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# Dead Time in the Gamma-Ray Spectrometry

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## Abstract

A review of studies of the dead time correction on gamma-ray spectroscopy is presented. Compensate for counting losses due to system dead time is a vital step for quantitative and qualitative analysis. The gamma-ray spectroscopy system consisting of electronic devices are used for detection of radiation due to gamma rays. The dead time of the spectroscopy system is based on time limitations of these electronic devices. Firstly, a new model for determination of this electronic dead time is proposed. Secondly, two alternative methods suggested for the correction of this electronic dead-time losse.

**Keywords:** gamma rays, gamma-rays detectors, semiconductor detectors, dead time, counting rate, peaking time

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## 1. Introduction

Development of a gamma spectrometer for each energy region of the electromagnetic radiation has progressed in parallel with the development of experimental tools. The first and rough detectors often just used to determine the presence of radiation. The second-generation radiation detectors used to determine the radiation intensity, but with only a very small part of information on its energy. The last types of radiation detectors measure the intensity as a function of the photon energy in addition to the determination of the presence of radiation.

After the first observation of the gamma rays with photographic plates, advances related to measuring in this field began with the development of various types of gas-filled counters at the beginning of 1908 [1]. The counters that are compared to the photographic detection process allowed the experimenter to obtain a more accurate quantitative measure of the

radiation as well as determining the presence of the radiation. The proportional counters did allow one to obtain energy spectra for gamma rays whose energies were low enough to interact primarily by the photoelectric effect and where the secondary electrons produced by these interactions could be completely stopped in the gas volume. However, generally these detectors are only used in determining the number of events that occur in the counter and not to measure directly the energy of the incoming photons [2].

The main improvement in determining the quantity measurement of gamma rays began with the development of NaI (Tl) detectors in about 1948. These detectors can supply energy spectra over a wide energy range. After a certain period of development, detectors consist of crystals with sufficiently large size to allow high absorption rates even above 1 MeV photons energy were produced. The main advantages of these detectors include their relatively fine resolution, the good physical and chemical stability of the crystal material used and their high relative yield. As these detectors have a good resolution, photon energies are well separated and it allows the observation of different energy photon peaks [2].

In 1962, semiconductor Ge (Li) detectors were manufactured [3]. As these detectors can be made from many different semiconductor materials, these are used as photon detectors as well as nuclear-charged particles detectors. To collect the secondary charges efficiently, these detectors need to be made of single crystals of a pure material. Due to difficulties in producing single crystals other than germanium, Ge (Li) detectors have, so far, been successfully used as high-resolution photon detectors of significant size. These detectors have a high resolution. The most serious drawback of semiconductor detectors is the need to keep them cold, generally at liquid nitrogen temperature.

In the coming years, there have been numerous studies on similar detectors of high atomic number. Mayer [4] proposed several detectors made from bicomponent material. Sakai [5] had worked on semiconductor detectors made from bicomponent material such as GaAs, CdTe and HgI<sub>2</sub> to make measurements at room temperature. However, there is not much use of these detectors up to now because of the relatively low yield due to their small surface area, low resolution and expensive production methods and techniques.

Characteristics of an ideal detector for gamma spectrometer can be expressed as follows [6]:

1. Output pulse number should be proportional to the gamma-ray energy.
2. It should have a good efficiency (that should be a high absorption coefficient).
3. To collect the detector signals, it should have an easy mechanism.
4. It should have good energy resolution.
5. It should have good stability over time, temperature and operating parameters.
6. It should be conferred at a reasonable cost.
7. It should have a reasonable size.

## 2. General characteristics of photon detectors

Modern photon detectors used in determining the radiation and in measuring the quantity of radiation run based on a series of joint steps. These steps are the same in almost all species and types of detectors. In this section, characteristics of gas detectors and of semiconductor detectors commonly used in the determination of radiation and in the measurement of the quantity of radiation are discussed. These detectors are used to count electrons, heavy charged particles and photons. We will only focus on their use as a photon detector. A photon detector operates over the following principles [2]:

1. First, the conversion of the photon energy to kinetic energy of electrons (or positrons) by photoelectric absorption, Compton scattering or pair production.
2. Second, the production of electron-ion pairs, electron-holes pairs, or excited molecular states by these electrons.
3. Third, the collection and measurement of the charge carriers or the light emitted during the deexcitation of the molecular states.

