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Dead time and count loss determination for radiation detection systems in high count rate applications

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DEAD TIME AND COUNT LOSS DETERMINATION FOR RADIATION DETECTION SYSTEMS IN HIGH COUNT RATE APPLICATIONS

by

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ABSTRACT

This research is focused on dead time and the subsequent count loss estimation in radiation detection systems. The dead time is the minimum amount of time required between two events to permit detection of those events individually by a radiation detection system. If events occur during the system dead time, they are lost. Such lost information can be important in many applications including high-precision spectroscopy, positron emission tomography (PET), and the scanning of spent nuclear fuel. Understanding of the behavior of radiation detection systems is important; thus this work included a comprehensive review of dead time and pulse pile-up models and methods. The most common way to estimate detector dead time is by one-parameter approximations known as nonparalyzable and paralyzable models. This research proposes a two parameter model that estimates the detector paralysis factor and the dead time based on a graphical method. To determine the two parameters characteristics of a detection system, this work tested a novel technique to saturate the detector using a decaying source. The modified decaying source method, unlike other methods, does not assume the idealized behavior of detection system in use and calculates the overall dead time of the detection system. The paralysis factor for high purity germanium detection system was estimated approaching 100% and the dead time was on the order of 5-10 μs which compares well with the literature.

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LIST OF ILLUSTRATIONS

NOMENCLATURE

Symbol	Description
n	True count rate
m	Observed count rate
τ	Dead time
τ_P	Paralyzable dead time
τ_N	Nonparalyzable dead time
τ_W	Pulse width
f	Paralysis factor
θ	Probability of paralyzing
λ	Radioactive decay constant
P_{loss}	Probability of count loss
υ	Frequency of quartz oscillator
δ_j	Interval between events

SECTION

1. INTRODUCTION

Every radiation detection system is inherently limited by dead time and high-count-rate applications are especially affected. Detection system dead time is defined as the time required by the system to process one event before it is ready to process another. Events that occur during the dead time are lost. For low-count-rate applications, detection systems can process most of the radiation events without much loss; however, in applications involving a higher rate of incoming radiation, detection systems can lose a significant amount of data. To assess the losses that occur in a detection system, the overall dead time of the counting system must first be determined. This information can become crucial in applications such as spent fuel scanning and positron-emission tomography (PET). In spent fuel scanning, the objective is to analyze the data obtained from the energy spectrum to estimate the quantities of various isotopes present. The data collected are those events remaining after the dead time losses, and for a better analysis, the lost counts should be added to the observed data. Similarly in PET systems, the knowledge of system dead time is important for accurate analysis.

Researchers have been interested in dead time and the count loss phenomenon since the early forties, and this research is still continuing due to the need for carrying out the measurements at higher count rates and the demand for higher accuracy. Many models have been developed that predict count loss behavior. Further, various methods have been developed to calculate a detection system's dead time, to correct the count rate loss, and to estimate the original count rate data. The motivation behind such research was originally to gain a sound understanding of the operation of detection systems at high-count-rate applications and to characterize detection systems effectively in terms of generalized dead-time models. Following is a summary of the two articles written to better understand the characteristics of radiation detection systems, with a focus on dead time determination and count loss correction.

1.1 RADIATION DETECTOR DEAD TIME AND PULSE PILE-UP - A STATUS OF THE SCIENCE

Since the early days of radiation measurement, researchers have been interested in the true behavior of counting systems. Over time, as the field progressed and new detection systems were invented, the demand for better accuracy has grown steadily. Continued interest in this field has produced hundreds of research papers on count loss correction and dead time measurement. An attempt has been made to gather some of the most important models, methods and techniques, which are scattered all around in the form of journal articles and books, and to compile them in one place for the ease of an interested user. While the list of publications in this area is huge (few hundred), the authors have tried to select the most important works, divided them into three main categories of: 1) dead time models, 2) methods and correction techniques for overall dead time of counting system, and 3) methods for estimation of instrumentation dead time. Each of model and measurement technique is described, with their applications and limitations noted.

1.2 MEASUREMENT AND APPLICATION OF PARALYSIS FACTOR FOR IMPROVED DETECTOR DEAD TIME

The idealized one-parameter dead time models (i.e., the paralyzable and nonparalyzable models) are inadequate to properly model the dead time response of a detection system. To address this deficiency, this work developed a two-parameter dead time model based on a more realistic hybrid model. The two parameters used in this model are the paralysis factor (f) and the total dead time (τ) of a detection system. The paralysis factor is a novel concept that characterizes a detection system. It varies from 0 to 1, where zero means that the detection system is nonparalyzable, and 1 indicates that it is completely paralyzable.

This measurement method uses a modified decaying source technique that relies on a high count rate, fast decaying source. The high count rate saturates the detector initially, and it is followed by an increase in count rate up to a peak and then a decrease. This characteristic rise and fall of count rate behavior is exploited to estimate the paralysis factor and dead time of the detection system. This model has advantage over other dead-time models in that it makes no initial approximations about the detection system type, and it estimates the overall dead time of the whole detection system.

PAPER

1. RADIATION DETECTOR DEAD TIME AND PULSE PILE-UP - A STATUS OF THE SCHENCE

Amol Patil and Shoaib Usman

ABSTRACT: Since the early forties, researchers from around the world have been studying the phenomenon of dead time in radiation detectors. Many have attempted to develop models to represent this phenomenon; so far, however, there is no general agreement on the applicability of any given model for a specific detector under specific operating conditions. Further, the related problem of pile-up is often confused with the dead time phenomenon. Much work, therefore, 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 dead-time count loss, and much research has addressed dead time and pulse pile-up. The modest goal of this article is to summarize the measurement and compensation techniques proposed in some of the most significant work on these topics and to review the dead time correction models applicable to present day radiation detection systems.

Index Terms—Dead-time, nonparalyzable, paralyzable, resolving time

I. INTRODUCTION

The counting of pulses, in a random process is inevitably 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 events. In some cases, the limiting time may be determined by processes in the detector itself, and in most other cases the limit arises from the associated electronics. This minimum time separation is usually called the *dead time* (or resolving time) of the counting system [i]. The total dead time of a detection system is usually due to the intrinsic dead time of the detector (e.g., the drift time in a gas detector), the analog front end (e.g., the shaping time of a spectroscopy amplifier), and the data acquisition process (e.g., the conversion time of ADCs, or the readout and storage times). Thus, there is a need for correction on 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 analogue to digital conversion time. It is possible to correct for counting losses only if both the nature of the original process and the effects of dead time are clearly understood. A typical pulse counting system is shown in Figure 1 which also gives an overview of the dead time associated with various units. In most detectors a small pulse lasting for only a fraction of a micro second 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 micro-second) 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 is generally needed for any high count rate application.

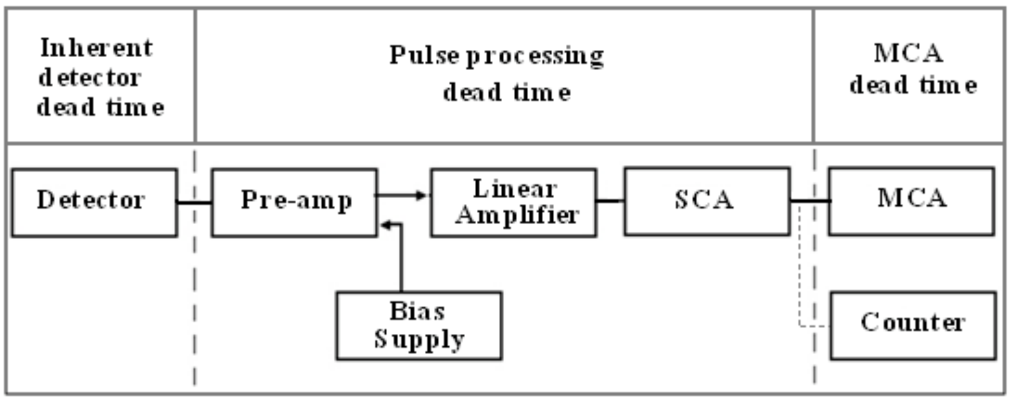

Figure 1. Sources of dead time in a typical detection system

To avoid ballistic deficit, the shaping time constant of the amplified pulse must be significantly larger than the rise time of the tailed pulse otherwise the amplitude 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 close to each other producing a combined pulse of summed amplitude. This situation is referred as the peak pile-up (Figure 2). The basic difference between the dead time and the pile-up is the fact that in pile-up summed pulse is produced when two pulses combine leading to energy resolution as well as count rate degradation. In case of dead time, the second pulse is lost without any energy degradation of the first pulse. In the literature both these problem are often mixed up.

