# Experimental Radiation Physics

2022-2023

**Introduction & Objectives**

In 1908, Hans Geiger would develop a machine that was capable of detecting alpha particles. Geiger's student, Walther Mueller, would go on to improve the counter in 1928 a way that would allow the counter to detect any kind of ionizing radiation. And thus, the modern Geiger-Mueller counter was born and the techniques in radiation detection were forever changed. The Geiger-Mueller tube, or GM tube, is an extremely useful and inexpensive way to detect radiation. While the GM tube can only detect the presence and intensity of radiation, this is often all that is needed. It is the purpose of this lab to become acquainted with this device and explore it's uses in detecting radiation and also to explore its limits. Using this device as a tool, it is also the purpose to explore attenuation coefficients through a beta attenuation experiment.

**1.1. Gas Filled Detectors**

Gas-filled detectors, like other proportional counters, use gas multiplication to significantly increase the charge represented by the ion pairs created by the ionizing radiation. With the proportional counter, each electron creates an avalanche that is independent of all other avalanches in the detector. These avalanches are nearly identical; therefore, the collected charge is proportional to the number of original electrons. Inside of a gas counter, the electric field causes to the electrons and the ions to drift to their respective sides of the collector. While these electrons and ions are drifting, the collide with each other. There is very little average energy that is gained by the ions because of their low mobility in the electric field. Free electrons, on the other hand, have the ability to have great amounts of energy inside the electric field. It an electron has enough energy, it is energetically possible for another ion pair to be created from the collision of an electron and a neutral gas molecule. There is a certain level of electric field strength that will always allow

this result from the collision. This free electron will then be accelerated by the electric field to higher kinetic energies and then has the potential to create even more ionization inside the tube. This process of gas multiplication forms a cascade and is known as a Townsend Avalanche.

**1.2. Geiger-Mueller Counter**

The G-M counter works slightly different than these other proportional counters. Inside of the actual gas chamber, strong electric fields are created to enhance the avalanche intensity.

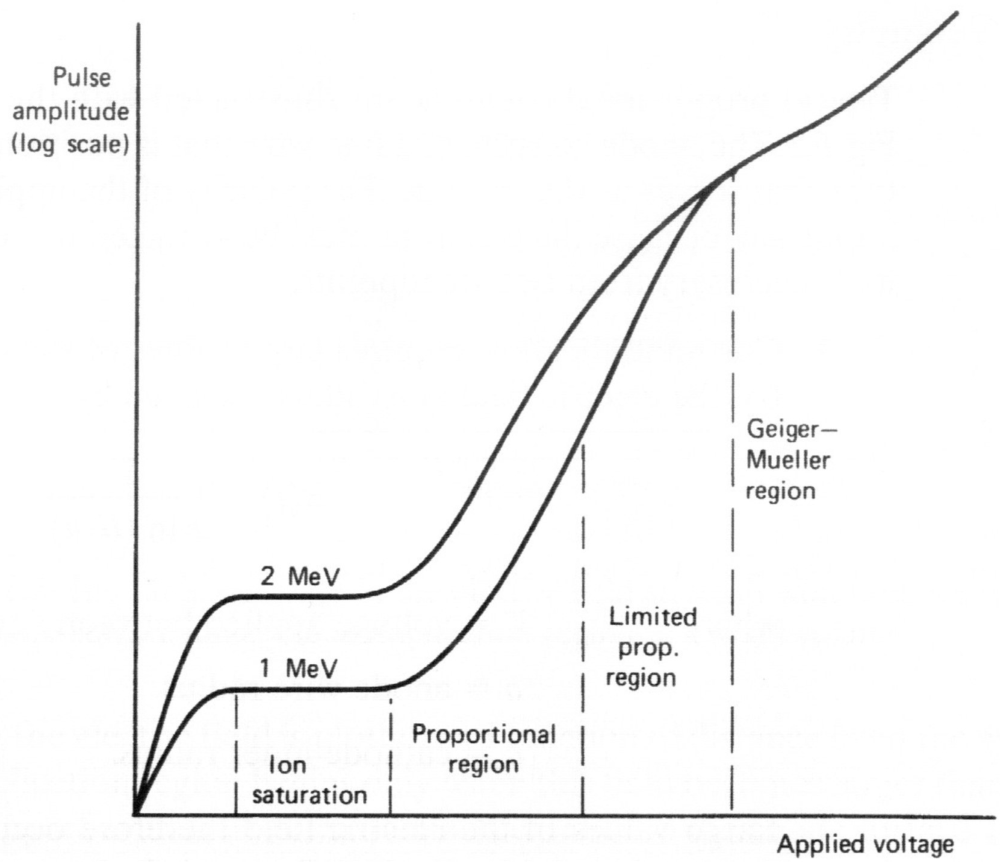


Figure 1: The different regions of operation of gas-filled detectors. the observed pulse amplitude is plotted for events depositing two difference amounts of energy within the gas.

In the G-M tube, these avalanches can cause more avalanches at a different position in the tube. At a certain level of electric field amplitude, the avalanches can cause an average of at least one more avalanche in the G-M tube. The significance of this is a self-propagated chain reaction of avalanches resulting inside the tube. This process is known as the Geiger Discharge. Figure 2 diagrammatically depicts how the Geiger discharge is triggered inside the tube. Once the magnitude of this Geiger Discharge reaches a certain size, all of the avalanches affect each other in such a way that all of the avalanches are terminated. This avalanche limiting point always contains the same number of avalanches, therefore all pulses that are measure from a Geiger tube have the same amplitude. In figure 1, it is shown that the Geiger counter only sees the same pulse for the two different energies. This is important due to that fact that a Geiger counter can only be used to detect or count radiation and nothing more.