A photon spectrum released by a source is usually consists of monoenergetic photons group. The detector converts such a line spectrum into a combination of lines and continuous components. Detectors can be used to determine the energies and intensities of the original photon as long as these lines are observable. However, if the lines are lost in the associated continuity it is usually not possible to determine these quantities. The ability of the detector to produce peaks and lines for monoenergetic photons is characterized by the peak efficiency and peak width. The peak width in the gamma-ray spectrometer is usually expressed as the full width at half maximum (FWHM) in terms of keV. In addition, FWHM referred to as the resolving power of the detector. The peak efficiency of the detector is the ratio of the number counts in the peak corresponding to the absorption of all the photon energy (so in the full energy peak) to the number of photons of that energy emitted by the source. Both the peak and the peak efficiency are functions of the photon energy [2].

## 3. Gamma-ray spectrometry system components

The magnitude of the pulses from the gamma ray is equal to the magnitude of electrical charge, which is proportional to the amount of absorbed gamma-ray energy by gamma-ray detectors. The function of the electronic system is to collect these electrical charges, to measure the amount of electrical charge and to store these information. The electronic system for a gamma-ray detector spectrometer is shown schematically in **Figure 1**.

The gamma-ray detector system consists of a detector bias supply, preamplifier, amplifier, analog-to-digital converter (ADC), multichannel analyzer (MCA), a data storage device (computer and spectrum analysis program), a pulse generator and oscilloscope if desired. Pulse generator is used in the spectroscopy system, which does not contain an electronic circuit with functions such as a base line restorer or a pileup rejector. Detector bias supply generates



**Figure 1.** General appearance of the gamma-ray spectrometry system.

electric field, this produced electric field sweeps the electron-hole pairs toward detector contacts. These swept electron-hole pairs are collected by preamplifier. The collected electron-hole pairs in the preamplifier are converted to a voltage pulse with a field effect transistor (FET). The amplifier changes the shape of the voltage pulse. This shape of the pulse increases linearly with the size of the incoming pulse. The analog-to-digital converter converts from the analog structure to the digital structure. The multichannel analyzer (MCA) sorts the pulses according to pulse height in addition; MCA counts the number of pulses in the individual pulse height ranges. Computers are used to check the measurements and to record the spectrum in modern gamma-ray spectrometers. The advantage of such systems is providing great convenience to users in fulfilling their various data-analysis calculations during and after measurement. During the measurement, the location and area of the peak of interest via a program used can be determined on screen, therefore, the collection rate of counting and the identity of radionuclide can be determined.

#### **4. The dead-time detection methods**

The main reason for the counting and pileup losses is the dead time of the gamma spectrometry system. In order to fulfill the necessary corrections primarily related to these losses, it is to be first determined the dead time of the gamma-rays spectrometry. The dead time is associated with limited time features known as constant separation time of electronic circuits of the

gamma-ray spectrometry. It has been generally accepted that the direct measurement of the dead time because of the pulse processing conditions in the gamma-ray spectrometry may change or not is accurately known. Traditional dead-time measurement techniques are based on the fact that the observed count rate varies nonlinearly with the true counting rate. Therefore, by assuming that one of the specific models is applicable and by measuring the observed rate for at least two different true counting rates that differ by a known ratio, the dead time can be calculated [7].

#### 4.1. Two sources method

This method is based on the observation of the counting rate from two individual sources and in combination of these two sources. Because of the counting losses are nonlinear, the observed counting rate resulting from the two sources combined is less than the sum of the observed counting rates resulting from each individual source counting. Thus, the dead time can be calculated from this mismatch [7]. Considering two sources, such as A and B, Prussin [8] gave this relationship:

$$n_A + n_B = n_{AB} + n_{BG} \quad (1)$$

Where  $n_A$ ,  $n_B$ ,  $n_{AB}$  and  $n_{BG}$  show the observed counting rate of A, B, A + B (A plus B) source and background, respectively. Considering the counting rate correction in the case of nonparalyzable and zero background, general solution to this statement is as follows:

$$T_D = \frac{n_A n_B - [n_A n_B (n_{AB} - n_A) (n_{AB} - n_B)]^{1/2}}{n_A n_B n_{AB}} \quad (2)$$

