The Geiger-Müller Tube
Detecting Radioactivity

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The purpose of this experiment is to explore the properties of the Geiger-Muller tube and how it can be used to detect radioactive particles, namely α, β, and γ rays. This is a three-part experiment. The first part focusses on the operating voltage for the Geiger-Muller tube. The second part uses the Geiger tube to explore the properties of Poisson statistics. And finally, the third part will explore the attenuation length of γ-rays in aluminum and lead.

I. BACKGROUND

The Geiger-Muller tube is a discharge tube with a single high voltage wire suspended along the axis-of-symmetry of a cylindrically shaped tube (See Fig. 1). The tube contains a rarified gas that becomes ionized when a charged particle passes through the volume. The ionization results in electrons *rapidly* drifting toward the high voltage anode, and the positive ions *slowly* drifting to the grounded cylindrical shell. As the electrons approach the high voltage wire they experience a very large electric field E and gain sufficient kinetic energy such that they "knock out" other electrons in nearby atoms causing an avalanche of electrons. The miniature showers occurring near the surface of the high voltage anode result in a multiplication of negative charges as electrons are collected on the wire. The multiplicative *gain* in the number of electrons makes it possible to detect the *negative* pulse due to the electrons collected on the HV line. More details can be found in the Leybold leaflet.

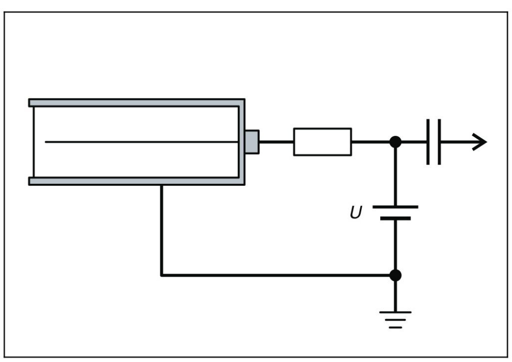

FIG. 1. In the Geiger-Muller tube above, electrons are produced by ionizing radiation passing through the cylinder. As a result, electrons rapidly drift to the high voltage anode wire at the center of the cylinder. An avalanche of electrons is produced near the wire due to the large electric field thus creating a measurable pulse on the high voltage line. In this figure, U corresponds to the high voltage.

II. THE THREE EXPERIMENTS

There are many experiments that can be performed using the Geiger-Muller tube, but we are going to limit ourselves to three. The first experiment is called "plateauing the tube." In this experiment, you will determine the threshold voltage and the operating voltage range for the tube. In the second experiment, you will explore Poisson statistics for a *low* mean value and a *high* mean value. In the third experiment, you will calculate the attenuation lengths for aluminum and lead as they absorbs γ-rays. The rate of absorption will depends upon the energy of the γ-rays and the thickness of the aluminum and lead absorbers.

A. Plateauing the Tube

Plateauing the Geiger-Mueller tubes is relatively straight-forward and its purpose is twofold. First, you will determine the threshold voltage (i.e., the voltage where the tube "comes alive"); and second, you will find the range of acceptable operating voltages where the GM tube's response is relatively constant (see Fig. 2). This region is called the *plateau* region.

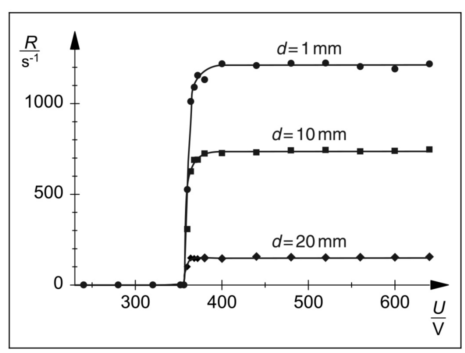

FIG. 2. This figure shows data collected by a Geiger-Muller tube and a radioactive source at three distances, d =1 mm, 10 mm and 20 mm. The rates R are measured in counts/sec as a function of the operating voltage U. The different rates for different distances are due to the $1/r^2$ falloff of the Intensity in radiation.

Notice that as the distance d increases between the source and the face of the GM tube, the rate R decreases. This reflects the $1/r^2$ dependence in the rate as the radioactive source is positioned at increasing distances from the face of the GM tube. Also notice that the threshold voltage for the tube is independent of the rate R. The operating voltage for the tube shown in Fig. 2 is anywhere between 400-600 volts (i.e., on the plateau). However, this voltage range (plateau) can vary from tube to tube. This is the reason why each tube must be plateaued before it is used. The range of operating voltages can vary from tube to tube. More details can be found in the Leybold leaflet.

