Significance of measured negative dead time of a radiation detector using two-source method for educational purpose

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\textbf{ABSTRACT}
This paper emphasizes on the correction of a misconception among the students about the presence of negative dead time values determined by using a two-source method. To specify the importance of this work, weak sources have been designed specifically so that broad distribution of dead time values can be obtained including 30–40% of the negative values. During the measurements, students usually eliminate the measured negative dead time data intuitively, which leads to an inaccurate average detector dead time. In this work, together with the experimental results from the two-source method, we also performed Monte Carlo simulation. Thus, we correlated the statistical average distribution of dead time and proved that negative value of dead time exists when the weak sources are applied. Furthermore, these negative dead time values play a crucial role in determining the accurate dead time. Thus, this work will serve to be an excellent model for the students to learn about the scientific discipline in handling the experimental data correctly and the importance of error propagation in counting statistics.

\textbf{1. Introduction}

Among various radiation measurement detectors, Geiger–Muller (G-M) counter is an excellent radiation detector, which is known for its stable operation and being inexpensive and versatile in detecting radiations. It has been used in a variety of applications such as radiation monitoring, industrial gauging and radiation detection (Elrefaei et al., 2019; Gomaa, 2020). The G-M counter is a pulse type detector and is known to have a longer dead time after each radiation encountered in it. In a G-M counting system with a low level discriminator (LLD), a minimum time interval between two pulse events is required before each pulse can be treated as an independent event, which is referred to as counting system dead time (Knoll, 2010; Muller, 1973; S.H. Lee & Gardner, 2000). During this period, the charge collection of the detector and pulse discriminator prevent the detector system to accept further incoming radiation, resulting in the loss of radiation counting. Existence of dead time usually led to significant loss of signal reaching the detector when the intensity of the source is strong. To measure the dead time of the detector system, a two-source method was developed by (Moon, 1997). The statistical error determination of the two-source method has been proposed further by Beers, 1942. Numerous methods have been proposed by different groups to modify and improve the ways of determining the dead time of G-M counters (Akyurek et al., 2015; Arkani et al., 2013; Yousaf et al., 2015). The precision of the two-source method depends on the source intensity. The higher the intensities of the sources, the better the precision of determining the dead time. However, if the counting rates are too high, then the detector statistics no longer follow the Poisson distribution due to higher counting loss (C.H. Lee & Wang, 2015). On the contrary, it is also interesting to see that negative dead time is determined occasionally when an extremely weak source is used.

During the last 40 years of teaching radiation measurement laboratory course in National Tsing Hua University, one of the experiments was to determine the dead time of the G-M detector using the two-source method. For radiation safety reason, weak sources were provided to the students and the instructor asked students to repeat the experiment three times to report the averaged dead time. A big faulty practice has been identified during this experiment. Most of the students performed the measurements more than three times, owing to the occurrence of a negative dead time value. They repeated the measurements and eliminated those
unreasonable negative dead time data Intentionally until all the measured dead time values are positive. This was found to be a common error during this experiment, which turned out to be a wrong practice against the scientific discipline and resulted in an over-estimated experimental averaged dead time. The instructor then gave a strong warning to correct this behavior and asked the students to respect all the experimental data offered by mother nature even when a negative dead time was obtained. The students must consider the negative dead time value because this negative dead time value also arises from the nature. Then, the instructor conveyed the student the importance of counting statistics with the error propagations, which possibly lead to the occurrence of negative dead time values.

Based on this conception, determination of dead time by the two-source method is applied and the measured counts of two sources (m_12) combined should be less than the counts of two semi-sources (i.e. m_1 and m_2) measured individually (i.e. m_1 + m_2 > m_12). The detector system dead time is calculated from the difference between m_1 + m_2 and m_12. However, due to the nature of statistical errors, sometimes, there is a possibility that the counts obtained by combining two sources are lower than the sum of the counts measured from each source individually (i.e. m_1 + m_2 < m_12). This will result in the measured dead time to be negative. Therefore, in this work, we emphasize the importance of this negative dead time values and correlate the relation existing between the negative dead time and the source intensity.

