Geiger Counter Calibration and Distribution

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I. Introduction

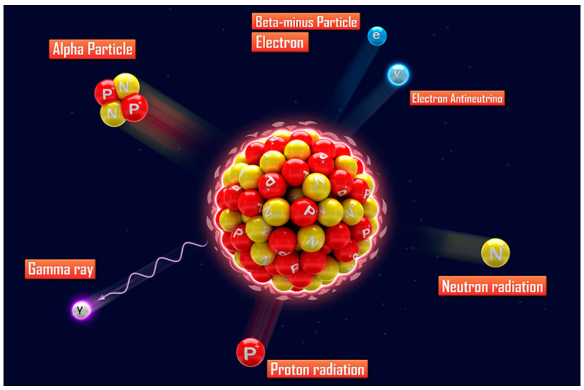


FIG. 1. Different forms of nuclear decay. Image credit: chernobylguide.com.

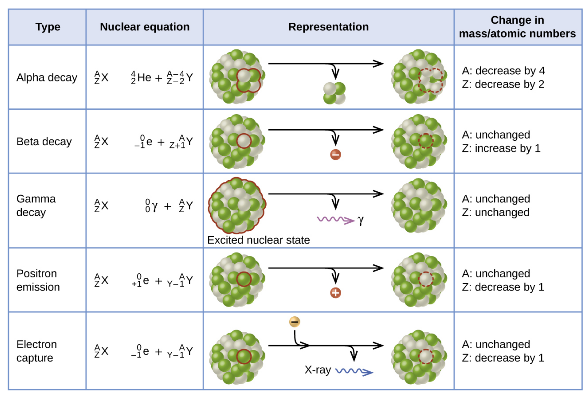
Purpose

The purposes of this experimentation were (i) to understand the function and operation of a Geiger-Müller (GM) counter, (ii) to calibrate a GM counter by determining its optimum voltage range of operation, (iii) to observe the inverse-square law with respect to radiation counts, and (iv) to prove that decay events are random, independent count events and follow normal distributions.

Radiation and Radioactive Decay

Radiation and radioactive decay are commonly perceived as dangerous phenomena, which is a good perception to have; over-exposure to any type of radiation will result in adverse effects to the human body. However, despite its dangers, radiation is vitally important, not only in the form of electromagnetic radiation provided by the Sun, but also as a subject of study concerning methods of energy production, primarily through radioactive decay. Radioactive decay is the process by which radioactive materials decrease their energy by emitting particles due to the presence of too many or too few neutrons. This excess or lack of neutrons is what causes an atom to be unstable; such atoms are called radioisotopes (radioactive isotopes).

There are three primary forms of natural radioactive decay: alpha decay (α), beta decay (β), and gamma decay (γ). Alpha decay occurs when a radioisotope emits a particle that is equivalent to a doubly ionized Helium atom, i.e., an atom with two protons, two neutrons, and no electrons. Thus, the process of alpha decay of an atom ${}^{A}_{Z}\mathrm{X}$ with atomic mass A and atomic number Z can be expressed as such: ${}^{A}_{Z}\mathrm{X} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{A-4}_{Z-1}\mathrm{Y}$, as conveyed in Figure 2. Beta decay is normally



Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^{A}_{Z}\mathrm{X}$ ${}^{4}_{2}\mathrm{He} + {}^{A-4}_{Z-2}\mathrm{Y}$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^{A}_{Z}\mathrm{X}$ ${}^{0}_{-1}\mathrm{e} + {}_{Z+1}^{A}\mathrm{Y}$		A: unchanged Z: increase by 1
Gamma decay	${}^{A}_{Z}\mathrm{X}$ ${}^{0}_{0}\gamma + {}^{A}_{Z}\mathrm{Y}$	Excited nuclear state; γ	A: unchanged Z: unchanged
Positron emission	${}^{A}_{Z}\mathrm{X}$ ${}^{0}_{+1}\mathrm{e} + {}_{Y-1}^{A}\mathrm{Y}$		A: unchanged Z: decrease by 1
Electron capture	${}^{A}_{Z}\mathrm{X}$ ${}^{0}_{-1}\mathrm{e} + {}_{Y-1}^{A}\mathrm{Y}$	X-ray	A: unchanged Z: decrease by 1

FIG. 2. Types of radioactive decay. Image credit: Rice University.

associated with the loss of an electron and an increase in atomic number; however, although this is the end result, this raises the question of how the loss of an electron affects the number of protons. What actually occurs to produce the ejected electron is the decay of a neutron into a proton, an electron, and an antineutrino[1].