#### 4.2. Decaying source method

This method can be applied if the source is a short-lived radioisotope. In this method, the decay constant of the radioactive source must be known. The dead time due to the observed count rate resulting from exponential decay of the source is determined. A graph is plotted using the observed counting rate and the decay constant of the source and dead time can be determined with the help of this graph [7]. A general approach to obtain accurate count rates in this method is that: first, the net count rate versus time is plotted on the semilogarithmic graph paper, to obtain a linear curve. This curve is fitted linearly by the least square method. The resulting fit equation is as follows [7, 8]:

$$n(t) = n_0 e^{-\lambda t} + n_{BG} \quad (3)$$

where  $n_0$  is the true rate at the beginning of the measurement and  $\lambda$  is the decay constant of the particular isotope used for the measurement. If the paralyzable model used for this case, the solution can be given as follows:

$$\lambda t + \ln m = -n_0 \tau e^{-\lambda t} + \ln n_0 \quad (4)$$

### 4.3. The electronic dead time

In this recently proposed method, the dead time is a result of the electronic components of the gamma-ray spectrometry [9]. Charged particles that are generated by incident radiation within the detector crystal are transported by an electric field to the detector electrodes [9]. The production and collection of the charged particle are subjected to random statistical variations, which depend on the incident energy and the detector medium. An intrinsic resolution limitation exists in the process of converting the incident radiation to an electrical signal [9, 10]. The output signal undergoes various processing steps in order to be correctly acquired and analyzed in semiconductor X or gamma-ray detectors. The time required to collect the charged particles produced by the incident radiation is important in many applications. If the collection time is not sufficiently short compared with the peaking time of the amplifier, a loss in the recovered signal amplitude occurs [9, 11]. The charge collection time depends on the detector geometry, medium, electric field and location of the interaction within the detector active volume [9].

An optimized spectrometer system provides the best energy resolution obtainable within a given set of experimental constraints. System optimization requires the proper selection of equipment and knowledge of the compromise of resolution and count rate performance in any system [9]. The detector and preamplifier combination is the most critical component of the system electronics. The best amplifier cannot compensate for poor signal-to-noise or count rate limitations caused by improper selection of the system front end. Selection of the proper amplifier will enhance the performance of the good detector and preamplifier combination. The source and detector interaction, detector and preamplifier combination, pulse processor shaping and the system count rate determine the system resolution [9, 10].

#### 4.3.1. Determination of the electric dead time

The relationship between the minimum resolving time, peaking time and overall pulse width is given by the following equation [9, 10]:

$$T_R \geq \frac{T_W}{T_P} - 1 \quad (5)$$

where  $T_R$  is minimum resolving time,  $T_W$  is overall pulse width and  $T_P$  is peaking time of the amplifier. Overall pulse widths in response to possible peaking times of the amplifier can be measurement using the oscilloscope. A graph is plotted using the measurement overall pulse widths and the possible peaking time of the amplifier (see **Figure 2**). The relationship between overall pulse width and peaking time can be determined with the help of this graph. The fitting equation of data in **Figure 2** is,

$$T_W = B_3 T_P^3 + B_2 T_P^2 + B_1 T_P + A \quad (6)$$

where  $A$ ,  $B_1$ ,  $B_2$  and  $B_3$  are coefficients of the equation fitted [9]. The minimum resolving times in response to possible peaking times of the amplifier were calculated using Eq. (5) and the minimum resolving time versus peaking time is plotted in **Figure 3** [9].