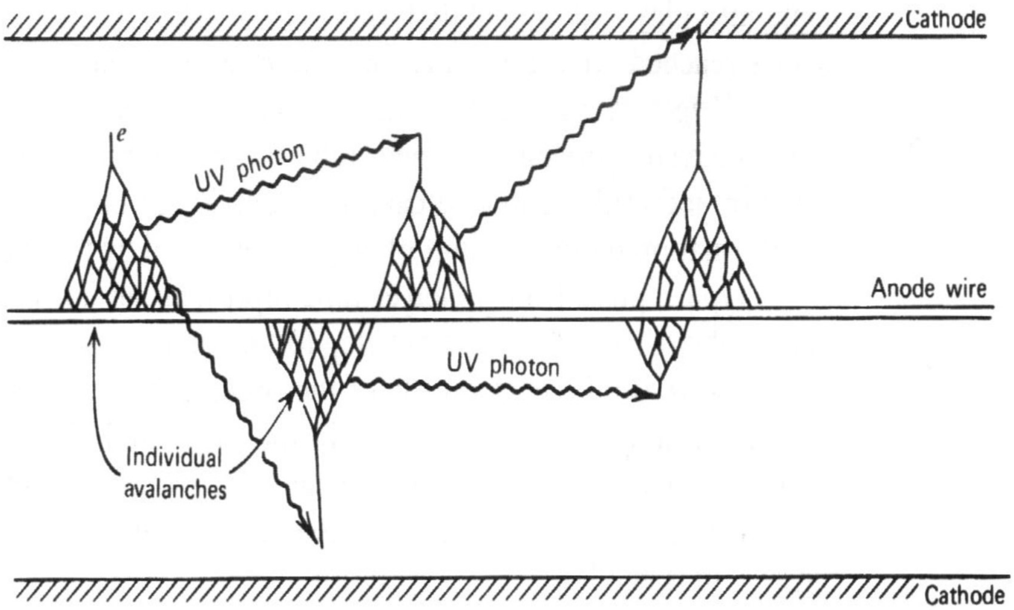


Figure 2: The manner in which additional avalanches are triggered in a Geiger discharge.

### 1.3. Fill Gasses & Quenching

Because the Geiger counter is based on positive ions that will be formed inside of the tube, gases that form negative ions, such as oxygen, should be avoided at all costs. Usually noble gases are used as the main component in the Geiger counter. There is a mixture of two gases in this chamber, however, to allow for quenching.

As radiation enters the detector it ionizes the gas inside the chamber. These ions drift away from the anode wire after the termination of a Geiger discharge. When these ions drift out to the cathode wall, they are neutralized by combining with an electron from the cathode surface. The amount of energy that is liberated in this process is equal to the ionization energy of the gas minus the energy it takes to remove an electron from the cathode surface. The energy to remove an electron from the cathode surface is known as the work function. In situations where the liberated energy is greater than the cathode work function, it is energetically possible to liberate more than one electron. This happens when the energy of the ionized gas particle is twice the magnitude of the work function. This is a significant issue that needs to be addressed as the free electron can drift into the anode and trigger another Geiger discharge which would penultimately cause the liberation of more free electrons and ultimately cause the Geiger counter to produce a continuous output of pulses.

To deal with this, a second gas, known as the quench gas, is added to the Geiger chamber in addition to the main gas. This gas is chosen to have an ionization potential that is lower than and a more complex structure then the main gas. Typically, concentrations of 5 – 10% are present inside the counter. The positive ions created from incident radiation are mostly the primary gas in the chamber. As these ions drift to the cathode wall, they interact with the quench gas and will transfer their charge due to the difference in ionization energies. The goal here is to have the quench gas bring the positive charge to the cathode wall. This is desirable because the excess energy will go into the disassociation of the quench gas molecule instead of liberating another electron. Ethyl alcohol and ethyl format have been popular choices for quench gas inside modern Geiger counters. Also, Halogens are a popular choice because they are a self-replenishing gas. It should be noted that organic quench gases lead to closer to a plateau slope of zero, where inorganic quench gases lead to larger slopes on the plateau.

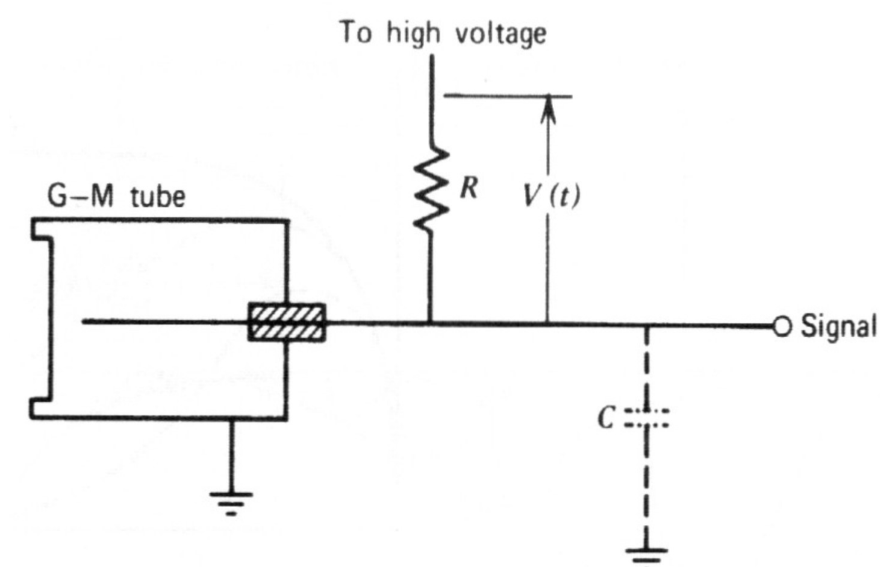


Figure 3 The equivalent circuit of a G-M tube.

There is another form of quenching known as external quenching. In this method, the resistance of R in Figure 3 is made to be quite large (on the magnitude of

108 ohms). The disadvantage is that it takes extra time for the anode to return to its normal voltage. Because of this, external quenching is only efficient at low counting rates.

### 1.4. Geiger Counter Dead Time

The Geiger counter has an unusually large dead time. Right after a Geiger discharge, the electric field is reduced below the critical level to trigger chain avalanches. The time that it takes the Geiger counter to build the electric field back up to the critical level is known as the dead time. This is because the counter is “dead” during this time and will not detect any ionizing radiation. This is depicted diagrammatically in Figure 4. This time is on the order of 50 – 100 μs in most modern Geiger counters.