To demonstrate the two source method using a weak source resulting in a high probability of occurrence of negative dead time, a Monte Carlo program with random number generation has been utilized to simulate and compare the effects in the statistical average distribution of dead time by including and excluding those negative dead time values. In addition, simulations have been performed to reveal the relation existing between the counting rate and the probability of negative dead time. Furthermore, a collection of students’ experimental dead time data using the two-source method has been compared with the simulation result, and their detailed description is described in the latter parts.

2. Experimental and methods

2.1. Experimental

To determine the dead time of the counting system using the two-source method, two semi-sources of ⁸⁵Sr were used. Four measurements (500 s each) were taken to measure the dead time, namely, m_1, m_2, m_12 and m_b, where m_1 and m_2 are counting rates of sources 1 and 2, respectively; m_12 is the counting rate by putting two sources together and m_b stands for the background counting rate.

In this experiment, a G-M counter (Oxford – 412, Oxford Instruments) was used. The radiation induced pulse signals then passed through consecutive signal processing modules: preamplifier specially designed for the G-M counter (Canberra – 148A, Canberra Industries Inc.), single channel analyzer (SCA) (Canberra – 2030, Canberra Industries Inc.) and counter/timer (Canberra – 2071A, Canberra Industries Inc.). Under a high applied voltage of 700 V, the output signal of the G-M counter was measured to be around 2 V by using an oscilloscope. There was no linear amplifier used in our system. The output of the G-M counter was tuned with the help of applied voltage. In this case, the system dead time was measured after setting the LLD of SCA closer to the end of recovery time to ensure that the detection system follows the non-paralyzable mode (Knoll, 2010).

2.2. Dead time simulation

Figure 1 shows the flow chart involved in generating counting statistics by the Monte Carlo method. Monte Carlo simulation was performed by using Dev-C++ program for random number generation to simulate our experimental parameters. We choose the random number following Poisson distribution to mimic the situation of nuclear decay. It is one of the popular mathematical techniques that is utilized to determine the most possible outcomes from an unexpected event. It allows us to project results farther out in time with higher accuracy. Moreover, Monte Carlo simulation also helps us to understand the impact of risk and uncertainty in predicting the values.

The counting rate of two sources m_10 and m_20 (for simplification, here, we assume m_10 = m_20 in the simulation), background m_b0, data acquisition time T_count and theoretical dead time τ_0 were pre-defined during the initial stages of the simulation. The value of m_120 (the estimated counting rate when two sources are measured together) can be obtained from Equation (1) (Knoll, 2010).

\[
\frac{m_{120}}{1 - m_{120} T_0} + \frac{m_{b0}}{1 - m_{b0} T_0} = \frac{m_{10}}{1 - m_{10} T_0} + \frac{m_{20}}{1 - m_{20} T_0}
\]

During Monte Carlo simulation, the background counting rate m_b0 was defined as 0.3024 cps, and the initial dead time τ_0 was set to 1.6 ms. The initial background of 0.3024 cps was determined after hours of measurement without any presence of the source in the G-M system. The initial dead time of 1.6 ms was obtained experimentally from our 200 measurements.
Define $T_{\text{count}} = m_{10} m_{20} m_{bg0} \tau_0$

$$m_{120} = \frac{k}{1 + k \tau_0}$$

$$k = \frac{m_{10}}{1 - m_{10} \tau_0} + \frac{m_{20}}{1 - m_{10} \tau_0} - \frac{m_{bg0}}{1 - m_{bg0} \tau_0}$$

$$m_{\text{el}} = m_{10} \times T_{\text{count}}$$

$$m_{\text{el}} = m_{20} \times T_{\text{count}}$$

$$m_{\text{bg}} = m_{bg0} \times T_{\text{count}}$$

$$m_{\text{el}2} = m_{120} \times T_{\text{count}}$$

Poisson distribution random sampling

$$P(i|\mu) = \frac{\mu^i}{i!} e^{-\mu}$$

$$m_1 = P(i|m_{11}) / T_{\text{count}}$$

$$m_2 = P(i|m_{12}) / T_{\text{count}}$$

$$m_{bg} = P(i|m_{bg}) / T_{\text{count}}$$

$$m_{\text{el}2} = P(i|m_{el2}) / T_{\text{count}}$$

Monte Carlo simulations were performed for 200 times and one million times to compare the statistical average distribution of dead time with the 200 experimental results. The parameter used during the simulation for 200 times and million times are identical. During the simulation for 1 million times, the fluctuation due to the limited number of observations can be eliminated as per ‘central limit theorem’ from the basic statistical theory.