The fitting equation of the data in **Figure 3** is [9],

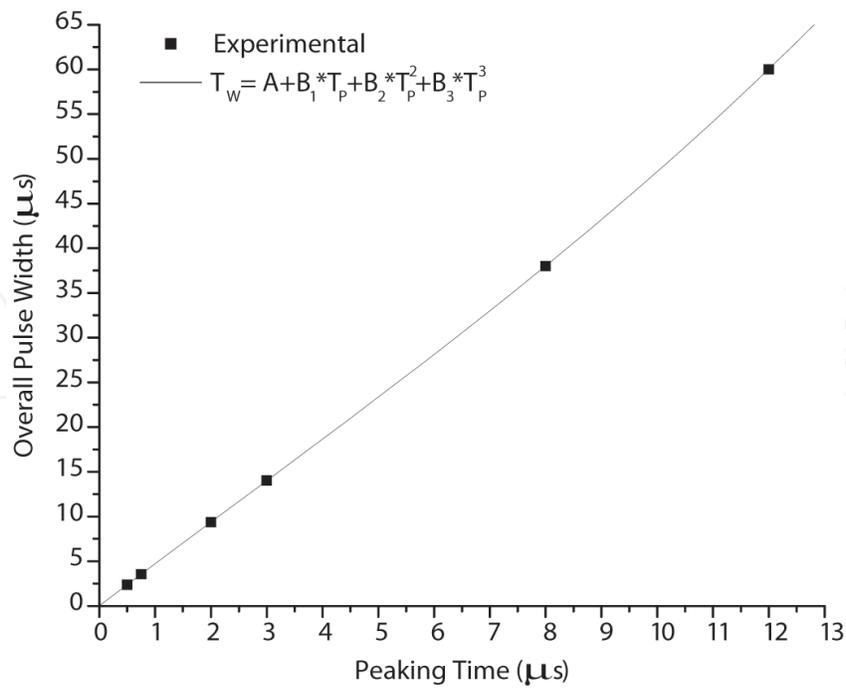


Figure 2. Change in the overall pulse width with peaking time [9].

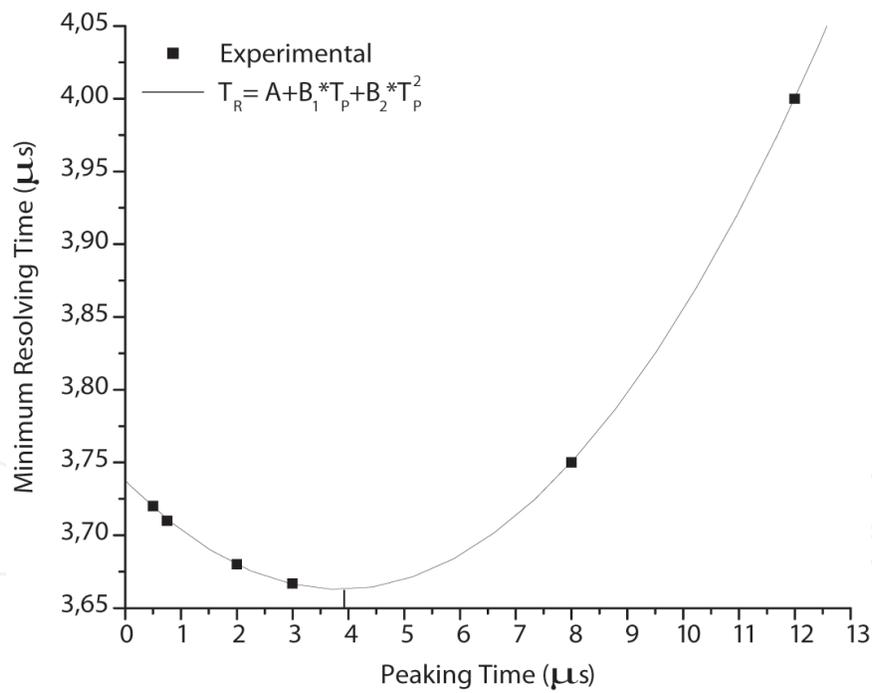


Figure 3. Minimum resolving time versus peaking time [9].

$$T_R = B_2 T_P^2 + B_1 T_P + A \quad (7)$$

The  $T_D$  effective system dead time can fall into one of the following categories [9]:

$$T_R > 1.5\mu s + T_C \quad (8)$$

or

$$T_R < 1.5\mu s + T_C \quad (9)$$

where  $T_C$  is conversion time of the analog-to-digital converter (ADC). If the minimum resolving time of the pileup rejector is greater than  $1.5\mu s + T_C$ , then the system dead time is simply [9]

$$T_D = T_P + T_R \quad (10)$$

Otherwise, the system dead time is

$$T_D = T_P + 1.5\mu s + T_C \quad (11)$$

The ADC conversion time for the relevant energy lines can be calculated [12] by using,

$$T_C = \frac{E}{\Delta E} T_{\text{Clock}} \quad (12)$$

where  $E$  is energy line,  $\Delta E$  is energy per channel and  $T_{\text{Clock}}$  is the amplifier operation frequency. Considering Eqs. (7) and (10)–(12), the system dead time can be written as [9]:

$$T_D = B_2 T_P^2 + (B_1 + 1) T_P + A \quad (13)$$

or

$$T_D = T_P + 1.5\mu s + \frac{E}{\Delta E} T_{\text{Clock}} \quad (14)$$

## 5. Some models for the dead-time correction

Illustration of the effect on the counting rate of the dead time can be done with the detector; a pulse-forming network consists of a square wave output with constant  $\tau$  length (amplifier and analog-to-digital converter (ADC) and a counter (multichannel analyzer (MCA)). This time  $\tau$  is variable due to caused dead time of the ADC.