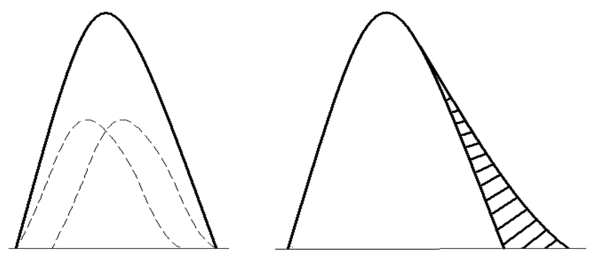

Figure 2. Pulse pile-up

In most high count rate situation both dead time as well as pile-up problems are possible. As Evans [ii] 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 to successive pulses until a time interval equal to or greater than its dead time, 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. Thus the detection system causes a loss of counts and distorts the distribution. Evans elegantly explains that the radiation counter systems do not actually count the nuclear events but the intervals between such events. This is an entirely different way of looking at the counting process in a detection system.

Figure 1 shows a typical counting system where each unit can possibly add some dead time and contribute towards the overall dead time and loss of counts. Identification of the individual contribution to the total dead time helps in recognizing the bottleneck areas of the counting system and devising measures to correct the count loss accordingly. The relative contribution of each component can significantly vary depending on the component design and operating conditions.

Detector is first unit in the counting system. As discussed in section II, depending on the choice of detector, a wide variation of detector dead time is observed. For Geiger-Muller (GM) counters, the detector dead time contribution is perhaps the most significant within the entire counting system. Detector pulses are only a fraction of a microsecond wide [1]. However, for extremely high count rates (exceeding million counts per second) it is foreseeable that these pulses may over ride each other and lead to the problem of pile-up. In most cases however, dead time is the primary concern arising from a detector. In some cases the detector is able to produce pulses at a much faster rate than the subsequent instrumentation can process and in such cases the instrumentation determines the overall dead time 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. It's main purpose, however, is to maximize the signal to noise ratio. The pulses from a preamplifier are long tail pulses with short rise time and a fall time of tens of microsecond to ensure full collection for charge from the detector.

In the shaping stage of the pulse processing, the problem of pile-up introduced in the preamplifier is removed. However, at high count rates some piled-up pulses may reach the preamplifier saturation limit. This situation results in the degradation of energy resolution.

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 to 10 volts. 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, a dead time is also associated with the amplified pulse, which is of the same order as the width of the shaped pulse and is only a few microseconds [1]. 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.

The SCA (Single Channel Analyzer) is not a major contributor to the dead time problem of the counting system. A total of 1-2 micro-second dead time is added because of their functioning [1]. Modern counters, another unit in counting chain, have even smaller dead time associated with them. For example ORTEC 994 [iii] counter reports a dead time for paired pulses of 10-40 nanosecond.

MCA or Multi Channel Analyzer is the next major contributor to the dead time in the counting system. Based on their design, MCA's can produce pile-up and/or dead time. The main contributor to the dead time in an MCA is the ADC or Analog to Digital Converter. The dead time 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 dead time by counting for a longer duration of time (live time) than the clock time. It is however important to point out the auto correction is only limited to the dead time associated with the MCA. MCA electronics is not capable of de-convoluting two or more piled-up pulses or correct for the dead time initiated in the detector.

Muller [iv] has complied a comprehensive bibliography on radiation measurement system's dead time 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 dead time 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 dead time and pile-up associated with measurement system. Rather, the authors have tried to present most prevalent and useful methods in this area.

The next section (II) discusses the physical phenomenon responsible for the occurrence of dead time in various detectors followed by major models for system dead time in section III. Section IV reviews the common methods for measuring system's dead time followed by a section devoted to dead time and pile-up measurement of electronic instrumentation.

II. PHYSICAL PHENOMENON OF DEAD TIME

Detector design, geometry and material can significantly impact the phenomenon of dead time 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. This section discusses the physical phenomena of dead time and pile-up in major radiation detectors.

A. GAS FILLED DETECTORS

In a gas filled detector, when an electron-ion pair is produced (say in a G-M tube) by radiation, the electron is accelerated toward the anode creating a cascade of secondary ionization leading to what is called as Townsend avalanches [i]. In G-M counter this avalanche propagates along the anode wire at the rate of 2-4 cm/micro-second [v] and eventually envelopes the entire anode. Collection of all the negative charge results in 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. Obviously one would also expect pressure, temperature and 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 any pulse height resolution degradation. 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 counting system. Therefore G-M counters are prone to dead time count losses. Duration of dead time will again depend on; the detector geometry, fill gas properties and operating condition of pressure, temperature and voltage.

Figure 3 illustrates the dead time, resolving time and recovery time of a GM 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 more dilute. There is a minimum electric field necessary to collect the negative charge and produce any pulse in the tube. By strict definition, dead time 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 dead time the electric field gradually recovers and the amplitude of the second pulse is hampered by the presence of the lingering positive charge, therefore immediately after the dead time if a second pulse is produced, its amplitude will be reduced.

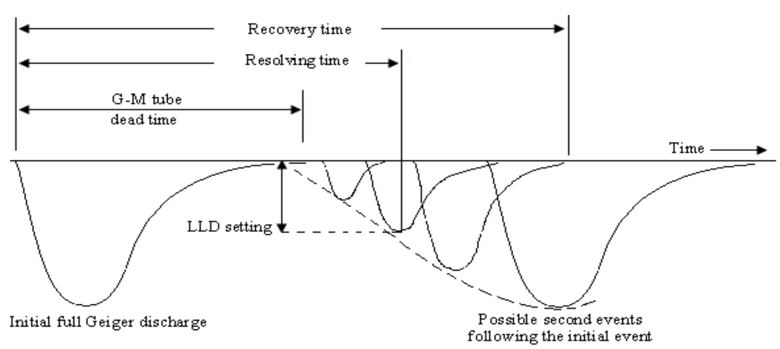

Figure 3. Dead time representation of a G-M detector

A minimum amplitude for the second pulse is needed for it to pass through the discrimination threshold and be recorded. The time needed between the two pulses to produce this minimum amplitude second pulse is called as the resolving time of the detector system. Since the true dead time is impossible to measure, resolving time is often referred to as dead time 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 the full amplitude pulse is called as the recovery time of the detection system. Typically, the dead time for a GM detector is on the order of hundreds of micro-seconds [i].

In proportional counters the avalanche is local, i.e. not engulfing the complete anode wire. The production of initial ion pair and its subsequent multiplication is proportional to the 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 pile- up with the first pulse producing a summed pulse degrading the energy resolution. Likewise, if the second event takes place before all the positive ions are neutralized, the amplitude of the second pulse will be reduced, again leading to degradation of the energy resolution. Therefore for proportional counter it is more of a pile-up problem than that of dead time.

B. 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 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 photon/light emission (Figure 4). Detailed discussion of scintillation process is beyond the scope of this paper. Interested readers are referred to the literature [vi,vii].

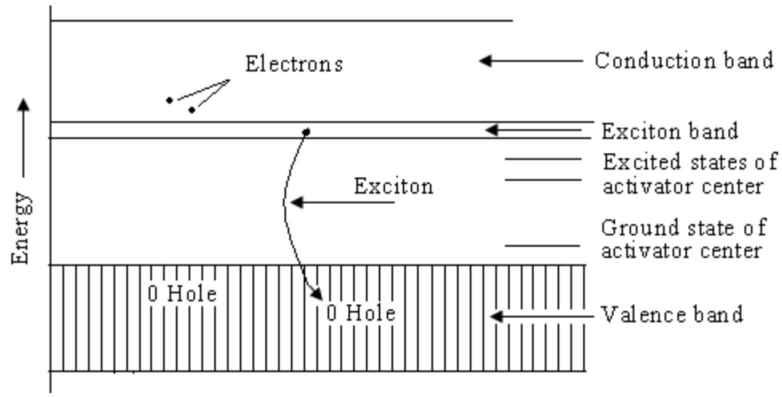

Figure 4. Energy band structure for semiconductor crystal

There is some 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 [viii,ix] have reported large variability in the performance of inorganic scintillators. In case of scintillators if the second interaction is within the dead time 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 it is 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 a small decay constant in the range of nano-seconds (e.g. Anthracene solvent has a decay time constant of only 3.68ns [x]) and are well suited for high intensity measurements. For scintillators, in general, the problem of 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. Furthermore additional dead time 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 dead time [1]. Proper choices of PMT electronics and operation conditions are required to optimize the system for high count rate applications.

C. SEMICONDUCTOR DETECTORS

Semiconductor detector operation is based on collection of charge carried by electron and holes, which are produced due to radiation interaction. 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 [xi]. Therefore for a typical detector the charge collection time is just a fraction of a micro-second [i].