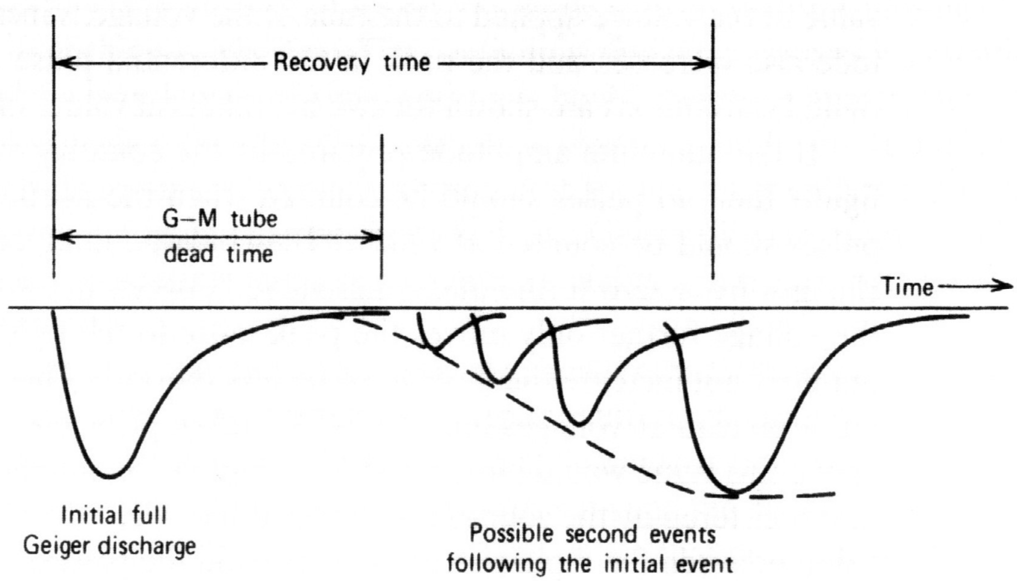


Figure 4 Illustration of the dead time of a G-M tube. Pulses of negative polarity conventionally observed from the detector are show.

An interesting phenomenon occurs right after the dead time. At this time, the electric field is at the critical point that it allows the counter to detect ionizing radiation, but the electric field is not built all the way back up to the magnitude that it was at. The time that it takes the Geiger counter to build the electric field back up to full strength after a full Geiger discharge1 is known as the recovery time.

If a radiation event is detected at a time after dead time but before the recovery time, the Geiger counter will produce a pulse, but this pulse will be smaller in amplitude than a pulse created from a full Geiger discharge. This time is also graphically depicted in Figure 7.

### 1.5. Geiger Counting Plateau

When setting up the Geiger counter, it should be connected to a high voltage source. For a Geiger counter, we know that the voltage that it is set to will determine the amount of radiation that it can detect. If the voltage is too low, there will not be enough potential to create a Geiger discharges. If the voltage is too high, the Geiger counter will enter a state of continuous discharge. There is a region of voltage that is the ideal voltage to set the Geiger counter to. This region is called the plateau.

As can be seen in Figure 8(a), there is a specific voltage at which the Geiger counter starts to register counts. This is called the starting voltage. The knee, the region where the curve transition from the initial rise into the plateau, can also be seen in Figure 8(a). When the voltage goes higher than the range of the plateau, then the counter enters the region of continuous discharge, as can be seen in Figure 8(b).

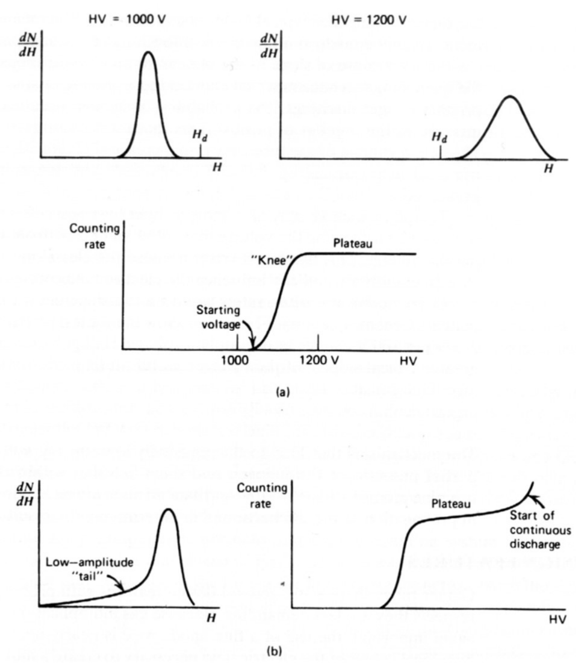


Figure 5 (a) The counting curve for G-M counter around 1000-1200 V. (b)The differential pulse height spectrum and the counting curve of the G-M counter.

While the ideal plateau is one with zero slope, this is never the case in practice.

Regions where the electric field has a lower strength than usual, such as the ends of the tube, the discharges may be smaller than normal. This will add a low-amplitude tail to the differential pulse height distribution and can be a contributing cause to the nonzero slope in the plateau.

Also, pulses that occur during the recovery time will be smaller than normal as well and will also contribute to the slope of the plateau. It is ideal to have the voltage set within the counting curve plateau when taking measurements with the Geiger counter. When inside this range, small fluctuations in voltage will not significantly alter measurements and will provide accurate data. It is ideal to keep the voltage at the lower end of the plateau range, just above and out of the way of the knee, to increase counter life.

### 1.6. Geiger Counter Counting Efficiency

Because of the way the Geiger counter is set up, it deals with detecting different types of particles in different ways. There are three types of particles to consider: charged particles, neutrons, and gamma rays. The Geiger counter excels are counting charged particles. This is because these particles ionize the gas in the G-M tube and these ion pairs are what cause the Geiger discharge in the tube. Essentially, the efficiency at which the Geiger counter counts charged particles is 100%. The Geiger counter is not a good device for counting neutrons. The gases that are usually used in Geiger counters have extremely low cross sections for thermal neutrons. The gas could be replaced with one that is better at capturing thermal neutrons, but the detector could be operated in the proportional region and then the difference between neutrons and gamma rays could be distinguished. Fast neutrons produce ion pairs that the Geiger counter will easily respond to. Proportional counters are usually tasked with this job instead of Geiger counters due to their ability to provide spectroscopic information. The Geiger counter's ability to detect gamma rays is contingent on the gamma ray interacting with the solid wall of the counter. Such is the way for any gas-filled counter. A secondary electron is produced if the interaction takes place close to the inner wall. This secondary electron is ionizing and the Geiger counter will easily detect it. The efficiency for counting these gamma-rays depends on two factors: the probability that the incident gamma will interact with the solid wall and produce a secondary electron, and the probability that the secondary electron reaches the fill gas of the tube before it reaches the end of its track. Only the innermost layer wall can produce the secondary electrons required to detect the gamma, as shown in Figure 6. To increase the probability that a gamma-ray will interact with the solid wall, the atomic number of the wall should be increased. With an atomic number of 83, bismuth has been the classic material to build cathodes with for many years. The counting efficiency of low energy gamma-rays and X-rays is increased by using a gas with an atomic number and a pressure as high as possible. Xenon and krypton are popular for these situations and often result in counting efficiencies close to 100%.

