The Geiger-Muller 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 parameters 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.

I. BACKGROUND

The Gegier-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. This 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.
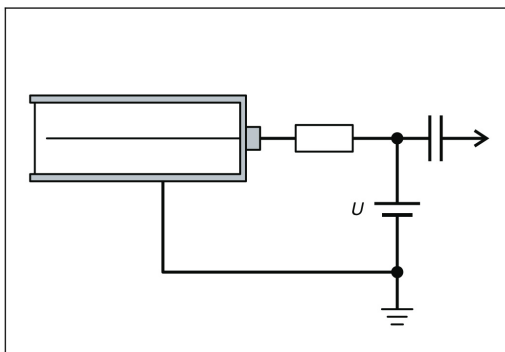

FIG. 1. In the Geiger-Muller tube above, electrons are produced by ionizing radiation passing through the cylinder. As a result, electrons rapidly drift to the high voltage anode wire at the center of the cylinder. An avalanche of electrons is produced near the wire due to the large electric field thus 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 length for aluminum as it absorbs γ-rays. The rate of absorption will depends upon the energy of the γ-rays and the thickness of the aluminum absorber.

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.
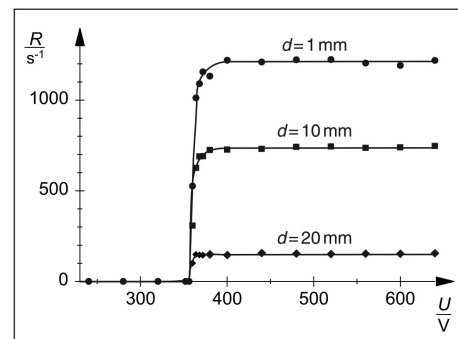

FIG. 2. This figure shows data collected by a Geiger-Muller tube and a radioactive source at three distances, d =1 mm, 10 mm and 20 mm. The rates R are measured in counts/sec as a function of the operating voltage U. The different rates for different distances are due to the $1/r^2$ falloff of the Intensity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

B.   Poisson Statistics

Poisson statistics occurs when physical observations 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. "Is it possible to ascribe a *mean value* to each measurement?" And, "What is the *standard deviation* for the measurement?" 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 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.

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 ($\sigma_\text{P} = \sqrt{\overline{x}}$). 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 material will be aluminum. The equation describing the attenuation is similar to that used in radioactive decay and is shown in Eq. 3.

$$I(x) = I_o\, e^{-\mu x} \qquad (3)$$

I_o is the intensity (i.e., rate, counts/sec, or counts/10 sec) with no material between the GM tube and the γ-ray source; x is the thickness of the material (e.g., aluminum) 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.

- Make a background measurement using the GM tube with no radioactive sources or aluminum present. In other words, "What is the number of counts in a 10 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$12 cm away from the face of the GM tube. Do not introduce any absorbing material (i.e., aluminum) yet. Record the number of counts over a 10 second interval to obtain a "ballpark" value for I_o. You will fit this value after you have collected all your data.

- Place approximately 10-12 cm of aluminum between the GM tube and the radioactive source and measure the rate over a 10 second interval. In this case $x \sim 10$ cm. Make sure this rate (e.g., *counts/10 sec*) is greater than the *background rate* you measured up above. If it is not, then you may need to start this section over and increase your time interval to 60 seconds for all your measurements.

- Remove $\sim$2 cm of aluminum and record the rate over a 10 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 $10sec$ 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, in order to improve the overall precision of your measurements, you may want to extend your time interval from 10 seconds $\rightarrow$ 60 seconds. This way you will accumulate more counts in your measurements and thus improve your precision by $1/\sqrt{N}$. Recording the number of counts in a *60 second time interval* usually leads to a more obvious exponential curve when fitting the data.

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 1.1732 MeV.

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 10 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 at ^{60}Co γ-ray energies.