1. Procedure for Plateauing the GM Tube

Increase the voltage in 40 V increments until you find the turn on voltage for the GM tube. Back up in 4 V increments and collect more precise data until the GM tube no longer responds due to the low voltage. Proceed forward to determine where the GM tube begins its plateau. Continue in 40 V increments and record data up to 640 volts. Plot your results similar to what is shown in Fig. 2.

B. Poisson Statistics

Poisson statistics most often occurs when physical measurements are made through a "counting" process. Usually these observations are due to a random source such that the *number of events counted* tends to fluctuate from observation to observation. Two questions naturally arise while pursuing the data analysis. "What is the *mean value*?" And, "What is the *standard deviation*?" This can be determined by using the statistical *probability density function* (PDF) called the Poisson distribution $P(\mu, n)$.

$$P(\mu, n) = \frac{e^{-\mu}\,\mu^n}{n!} \qquad \text{(Poisson function)} \qquad (1)$$

The Poisson function shown in Eq. 1 is the probability of finding the integer value n when the mean value of an ensemble of measurements is μ (where μ is most often not an integer value). The Poisson distribution is also a *normalized* distribution so, $\sum_{n=0}^{\infty} P(\mu, n) = 1$.

In this particular experiment you will want to collect data from a radioactive source (^{60}Co) using the GM tube. You should select two different distances between the radioactive source and the GM tube (or two different time intervals) so you can observe:

1. a mean value of μ between 2-5 counts, and
2. a mean value of μ between 15-30 counts.

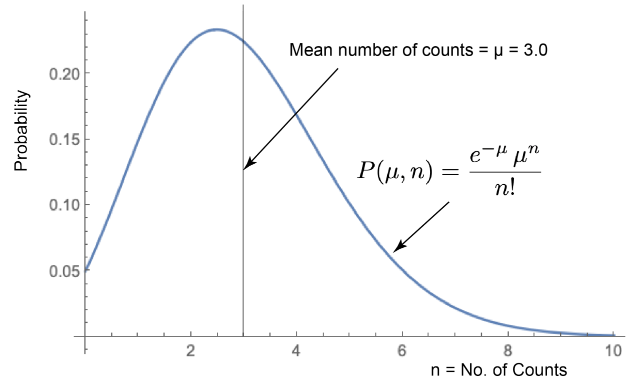

FIG. 3. The Poisson distribution shows the probability for observing n number of counts in a random distribution where the mean number of counts is μ. This particular representation shows a continuous distribution; however, the above equation can also be used for discrete distributions ($n = 0, 1, 2, \ldots$).

N.B. Make sure you plot the "number of counts," not the "counts/sec," unless, of course, you're measuring interval happens to be one second.

Take at least 50 measurements at each of the two distances (100 measurements would be better), and plot your values on a histogram. Calculate the mean (μ) and standard deviation (σ) for each of these two histograms. One of the properties of a Poisson distribution is that its standard deviation is simply the *square root* of the mean, $\sigma = \sqrt{\mu}$. Confirm that this is true for the two histograms you constructed. Using the two histograms you constructed from your data collection, calculate the variance σ^2 for any distribution using the following equation:

$$\sigma^2 = \overline{x^2} - \overline{x}^2 \qquad (2)$$

where

$$\overline{x^2} = \frac{1}{N}\sum_{i=1}^{N} x_i^2$$

and

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

Compare the standard deviation σ using the above technique with the standard deviation σ_{P} from the Poisson distribution ($\sigma_{\mathrm{P}} = \sqrt{\overline{x}}$). Do they agree? If they do, then your histogram exhibits one of the fundamental properties common to all Poisson distributions. Try overlaying the Poisson function (Eq. 1) to see how the shape of this function matches the shape of your histogram. Multiply the Poisson function by a factor A (e.g., the number of entries in your histogram as a starting value), and adjust A until it "takes on" the shape and height of your histogram. For more information refer to the Leybold leaflet. I also wrote a Mathematica program showing how to plot the Poisson function. Mathematica is able to extend the Poisson function (Eq. 1) through non-integer values when you plot it (e.g., it knows how to calculate 3.2! using Gamma functions).

C. Attenuation of γ-Rays

In this experiment, you will determine the attenuation coefficient μ ("Oh great," another definition for μ). The attenuation coefficient μ (units of 1/length) is used to describe the flux of γ-rays as a function of depth x into a material. In this particular lab, the materials will be aluminum and lead. The equation describing the attenuation is similar to that used in radioactive decay and is shown in Eq. 3.

$$I(x) = I_o e^{-\mu x} + c \tag{3}$$

where I_o is the intensity (i.e., rate, counts/sec, or counts/60 sec) with no material between the GM tube and the γ-ray source; x is the thickness of the material (e.g., aluminum, lead) between the GM tube and the γ-ray source; and $I(x)$ is the rate recorded at the GM tube when x cm of absorbing material is placed between the radioactive source and the GM tube.