**Experiment 1**

## Characteristics of Geiger Muller Counter

**Objective:**

1. Plotting the characteristic curve of the GM counter.
2. Determination of:
    a. Starting voltage $V_s$ of the GM counter.
    b. Threshold voltage $V_{th.}$ (or $V_1$) of the GM counter.
    c. Plateau length of the GM counter.
    d. Operating voltage $V_0$ of the GM counter.
3. Calculation of the percentage gradient of the GM detector.

**Theory:**

The relation between the counting rate and the voltage applied to the counter is called the Characteristic curve and from which we deduce the following characteristics:

- Starting voltage ($v_s$): It is the minimum voltage applied the detector in order for it to operate.
- Plateau length (or operating plateau region): The range voltage corresponding to the flat part of the characteristic curve.

  Plateau length = $v_2 - v_1$.
- Operating voltage (or working voltage) ($v_0$): It is the voltage corresponding to the midpoint of the plateau region.

$$v_0 = \frac{v_1 - v_2}{2}$$

- Percentage gradient: It is the percentage change in counting rate per volt.

$$\text{Percentage gradient} = \frac{N_2 - N_1}{N_0(V_2 - V_1)} \times 100$$

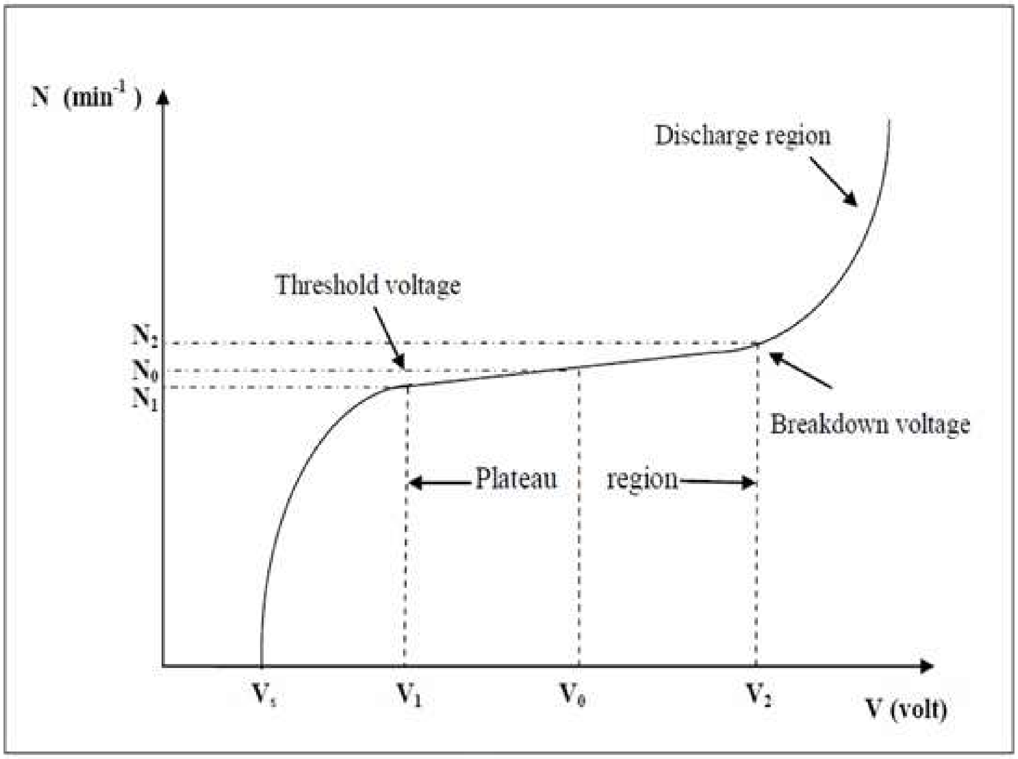


Figure 9 characteristic curve of the GM counter.

**Apparatus:**

- Source of radiation
- Geiger detector
- HV power supply.

**Procedure:**

1. Connect the plugs of the electric mains.
2. Set the timer to 60 s and the HV to 280 Volt.
3. Record the count rate per one minute for the back ground (NB. G).
4. Put the source in front of the Geiger tube on the second shelf from top.
5. Set the high voltage to 220 V and start counting. Increase the applied voltage in steps of 20 V until the detector begins to operate, this is the starting voltage (Vs).
6. Increase the applied voltage and record the count rate per one minute (N1) for each

voltage. Take two readings for each voltage and take their average.

7. Plot the counting rate (N) versus the applied voltage (V) deduce the threshold voltage, the plateau length, the operating voltage and the percentage gradient of the detector.

**Data Sheet of Experiment 1**

**Source description**

| Element | Activity ($A_o$) (…….) | Half-life (……) | Date of calibration |
|---|---|---|---|
| | | | |

Background radiation: NB. G = (….… + ……. )/2 =………. (………).

**Data:**

| Voltage (…...) | $N_1$ (……..….) | $N_2$ (……..….) | $N_{av}$ (……..….) | $N = N_{av} - N_{B.G.}$ (……..….) |
|---|---|---|---|---|
| 50 | | | | |
| 100 | | | | |
| 150 | | | | |
| 200 | | | | |
| 250 | | | | |
| 300 | | | | |
| 350 | | | | |
| 400 | | | | |
| 450 | | | | |
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| 700 | | | | |
| 750 | | | | |
| 800 | | | | |
| 850 | | | | |
| 900 | | | | |
| 950 | | | | |
| 1000 | | | | |
| 1050 | | | | |
| 1100 | | | | |
| 1150 | | | | |
| 1200 | | | | |

**Calculations and results:**

- $V_s$ = …......… (………)
- $V_1$ = ……...…. (………)
- $N_1$ = …..….. (………).
- $V_2$ = ..…...….. (………)
- $N_2$ = ……..… (………)
- $V_0$=

  = ………... (………)

- $N_0$ = …….... (………).
- Plateau length =

  =………….. ( ……..)

- Percentage gradient =

  =…...……... % (……….)

**Experiment 2**

## Geiger-Müller Counter half-life measurement

**Purpose:**

Do some measurements in nuclear decay, notions of statistics

**Apparatus:**

- Scaler-Timer (Spectrum Techniques model ST-350)
- Geiger-Müller tube
- oscilloscope
- radioactive sources

**Introduction:**

A typical Geiger-Müller (GM) Counter consists of a GM tube having a thin end-window (e.g. made of mica), a high voltage supply for the tube, a scaler to record the number of particles detected by the tube, and a timer which will stop the action of the scaler at the end of a preset interval.