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[1] Berkeley Labs. (2009, February). *Neutron beta decays.* http://www.particleadventure.org/npe.html.

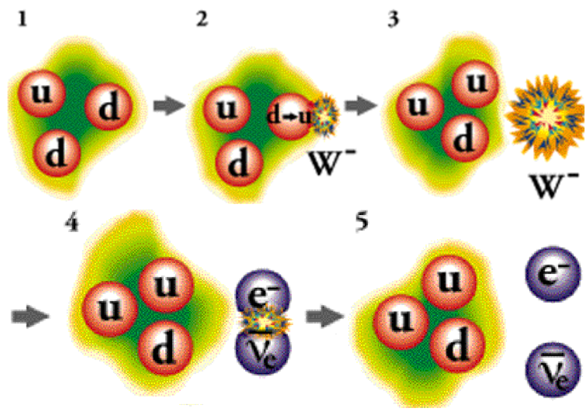

FIG. 3. The process that occurs during beta decay. (1) An up quark ($+\frac{2}{3}e$ per particle)[a] and two down quarks ($-\frac{1}{3}e$ per particle) comprise a neutron. (2) A down quark becomes an up quark and a W- boson carries away a negative charge (charge conservation). (3) The up quark moves away from the W- boson and the neutron has become a proton. (4) An electron and antineutrino arise from the W- boson. (5) The proton, electron, and antineutrino move away from one another. Image and content credit: particleadventure.org.

[a] The symbol e denotes the minimum magnitude of electric charge 1.602×10^{-19} C. Every other charge is a multiple of e and is either positive or negative.

Figure 3 portrays what occurs during beta decay[2]. The last of the primary types of decay is gamma decay. Gamma decay is unique compared to alpha and beta decay in that the atomic mass and the atomic number are conserved, at the expense of an ejected high energy photon. Gamma decay typically occurs after alpha and beta decay, since both decays leave the nucleus in a high energy state. Thus, gamma decay occurs to bring the nucleus to a lower energy state.

Geiger-Müller (GM) Counters

Because it is important to understand how various radioactive materials affect different environments, there are many instruments that detect radiation; the number of decay events that occur is referred to as the activity of the radioisotope. Of the devices that are used to measure radiation, the most common are Geiger-Müller (GM) counters, scintillation counters, ionization chambers, dose rate meters, and personal radiation monitors. The GM counter contains a tube called the GM Probe, which is a metallic cylinder containing the mica window (a thin sheet of silicate glass) and an inert gas (usually Argon, Helium, or Neon), as shown in Figure 4. Another component inside the tube is a wire that runs through the center of the tube. This wire acts as the anode and the interior walls of the casing act as the cathode.

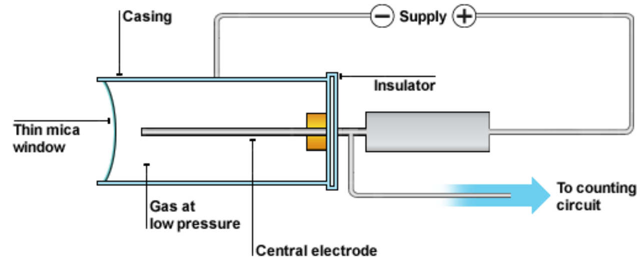

FIG. 4. The schematic of a Geiger-Müller tube.

GM Counter Operation

The GM counter operates when a voltage is applied to the tube and a radioactive source is present. When a voltage is applied to the anode, a potential difference is formed between the anode and the interior of the casing, establishing an electric field.