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 dead time 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 (Figure 5). Therefore detector geometry, operating voltage, and temperature play important role in pile-up time for a semiconductor detector.

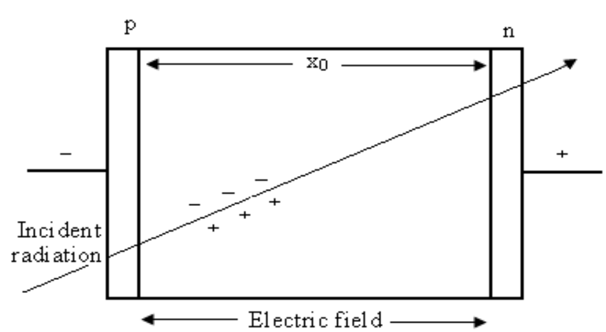

Figure 5. A p-n junction with reverse bias as a semiconductor detector

III. DEAD TIME MODELS

Over the last sixty years many researchers have proposed models to correct for dead time. 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 [xii], 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. Feller [xiii] and Evans [ii] have developed the two basic types of idealized models for dead time, 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;

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

The nonparalyzable or the type I detector system is non-extending and is not affected by events which occur during its recovery time (dead time) 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 $m\tau$. 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;

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

or $$n = \frac{m}{1-m\tau}. \qquad \textbf{(3)}$$

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

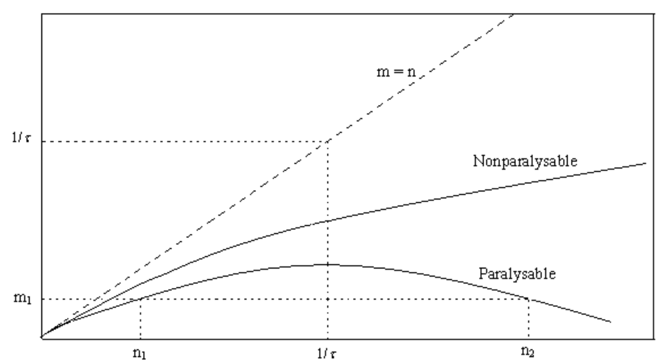

Figure 6. Paralyzable and nonparalyzable models of dead time

Feller [xiii] while proposing the idealized dead time 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 Figure 7. The first attempt to develop a generalized dead time model was reported by Albert and Nelson [xiv]. 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 dead time model, only a fraction θ of all incoming events are capable of triggering an extension of the dead time. For the extreme case, θ=1, the model approaches Type II (paralyzable). For the other extreme, θ=0, the model becomes type I (nonparalyzable).

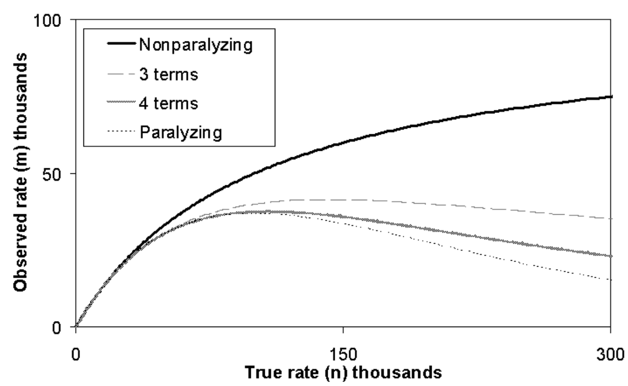

Figure 7. Taylor expansion of paralyzable model

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

$$m = \frac{n\theta}{e^{\theta n\tau} + \theta - 1} \quad \textbf{(4)}$$

where τ is the generalized dead time and θ is the probability of paralysis.

Another representation of this development is presented by Lee and Gardner [xix] who made use of two independent dead times. The hybrid model proposed by them;

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

makes use of the paralyzable dead time τ_P and the nonparalyzable dead time τ_N. Least square fitting of the data obtained from the decaying of Mn^{56} source, they obtained the two required dead times for a GM counter. While in their discussion the order of the two dead times was alluded, but not identified precisely. It appears that for G-M counter they placed a nonparalyzable dead time before the paralyzable dead time. They did not offer any justification for this order of the two dead times. Obviously one would expect a significant change in the dead time behavior if the order of the two dead times were reversed. The hybrid model is a good application of the generalization originally proposed by Albert and Nelson [xiv]. However, Lee and Gardner did not offer any practical method to determine the two dead times.

Patil and Usman [xx] presented a graphical technique to obtain the two parameters for a generalized dead time model using data from a fast decaying source. They offered a simple modification to the hybrid model [xix] simplifying it back to another form of the original Takacs equation (equation 4);

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

In their paper, Patil and Usman, referred to the probability of paralyzing as the paralysis factor (f). Measurements were made to obtain the paralysis factor and the dead time for an HPGe detector. Using the graphical technique they found the dead time of 5-10 micro-second and the paralysis factor approaching unity.

Hasegawa and co-workers [xxi] 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. This way 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,

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

For a fast system clock there can be significant improvement in the counting efficiency. This model is considered to be of the nonparalyzable kind, however, by relying on the system clock it counts more than a standard nonparalyzable model.

IV. DETECTION SYSTEM DEAD TIME MEASUREMENT AND CORRECTION METHODS

One of the simplest methods of estimating the overall dead time of a counting system is the two-source method originally developed by Moon [xxii] and later incorporated in the work of other researchers [xxiii, xxiv]. This 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 were counted individually and the dead time can be counted from the difference.

The advantage of the two-source method is that it uses observed data to predict the dead time. 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 dead time.

Repeating well-defined geometry is necessary to measure dead time using two-source method which might be difficult in some situations. A dummy source is used to replicate the exact geometry when counting the sources individually. Likewise if the background is not negligible the algebraic expression for the dead time 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 dead time of detection system [i]. 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:

$$n = n_0 e^{-\lambda t} + n_b \quad \textbf{(8)}$$

where 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 i.e., $n - m = nm\tau$, one obtains:

$$me^{\lambda t} = -n_0 \tau m + n_0 . \quad \textbf{(9)}$$

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 can be obtained by finding the intercept of the straight line with the y-axis (Figure 8). Finally the dead time 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 would be $-n_0\tau$ and the intercept is $\ln n_0$.

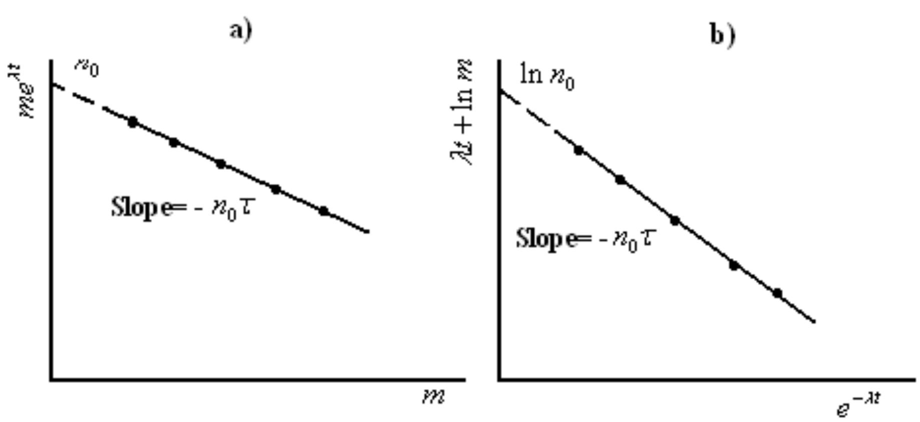

Figure 8. Decaying source method for (a) nonparalyzable and (b) paralyzable model

The decaying source model has the advantage of not only measuring the value of dead time, but also testing the validity of the idealized paralyzable and nonparalyzable models. However, care should be taken that the isotope used for this technique is 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. The half-life of the decaying isotope must be known with good accurately. A disadvantage of this method is that it takes a long time for dead time determination. Yi and coworkers recently applied the decaying source method for calibrating dose rate meters [xxv] 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 measurement. 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 [xx] contributed to the effort by proposing a modified decaying source method to measure the two detector parameters i.e., the dead time 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 (Figure 9) shows the characteristic rise and fall behavior as the source decays away.

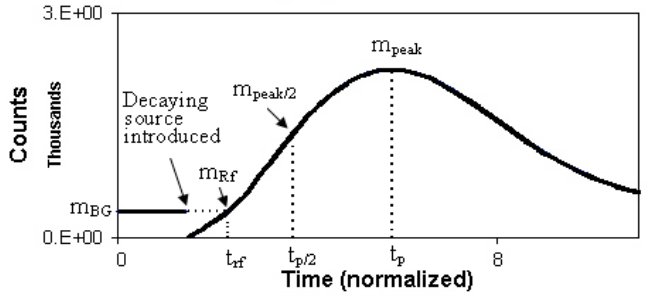

Figure 9. Characteristic decay of V^{52} with HPGe counting system

The two variables in equation 6 were introduced: the total dead time of detection system τ and the paralysis factor f, which is a property of a detector system and tells about the amount of paralysis present.

