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Original Article

A new dead-time determination method for gamma-ray detectors using attenuation law

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ABSTRACT

This study presents a new dead-time measurement method using the gamma attenuation law and generalized dead-time models for nuclear gamma-ray detectors. The dead-time of the NaI(Tl) detection system was obtained to validate the new dead-time determination method using very thin lead and polyethylene absorbers. Non-paralyzing dead-time was found to be 8.39 μs, and paralyzing dead-time was found to be 8.35 μs using lead absorber for NaI(Tl) scintillator detection system. These dead-time values are consistent with the previously reported dead-time values for scintillator detection systems. The gamma build-up factor's contribution to the dead-time was neglected because a very thin material was used.

1. Introduction

Radiation counting is a random process and is inevitably affected by some count losses. A minimum separation time is required for two radiation events to be recorded in radiation detectors. This separation time is called the dead-time of the detection system [1]. Two different factors affect the detector system's dead-time; the detector's intrinsic dead-time and pulse processing dead-time. The intrinsic dead-time of a radiation counting system depends on different parameters including geometry, material, and design of the detector as well as operating conditions such as applied voltage and temperature [2–5]. The pulse processing dead-time is associated with the electronic circuitry of the detection system. The most important contribution for pulse processing dead-time is analog to digital transition for pulses [6]. Dead-time effect on the detector system will result in lower observed counts than the true counts. Therefore, a mathematical correction is required to make up for the lost counts, that would bring the count rate close to the true counts.

Researchers have suggested dead-time correction models for more than seven decades to correct count losses [7]. There are two simple generalized dead-time correction models, one paralyzed and one non-paralyzed [8,9]. The paralyzable correction model assumes that if a radiation interaction occurs within the dead-time duration of the detection system, radiation interaction is not recorded as an individual event, and will reset dead-time hence extending dead-time. The paralyzable correction model is mathematically expressed as

$$m = ne^{-n\tau} \tag{1}$$

where n, m, and τ represent the true count rate, the observed count rate, and the dead-time, respectively. In the non-paralyzing model, the dead-time for a detector system is fixed, and interactions that occur during this dead time cannot be recorded. Unlike the paralyzing model, after the initial event is recorded by the detector, the non-paralyzing model allows the system to recover after a fixed dead-time. The non-paralyzing correction model is mathematically expressed as

$$m = \frac{n}{1 + n\tau} \tag{2}$$

it is important to emphasize that no detector, in reality, follows these two generalized correction models exactly. The behavior of a real detector falls in between non-paralyzing and paralyzing dead-time models [10]. For example, Lee and Gardner have developed their hybrid model that includes two dead-times as shown in Eq. (3) [11]. They applied the decaying source method with ^{56}Mn to validate the proposed hybrid model and obtained less than 5% deviation from observed counting rates for the GM detector.

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$$m = \frac{ne^{-n\tau_p}}{1 + n\tau_{np}} \tag{3}$$

In their expression, τ_p is the paralyzing dead-time, τ_{np} is the non-paralyzing dead-time. Likewise, Patil and Usman [6] developed a new hybrid correction model (shown in Eq. (4)) by developing the model previously proposed by Müller [12]. They implemented the decaying source method with ^{56}Mn and ^{52}V to validate the proposed hybrid model using HPGe (High Purity Germanium) detector. For a HPGe detector, they obtained a paralysis factor between 50 and 77%, and the dead-time value was between 6 μs and 10 μs [6].

$$m = \frac{ne^{-n\,\tau\,f}}{1 + n\tau(1-f)} \tag{4}$$

where f is the paralysis factor, which is the paralyzing probability of the detection system and τ is the total dead-time of the system.

2. Dead-time determination methods

One of the most common methods for determining the dead-time of a detection system is the two-source method [13,14]. It is commonly used method to estimate the dead-time of gas-filled detector systems. The method can be implemented simply by obtaining the radiation rate from two sources, both individually and in combination. In order to estimate the dead-time of the detection system using two-source model, the sum of the radiation rates observed individually from both sources must be greater than the radiation rate observed for combined sources. It is essential to keep the radioactive sources in the same geometry during measurement. In addition, scattering around the detector may affect the measurements. All mathematical expressions for two-source method are explained well in the literature [1,2].