The sensitivity of the GM tube is such that any particle capable of ionizing a single atom of the filling gas of the tube will initiate an avalanche of electrons and ions in the tube. The collection of the charge thus produced results in the formation of a pulse of voltage at the output of the tube. The amplitude of this pulse, on the order of a volt or so, is sufficient to operate the scaler circuit with little or no further amplification. The pulse amplitude is largely independent of the properties of the particle detected, and gives therefore little information as to the nature of the particle. Even so, the GM Counter is a versatile device which may be used for counting alpha particles, beta particles, and gamma rays, albeit with varying degrees of efficiency.

## Set-up:

Set up equipment as shown in the following Figure. Scaler, Timer, and High Voltage Supply may well be contained in one package.

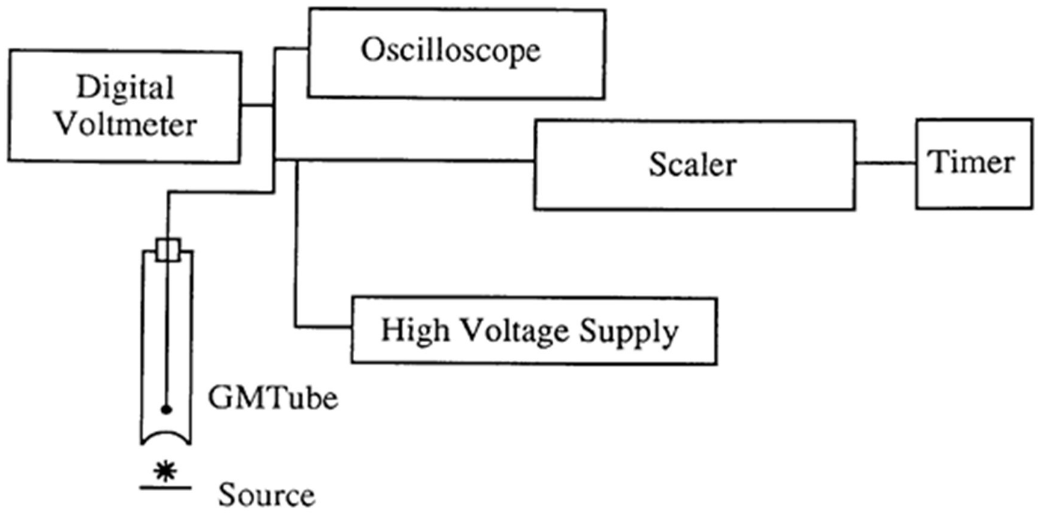


Fig.1: possible set-up for Geiger-Müller experiment

**Measurements to be performed:**

**Characteristics of the GM counter:**

Put a radioactive source below the GM tube. Put the counter in counting mode and raise the voltage until counts are observed. Note the shape of the pulse and what happens as the voltage on the GM tube is increased. What is the minimum voltage pulse necessary to activate the counter? Measure the pulse height with the oscilloscope. Sketch a picture of the pulse shape. How would you describe it?

Every GM tube has a characteristic response of counting rate versus voltage applied to the tube. A curve representing the variation of counting rate with voltage is called a plateau curve because of its appearance. The plateau curve of every tube that is to be used for the first time should be drawn in order to determine the optimum operating voltage. Find the plateau curve for your tube using the procedure outlined below.

a) Check to see that the high voltage as indicated by the meter on the instrument is at its minimum value.

b) Insert a radioactive source into one of the shelves of the counting chamber. Turn on the count switch and slowly increase the high voltage until counts just begin to be recorded by the scaler. The voltage at which counts just begin is called the "starting voltage" of the tube. Using the oscilloscope, measure the minimum signal size necessary to trigger the scaler.

c) Set counting time to 30 sec. Beginning at the starting voltage, take counts every 40 volts. Choose shelf such that you have at least 1000 counts when the high voltage is about 50V above the starting voltage. Reset scaler to zero before each count. Tabulate counts versus voltage. Continue taking counts until a voltage is reached where a rapid increase in counts is observed (or when the maximum allowed HV value is reached). Do not continue raising the voltage beyond that point – reduce voltage to about 200V above starting voltage.

d) Plot the data of (c). Identify the "plateau" (i.e. the flattest part of the curve between the knee and before the onset of the fast rise).

The slope S of the plateau of a GM tube serves as a figure of merit for the tube. The slope is defined to be the percent change in count rate per 100 volts change in applied voltage in the plateau region. A slope of greater than 10% indicates that the tube should no longer be used for accurate work.

The slope may be computed using

$$S(\% per 100V) = \frac{2(N_2 - N_1)\times 10^4}{(N_1 + N_2)(V_2 - V_1)}$$

where $V_2$ is the voltage at the high end of plateau, $N_2$ is the number of counts at this voltage, $V_1$ is the voltage at the low end of the plateau (just above the "knee"), and $N_1$ the corresponding number of counts. Do you understand this equation and can you explain it?

In order to compare, obtain a similar plateau curve for an old tube (if available).

The optimum operating voltage will be about the middle of the plateau, usually some 150 to 200 volts above the knee of the curve. Set the high voltage to this point and record the value. All the subsequent measurements are to be done with the HV set to this optimum operating voltage.

**Dead-time of the GM counter**

There is an interval of time following the production of a pulse in the GM tube during which no other pulse can be recorded. This interval is called the dead-time of the system. If this time is known it can be used to make a correction to the observed count rate to yield the true count rate. The procedure below can give a good estimate of the dead-time.

a) Obtain a dead-time source (a "split source") from the instructor. This source is split into two parts. Remove one half of the source and set it aside.

b) Place the carrier containing one part on the second shelf of the counting chamber and make a trial count of 1 minute duration. Get the maximum count rate you can. This should be more than 20,000 counts per minute, but if not use what you can get.

c) View the pulses on the oscilloscope and record the shortest time interval that you can see between successive pulses; this gives you an order-of-magnitude estimate of the dead time

d) Count for 200 seconds and record the counts, $N_1$.

e) Put the two parts of the source back together, taking care not to disturb the position of the first part. Do a 200-second count of the combined parts and record as Nc.

f) Remove the part initially counted and make a 200-second count on the second part -- record counts as $N_2$.

g) Estimate the dead-time of the GM counter using the relation:

$$\tau = \frac{N_1 + N_2 - N_C}{2N_1N_2} \qquad (2)$$

h) Convert the time thus found to microseconds (note that T is the duration of your counting -- careful – use the correct time) and record. To understand the origin of the equation, see refs [1 - 3].

i) calculate the dead-time uncertainty, using Poisson uncertainty for the numbers of counts

j) The dead-time τ may be used to correct an observed *count rate* using the expression: $$R = \frac{r}{1 - r\tau} \qquad (3)$$

Where r = Observed count rate, R = True count rate

k) Apply this dead time correction to $N_1$, $N_2$, $N_c$ and verify that the corrected numbers, $N^{(c)}$ (approximately) satisfy the equation $N_1^{(c)} + N_2^{(c)} = N_c^{(c)}$.

l) Calculate the rate at which the error due to dead time effects (i.e. the difference between raw and true counting rate) is 1%.