3. Results and discussion

Figure 2(a) reveals the simulated statistical average distribution generated using the Monte Carlo method, which is plotted in the form of a histogram between numbers of measurements vs. dead time. The inset of Figure 2(a) shows the experimental data obtained by utilizing the $^{90}\text{Sr}$ source (2 $\mu$Ci). It can be seen from Figure 2(b) that around 40–45% of the total simulated values are negative, whereas around 25–30% of the experimentally measured dead time values are negative. The measured and calculated dead time are summarized in (Table 1). The mean experimental dead time obtained is around 1.6 ms, whereas the mean dead time is around 8.3 ms if the negative dead time values are eliminated. The Monte Carlo method and experimental results revealed similar trend of dead time values, as shown in Table 1. It can be noted that the statistical error of the simulation data is similar to that of the experimental data for 200 times, whereas the statistical error gets reduced further at 1 million cycles.

Furthermore, Figure 3 shows the relation between the percentage of negative dead time vs counting rate at various simulation intervals. The average counting rate obtained from this experimental work has been highlighted together with the Monte Carlo simulation result. In addition, from Figure 3, it can be noted that the percentage of negative dead time follows a decreasing trend as a function of counting rate. It can also be clearly observed that when $m_{10}$ approaches the higher counting rate, the ratio of negative dead time almost approaches 0, whereas at lower counting rates, the ratio of negative dead time seems to be remarkably high. This clearly states that the probability of negative dead time tends to be larger at lower counting rates. In general, to avoid the occurrence of statistical negative data, higher counting rates are required to obtain a true dead time with limited number of measurements in a two source method.

In order to show that the negative dead time can be easily obtained using a two source method for the teaching purpose, the weak source of $^{90}\text{Sr}$ has been
used. Utilizing a weak radioactive source is more advantageous for obtaining higher change in negative dead time. Furthermore, this work emphasized the necessity of respecting each data point being measured, even though the negative dead time is not possible intuitively. This behavior of students’ elimination of doubtful data personally is against the scientific discipline, which should be corrected to cultivate among the students for becoming a successful scientist in the future. Overall, this study implies the importance by stating that all the experimental values must be taken into account without eliminating any value, which in turn will result in the accuracy of the statistical average of the dead time.

Figure 2. (a) Simulation result of No. of measurements vs dead time by considering its negative value: the inset shows the dead time obtained experimentally. (b) Enlarged representation of the percentage of negative ratio obtained from experimental and Monte Carlo simulation.

Table 1. Comparison of statistical average distribution of dead time between experimental and simulation parts.

| Condition                      | Experimental dead time (ms) | Simulation dead time (ms) |
|--------------------------------|-----------------------------|---------------------------|
|                                | After 200 times             | After one million times   |
| Total data averaged            | 1.6 ± 1.03                  | 1.40 ± 0.72               |
| Only positive values are taken | 8.3 ± 0.55                  | 8.62 ± 0.60               |
|                                |                             | 8.44 ± 0.01               |
4. Conclusion

In this work, we stated the importance of considering all the experimental values measured and the drawbacks in the statistical average distribution by excluding those negative values. The two-source method using a weak source lead to the broad distribution of dead time values. From our experimental results, we observed that about 25–30% of the dead time values determined by the students are negative, which are reasonably consistent with the simulation results. Overall, this is an important teaching practice in scientific discipline to demonstrate the students not to discard any data that mother nature has given statistically and do not make a personal judgment.

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Figure 3. Relation between the percentage of negative ratio and mean counting rate for various simulation time intervals.
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