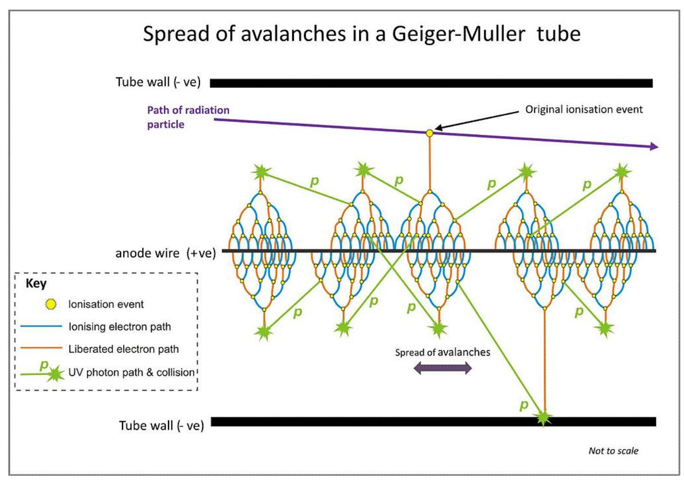

FIG. 5. What occurs when ionizing radiation enters an operating GM counter.

Then, when a radioactive source is present, the ra-

[2] Technically, there are four types of beta decay: beta-plus decay, beta-minus decay, electron capture, and double beta decay.

diation emitted from the source enters the GM tube through the mica window and ionizes the gas. As a result of the scattering event, the scattered electron and the positively charged gas particles scatter neighboring neutral gas particles, causing more scattering. This is referred to as the Townsend Avalanche, as shown in Figure 5. As a result of the potential difference, and hence the presence of an electric field, the positively charged gas particles collect on the inside of the casing and the electrons accumulate at the anode, sending a pulse to the counter as an output.

Other important components of GM counter operation is the voltage range and the dead time. Various radiation detectors have different operating voltage ranges. This can be seen in Figure 6.

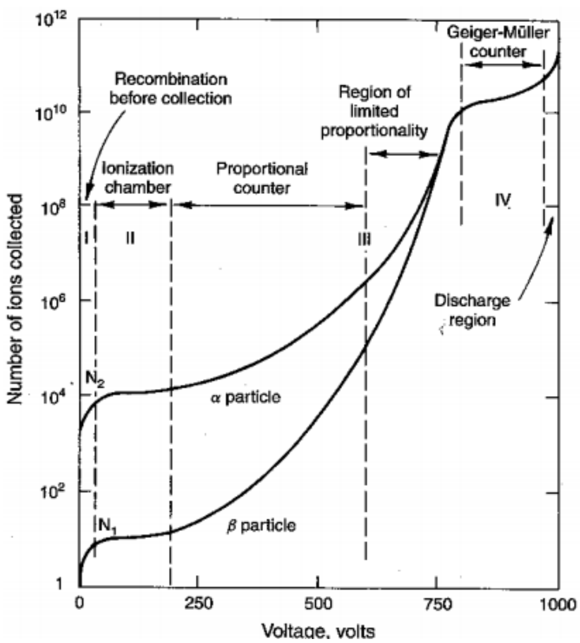

FIG. 6. Various operating voltage ranges for different radiation detectors.

The Geiger range lies approximately between 800 and 975 V, preferably when the rate of change of ions collected with respect to change in voltage is low (the plateau region). This is primarily due to the fact that at a given voltage within the plateau region, the number of counts detected will not drastically change, providing consistent outputs[3]. Further, this allows for a complete discharge at the anode. At this voltage, the gas inside the GM tube completely ionizes in the presence of ionizing radiation. At voltages outside of the the optimum range, undesired effects occur; at voltages higher than the plateau region, continuous discharges occur, disallowing for the GM counter to detect radiation, potentially damaging the device.

The dead time of the GM counter is the time during which an output pulse is not detected by the counter; a pulse is not be generated until the ionized gas returns to its neutral state. The importance of knowing the dead time of a GM counter is understanding how this is a limiting factor in the operation of a GM counter. The presence of the dead time suggests that there is uncertainty in the number of counts measured.

II. Data Acquisition

Materials

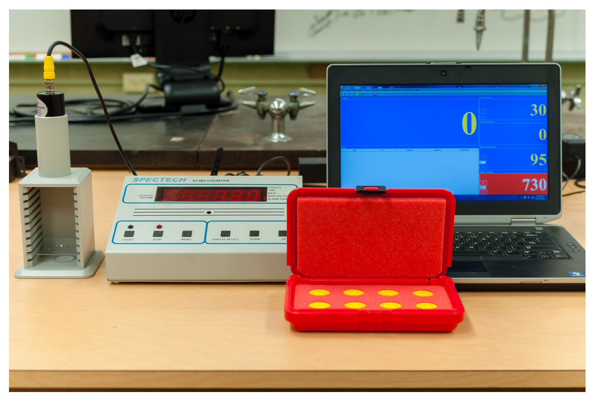

FIG. 7. The experimental set-up of the GM counter.