### 5.1. Paralyzable (extended) model

One model of dead time behavior of gamma-ray spectroscopy system is paralyzable (extended) response. This model has come into common usage. The model represents idealized behavior. True events that occur during the dead time are lost and assumed to have no effect, whatsoever on the behavior of the detector. True events that occur during the dead time, however, although still not recorded as counts, are assumed to extend the dead time by another period  $\tau$  following the lost events. This method can be expressed as follows [7]:

$$m = ne^{-n\tau} \quad (15)$$

where  $m$  is the recorded count rate,  $n$  is the true count rate and  $\tau$  is the system dead time.

For the so-called paralyzable (extendable) systems, the dead time is extended by starting from the last arrival time. Pulse pileup can also be interpreted as a kind of pulse loss of the paralyzable type [13]. Consecutive pulses falling within a time interval peaking time,  $T_B$  are treated as pileup and excluded from the spectrum, as a pileup rejector (PUR) [14]. To generate second output pulse without a time interval of at least  $s$  between two consecutive true events is not possible in the paralyzable model. In this model, the recovery of the electronic device is further extended during the respond time  $s$  to an initial event for an additional time  $s$  by some additional true events, which occur before the full recovery has taken place [15].

### 5.2. Non-paralyzable (nonextended) model

Another model of dead-time behavior of gamma-ray spectroscopy system is nonparalyzable (nonextended) response. This model has come into common usage. The model represents idealized behavior. A fixed time  $\tau$  is assumed to follow each true event that occurs during the live time of the detector. True events that occur during the dead time are lost and assumed to have no effect, whatsoever on the behavior of the detector. True events that occur during the dead time, however, although still not recorded as counts, are assumed to not-extend the dead time by another period  $\tau$  following the lost event. This method can be expressed as follows [7]:

$$n = \frac{m}{1-m\tau} \quad (16)$$

where  $m$  is the recorded count rate,  $n$  is the true count rate and  $\tau$  represents the system dead time.

In nuclear spectrometry measurements, the pulse loss is traditionally related to the nonparalyzable (nonextendable) dead time per incoming pulse caused by an ADC during pulse processing. Nonparalyzable means that the dead time period is not prolonged by a new pulse arriving during that time [14]. In the nonparalyzable model, recovery period of electronic device is not affected by events that have come into being during the  $s$  dead time [16].

### 5.3. Live-time correction model

On the assumption that all the MCA dead-time losses are manifested through the input rate, the accumulated live time takes as the proper counting time of the measurement should be both necessary and sufficient. The live time is the actual time during which the system is open and available for collecting counts. Thus, the counts within a spectral peak must be divided by live time ( $T_{\text{live}}$  in seconds) to obtain the counts per second. This model is well in low count rate situations [6].

#### 5.4. Gedcke-hale model

This model is a development of the previous one, which also compensates for losses due to leading edge pileup in the amplifier and is favored by EG&G Ortec. It predicts a correction based on Poisson statistics. This method can be roughly expressed as follows [6]:

$$\text{Counts to memory} = \text{input pulses to amplifier} \frac{T_{\text{Live}}}{T_{\text{Real}}} \quad (17)$$

Where  $T_{\text{live}}$  is the live time and  $T_{\text{real}}$  is the real time of the counting system.

#### 5.5. Pulser Model

In this model, the pulser generates constant amplitude pulses that are similar to the pulses output from the detector. These pulses are sent to preamplifier. Through the electronic components of the gamma-ray spectrometry, the produced pulses are transported and stored in the memory as a pulser peak. It is a fair assumption that the fractional losses sustained by the pulser counts are the same as those sustained by the gamma-ray derived counts. Thus, dead-time losses in the gamma spectrometry may be allowed for by multiplying the gamma peak areas by the following simple ratio [6]:

$$\frac{\text{pulses produced by pulser}}{\text{Pulser counts in pulser peak}} \quad (18)$$

#### 5.6. Loss-free counting model

There is a number of methods can be grouped under this general heading. All of them make use of a subsidiary circuit to monitor the instantaneous count rate and based on that generate a weighting factor,  $n$ . Thus, the high instantaneous count rate is reflected by a high count in a channel in the spectrum that is appropriate at that time [6].

The Harms procedure was a pioneering effort. It counts those pulses that are presented for processing but which are rejected because the system is busy. The number of discarded pulses in such a scale is read and used to weight the next real event. However, the ADC processing time is not necessarily the major problem at high count rates as losses due to pulse pileup can dominate [6].