The second common dead-time determination method for a detection system is the decaying source method [1]. This method can be applied according to the known exponential decay behavior of a radioactive source using isotopes with short half-lives.

$$n = n_0 e^{-\lambda t} + n_b \tag{5}$$

where λ is decay constant of the isotope, n_b is the background count rate, n_0 becomes the true count rate when t = 0. Assuming there is no background radiation and substituting Eq. (5) into the non-paralyzing dead-time model equation that is given in Eq. (2), decay source equation becomes,

$$me^{\lambda t} = -n_0 \tau m + n_0 \tag{6}$$

when the value of $me^{\lambda t}$ is plotted with respect to the value of m, the slope of this line provides $-n_0\tau$. Therefore, the dead-time can be obtained from the ratio of the slope to the intercept value. A more detailed description of this method can be found in the literature [1,14,15].

3. Deadtime Measurement with Radiation Absorption Law (DMRAL)

When a beam of photons penetrate through a material, the transmitted beam intensity (I_1) of gamma-rays passing through a material is expressed by

$$I_1 = I_0 e^{-\mu x} \tag{7}$$

where I_0 incident beam intensity, μ is linear attenuation coefficient, and x is the thickness of the material. The linear attenuation coefficient (μ) represents all possible interactions with material including photoelectric effect, Compton scattering, and pair production [1]. Eq. (7) is based on the assumption that there is no build-up (build-up factor = 1), an assumption valid for thin shield approximation [16]. For other cases it would be necessary to account for the build-up factor. A similar method for neutron detector dead-time measurement was reported to have produced good results [17].

In this study, a new method to determine dead-time for gamma-ray measurement systems is introduced using gamma-ray attenuation law and generalized dead-time correction models. Assuming the gamma attenuation law given by intensity in Eq. (7) is expressed by true gamma-ray counts (n and n_0) as;

$$n_1 = n_0 e^{-\mu x} \tag{8}$$

where n_0 is the incident number of true gamma rays, and n_1 is the transmitted number of true gamma-rays. It should be noted that the number of measured gamma rays is m_0 when gamma-ray measurement is obtained without using any shielding material between the detector and the radioactive source. The detector measures m_1 (transmitted number of measured gamma-rays) when a layer of material is placed between the detector and radioactive gamma source, this should be in fact n_1 (transmitted number of true gamma rays). Alternatively, Eq. (8) can also be written using the mass attenuation coefficient.

$$n_1 = n_0 e^{-\left(\frac{\mu}{\rho}\right).\rho x} \tag{9}$$

where μ/ρ is the mass attenuation coefficient, and ρ is the density of the material. The mathematical non-paralyzing dead-time model can be expressed with Eq. (10) with no absorber between detector and the radioactive source.

$$m_0 = \frac{n_0}{1 + n_0\tau} \tag{10}$$

If a very thin material is to be placed between the detector and the radioactive source, the non-paralyzing model can be written as

$$m_1 = \frac{n_1}{1 + n_1\tau} \tag{11}$$

where m_1 is the measured transmitted gamma-rays, n_1 is the true transmitted gamma-rays, and τ is the dead-time of the detection system. The ratio of m_0 and m_1 can be written as

$$\frac{m_0}{m_1} = \left(\frac{n_0}{1 + n_0\tau}\right) \cdot \left(\frac{1 + n_1\tau}{n_1}\right) \tag{12}$$

Combining Eq. (9) and Eq. (12), the following ratio is obtained

$$\frac{m_0}{m_1} = \left(\frac{n_0}{1 + n_0\tau}\right) \cdot \left(\frac{1 + \left(n_0.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)}\right).\tau}{\left(n_0.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)}\right)}\right) \tag{13}$$

The $n_0\tau$ term can be obtained from Eq. (13) and written as

$$n_0.\tau = \frac{m_1 - m_0.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)}}{m_0.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)} - m_1.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)}} \tag{14}$$

If the mass attenuation coefficient of the material and the density of the material are known, then the value of $n_0\tau$ can be easily calculated since m_0 and m_1 values will be determined by the detector. It should be noted that the material must be very thin to ensure the validity of the build-up factor = 1 assumption. The only unknown parameter is the incident number of true gamma rays (n_0) in Eq. (10) after $n_0\tau$ parameter determined using Eq. (14) for the non-paralyzing dead-time model. Once the incident number of true gamma rays (n_0) is obtained, the dead-time of the detection system can be easily determined using Eq. (10). This procedure can also be done with the linear absorption coefficient of a material instead of mass attenuation coefficient.