I would suggest the following procedure for measuring the attenuation length of the aluminum.

- When measuring the aluminum absorption coefficient, place the GM tube 20 cm above where you plan to put the cobalt source. When measuring the absorption coefficient for lead, place the GM tube 5 cm above where you plan to put the cobalt source.

- Make a background measurement using the GM tube with no radioactive sources or aluminum/lead present. In other words, "What is the number of counts in a 60 second interval?" In this case, the source of the background is cosmic rays.

- Next, take the γ-ray source (^{60}Co) and place it $\sim$20 cm away from the face of the GM tube (aluminum). Do not introduce any absorbing material (i.e., aluminum) yet. Record the number of counts over a 60 second interval to obtain a "ballpark" value for I_o. You will fit this value after you have collected all your data. **Note:** When you collect your data and determine the error bars, make sure you record integer values for your counts. For example, plot the number of counts / 60 seconds in the y-direction, and use the square root $\sqrt{y_i}$ as your error bar for that data point (aha!! You're using Poisson statistics).

- Place approximately 20 cm of aluminum between the GM tube and the radioactive source and measure the rate over a 60 second interval. In this case $x \sim 20$ cm. Make sure this rate (e.g., *counts/60 sec*) is greater than the *background rate* you measured up above. **Note:** I would encourage you to record all your data using at least a 60-second interval.

- Remove $\sim$2 cm of aluminum and record the rate over a 60 second interval, and record this value. Keep repeating this step until you have removed all the aluminum. **Note: Do not change the distance between the GM tube and the radioactive sources.**

- Plot your data: Counts (counts in your 60*sec* interval) vs. x(cm) and fit it to Eq. 3 to determine the attenuation coefficient μ [cm^{-1}]. You will probably want to add a constant term c to Eq. 3 in order to account for the cosmic ray background in your measurements.

- Finally, using a time interval of 60 seconds will improve your precision by $1/\sqrt{N}$. Also, recording the number of counts in a *60 second time interval* allows you to use Poisson statistics. In other words, your error bars are always the square root of your measured values, $\sigma = \sqrt{N}$.

- Repeat the above process for lead (Pb) and compare your values of the absorption coefficient for aluminum (Al) and lead (Pb) to the accepted values. The inverse of the absorption coefficient is called the absorption length λ. Notice that the absorption lengths for aluminum and lead are noticeably different.

$$\lambda = \frac{1}{\mu} \text{ [cm]} \tag{4}$$

For more information refer to the Leybold leaflet describing "Attenuation of α, β, and γ radiation."

For your convenience, there is also a pdf file describing what the measured attenuation lengths are for γ-rays in aluminum at various energies. See how your result compares to the accepted value. Note: the value of ρ in this pdf file refers to the mass density of aluminum. A second file containing attenuation lengths for aluminum can also be found at this location.

I also included an energy diagram on my website showing the energy carried by γ-rays resulting from ^{60}Co decays. Most of the γ-ray energies are at 1.1732 MeV or 1.3325 MeV. Using a γ-ray energy of 1.25 MeV is a good compromise for comparing to the accepted results.

I also found this useful website describing the stopping powers of α, β, and γ rays incident upon various materials. When you go to the website, click on "In-Depth-Discussion" for α, β, γ Penetration and Shielding. When it comes to γ-rays, you can see that they are much more penetrating because they do not carry charge.

III. IMPORTANT CONSIDERATIONS

Here are some things to remember when using the equipment.

- Remove the soft hemispherical cap covering the front of the cylindrical Geiger-Muller tube. It covers a very thin window separating the atmospheric pressure from the partial vacuum inside the tube. Remove the cap when you're using the tube in the lab, and put the cap back on it (to protect the window) when you are finished.

- If your counting rates are too low, extend the time interval over which you record the *number of counts* to a 10 second time interval, or possibly a 60 second time interval. This is particularly important when you make your first attenuation measurement with 20 cm of aluminum between the GM tube and the radioactive source (^{60}Co). You need to observe a counting rate that is above the cosmic ray background before proceeding to smaller thicknesses of aluminum.

- Don't forget to perform your error analysis when calculating the attenuation length of aluminum and lead ($\lambda = 1/\mu$) at ^{60}Co γ-ray energies. The units for attenuation length is typically cm's.

- Following the same procedure for calculating the attenuation length of lead.