#### 5.7. Zero dead-time counting model

Changing the dead time problems of gamma-ray spectrometry is a source of a well-known error. The dead-time correction under such conditions may be true if changing the dead time dominantly affected measured radioisotopes [17, 18]. Zero dead-time losses correction is almost the same as the loss-free counting. The difference between them is completely quantified of zero dead-time correction.

## 5.8. Integral dead-time correction model

The major constraint in the gamma-ray spectrometers is both the time required to collect the charge produced by ionizing radiation in the active detector volume and subsequently the pulse processing by the electronics [14, 19]. In this major constraint of all gamma-ray spectrometers, there is a minimum amount of time called dead time of the spectrometer system. During this dead time, the system cannot respond to other incoming photons and these events cannot be counted and thus can be lost [14]. One of the major problems confronting the user of gamma-ray spectrometer is to correct the results for counts lost due to the spectrometer dead time. This problem can be solved automatically by carrying out all counting runs for a known or measured total instrument live time rather than for real time [14, 20].

When count rate is kept nearly constant, counting losses due to dead time can be corrected by a simple formulae for both types of nonextendable and extendable dead times [14, 21]. However, when the count rate changes or fluctuates significantly, the correction based upon mathematical means becomes difficult and complex. In order to overcome this problem, a method was demonstrated by Kawada [14, 22], which allows compensating the dead time effects automatically at every moment during the counting experiment. In this method, pulses whose number is equivalent to the dead-time losses were generated as random coincidence pulses using a gating technique in a first-order approximation and added to the output pulse train after delay [14, 23].

The problem of varying dead time is a well-known source of error in nuclear spectrometry measurement. In this case, dead-time corrections can only be accurate if the varying dead time is dominantly caused by a radiation source. Solutions have been offered in several forms: dead time stabilization [14, 24–26] solves the problem at the cost of a fixed, perhaps unnecessary, dead time and resulting loss of counting efficiency [17]. However, results of the other dead-time correction models have not been forthcoming for counting losses due to the system dead time. It is a reliable estimation of the original count rate or of the number of original events for the interval of time considered. To do this, we need either an accurate value for the average loss per dead time or a method that allows us to arrive at individual corrections. An analytic correction method was developed instead of using a pulser or a radioactive source. This proposed model by Karabidak et al. [14] is based on a measuring principle on the total live time.

### 5.8.1. Background of the integral dead-time correction model

In Galushka's study [14, 27], a method is described for restoring dead-time losses in real time so that at the output of a counter, constructed according to this new scheme, one obtains directly by the number of events expected in the absence of dead time. This is accomplished by inserting additional pulses into actual series of registered events. In such a situation, let the observed sequences of events be characterized by the arrival times  $T_0, T_1, T_2 \dots$  [14, 28]. Consecutive arrivals are separated at least by the peaking time,  $T_B$ , applied. If we put  $T_0 = 0$ , then pulse number,  $k$ , occurs at the instant [14]:

$$\begin{aligned}
T_k &= T_1 + T_2 + \dots + T_k \\
&= (\tau + \delta_1) + (\tau + \delta_2) + \dots + (\tau + \delta_k) \\
&= k\tau + \sum_{j=1}^k \delta_j \text{ for } k \geq 1
\end{aligned} \tag{19}$$

where  $\delta_j$  is the width of each pulse, which is separated from each other by steady dead time arising from peaking time of the amplifier. However, peaking time is important for calculations of counting losses due to the dead time of the system. Therefore, the dead time of the system is determined by adding the peaking time to the ADC converting time. To determine the dead time of the system, minimum resolving time should be ascertained first [14].

For counting losses due to systems dead time, both approaches are possible. Traditional correction formulae were used for the first method: they are based on the observed count rate and are applied at the end of a measurement period [14]. On the contrary, methods of a second type work in a different way by instantly correcting or compensating for losses, apparently without requiring knowledge of the measurement or calculate count rate. In the second method, it is possible to estimate the probability of losing a specific number  $k$  of counts in a dead time of length  $TD$ . Since we deal with a Poisson process, this probability is given by Refs. [14, 23, 28]:

$$P_k = \frac{(nT_D)^k}{k!} e^{-nT_D} \tag{20}$$

where  $n$  is the count rate in each channel. The expected counting losses due to each dead time are given as follows [14]:

$$L = \sum_{k=1}^{\infty} kP_k = e^{-nT_D} \sum_k \frac{(nT_D)^k}{(k-1)!} = nT_D \tag{21}$$