The materials used to perform this experimentation, from left to right according to Figure 7, are: the GM 35 Probe, the GMS 35 Stand, the source tray, the BNC cable, the ST360 Counter, radioisotopes (^{22}Na and ^{133}Ba), the USB connector, and the laptop with the appropriate Spectrum Techniques software.

Procedure and Methods

Calibrating the Geiger-Müller Counter

In order to properly use the GM counter, it needed to be calibrated. Thus, in order to determine the plateau region of the GM counter,

[3] Toloba, Elisa. (2018) *Geiger Counter, Part I.* [Class PDF]. Department of Physics, University of the Pacific. Stockton, CA.

the graph in Figure 6 was used to determine the approximate Geiger range, which was between 800 and 975 volts. Then, in order to measure the plateau range, both Ba-133 and Na-22 were used as the radioactive sources. At first, a test run was performed to see if the GM counter was operational. Afterwards, both sources were used, at different times, to determine the plateau range of the GM counter. Each source was placed in the top slot, the fifth slot from the top, and the ninth slot from the top. This resulted in a total of six measurements for a decent distribution of data. Each run began at 700 V with intervals of 10 V ending at 1000 V, having a 100 second duration at each voltage. The data for each radioactive element was plotted. Afterwards, the data was aggregated and normalized to obtain a general trend for the plateau region for the GM counter.

Determining the Distribution of Decay Events

In order to determine the distribution of decay events, the calibrated GM counter was used with the Na-22 source. The source was placed in the top slot and there was a total of 1000 runs with 20 seconds per run at the calibrated voltage. Then, the data was collected and plotted, giving a distribution. Afterwards, two fits of the data were obtained to determine whether or not if the distribution of the decay events were random or not.

III. Analysis

Determining the Plateau Range of the GM Counter and the Effect of Distance

The optimum voltage of the plateau region for the GM counter was determined from the data obtained from the Ba-133 and the Na-22 runs. For each source, the number of counts was plotted against the voltage. Figure 8 shows the data for Ba-133, the data for Na-22, and the normalized data for both, providing an overall distribution. The normalized result was obtained by dividing the data and the error for each run by the maximum value of that run. This allowed for a more uniform analysis of the data in order to estimate the optimum voltage, which was determined to be 950 $\pm$ 20 V. In order to examine how the distance affects the number of counts, the arithmetic mean was taken for each run of both Ba-133 and Na-22. Then, the average voltages for each run was plotted against the slot number. Additionally the the relationships of