The paralysis factor for a detection system is the ratio of paralyzable-to-total-dead-time. 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 method has advantage over other methods that in the calculation of dead time, there is no assumption made about the kind of model associated i.e., paralyzable or nonparalyzable. Further, this technique, which can be used at high counting rates, calculates the overall dead time for the detection system which includes the radiation detector.

Pomme [xxvi, xxvii, xxviii] has contributed significantly to the study of Pile-up and dead-time. His work addresses the count loss issues in counter systems when pile-up losses and dead-time occur in combinations as a series arrangement of dead-time. In this work, a counter is injected with artificial dead time (paralyzable and nonparalyzable) for every counted event to calculate the count losses and errors arising due to both the pile-up and dead time. 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 dead time imposed (paralyzable or nonparalyzable) on every counted event and combination of pile-up and dead time 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 dead time:

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

and for pile-up with paralyzable dead time:

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

Where, $$P_{loss} = -\sum_{j=1}^{J} \frac{[-n(\tau_P - j\tau_w)e^{n\tau_w}]^j}{j!}.$$

In addition, Pomme has 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 dead time and nonparalyzing dead time assumptions to calculate the system dead-time while these are the two extreme cases for dead time determination.

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

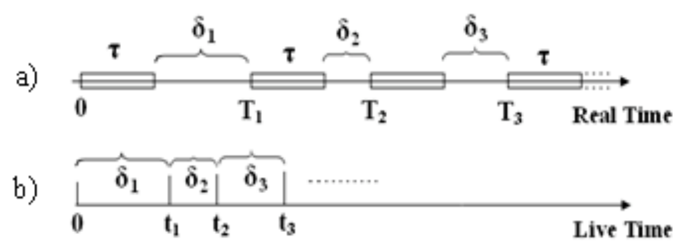

Figure 10. Relationship between (a) the observed arrival times T_j followed by a dead time τ (b) the corresponding Poisson process t_j

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,

$$t_k = \sum_{j=1}^{K} \delta_j \quad \textbf{(12)}$$

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 dead time 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, and care must be taken to use appropriate observation intervals to determine average arrival interval. Further this 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 rate. This shortcoming can be removed by additional level of checks for the count loss correction data. After the actual logical circuit proposed by Galushka, one can have additional circuit to compare between the original count and the corrected count rate to correct for any over/under compensation for fast varying source.

This method has not so far been given the attention that it deserves. Muller suggested that this method cannot be applied to paralyzable dead times. This limitation may not be true and further work is needed to investigate the feasibility of extending this method for paralyzing dead times. Incorporating a known expression of extendable dead time, which could depend on count rate and using the extendable dead time for all corrections may be a plausible solution to the limitation. Likewise, as Muller pointed out this method compromises on accuracy, however additional research can possibly overcome some of these deficiencies.

V. METHODS FOR MEASURING INSTRUMENTATION DEAD TIME

In the previous section some important methods and techniques were discussed which are used to measure the overall dead time of the entire measurement system. Dead time of the entire measurement includes not only the dead time introduced in the detector while generating these random pulses but also the additional dead time introduced in the electronic pulse processing. Techniques and methods have been developed to measure the dead time associated with the electronic components involving pulse processing. This section will briefly discuss a few of those important techniques and methods.

The two-source method discussed in previous section was modified by Baerg [xxx] with the use of a source-pulser combination. Muller [xxxi] later developed a technique with the use of two pulse generators for better dead time characterizations. Another variation of the two-source method was proposed by Schonfeld and Janssen [xxxii], in which electronic switches were used to keep the source geometry fixed, to achieve ideal measurement conditions. Vinagre and Conde [xxxiii] developed a method for instrumentation dead time 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 dead times.

Another pulser based technique was introduced by Strauss and co-workers, [xxxiv] who developed a solid-state pulse generator along with electronic circuitry to count logic pulses for true and observed radiation events. It is to be noted that the dead time calculated with all the methods described below is only the instrumentation dead time and one is required to add the detector dead time to obtain the overall dead time of the counting system.

Baerg [30] proposed the modified source-generator method (MSGM), which is one of the earlier methods of instrumentation dead time 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 a 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 dead time.

If the periodic pulse rate is $m^0{}_p$ and random source rate is m_r, and the total counting rate is m_{rp}, then the dead time can be shown as;

$$\tau = \frac{1}{m_r}\left[1 - \left(\frac{m_{rp} - m_r}{m_p^0}\right)^{\frac{1}{2}}\right]. \tag{13}$$

The two-source method was derived only for nonparalyzing dead times, however, with proper modifications the MSGM can be extended for paralyzable dead times. 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 shape and size from that of the detector.

In a similar approach, called as the Source-Pulser method [xxxv,xxxvi] 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 dead time for paralyzable and nonparalyzable systems can be calculated. It is observed that the superposition of regularly spaced pulses the ones from the source, gives rise to some complicated interval densities. Other researchers [xxxvii,xxxviii] have treated the problem rigorously and derived the corrections applicable for the nonparalyzable case.

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

$$\tau = \frac{(m_1 + m_2 - m_s)t}{2m_1 m_2} \tag{14}$$

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 included. This method can also be a used as a check for extendable dead time, by using variable frequencies and measuring the dead times thus obtained.

Schonfeld and Janssen [32] 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 dead time is given as;

$$\tau = \frac{1}{m_s}\left\{1-\left[1-\frac{m_s}{m_1 m_2}(m_1+m_2-m_s)\right]^{1/2}\right\} \tag{15}$$

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 rate have some inherent uncertainty associated with it. With the ratios taken to arrive at the dead time, the error will further propagate. Thus, care must be taken to check each individual unit, especially the known dead time circuit before the experiment is conducted.

Vinagre and Conde [33] have suggested a method to measure the effective dead time 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 dead time 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 (PA) and a linear amplifier (A). A pulse discriminator then converts it to logic pulse (free of noise) and it further goes to an electronic counter (EC) 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 dead time, the measured count rate increases quickly as the counting system is capable of resolving the events. The effective dead time 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 dead time. The DMP method requires extra instrumentation, and the effect of this instrumentation (uncertainty with each unit) on the dead time measurements should also be analyzed.

There are many variations for measuring the instrumentation dead time and one such approach makes the correction with the insertion of an electronic unit with a fixed dead time in the analog or digital part of the signal chain. The basic requirement for this technique is that the inserted dead time must be longer than the dead time of any other unit of chain [xli,xlii,xliii]. Other variation of the source-pulse technique discussed above is known as the pulser method which uses the pulses from an electronic pulse generator, with known frequency, to mix them with detector pulses [xliv,xlv,xlvi]. Additional procedures to deal with dead time involve the detection of pile-up pulses with electronic PUR (Pile-Up Rejecters) [xlvii,xlviii] circuits or their correction using digital-processing techniques [xlix].

The pulser technique with event tagging proposed by Strauss and co-workers [34] 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 a scaler with 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 contents of the two scalers gives the overall dead time 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 dead time calculation. While this method is straightforward, it misses out on accounting for the dead time arising from the detector, which the user will need to calculate separately to find the total detection system dead time.

VI. CONCLUSION

Years of research on dead time has produced new models and techniques to clarify our understanding of the subject of detection system dead time and pile-up. By knowing the system dead time 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 dead time determination are becoming increasingly insufficient in modeling the true behavior of counts lost. Thus there is a need for a more realistic generalized model which better characterizes the detector dead time. The concept of a two parameter generalized dead time, which has been introduced decades ago by Albert and Nelson [14] and Muller [18], has however not been embraced by the community because of the challenges in its application. The main issue in the realization of a generalized dead time remains the development of measurement techniques, to estimate the two parameters. Some of the recent studies [19, 20] have developed generalized models and techniques to estimate a total dead time for a detection system.

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 dead time and pile-up caused by the instrumentation systems. The pioneering work of Pomme [26] and others have shown the possibility of having dead time and pile-up occur in cascades, and given methods to correct for count losses due to such phenomenon. Many studies have assumed a pure Poisson distribution at the input of the electronic devices in calculation of the instrumentation dead time. This assumption made by many researchers is incorrect, as presence of dead time 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 that are incorporating this fact and one needs to take note of this while estimating the count loss.