If there is no material placed between detector and radioactive source, the mathematical expression for the case of paralyzing dead-time model can be written as

$$m_0 = n_0 e^{-n_0.\tau} \tag{15}$$

If a very thin material is to be placed between the detector and the radioactive source, the paralyzing model can be expressed as

$$m_1 = n_1 e^{-n_1.\tau} \tag{16}$$

Again, using Eqs. (15) and (16) for paralyzing model and gamma-ray attenuation law with mass attenuation coefficient (Eq. (9)), the ratio of m_0 and m_1 can be expressed as

$$\frac{m_0}{m_1} = \frac{n_0.e^{-n_0.\tau}}{n_1.e^{-n_1.\tau}} \tag{17}$$

$$\frac{m_0}{m_1} = \frac{n_0.e^{-n_0.\tau}}{\left(n_0.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)}\right).\left(e^{-n_0.\tau e^{-\left(\frac{\mu}{\rho}\right).(\rho x)}}\right)} \tag{18}$$

After the necessary mathematical operations are performed, Eq. (18) becomes

$$ln\left(\frac{m_0}{m_1}\right) = -n_0\tau + n_0\tau.e^{-\left(\frac{\mu}{\rho}\right).(\rho x)} + \left(\frac{\mu}{\rho}\right).(\rho x) \tag{19}$$

Then, the $n_0\tau$ term can be obtained from Eq. (19) and written as

$$n_0.\tau = \frac{\ln\left(\frac{m_0}{m_1}\right) - \left(\frac{\mu}{\rho}\right).(\rho x)}{e^{-\left(\frac{\mu}{\rho}\right).(\rho x)} - 1} \tag{20}$$

Again, the only unknown parameter is the incident number of true gamma-rays (n_0) in Eq. (15) after $n_0\tau$ parameter determined using Eq. (20) for the paralyzing dead-time model. Once the incident number of true gamma-rays (n_0) is obtained, the dead-time of the detection system can be easily determined using Eq. (15). In the light of all these theoretical statements, dead-time calculations of a NaI(Tl) scintillator detector were implemented to validate this method.

4. Validation of DMRAL Method

The experimental part of DMRAL method was carried out at Marmara University Nuclear Physics Laboratory (MUNPL). A NaI(Tl) scintillator detection system manufactured by Ortec was tested to validate the DMRAL method, a newly introduced dead-time determination method. A 370 kBq (10 μC) ^{137}Cs radioactive gamma source (as shown Fig. 1) produced by Eckert & Ziegler company on December 1, 2018 was used for experiments.

Polyethylene (PE) and lead absorber materials were used in the experiment by individually placing them between the detector and

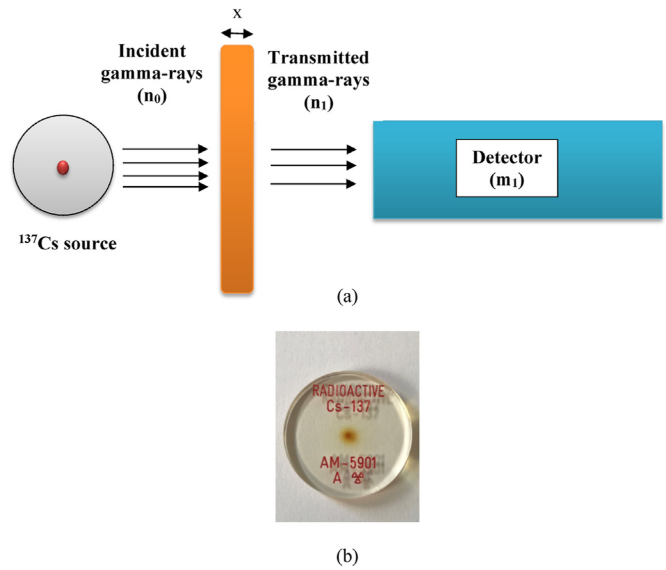

Fig. 1. (a) Experiment design for radiation measurement system to validate DMRAL method. **(b)** Cesium-137 gamma-ray disk source.

the radioactive source. The gamma-ray attenuation measurements were taken using 0.07620 cm thick PE and 0.08128 cm thick lead as an absorber to determine the dead-time of the NaI(Tl) detection system. The reason why the thicknesses of absorber materials are chosen so small is to be able to neglect the build-up factor.

The gamma-ray measurements were taken for 5 min with ^{137}Cs radioactive gamma-ray source (at 662 keV energy) for each individual case for the scintillation detection system. The three consecutive measurements were implemented to reduce statistical errors with and without absorber material. In order to prevent the detector from being saturated, a 2 cm space is left between the detector and the material, and 2 cm between the material and the source. First, the background radiation of the environment was obtained for 5 min. Second, the measurements (m_0) were taken for NaI(Tl) detector with no material between the detector and radioactive source for 5 min. Then, the measurements (m_1) were taken with the material placed between the detector and the radioactive source before calculating the dead-time of detection system for both generalized models. Using the equations provided above, the results of the ^{137}Cs peak measurements and material information given in Table 1, the dead-time of the NaI(Tl) detection system were calculated for both generalized models with the DMRAL method.