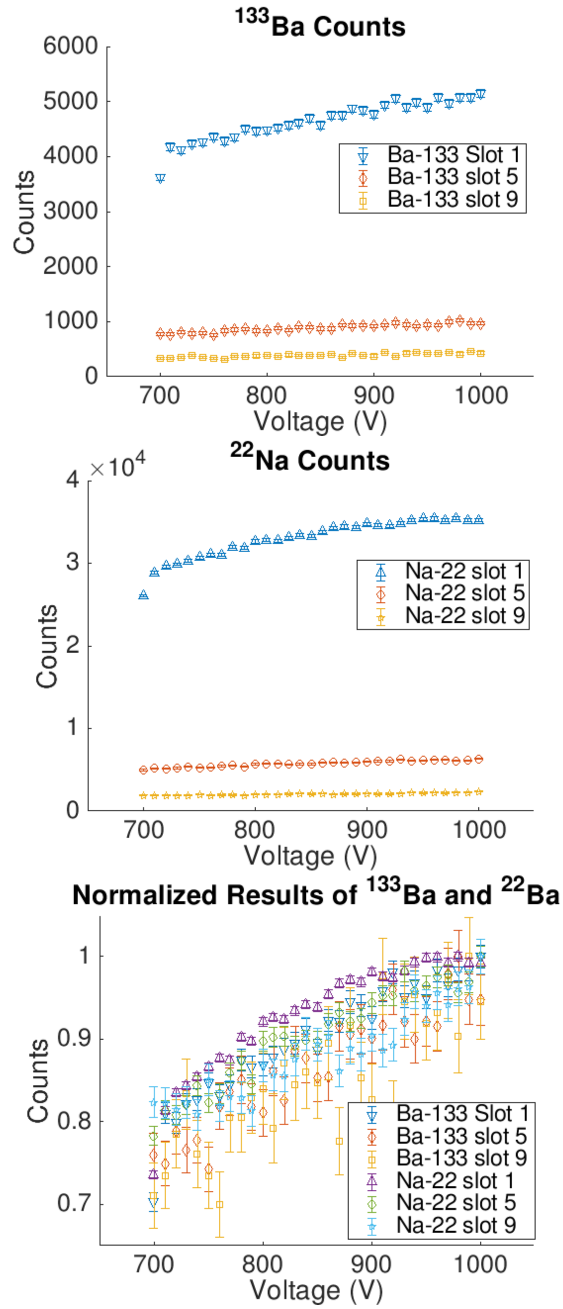

FIG. 8. The data for the decay of Ba-133 and Na-22 at varying voltages and varying distances. The third figure conveys the normalized data.

$y = 1/r$ and $y = 1/r^2$ were plotted, where y is the number of counts and r is the slot number. For the plots, the slot number was decreased by one unit to avoid shifting the inverse distance and inverse distance squared equations. This is depicted in Figure 9.

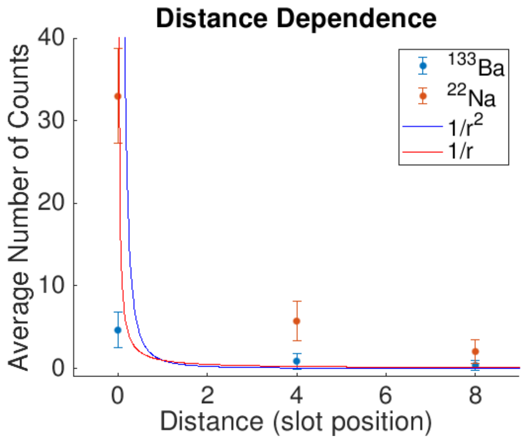

FIG. 9. The relationship between the average number of counts and the slot number.

Determination of the Distribution of Decay Events

Data that follows a normal, or Gaussian, distribution is described as having random and independent events. Such distributions obey the following equation

$$y(x) = \frac{1}{s\sqrt{2\pi}}\ e^{-(x-\bar{x})^2/2s^2} \tag{1}$$

where s is the standard deviation of $\bar{x}$, which is the mean of the data. To determine whether or not decay events follow normal distributions, the calibrated GM counter was used for the Na-22 source. The data obtained from running the GM counter at the optimum voltage for 1000 runs was plotted in the form of a histogram with 35 bins, which was arbitrarily chosen, shown in Figure 10. Then, in order to determine whether or not the data consisted of random and independent events, the arithmetic mean of the data was calculated. Then, the standard deviation of the data was determined in two ways: (1) using the formula

$$s = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n-1}}, \tag{2}$$

where x_i denotes the different data points,$\bar{x}$ denotes the mean of the sample size, and n represents the number of data points, and (2) using the relation that if there are N data points that are counts, then the standard deviation of the mean number of counts is $\sqrt{N}$. In using these relations in conjunction with equation (1), Figure 10 was produced by substituting the mean and the different standard deviations into the equation, producing the blue and red curves. The value obtained for the standard deviation using method (1) was 64 counts and the value obtained by method (2) was 65 counts.

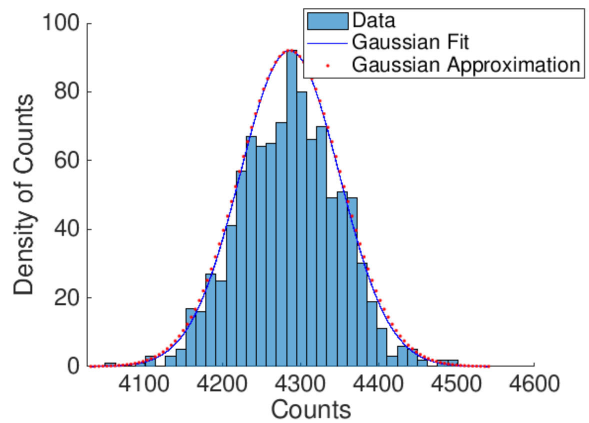

FIG. 10. A plot of the distribution of counts from Na-22. The Gaussian Fit was plotted using method (1) and the Gaussian approximation was plotted using method (2).