In addition, for many application oriented users, the distinction between the dead time and pulse pile-up is not obvious and in some cases the naïve researcher incorrectly believes that MCA live-time correction is capable of correcting all types of dead time losses. The MCA live-time time correction can only correct for the time lost in the analog to digital conversion, and not the losses originating in the detector or electronic modules. Thus one must thoroughly understand the working of every single unit in a detection system before making any kind of assumptions to estimate the detector dead time.

VII. NOMENCLATURE:

n = True count rate

m = Observed count rate

τ = Dead time

τ_P = Paralyzing dead time

τ_N = Nonparalyzing dead time

τ_W = Pulse width

f = Paralysis factor

θ = Probability of paralyzing

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2. MEASUREMENT AND APPLICATION OF PARALYSIS FACTOR FOR IMPROVED DETECTOR DEAD TIME CHARACTERIZATION

Amol Patil, and Shoaib Usman

ABSTRACT: This paper describes the finding of an experimental study to measure detector paralysis factor and the use of this parameter in conjunction with detector dead-time to better model detector dead time response. The idealized one-parameter; paralyzable and non- paralyzable models are inadequate to properly model dead-time response of any real detector system. To address this deficiency, a more realistic two parameter model is proposed which incorporates paralysis factor of the detector in addition to the dead-time. The revised two parameters based model is an extension of Lee and Gardner's two dead-times model. A simple scheme is proposed to deduce these parameters from the recorded data based on rise and drop of count rates from a decaying source. Measurements were made using ^{56}Mn and ^{52}V. The data collected in this study shows that a high purity germanium (HPGe) detector has a paralysis factor of close 50-77% and a dead time of 5-10μs. Using the data collected by Lee and Gardner, the paralysis factor for a Geiger-Muller (G-M) counter is estimated to be approximately 5%. These results are consistent with the approximating assumption that GM counters are non-paralyzable and HPGe detectors are paralyzable.

Index Terms — Dead time Model, Detector Paralysis, Loss of Count Rate, Decaying Source Method, Germanium radiation detectors.

1. INTRODUCTION

All detectors systems under intense radiation environment exhibit count loss due to dead-time. As the name implies, dead-time is an interval of time during which a detector is unable to respond to a new event that would ordinarily produce a count. During this time the detector is said to be 'dead' or 'paralyzed'. Therefore, for every detector system there is a minimum amount of time which must separate two events in order for them to be recorded as two independent events.

The total dead time of a detection system is due to two contributing factors. Firstly, the intrinsic dead-time of the detector itself leads to count loss. This intrinsic dead-time of the detector depends on the physical phenomena involved in radiation interaction and detection. For example, a GM counter could be dead during the charge collection time while positive ions are drifting to the wall and the electrons are being collected at the anode. For a simple counting system this intrinsic dead-time also includes the initial pulse processing in the pre-amplifier and possibly the amplifier unit. Figure 1 demonstrates the sources of dead-time in a typical counting system.

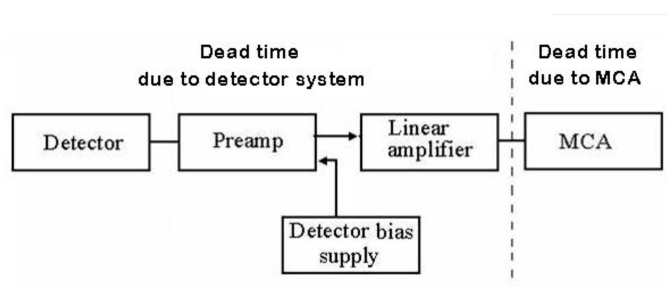

Figure 1. Sources of a counting system's dead time

It is important at this point to discuss the phenomenon of pile-up, which is closely associated with the phenomenon of detector dead-time. Pile-up is the phenomenon when a single pulse is produced as a consequence of two or more events in the detector. Or in other words, multiple pulses are superimposed leading to a 'summed peak' in a spectroscopy system. This results in count loss and degradation of spectrum resolution.

The other source of count loss is due to the finite time associated with pulse processing in the electronics. The most significant contribution in electronic dead-time is from the analog to digital converter (ADC) module for pulse height analysis. Thus there is a need for correction at two different levels, i.e. to correct for the system-circuitry generated losses and the inherent internal losses of the detector itself. With the help of modern electronics and available software systems, circuit dead-time is corrected by measuring for live-time. Live time is the sum of the real-time and the lost time during ADC conversion. Live-time correction will only address the counts lost during the spectral analysis – that is while the MCA is sorting the first pulse to select the correct bin appropriate for its height. During this time if a second pulse is presented by the detector system to the MCA, it will be lost. It is important to point out that live-time correction will not recover the loss of pulses in the detector system. Due to pile-up, pulses presented to MCA are convolution of two or more detector events and no MCA system is able to perform the de-convolution to separate the two or more events responsible for the piled-up pulse. Therefore in addition to live-time correction, the detector observed counts need to be corrected using a suitable model. The central theme of our work is to develop an experimental technique to measure detector system's count loss. This manuscript will present;

a) A revised two parameters model based on paralysis factor and detector dead-time, which is an extension of Lee and Gardner's [1] hybrid model.

b) A practical method to measure paralysis factor and detector dead-time using an intense fast decaying source.

The detector dead-time correction is critical in many medical as well as high precision spectroscopy applications [2, 3]. Likewise, for nuclear reactor application and monitoring of spent fuel, dead-time correction is vitally important [4]. When the detector system is operated in current mode, the effect of dead-time is not as obvious; however, slow and reduced response to radiation intensity changes is the result of detector dead-time in current mode operation.

Detector dead-time has been a topic of interest for more than five decades now. Recently, researchers [5, 6] have proposed dead-time compensation techniques to automatically correct for dead-time losses. However, there is no realistic dead-time model commonly acceptable to the radiation measurement community. Most models presume the detector behavior to be either paralyzable or non-paralyzable [7,8,14,16]. Based on this assumption a dead-time is calculated and correction is applied. The response of any real detector lies in between the two idealized models. This research has developed a method to measure the extent of paralysis. Based on this "paralysis factor," and the detector dead-time, a more realistic two parameter dead-time correction model is proposed. The new model does not require any idealized assumption about the detector being paralyzable or non-paralyzable detector. Therefore, using this new model, detector response can be described in a more precise manner.

2. BACKGROUND – DEAD TIME MODELS AND MEASUREMENT

The non-paralyzable or Type I model given by Feller [7] and Evans [8] is perhaps the simplest and most widely used representation of detector loss of count behavior. This model essentially states that the dead time remains fixed and any events taking place during this time are lost. However, after this fixed duration of time, independent of the number of events lost during the time, the detector fully recovers. Therefore, if 'm' is the observed count rate and 'n' the true count rate then the non-paralyzable model is given as;

$$m = \frac{n}{1 + n \cdot \tau} \quad \text{or} \quad n = \frac{m}{1 - m \cdot \tau} \tag{1}$$

The paralyzable model or the Type II model also proposed by Feller [7] and Evans [8] assume that the duration of paralysis is not fixed but is extendable. The extension in dead-time is dependent on actual count rate. That is, if a second event occurs during the dead-time before the detector is fully recovered, the event will be lost and the paralysis will prolong for another fixed duration of time. Mathematically;

$$m = n \cdot e^{-n \cdot \tau} \tag{2}$$

Both these models are the highly idealized and the response of an actual detector is likely to fall in between the two extremes. Müller [9] showed that an expansion series of the paralyzable equation (2) leads to;

$$n = \frac{m}{1 - m\cdot\tau - \frac{1}{2}(m\cdot\tau)^2 - \frac{2}{3}(m\cdot\tau)^3 - .....} \tag{3}$$

And in fact, the non-paralyzable model is an approximation of the paralyzable model, when only the first two terms are included in the expansion. Response of an actual detector which may fall between the two idealized models can be represented by including an appropriate number of terms in the denominator of equation (3). Figure 2 graphically shows the two idealized models and two approximation including first 4 and first 6 terms of the Taylor's expansion. As Müller [9] concluded, the two traditional dead-time models are arbitrarily chosen mainly for convenience and that the actual experimental results "always fall somewhat in between" the two models. Subsequently, additional efforts are made to develop a more realistic model to describe dead-time behavior of an actual detector. Gardner and Liu [10] studied the feasibility of developing a true count rate dependent dead-time formula. And use of this variable dead-time to estimate the true count rate from the observed count rate. They also reported the inadequacy of the simple idealized models (equation 1 and 2) to predict the actual behavior.