Table 1 shows the average values of the measured count rates and the net count rates with lead and PE absorbers' error rates. The average net count rate at 662 keV peak with no absorber was measured as 650.22 cps with an error of ±2.09. This value was used as m_0 at all times to determine the dead-time of the detection system for both non-paralyzing and paralyzing models. The average count rates at 662 keV peak with lead and PE absorber were 593.15 cps with an error of ±0.52 and 646.00 cps with an error of ±0.82, respectively. These values were used as m_1 to determine the detection system's dead-time for both non-paralyzing and paralyzing models.

Fig. 2 shows the experimental counting results without absorber and 0.08128 cm thick lead absorber at 662 keV energy using ^{137}Cs source for NaI(Tl) detection system. Based on the DMRAL method and non-paralyzing and paralyzing model, the NaI(Tl) detection system's dead-time was calculated. Eq. (14), Eq. (10), the information provided in Table 1, and physical properties of the absorbers

Table 1
Gamma absorption measurements with NaI(Tl) scintillator detector at 662 keV peak using lead (0.08128 cm) and PE (0.07620 cm) absorber.

# of Counts	Background (5 min)	Background (cps)	No absorber (5 min)	No absorber (cps) m_0	Lead (5 min)	Lead (cps) m_1	PE (5 min)	PE (cps) m_1
1	61	0.20	195387	651.29	178072	593.57	193941	646.47
2	39	0.13	195564	651.88	178097	593.66	194031	646.77
3	45	0.15	194396	647.99	177815	592.72	193569	645.23
Mean	48.33	0.16	195115.67	650.39	177994.67	593.32	193847.00	646.16
Net Error				**650.22** ± 2.09		**593.15** ± 0.52		**646.00** ± 0.82

were used to obtain dead-time for the non-paralyzing model for lead and PE absorbers. Eq. (20), Eq. (15), the information provided in Table 1, and physical properties of the absorbers were used to obtain dead-time for paralyzing model for lead and PE absorbers. It is important to note that the mass attenuation coefficients of the absorbers are taken from literature as provided in Table 2 since they are not provided by the manufacturer.

Table 2 shows the physical properties of the absorber materials and the calculated dead-time values of the NaI(Tl) detection system for both non-paralyzing and paralyzing models. The dead-time value for the non-paralyzing model using the lead absorber was calculated as 8.39 μs, while the dead-time value for the paralyzing model using the lead absorber was calculated as 8.35 μs.

In addition, PE absorber material was used to verify the values found with the lead material. The dead-time value for the non-paralyzing model using PE absorber was calculated as 19.02 μs, while the dead-time value for the paralyzing model using lead absorber was calculated as 18.79 μs. In the dead-time calculations, the build-up factor has been neglected for both absorber materials due to the materials' minimal thickness. “No build-up” approximation is valid for thin shields when the shape symmetry of the peaks is examined in Fig. 2b at 662 keV peak.

5. Conclusion

This study introduced a new dead-time determination method for radiation detection systems using gamma attenuation law. The two-source method is one of the traditional methods to determine the dead-time of the radiation measurement system using two similar radioactive sources. On the other hand, the decaying source dead-time determination method can only be used when there are radiation sources with sufficiently short half-lives. Since this can