Estimating Uncertainties

In this experimentation, the primary sources of uncertainty were the dead time of the GM counter, the presence of other radioactive sources (despite being kept in the container), potential background radiation, and the natural uncertainty in the activity of the radioisotopes. These uncertainties have a direct effect on the counts observed. The dead time causes uncertainty because when the GM counter is quenched, then the counter is unable to detect an electric pulse. Of course, this is an instrumental limitation, which cannot be minimized. The presence of other radioactive sources and background radiation could influence the number of counts by causing there to be a reading of more counts than the source emitted. Although the plateau region is used for calibration to ensure that counts are consistent, for more sensitive counters and highly active sources, this could contribute significantly to the error. Errors of this nature can be reduced by moving radioactive materials away from the GM counter and by subtracting potential background radiation from collected data. Because activities can not be measured precisely, there will always be a natural uncertainty with the activity of a radioisotope, which too cannot be minimized.

In terms of estimating the plateau range, because the optimum voltage was estimated using sight, this causes uncertainty. If analytical methods were used to determine the optimum voltage in the Geiger range, then the uncertainty could be better quantified. The uncertainty in determining whether or not decay events are random and independent can also be associated with the uncertainties aforementioned, which primarily influence the number of counts. However, if decay events are random and independent, and because the uncertainty is the parameter that was being determined, then it should follow that the uncertainty obtained in methods (1) and (2) should agree.

IV. Discussion

The Plateau and the Optimum Voltage

The value of the optimum voltage in the Geiger range was determined to be 950 $\pm$ 20 V. In looking at the third plot in Figure 3, the plateau doesn't begin to form until the last 100 volts. This suggests that the experiment for each run should have lasted slightly longer including voltages higher than 1000 volts in order to obtain a less ambiguous graph for the determination of the calibration voltage. This is the primary reason why there is an uncertainty of $\pm$ 20 V, which represents an uncertainty of 2.1%, to account for estimating the optimum voltage by sight. However, in looking at the first two plots in Figure 8, it shows that the operating range of a GM counter is independent of distance and independent of the radioactive source, which should be expected, because the GM counter is calibrated such that the gas inside completely ionizes and that complete discharges occur consistently.

The first two graphs of Figure 8 and Figure 9 convey what occurs as the distance between the source and the GM tube increases. The number of Ba-133 decays appear to decrease proportionally as the distance increases. For Na-22, it seems to obey the inverse-square law initially, but appears to have a dependence that is neither inversely proportional to the distance nor inversely proportional to the distance squared as the distance increases. This could potentially be due to not only the nature of how the radiation is emitted from the sources, but also on the density and kinetic energy of air and the energy of the emitted particles (E. Toloba, personal communication, October 11, 2018). Thus, in a vacuum, it is very well possible that alpha, beta, and gamma decay obey the inverse-square law.

Understanding the Distribution of Decay Events

The values obtained for method (1) and method (2) of calculating the standard deviation of the distribution were 64 and 65 counts, respectively, resulting in a percent difference of 1.5%. Even though there are no error bars, that the standard deviations determined by both methods only differ by one count confirms that decay events are random and independent. Further, Figure 10 provides even more evidence that both methods agree. Thus, it should follow that as the number of trials performed increases infinitely, then the values obtained in methods (1) and (2) should be the same.

V. Conclusion

To conclude, the purposes of this experimentation were (i) to understand the function and operation of a GM counter, (ii) to calibrate a GM counter, (iii) to observe the inverse-square, and (iv) to prove that decay events follow normal distributions. The GM counter was calibrated with an optimum voltage of 950 $\pm$ 20 V, with an uncertainty of 2.1% to account for the uncertainty in visual estimation. The type of radionuclide and the distance between the radionuclide and the GM tube does not affect the calibration voltage. Additionally, decay events are random and independent, as confirmed by the fact that method (1) and method (2) produced standard deviations of 64 and 65 counts, respectively, with a percent difference of 1.5%.

VI. References

1. Berkely Labs. (2009, February). *Neutron beta decays.* http://www.particleadventure.org/npe.html.

2. Toloba, Elisa. (2018) *Geiger Counter, Part I.* [Class PDF]. Department of Physics, University of the Pacific. Stockton, CA.