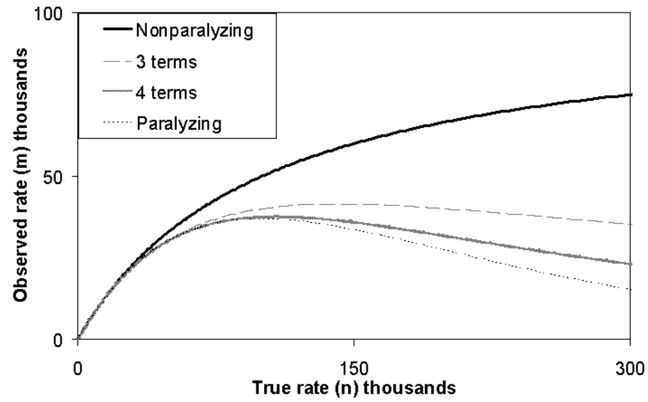

Figure 2. Taylor expansion of paralyzable model

Probably the most notable work to better describe the dead-time behavior is the hybrid model proposed by Lee and Gardner [1]. This two parameter model takes into account both non-paralyzable and paralyzable dead-times. This is the only model so far to have both kinds of dead-times incorporated in the equation;

$$m = \frac{n \cdot e^{-n \cdot \tau_P}}{1 + n \cdot \tau_N} \tag{4}$$

Lee and Gardner [1] applied their new model to study the dead-time behavior of a Geiger-Mueller counter and reported good success in extending the useful range of GM counters.

Several techniques have been developed to measure the dead-time [11, 12] of a detector system. However, most of these techniques require an assumption to be made about the applicability of one of the two idealized models. The two most commonly used methods are; *the two source method* and *the decaying source method* [13, 14]. A single source can also be used at varying distance from the detector to measure the dead-time for a wide range of count rates. However, in view of several practical challenges including; interference from scattered radiation, questionable validity of point source and point detector assumption and the uncertainty in distance measurement, this technique has not been used extensively. Therefore, the two source method and the decaying source method remain the most widely used experimental methods to measure detector dead-time. Gardner and Liu [10] have provided a detailed description of these techniques.

3. MODEL AND MEASUREMENT TECHNIQUE

The hybrid model proposed by Lee and Gardner [1] has many advantages including a sound physical basis for GM counters. We have made a slight modification to this model, that is, instead of using both dead-times for non-paralyzable and paralyzable, i.e. τ_N and τ_P, a single total dead time τ and a '*Paralysis Factor*'- f, is used to model the dead time response;

$$m = \frac{n \cdot e^{-n \cdot f \cdot \tau}}{1 + n \cdot (1 - f) \cdot \tau} \tag{5}$$

The paralysis factor (*f*), is an inherent property of the detector system and is a measure of the dead-time elongation as a consequence of a second or subsequent event. In other words, an ideally paralyzable detector would have f =1 and an ideally non-paralyzable detector will have f =0. Measurement of two dead-times would require careful monitoring of detector recovery process using an oscilloscope and separate observation of the two dead-times (i.e. τ_N and τ_P) under the operating condition.

The advantage of using the paralysis factor based dead-time model over the traditional one parameter models is that no presumption about the detector being ideally paralyzable or non-paralyzable is required before using the raw data to estimate the dead-time.

When a detector is exposed to a fast decaying source, it is observed that after the initial period of absolute paralysis (when the observed count rate is zero), the observed count rate increases to a maximum value before decreasing due to the decaying source. Moreover, the initial rise is highly dependent on the extent of paralysis. In the case of non-paralyzable detector, the increase is rapid and a step increase in count rate is observed. On the other hand, if the detector is paralyzable, a slow increase in the count rate is observed. Moreover, it was observed that the time to reach peak observed count rate, also depends on the decay constant (or half life) of the decaying source.

The typical behavior of a realistic detector is shown in Figure 3. If the initial count rate before the introduction of the fast decaying source was small (i.e. either background or a very weak constant source) and the initial activity of the fast decaying source is strong to ensure absolute paralysis, a drop in count rate will be observed. Depending on the initial strength and the half life of the fast decaying source, the detector will remain completely paralyzed for some duration of time, until the true event rate has reduced to a level that the detector is able to process the information. From this point on, the count rate will increase. The observed count rate will soon become equal to the count rate before the introduction of the fast decaying source (m_{Rf}). The observed count rate will continue to increase till it reaches a maximum value (m_{peak}). Subsequently, the observed count rate will decrease as the fast decaying source diminishes to zero.

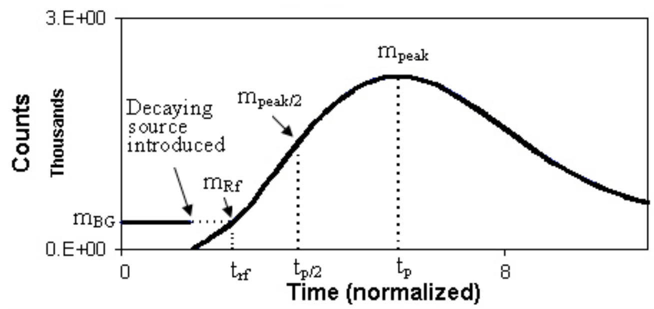

Figure 3. Typical peaking behavior of a realistic detector

This rise and drop of observed count rate can be explained with the help of Figure 4, which shows the effect of true count rate on the observed count rate under the assumption of either ideally paralyzable detector or ideally non-paralyzable detector.

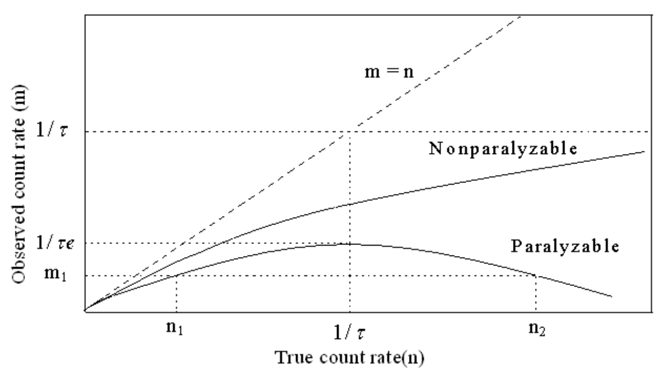

Figure 4. Observed vs. true count rate

The curve in Figure 4 shows that for non-paralyzable detector, an increase in the true count rate will result in an increase in the observed count rate which approaches an asymptotic value of $1/\tau$. The paralyzable detectors exhibit a different behavior. At low count rates, an increase in the true count rate results in an increase in the observed count rate. However, a maximum count rate of $1/(\tau.e)$ is observed when the true count rate is $1/\tau$. If the true count rate is increased further, the observed count rate will decrease. This situation may be referred to as '*over-killing*'. In fact, if the true count rate is extremely high, the detector can be completely paralyzed and no counts would be observed. Likewise, the term '*under-kill*' can be introduced to describe the situation when the true count rate is lower than $1/\tau$ and hence an increase in the true count rate would yield an increase in the observed count rate. Maximum count rate will be observed at the point when the true count rate is exactly $1/\tau$. This point can be referred as the "*peaking point.*'

As suggested by several previous researchers [1, 9, 10] all real detectors are partly paralyzable. It was observed in this research that the rise and drop of the observed count rate with decreasing true count rate is the characteristic of a given detector. Moreover, the rate of rise and fall depends on the extent of paralysis. For an ideal non-paralyzable detector, the rise due to the introduction of a strong source will be instantaneous. While an ideal paralyzable detector will have a much slower response. Depending on the extent of paralysis, the actual detector's behavior falls in between the two ideal cases.

We proposed to make use of this characteristic rise and fall of count rate observed by an actual detector to measure the paralysis factor of the detector in question. In fact, the data collected in the decaying source method is adequate for the purpose of determining the paralysis factor as well as the detector dead-time.

When a decaying source experiment is conducted in the presence of a constant background, (n_{GB}), before the introduction of the decaying source, the observed count rate is;

$$m_{BG} = \frac{n_{GB} \cdot e^{-n_{BG} \cdot f \cdot \tau}}{1 + n_{BG} \cdot (1 - f) \cdot \tau} \tag{6}$$

This would be the case of *under-kill.* When a high-activity, fast-decaying source is then introduced, the detector is *over-killed* and the observed count rate is zero. This over kill situation will continue till the fast decaying source has diminished to a level such that the detector begins to respond. Shortly after this time the observed count rate will return to the background count rate which one could use as a reference count rate (m_{Rf}) which is equal to m_{BG}. However, the true count rate at this point (n_O) is much higher than the background. It is because of the over killing that the observed counts are so small;

$$m_{Rf} = \frac{n_O \cdot e^{-n_O \cdot f \cdot \tau}}{1 + n_O \cdot (1 - f) \cdot \tau} \tag{7}$$

The count rate will continue to increase and will reach the peaking count rate m_p at a true count rate;

$$n_p = n_O \cdot e^{-\lambda \cdot t_p} \tag{8}$$

Where, n_O is the initial true count rate and t_p is the time lapse between n_O and n_p. While λ is the decay constant for the fast decaying source. At this point the observed count rate would be;

$$m_p = \frac{n_p \cdot e^{-n_p \cdot f \cdot \tau}}{1 + n_p \cdot (1-f) \cdot \tau} \tag{9}$$

Moreover, at this peaking point;

$$\frac{dm}{dt} = 0 \tag{10}$$

The above four equations (6, 7, 9 and 10) have four unknowns; n_{BG}, n_O, *f, and*, τ. Therefore, in theory one can solve for the unknowns. Or one could use standard curve fitting techniques to determine the four unknowns using the entire set of data points. However, because of the model being an ill-conditioned problem an explicit analytical solution is not feasible. Regression solution using standard tools like SigmaPlot failed to converge on a solution due to singularity problem. We feel that the complex non-linear nature of the model equations is responsible for this non-convergence. To avoid this problem we have devised a graphical technique to determine both the paralysis factor and the detector dead-time.

