_1 m_2}(m_1 + m_2 - m_s)\right]^{1/2}\right\}. \tag{16}$$

where m_1, m_2, and m_s are count rates obtained by operating the switches in different positions.

This method, overcomes the some of the problems arising due to counting statistics and scattering because of the geometry at the cost of some extra instrumentation. Each of the seven measurements for the count rates have some inherent uncertainty associated with it. With the ratios taken to arrive at the deadtime, the error must be propagated. Care must be taken to check each individual unit, especially the known deadtime circuit before the experiment is conducted.

Vinagre and Conde [37] have suggested a method to measure the effective deadtime of a counting system based on the artificial piling-up of the detector pulses with electronic pulses delayed by a specific time interval. This method is different from the pulser method described above in that here the deadtime is estimated based on time correlation between the pulses from the detector and those from the pulse generator. In the experiment, signal from the detector is passed through a preamplifier and a linear amplifier. A pulse discriminator then converts it to logic pulse (free of noise) and it further goes to an electronic counter or gets processed through an MCA. The pulse rate at the output is measured as a function of the delay introduced between the detector pulses and the electronically generated pulses.

For no delay the pulses are summed and the counting system cannot resolve the electronic pulses from the detector pulses. By increasing the delay beyond the system effective deadtime, the measured count rate increases quickly as the counting system is capable of resolving the events. The effective deadtime is obtained from the point where the count rate is the mean of the maximum and minimum total count rate. This method can be applied to most counting systems using a radiation detector. It cannot be applied to the cases in which the detector itself has a large intrinsic deadtime. The effect of this instrumentation (uncertainty with each unit) on the deadtime measurements should also be analyzed.

There are many variations for measuring the instrumentation deadtime and one such approach makes the correction with the insertion of an electronic unit with a fixed deadtime in the analog or digital part of the signal chain. The basic requirement for this technique is that the inserted deadtime must be longer than the deadtime of any other unit of chain [45,46]. Other variation of the source-pulse technique discussed above is known as the pulser method which mixes the pulses from an electronic pulse generator with detector pulses [47–49]. Additional procedures to deal with deadtime involve the detection of pile-up pulses with electronic PUR (Pile-Up Rejecters) [50,51] circuits or their correction using digital-processing techniques [52].

The pulser technique with event tagging proposed by Strauss and co-workers [38] uses a pulse generator of known repetition rate. The pulser input is mixed with the pulses coming from the detector at the preamplifier which is followed by a multichannel spectroscopy system. A pulse selector unit is used which sends logic signal to the scaler with an AND gate. When a busy signal is sent by the pulse selector the scaler does not record the count. Therefore it only counts the observed events during the AND gate and rejects events when the system is busy. Another scaler is used to count the original incoming events into the preamplifier. The fractional difference between the count rates of the two scalers gives the overall deadtime estimate. In this method care must be taken that the events in the AND gate from MCA and pulser coincide well within a short time interval for true data collection. Alternatively an OR gate could be used instead of the AND gate to count for the sum of original and observed count rate in one of the scalers for deadtime calculation. While this method is very straightforward, it misses out on accounting for the deadtime arising from the detector, which the user will need to calculate separately to find the total detection system deadtime.

Another significant development in this area has been the ability to post process the spectral information and the deconvolution [53] techniques. For example, Gamma Detector Response and Analysis Software (GADRAS-DRF) [54] is one such effort from Sandia National Laboratories (SNL). Advanced Synthetically Enhanced Detector Resolution Algorithm (ASEDRA, also from SNL) [54] is capable of synthetically enhancing the raw spectral data's resolution. Implementing high tech noise reduction and Monte Carlo based detector response functions are also being utilized in modern radiation detection system to improve the data quality. The software performs a differential spectrum attribution to reconstruct the spectrum and cumulative extraction ensures proper representation of the raw data. These computational approaches are based on developing detector response function (DRF) and using DRF to compute spectral response for the gamma-ray detector. This synthesized technique is enable fast and accurate and offer a powerful tool for radiation measurements.

6. Conclusion

Years of research on deadtime has produced new models and techniques to clarify our understanding of the subject of deadtime and pile-up. By knowing the system deadtime along with pulse pile-up, one can easily find the losses occurred in a given interval of time and estimate the original count rate. The traditional one parameter models for deadtime determination are becoming increasingly insufficient in modeling the count loss behavior. Thus there is a need for a more realistic generalized model which better characterizes the detector deadtime. The concept of a two parameter generalized deadtime, which has been introduced decades ago by Albert and Nelson [18] and Muller [20], has however not been embraced by the community because of the challenges in its application. The main issue in the realization of a generalized deadtime remains the development of measurement techniques, to estimate the two parameters. Some of the recent studies [22–25] have developed generalized models and techniques to estimate a total deadtime for a detection system. It is generally agreed that no real world detector is ideally paralyzing or nonparalysing. Therefore, the need for hybrid model is obvious. However, the available hybrid model had failed in the area of providing tools and techniques for the users to estimate the additional parameters. Use of these hybrid models for deadtime correction will significantly extend the operational range of the available detectors.

For many applications the bottleneck in pulse counting occurs in the electronics and instrumentation part of the detection system. A number of methods are available to determine the deadtime and pile-up caused by the instrumentation systems. The pioneering work of Pomme [30–32] and others have shown the possibility of having deadtime and pile-up occur in cascades, and given methods to correct for count losses due to such a phenomenon. Many studies have assumed a pure Poisson distribution at the input of the electronic devices in calculation of the instrumentation deadtime. This assumption made by many researchers is incorrect, as presence of deadtime in the previous electronic modules and the detector itself may change the original Poisson distribution from the radioactive source. There are only a few researchers who have incorporated this fact, therefore one needs to take note of this while estimating the count loss. In addition, for many application users must identify the distinction between the deadtime and pile-up as it is not obvious. And in some cases the naïve user incorrectly believes that MCA live-time correction is capable of correcting all types of deadtime losses. Thus one must thoroughly understand the working of every single unit in a detection system before making any kind of assumptions to estimate the systems' deadtime.

Nomenclature

N	True count rate
M	Observed count rate
τ	Deadtime
τ_P	Paralyzing deadtime
τ_N	Nonparalyzing deadtime
τ_W	Pulse width
f	Paralysis factor
θ	Probability of paralyzing

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