**Statistical treatment of counting data**

The emission of particles by radioactive nuclei is a random process. If the time over which the decays are observed is small compared to the (mean or half-) lifetime of the radioactive nucleus, the probability for a decay to occur during a given time interval is constant (the same for every time interval of the same length). When, under identical conditions, a series of N measurements is made of the number of particles detected per unit time it will be observed that the individual measurements will vary about some average or mean value. The true mean, m, can be determined only by averaging an infinite number of measurements. However, for a finite number of observations (a finite "sample") the best approximation of the true mean is simply the "sample mean", i.e. the arithmetic average $\overline{n}$

$$m \approx \overline{n} = \frac{1}{N}\sum_{k=1}^{N} n_k = \frac{1}{N}(n_1 + n_2 + \ldots. n_N)$$

The magnitude of the deviations of individual measurements from the true mean is usually expressed in terms of a "standard deviation" ($\sigma$). The standard deviation is defined to be the square root of the average value of the squares of the individual deviations (rms = "root-mean-square"). The number of counts of radioactive decays for a fixed time is a random variable whose probability distribution is a *Poisson distribution*; the Standard Deviation for such a distribution is simply the square root of the true mean:

$$\sigma = \sqrt{m}$$

Given a finite set of N measurements, the best approximation (the "unbiased estimator") of the standard deviation is given by the square root of the "sample variance",

$$\sigma_n = \sqrt{\frac{\sum_{k=1}^{N}(n_k - \overline{n})^2}{N-1}}$$

For values of m > 20 the Poisson distribution is very well approximated by the Gaussian (or "normal") distribution for which certain confidence levels have been established in terms of the standard deviation. These confidence levels are as follows:

- ✓ About 68% of the number of observations made will fall within the limits of $\overline{n} \pm \sigma_n$.
- ✓ About 95% of the number of observations made will fall within the limits of $\overline{n} \pm 2\sigma_n$
- ✓ About 99% of the number of observations made will fall within the limits of $\overline{n} \pm 3\sigma_n$

This means that if one additional measurement is made, it should have a 68% chance of falling within $\overline{n} \pm \sigma_n$.

When circumstances permit the making of only a single observation, the number of counts obtained, n, is used as an estimator of the true mean m and $\sqrt{n}$ as an estimator for its uncertainty (standard deviation).

The Standard Deviation of a gross counting rate, $R_g$ is:

$$\sigma_{R_g} = \frac{\sqrt{n}}{t} = \frac{\sqrt{R_g t}}{t} = \sqrt{\frac{R_g}{t}}$$

where $t$ is the duration of the counting.

To test the statistical nature of nuclear decay, do the following experiment:

a) Adjust the height of a source in the counting chamber to produce about 2000 counts per minute.
b) Take a set of 10 counts of 30 seconds duration ("set A").
c) Compute the arithmetic mean $\overline{n}$ .
d) Compute the standard deviation for a Poisson distribution of mean $\overline{n}$.
e) Compute the individual deviations from the mean $(n_k - \overline{n})$ and record in a table. Do they sum very nearly to zero? Explain why they do.

f) Square the $(n_k - \overline{n})$, sum the square and apply Equation (6) to obtain the standard deviation □$_n$. Compare □$_n$ with □$_s$

g) Count the number of measurements whose values lie within $\overline{n} \pm \sigma_n$.

Now take a second set of ten measurements (“set B”) and repeat the same analysis. Compare the two mean values and stigmas. How many measurements of set (B) fall within the one-sigma interval of set (A)?

**Background Measurements**

Extraneous radiation called background radiation is always present. Gamma rays emitted by certain radioisotopes in the ground, the air, and various building materials as well as cosmic radiation can all provide counts in a detector in addition to those from a sample being measured. This background counting rate should always be subtracted from a sample counting rate if you need to obtain the rate from the sample alone. Obtain a background counting rate using a 5-minute sample time.

**Decay constant of an unknown radioisotope**

The activity (number of disintegrations per unit time) of a radioisotope is expressed as

$$A(t_2) = A(t_1)\exp(-\lambda(t_2 - t_1))$$

where

A(t) = activity at time t, $\lambda$ = decay constant, characteristic of the radioisotope=probability per unit time, for a radioactive decay to occur (the mean-life $\tau = 1/\lambda$)

The half-life, $T_{½}$ of a radioisotope is defined to be that interval during which the activity decreases to one-half its value at the beginning of the internal. The half-life is given by

$$T_{1/2} = \tau \cdot \ln 2 = \frac{\ln 2}{\lambda}$$

The counting rate of a sample of a radioisotope may be considered to be directly proportional to the activity at the moment of measurement provided that the counting interval is short compared to the half-life. Reasonably short half-lives can be determined by measuring activity at regular intervals.

The logarithm of the activity when plotted as a function of elapsed time should yield points falling on a straight line. Explain why?

Obtain your unknown sample from the instructor, measure the activity as a function of time and find the decay constant. You should take at least 20 measurements of the activity, for half-minute intervals, making sure that the time between counting periods is minimized (why is that important?) For the decay constant determination, you should correct the counts for dead-time and background (explain why you should do this).

**Analysis, error estimation:**

**Dead-time:**

Estimate the uncertainty on your dead-time measurement from the uncertainties on the number of counts (use Poisson uncertainties for these); are there any other sources of error that could influence this measurement?

**Decay constant measurement:**

Having N measurements of activity gives you N-1 independent measurements of the decay constant. Estimate the uncertainty on each individual decay constant measurement from the uncertainties on the number of counts (remember that they are Poisson-distributed!). Determine the average of the N-1 values for the decay constant, and calculate the standard deviation. In addition, determine also a weighted mean of these values, with weight = ($1/\sigma_i^2$). Taking a weighted average like this is the appropriate method if the uncertainties of the individual measurements are very different from each other. Furthermore, you should also determine the decay constant from the slope of the straight line fitted to a graph of the logarithm of the activity versus elapsed time. The uncertainty on this slope gives you another estimate of the uncertainty on the decay constant. (See the statistics hand-out or the statistical methods chapter of the textbook on how to determine the uncertainty on the slope). From the decay constant, derive the mean life and the half-life (with their uncertainties). Compare the values and uncertainties obtained by the different methods, and discuss their relative merits.