When these *underkill-overkill-full recovery* experiments were conducted, it was found that the peaking and decay of observed count rate depends on some characteristic property of the detector and the decay constant of the fast decaying source. To facilitate inter-comparison of these experiments, the sampling time was normalized with the half life of the decaying source. At this time it was observed that the *half rise time* that is the time from half peaking-value to peaking-value depends solely on the paralysis factor. It was found to be independent of dead-time, half life of the decaying source and the initial activity of the decaying source. This is true particularly if the initial background activity is small/negligible. A plot of paralysis factor vs. rise time is shown in Figure 5. It is important to point out that this rise time (i.e. $t_{P/2}$ to t_p) is unitless because of the normalization. Figure 5 can be useful for determining the paralysis factor of a detector.

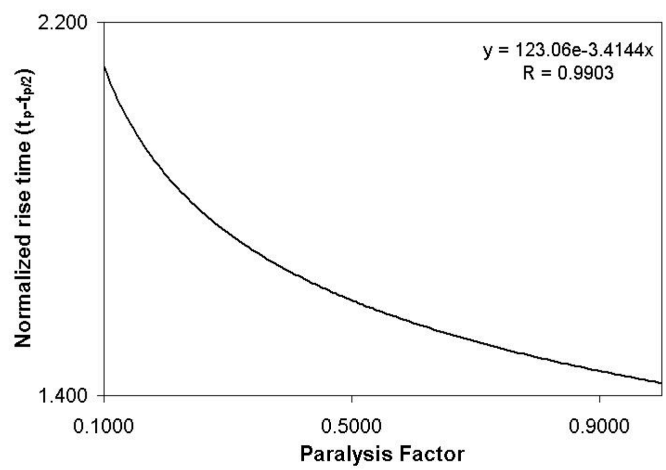

Figure 5. Paralysis factor vs. rise time plot

After performing a decaying source measurement, the data can be plotted on a normalized time scale, and the half peaking time can be determined. The paralysis factor can be obtained by using Figure 5 and the measured half peaking time. Once paralysis factor is determined, only the detector dead-time remains to be estimated.

Further analysis of the experimental data also revealed that peaking count rate is also a characteristic of the detection system. Moreover, the peaking count rate only depends on the paralysis factor and the detector dead-time. To facilitate use of this technique, peaking count rate is plotted against paralysis factor for various dead-times. These curves are shown in Figure 6. Once the user has collected the decay source data, estimated the paralysis factor, and noted down the peaking count rate, it is quite easy to read the corresponding dead-time from Figure 6. Once both the dead-time and the paralysis factor are ascertained the dead-time model is complete.

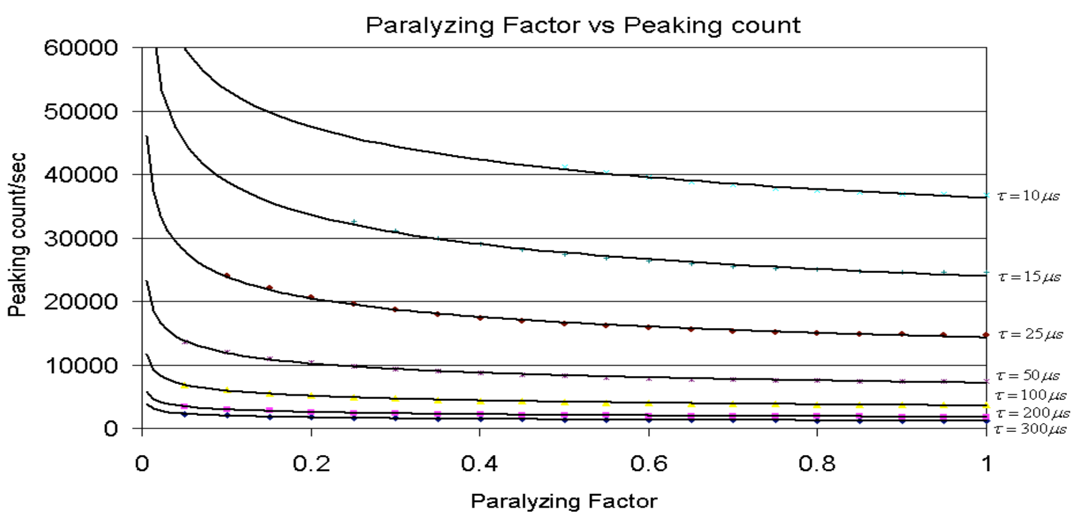

Figure 6. Maximum peaking count vs. paralysis factor

4. EXPERMENTAL RESULTS

Most of the traditional work to investigate the phenomenon of detector dead-time has been focused on GM counter [1, 5, 10, and 15]. We opted to test our dead-time model for a High Purity Germanium (HPGe) detector. This choice is due to the extensive use of HPGe for gamma spectroscopy and proposed use of the device for high intensity measurements for spent fuel monitoring [4]. For this investigation an ORTEC coaxial

HPGe detector (model-GEM15P4) with a relative efficiency of 17% was used. The detector has a diameter of 47.0mm and a length of 49.6mm.

For data acquisition an ORTEC multichannel scalar (Model MCS-pci) with MCS-32 software was used. The MCS has a total of 65,535 channels. The time resolution can vary between 100ns to 1300sec with no dead-time losses between shifting channels.

The decaying source (^{56}Mn) was produced at the UMR nuclear reactor by irradiating 99.99% pure ^{55}Mn. Manganese is a very good element for this type of irradiation experiment because of it 100% natural abundance and significant thermal neutron cross section. Once ^{56}Mn is produced, it decays with a half life of 2.578 hours. Subsequently, we validated our results by using a ^{52}V (half life of approximately 3.76 min). For the case of ^{56}Mn, the MCS was set to collect sequential count rate data for sampling interval of 1 or 2 intervals. However, due to much smaller half life of ^{52}V this time interval was reduced to 30 milliseconds. A constant background source (^{137}Cs) was used. The exact value of this background source is not critical for the proposed technique.

Figure 7 shows the data collected using ^{52}V. As expected, after normalization both ^{52}V and ^{56}Mn (Figure 8) data show a very similar behavior of rise and fall. It is also interesting that in both cases, the maximum observable count rate (peaking count rate) was found to be approximately 6E4 counts per second.

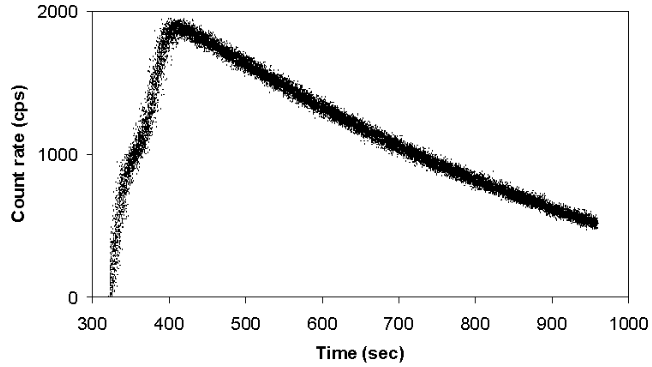

Figure 7. Decaying source data for ^{52}V (τ=5.5μs, f=44.0%)
using HPGe detector (Bin Size = 30ms, Max. count Rate=1940 counts per 30 ms and $T_{1/2}$=3.76 min)

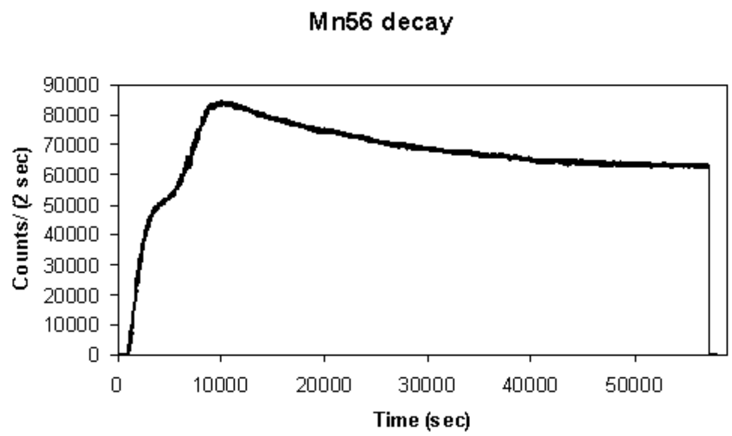

Figure 8. Decaying source data for ^{56}Mn (τ=9.78μs, f=49.9%)
using HPGe detector (Bin Size = 2s, Max. count Rate=84,000 counts per 2 s and $T_{1/2}$=2.58 hr)

Half peaking time was estimated after plotting the data on a normalized time scale. This half peaking time was used in conjunction with the graph illustrated in Figure 5 to estimate the paralysis factor. For HPGe tested at MST, a paralysis factor between 90 to 100% was recorded.