Thus, correction counting is given by Ref. [14]:

$$C_C = \text{Count} + L \tag{22}$$

### 5.9. Differential dead-time correction model

Recording two pulses apart as two different events at almost all detectors systems requires to be separated from another pulse. This situation needs the minimum time interval [15]. The minimum time interval based on electronic devices using the counting system is usually called the dead time of the counting system. This is generally determined by pileup reject time, paralyzable or nonparalyzable system dead time or a combination of these mechanisms [13]. The photons arriving to the detector at the dead time period are not being counted. Thus, count rate, which is expressed as the count of per unit time, decreases [15].

The paralyzable and nonparalyzable models are assumed to express the idealized behavior. Every true event came into being during live time of detector was assumed to occur in a stable dead time at every two models [7, 15]. However, this situation is only valid in the dead time depending on peaking time of amplifier. Nevertheless, a counting system can be containing analog-to-digital converter (ADC) which determines the energy value of pulse. The dead time of such a counting system is variable with ADC conversion time [14]. Therefore, fulfilled corrections, which are taken into account for a fixed dead time, cannot be realistic. In addition, modern counting systems consist of electronic devices, which contain paralyzable (amplifier), nonparalyzable (ADC) and pileup reject (amplifier) [15, 29]. The paralyzable and nonparalyzable models predict the same first-order losses and differ only when true event rates are high. These models have two extreme idealized system behaviors and real counting systems often display a behavior that is intermediate between these extremes. The detailed behavior of a specific counting system may depend on physical processes taking place in the detector, delay introduced by the pulse processing and recording electronics [15].

In medium and high-count rate events, both of the two models are not applicable. The corrections, which are done by these models, are problematic because of the limitations expressed below. The troubling aspect of nonparalyzable model is the singularity at  $m\tau - 1$  and the fact that a maximum observed counting rate of  $1/\tau$  is approached in the limit as  $n$  approaches infinity. In the paralyzable model, the observed counting rate becomes zero at high-count rate. In addition, it should be noted that this model could not be explicitly solved for  $n_0$ . Nevertheless, this model solves a transcendental equation to obtain the true counting rate. In addition, the observed counting rate is either double valued or does not exist above a maximum value given by  $\exp(-1/\tau)$  [14, 30].

This model can be applied to the counting systems at which the system dead time is not predominant on count rates. That is, this method adequately corrects counting lost at steady counting rate. In addition, the dead-time or count-rate corrections based on live time can be ideal in the count rates which are not predominate at the system dead time [15]. In addition, on a mathematical essence, the principle of the live time is an integral mathematics. The integral mathematics is correct if applied only to stationary Poisson processes (invariable in time). It should be noted that time-invariant Poisson processes are valid in experimental studies with radionuclides having long half-lives. The current study includes count-rate corrections based on differential mathematics and the proposed model in this study is ideal in the count systems at which the system dead time is predominant on count rates. Differential mathematics is also correctly applicable to Poisson process changing in time [15].

### 5.9.1. Background of the differential dead-time correction model

Kurbatov et al. [15, 31] proposed a correction method that included to a statistical approach for Geiger–Muller counter. All of photons emitted from source are assumed to be caught by the detector and transmitted to counting system without loss. Let  $P(t)$  be the probability that a photon is emitted from a source in the interval  $(t-\tau, t)$ . Let  $a(t)dt$  be the probability that a photon is caught by detector and transmitted to counting system during the interval  $(t, t + dt)$ . The fact that  $P(t)$  is a continuous function of  $t$  is used here. In order that a photon

can be caught by the detector and sent to counting system, it is necessary and sufficient that; (i) a photon is sent counting system from detector in the time interval  $(t, t + dt)$  and (ii) no counting take place in the time interval  $(t - \tau, t)$ . Since these are independent events, the realization probability of one counting in the time  $dt$  becomes. Then, since only one counting can occur in the interval  $(t - \tau, t)$ , the probability of one counting in that interval is [15, 31]:

$$P(t) = \int_{t-\tau}^t [1-P(x)]a(x)dx \quad (23)$$

When  $1-Q(x) = P(x)$  conversion is taken into consideration, the following equation can be written as:

$$Q(t) = 1 - \int_{t-\tau}^t Q(x)a(x)dx \quad (24)$$

If  $t$  is too large of  $\tau$ ,  $a(t)$  is independent of  $t$ . For a preparation whose decay constant is  $\lambda$ , containing  $N_0$  atoms at time zero,  $f$  approaches to while  $N_0$  increases [15, 32, 33]. Then, the expected number of photons reaching the detector in  $t$  time without dead time (the  $P(x)$  probability equal zero) is given by Ref. [15]:

$$C(t) = \int_0^t N_0 \lambda e^{-\lambda t} dt = N_0(1 - e^{-\lambda t}) \quad (25)$$