**Report:**

You should treat every step in this experiment as a different measurement, with its data, analysis and conclusion together in one section.

Your report should have a clear and complete discussion of the principles underlying the functioning of a GM Counter, as well as its characteristics as determined from your experimental data. In addition, you should have a complete description of the data analysis, including determination of uncertainties. You need to have a calculation of the uncertainty on dead-time, decay constant and half-life (for all methods of determining the decay constant and half-life).

You must also answer the following questions:

1. what are physical phenomena that are initiated by the passage of an ionizing particle in the GM tube?
2. What makes it possible for the GM tube to also count X-rays and $\gamma$-rays (photons)?
3. what is the size (in V) of the *smallest signal* from the GM tube that is big enough to trigger the counter circuit?
4. what is the smallest time between two successive GM tube output signals that you can see on the oscilloscope?
5. Given the dead-time determined by you, what is the counting rate at which the error due to the finite dead-time is 1% of the rate?
6. When taking the counts for the decay constant measurement, why is it important that the time between two successive measurement periods be minimized? If you had appreciable delays between successive counting periods (without correcting for this), would that cause you to over- or underestimate the half-life? (Explain).

## 2. Experiments 3

### Statistics of radioactive decay process (Counting statistics)

**Theory**

Radioactive decay is a random process. Consequently, any measurement based on observing the radiation emitted in a nuclear decay is subject to some degree of statistical fluctuations. These inherent fluctuations are unavoidable in all nuclear measurements. The term counting statistics includes the framework of statistical analysis required to process the results of nuclear counting experiments and to make predictions about the expected precision of quantities derived from these measurements.

Although each measurement (number of decays in a given interval) for a radioactive sample is independent of all previous measurements (due to randomness of the process), for a large number of individual measurements the deviation of the individual count rates from the average count rate behaves in a predictable manner. Small deviations from the average are much more likely than large deviations. These statistical fluctuations in the nuclear decay can be understood from the statistical models utilizing Poisson distribution or Gaussian (Normal) distribution. If we observe a given radioactive nucleus for a time t and define the success as "the nucleus decays during the process" then the probability of success "p" is given by ($1-e^{-\lambda t}$). The Poisson distribution applies when the success probability p is small and the number successes (i.e. number of counts measured) is also small (say <30).

In practical terms, this condition implies that we have chosen an observation time that is small compared with the half-life of the source. When the average number of successes becomes relatively large (say > 30) we can utilize the Gaussian model of distribution. Since in most of the cases the count rates are reasonably large (few tens of counts per second) the Gaussian model has become widely applicable to many problems in counting statistics. On the other hand, the Poisson distribution is applicable in the case of background counts. The details of experimental, Poisson and Gaussian distributions are given below.

**Experimental distribution function**

We assume that we have a collection of N independent measurements of the same physical quantity. In this particular case the quantity is the number of counts recorded by the detector in a specific time interval. We denote the result of these N measurements as:

$$y_1, y_2, y_3 \ldots\ldots\ldots\ldots y_i \ldots\ldots y_N .$$

The experimental mean is given by:

$$\bar{y} = \frac{\sum_{i=1}^{N} y_1}{N}$$

The data set is conveniently represented by a frequency distribution function F(y). The value of F(y) is the relative frequency with which the number appears in the collection of data. By definition

$$\mathrm{F(y)} = \frac{number\ of\ occurrences\ of\ the\ value\ y(\equiv v(y))}{number\ of\ measurements\ (= N)}$$

A plot of *F(y)* versus *y* gives the frequency distribution of the data (The number of occurrences can also be calculated by choosing a suitable interval for the values of *y*).

The standard deviation of the distribution is given by:

$$\sigma_{\exp} = \left( \frac{1}{N} \sum_{i=1}^{N} (y_i - \bar{y})^2 \right)^{1/2} . \qquad (9)$$

Notes regarding $\sigma_{exp}$ and $\bar{Y}$

Remember that Eq. (9) is applicable to the quantities directly measured in the experiment and not to the derived quantities. To illustrate, in the present experiment if you measure the number of counts for a preset time interval (say 30 s) and call it $y_i$. Then Eq. (9) is applicable to these counts only and not to the counting rates calculated using these values. To determine the deviations for the derived quantities proper error propagation methods should be used. To be precise, y is the true mean value determined from a set having infinitely large number of measurements and cannot be determined experimentally as such. However, for a reasonably large set of measurements the value of y can be set equal to y (Eq. (7)).

**The Poisson distribution**

As mentioned above it is applicable when $p$ <<1 and the number of successes are very few.

$$P(y) = \frac{(\bar{y})^y e^{-\bar{y}}}{y\,!}$$

In this case the standard deviation is given by

$$\sigma_p = \sqrt{\bar{y}}$$

**The Normal or Gaussian distribution**

When $p$ << 1 and the successes are large one can model the experimental data using the Normal distribution which is also called Gaussian distribution ( as per R.D. Evans it is erroneous to call this as Gaussian because its derivation by Gauss (1809) was antedated by those of Laplace (1774) and DeMoivre (1735)). This is given by:

$$P(y) = \frac{(\bar{y})^y e^{-\bar{y}}}{y\,!}$$

The standard deviation in this case is the same as that for the Poisson distribution

$$\sigma_G = \sqrt{\bar{y}}$$

We will denote both $\sigma_p$ and $\sigma_G$ as $\sigma_{th}$.

**Applications of statistical models in nuclear physics**

There are two major applications of counting statistics in nuclear measurements. The first application involves the use of statistical analysis to determine whether a set of multiple measurements of the same physical quantity shows an amount of internal fluctuation that is consistent with statistical predictions. In this case the motivation is to determine whether a particular counting system is functioning normally. The second application is more important in which we examine these methods to make a prediction about the uncertainty one should associate with a single measurement. The following procedure and analysis will give you a feel as to how an experimental distribution in a nuclear counting experiment looks like and how does it compare with theoretical distributions.

**Procedure**

a) Set the operating voltage of the Geiger counter at its proper value.

b) Don't put any source in the lead castle. Also remove all the sources in the vicinity of the castle.

c) Take 100 independent readings of the background counts for a preset time of 10 s. (To set Preset time 10 sec. follow step (ii) of initial procedure).

d) Save the data by pressing STORE key. While taking 100 independent reading set ITERATION (Step (iii) of initial procedure) to 1.

e) Place one of the g sources ($^{137}Cs$ or $^{60}Co$) far enough away from the window of the Giger tube so that approximately 2000 counts are recorded in a time period of 30 s.

f) Save the data by pressing STORE key. While taking 100 independent reading set ITERATION (Step (v) of initial procedure) to 1.

g) Transfer the data on PC and plot the required function.