Using this paralysis factor and the curves presented in Figure 6 the detector dead-time was estimated using interpolation between the available curves. Measured detector dead-time ranged between 6 – 10μs. These values are within the expected range. Since there are no reports on the part paralysis factor, the high values of 50-77% are in agreement with the general belief [16] that solid state detectors are mostly paralyzable. Likewise, the dead-time values are also well within expected range.

No data for GM counter was directly collected. However, using the data reported by Lee and Gardner [1] the paralysis factor for GM counter is estimated to be 5%. This result also supports general agreement that GM counters are non-paralyzable.

5. PARAMETER MEASUREMENT SCHEME AND MODEL APPLICATION

It is ease to recognize that a two parameter based deadtime correction scheme either using a single deadtime in conjunction with a paralysis factor (as proposed here) or using two deadtimes [1] would produce better results. However, application of such scheme is not viable unless a practical method is available for measuring these parameters. Lee & Gardner [1] reported the non-paralyzable (τ_N) and paralyzable deadtimes (τ_P) for the GM counter to be 285 and 16 μs respectively. But they did not offer any further explanation on the procedure used to obtain these numbers and how other users could test their detectors for their deadtime behavior.

Present work provides a simple method for users to experimentally determine the detector deadtime and paralysis factor. The procedure is quite simple and would require the following steps;

1) Bring a fast decaying source close to the detector and record the changes in

count rate. Multi channel scaler (MCS) can be used for this data collection. The source must be strong enough to ensure that the detector is completely paralyzed, and in the beginning no counts are recorded. The observed count rate will increase as the source decays away and the detector will recover from paralysis. The observed count rate will continue to increase and will reach a maximum (peaking count) before decreasing due to source decay.

2) Plot this count rate data on a normalized time scale (i.e. actual time divided by the half life of the fast decaying source).
3) Determine the *Normalized Rise time* or *Half Peaking Time* ($t_p - t_{p/2}$) – that is the time for the observed count rate to its peak value from half of the peaking value. This time will have no units as the plot is on normalized time.
4) Using this *Normalized Rise Time* and Figure 5 determine the *Paralysis factor*.
5) Using this *Paralysis factor* and the *Peaking Count Rate* that was recorded by the system determine the *deadtime* of the system by interpolating between the curves on Figure 6.

We have used a graphical method to estimate the dead time and paralysis factor because of the nature of the equations which lead to an ill-conditioned problem for a numerical solution. In the absence of a simple numerical solution, the proposed graphical approach (as described above) can provide a quick and easy means for the user(s) to determine detector's dead time and paralysis factor. Using these two parameters one can apply an improved dead time correction (equation 5) to determine the true count rate with better accuracy.

6. CONCLUSION

An improved method of characterizing detector dead-time behavior is proposed. The new two parameter model uses the traditional dead-time in conjunction with a paralysis factor a newly introduced parameter. This paper also describes an experimental method to deduce the two parameters from a decaying source experiment.

The authors feel that this new way of looking at detector dead time enhances the understanding about the phenomenon of detector dead-time. The paralysis factor based detector dead-time model is superior to any existing model, in that this scheme allows us to quantify the extent of paralysis the detector experiences under a given operating condition. Quantitative results obtained on paralysis factor and the detector dead-times are in good agreement with the existing literature.

Successful use of ^{52}Vas the fast decaying source suggests that the proposed technique can be used with any fast decaying source. This feature of the new technique is particularly useful for its practicality. We observed a lower paralysis factor for ^{52}V (61%) experiment and the corresponding dead-time was also found to be smaller (6.05 μs) than the dead-time found using ^{56}Mn as the fast decaying source. This difference could be due to a number of factors including changes in the operating conditions and also possibly a difference in the average radiation energy.

The ongoing study on the energy dependence of paralysis factor and detector dead-time should reveal more information on our understanding of the phenomenon. It is however important to point out that in our initial investigation these parameters are system dependent and are likely to be impacted by electronic settings, amplifier gain, high voltage setting etc. Overall, agreement between the results obtained by using ^{56}Mn and ^{52}V was reasonable.

7. ACKNOWLEDGEMENTS

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SECTION

2. CONCLUSION

The field of radiation measurement has numerous applications, and the number is constantly growing. With improvements in the instrumentation of radiation detection applications over the years, especially in high-count-rate applications, measurement accuracy is more important than ever. The research presented here has investigated the count loss problem and developed more accurate models and methods to estimate detection system dead time and characterize radiation measurement systems. This work involved two parts:

1. a comprehensive review of the literature on count loss and dead time for radiation detectors, and
2. experiments to test the detector performance and analyze the data generated

In a typical detection system overall dead-time and pile-up losses originate from the various components of the system. The user must understand the sources of loss in these components before applying any correction methods. Dead-time and pile-up losses can originate in any of three areas: a) at the detector, b) in the processing instrumentation, and c) in the multichannel analyzer. The review of dead-time and pile-up models and count loss correction methods provides the first comprehensive summary of issues related to the origination of these phenomena in a detection system. It also describes the important models and methods developed to address dead time, pile-up, and count loss correction, including their applications and limitations. Traditionally researchers have relied on idealized one-parameter dead-time models to correct for count loss. Although originally proposed decades ago, the generalized model for dead time correction as never been fully accepted. Some work has experimented with the concept of a two-parameter generalized dead time; however, much more work must be done to make this model acceptable to the scientific community.

The modified decaying source method proposed here introduces a new measurement technique to estimate the total dead time of a detection system. It modifies the existing hybrid dead-time model and proposes a new parameter, the paralysis factor, *f*. This factor indicates the extent to which a detector can be paralyzed. This method uses the paralysis factor and peaking count rate to estimate the dead time of the counting system. This technique can be used with moderately fast decaying sources (e.g. V^{51}) and requires no assumption of idealized dead time model.

The research on detection system dead time behavior has clarified the count loss behavior of radiation detection systems. Its the major highlights include:

- review of detector dead time and pulse pile-up
- description of important models and methods with their limitations
- introduction of a generalized two-parameter dead time model to determine the paralysis factor and dead time of detection system
- use of a paralysis factor to define detector behavior

- proposal for a novel technique to determine detection system dead time using a high-activity, fast-decaying source
- presentation of a simple graphical approach for dead time determination

3. FUTURE WORK

This research has laid foundation for significant investigations that could compliment the present work. The ideas which came up during the investigation of detector dead time problem are listed below.

A. Simulation for detector dead time: A lot of work has been done to replicate the exact experimental behavior of a detection system using Fortran simulations. It was felt the need to better understand the dead time response of amplifiers and other instrumentation, addition of which would be useful to generate the overall dead time of the detector system.

B. Count rate dependence of dead time: The extension of dead time is a known phenomenon but something which has not been studied extensively. In the above paper the dead time dependence on count rate has been shown and modeled to fit the estimated probabilities. Further studies are needed to precisely model this behavior and confirm the results from the present study.

C. Chi-square – dead time relationship: On analyzing the source decay data from V^{52} and Mn^{56} it was found that the Chi-square data for the observed count rate always behaves in a certain way throughout the decay process. More in depth study is needed to understand the relationship between the observed count rate and detector dead time.

D. Energy and Voltage dependence of dead time: Some of the studies have revealed that the count rate measurement is dependent on the applied voltage, especially in the case of Geiger Muller counters. The voltage applied to a detector is responsible for pulling the charge particles to the respective electrodes to collect the total charge for pulse formation. Thus a variation in count loss can be studied to estimate the optimum voltage for obtaining a low dead time for a given application. Similarly the count rate dependence on energy needs to be studied to better characterize the losses in the energy spectrums thus obtained.

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VITA

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