Considering these inferences, the differential correction model can be created in the following way:  $\lambda$  on Eq. (17) is known as "decay constant" and is defined as the number of decay particles per second. In addition, unit of  $\lambda$  is 1/second. On the other hand, the number of particles counted per second by the detector defines counting rate. Therefore, unit of the counting rate is 1/second. Decay constant and counting rate are equivalent from the perspective of analogical. Therefore, the counting system consisting of only amplifier or ADC or both amplifier and ADC can be considered as a decaying source. In that case,  $n_0$  maximum number of counting rate of the amplifier or the ADC or both the amplifier and ADC can be compared with  $N_0$ , the number of particles at  $t = 0$  in a radioactive source. Thus, Eq. (25) may be rearranged when  $n_0$  instead of  $N_0$  and  $\lambda$  [15]:

$$n(t) = \int_0^t n_0 n_0 e^{-n_0 t} dt = n_0(1 - e^{-n_0 t}) \quad (26)$$

Where  $n(t)$  is the count rate recorded by the counting system which consists of a detector, an amplifier and ADC.

For a compound system, observed counting rate in each channel of X or gamma-ray spectrum is given by Karabıdak et al. [14]. Karabıdak and Çevik [15] calculated the dead time for amplifier, ADC, or both amplifier and ADC. Thus, for a compound system, counting rate correction, (or true counting rate) corresponding to each channel can be satisfied by:

$$n_0 = \frac{1}{T_D} \ln\left(\frac{1}{1-m \cdot T_D}\right) \quad (27)$$

In this case, corrected count in each channel at a counting period in a spectrum is given by Ref. [15]:

$$C_C = n_0 T_{\text{Real}} \quad (28)$$

where  $T_{\text{Real}}$  is the real time of the counting system.

## 6. Conclusion

A practical method to determine the dead time is proposed by Karabıdak and colleagues [9]. In other methods to determine the dead time, the dead time due to the amplifier and ADC is determined separately. In addition, to compensate for the counting losses kept constant dead time is fulfilled by considering a fixed dead time. Wherein, the dead time in this method is obtained at the same time for both the amplifier and ADC. An effective way of decreasing counting losses is by decreasing the system dead time in quantitative and qualitative analysis. Thus, the dead time is that variables in the counting process are fulfilled and the counting losses for a unified system are easily compensated. Because the system dead time is linked to the amplifier peaking time, the amplifier peaking time can be set to lower and optimum values.

The integral dead-time correction is effective both for low count rates and for medium count rates. It is possible to observe the dead time contributions due to ADC conversion time and peaking time in this model. Thus, counting losses correction arising from system dead time can be made for demanded situation (nonparalyzable or paralyzable or both). The dead time of the counting system was determined with an analytic formula. Counting losses occurring during this dead time were compensated for by considering uncorrected spectra obeying the Poisson behavior. This new method adequately corrects counting loss at steady counting rate [14].

The differential dead-time correction is effective both for medium count rates and for high-count rates. Output count rates of the only ADC and both the amplifier and ADC are the same. In addition, output-counting rates of the only amplifier are higher than others output counting rates. Moreover, increasing peaking time of the amplifier increases both the dead time and the counting losses. In addition, this model easily determined the relationship between the output counting rates and input counting rates. According to the dead time of the counting system, the amplifier or ADC or both the amplifier and ADC may be taken into account up to a certain limit value. This limit value of such electronic devices represents a saturation point. This saturation point is determined by the size of the dead time of the counting system. This is a result of Poisson statistics. Since the dead time is a function of the peaking time of the amplifier and photon energy, this saturation point is directly related to them. Therefore, while low peaking time determines low dead time, low dead time determines the high saturation point (or counting rate) [15].

The dead time increases as long as the counting rate increases. This increase in dead time becomes stable at around 1 s after a certain point. This fixed point corresponds to the counting

rate at saturation point of the electronic system at which the detector is not considered to be receiving the photons [15].

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