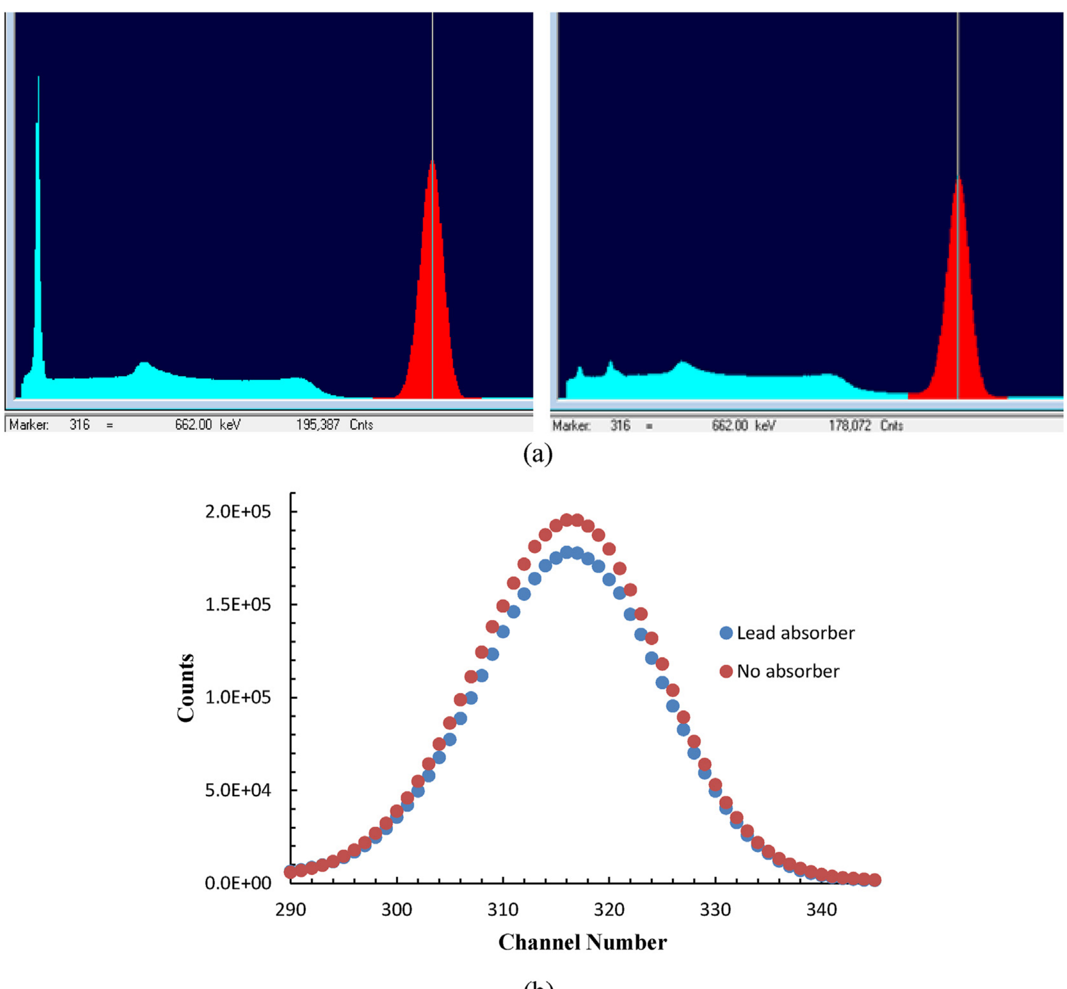

Fig. 2. (a) Experimental counting results without absorber and 0.08128 cm thick lead absorber at 662 keV energy using ^{137}Cs source. **(b)** Peak difference with and without absorber material.

Table 2
Absorber information and dead-time results of NaI(Tl) detector using DMRAL method.

Material	Density (g/cm^3)	Mass attenuation coefficient (cm^2/g) [18,19]	Non-paralyzing dead-time (μs)	Errors	Paralyzing dead-time (μs)	Errors
Lead	11.35	0.10010	**8.39**	±0.46	**8.35**	±0.46
PE	0.950	0.09107	**19.02**	±1.05	**18.79**	±1.04

only be done in facilities that can produce radioactive sources, there is a limitation of the dead-time determination method. In the proposed DMRAL method, it has been observed that the dead-time results are reasonable for NaI(Tl) detection system. In the calculations, non-paralyzed dead-time was 8.39 μs, and paralyzed dead-time was 8.35 μs using 0.08128 cm thick lead absorber. The NaI(Tl) detection system's dead-time values were expected in the range of 0.5 μs and 10 μs [20,21]. The dead-time of the NaI(Tl) detection system found to be 19.02 μs for non-paralyzing model and 18.79 μs for paralyzing model using 0.07620 cm thick PE absorber. These values were a little higher than expected dead-time for NaI(Tl) detection system but Grozdanov and coworkers have been reported similar results [22]. The reason why PE dead-time values are two times higher than those of lead is attributed to the fact that the mass attenuation coefficients are taken from the literature as they are not provided by the manufacturer. The gamma build-up factor was provided in the literature depending on the thickness and photon's energy for some materials [16]. The build-up factor at 0.5 MeV energy is specified as 1 and 1.14 for 0 cm lead and 0.5 cm lead, respectively [16]. Since the thicknesses used in this study were 0.07620 cm and 0.08128 cm, the build-up factor's contribution to the calculations is negligible. Another confirmation that the build-up factor can be neglected in the dead-time calculations for the thin shield is shown in Fig. 2b where the shape symmetry presents between the shielded and unshielded photopeak. These dead-time calculations can also be obtained using linear attenuation coefficient equations instead mass attenuation coefficients.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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