**Analysis of Background counts (data set (iii) above)**

1. Determine frequency of occurrence v (y) which is the number of measurements in which y = 0, 1, 2 , 3, 4 ….counts have been observed and plot the experimental distribution v ( y) versus y .

2. Calculate the average number of counts $\bar{y}$ and the Poisson distribution

$$P(y) = \frac{(\bar{y})^{y} e^{-\bar{y}}}{y\,!}.$$

Compare this distribution with the experimental distribution.

3. Calculate $\sigma_{th}$ *and* $\sigma_{exp}$ and compare. The comparison gives clue to the reliability of the measuring equipment. If $\sigma_{exp}$ is larger than $\sigma_{th}$ , it means that additional fluctuations have been introduced by the apparatus, such as spurious counts due to voltage surges, sparks in the tube or change of the background during the course of the experiment which can occur when you handle the sources (move from one place to another) while the measurements are going on.

4. Determine the actual number of intervals for which the absolute value of the deviation from the average is larger than the standard deviation $\sigma = \sqrt{\bar{y}}$ and the probable error 0.6745s. Compare with theory.

**Analysis of the counts taken with the source data set (v) above**

5. Carry out the analysis following steps (g) to (f) above. However, in this case use Gaussian distribution. Also, in order to represent the distribution in the best possible manner, frequency of occurrence may be calculated by choosing equally spaced, nonoverlapping, contiguous intervals for the counts. The width of the interval can be anywhere from 2 to 10 counts or more depending on the data set.
6. In addition, you may use different methods of testing the "Gaussian" nature of an experimental data which are illustrated in the book: Measurement systems, Applications and Design ($4^{th}$ edition) by E. O. Doebelin, pages 44-58

**Data Sheet**

| Run | Counts | Run | Counts |
|---|---|---|---|
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| Data Set | Mean | Gaussian σ | Poisson σ |
|---|---|---|---|
| Background | | | |
| Cs-137 | | | |

## 3. Experiments 4:

### Efficiency of a Geiger-Muller counter

From earlier experiments, you should have learned that a GM tube does not count all the particles, which are emitted from a source (like, dead time). In addition, some of the particles do not strike the tube at all, because they are emitted uniformly in all directions from the source. In this experiment, you will calculate the efficiency of a GM tube counting system for different isotopes by comparing the measured count rate to the disintegration rate (activity) of the source. To find the disintegration rate, change from micro Curies (mCi) to disintegrations per minute (dpm). The disintegrations per minute unit is equivalent to the counts per minute from the GM tube, because each disintegration represents a particle emitted.

The conversion factor is: 1 Ci = $2.22 \times 10^{12}$ dpm, or 1 mCi = $2.22 \times 10^{6}$ dpm

Multiply this by the activity of the source and you have the expected counts per minute of the source. We will use this procedure to find the efficiency of the GM tube, by using a fairly simple formula. You want to find the percent of the counts you observe versus the counts you expect, so you can express this as:

$$\% \text{ Efficiency} = r(100)/CK$$

In this formula, r is the measured activity in cpm, C is the expected activity of the source in mCi, and K is the conversion factor from Equation 1.

**Procedure:**

1. Setup the Geiger counter as you have in the previous experiments. Set the Voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. Set Runs to zero and set Preset Time to 60 to measure activity in cpm.
3. First do a run without a radioactive source to determine your background level.
4. Next, place one of the radioactive sources (Po-210, Sr-90, Co-60) in the top shelf and begin taking data.
5. Repeat this for each of your other two sources. Remember that the first run is a background number.

6. (OPTIONAL) From the Preset menu, change the Preset Time to 300, and take data for all three sources again.
7. Save your data to disk or to a data table before exiting the ST350 program.

**Data Sheet**

Date time: ……………………… Run duration: ………….

| Source Counts | Corr. Counts | Expected | Cunts | Efficiency |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |

Date time: ……………………… Run duration: ………….

| Source Counts | Corr. Counts | Expected | Cunts | Efficiency |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |

Are your results reasonable? How do you know? You should have numbers above zero but below 10 if you performed the experiment correctly.

## 4. Experiments 5

### Absorption of gamma rays in materials

When gamma rays pass through a foil a certain fraction of them is removed from the primary beam. If N is the number of gamma rays which enter a medium the number that emerge through thickness x is

$$N = N_0 e^{-\mu x}$$

where μ is called as the absorption coefficient of the medium. We therefore have

$$\ln N = -\mu x + \ln N_o$$

A plot of lnN vs x is thus a straight line where the slope gives μ. Find μ for Al and Cu using Cs-137 and Co-60 source. Compare your results with those reported in the literature (see page 686 of Ref. 2)

μ is also called as linear attenuation coefficient. The absorption of gamma rays in matter
can also be characterized by mass absorption coefficient ( $m$ μ ). The last Eq. then becomes

$$N = N_0 e^{-\mu_m \rho_s}$$

where $\mu_m$ is the mass attenuation coefficient ( $m^2kg^{-1}$) and $\rho_s$ is the mass per unit area of the absorber.

The probability of interaction is given in terms of the total cross-section σ which is the summation of individual cross-sections related to the photoelectric effect, the Compton effect and the pair production and is written as:

$$\sigma = \sigma_{PE} + Z\sigma_c + \sigma_{pp}$$

The factor Z in the second term embodies the assumption that all the atomic electrons contribute individually (and incoherently) to Compton scattering. For gamma ray energies above K-shell ionization energy of the atom, the Compton effect is more dominant and for the purpose of the present experiment the first and the third terms of Eq. can be neglected. The cross-section σ $C$ is related to the absorption coefficient μ by:

$$\sigma_c = \frac{\mu}{n_e}$$

where *ne* is the number of electrons per unit volume in the material. Using the last Eq. find the value of $\sigma_C$ (express it in the units of barn (1 barn = $10^{-28}$ $m^2$)). Compare the values obtained for Cu and Al and give your comments on the findings.

Data: Density of Aluminum: 2.7 x $10^3$ kg $m^{-3}$, Z =13.

Density of Copper: 8.92 x $10^3$ kg $m^{-3}$, Z= 29.

Avogadro Number: 6.023 x $10^{26}$ molecule per kg mole.

Radiation is emitted from a source in all directions. The radiation emitted within the angle subtended by the window of the GM tube is the only radiation counted. Most radiation is emitted away from the tube but it strikes matter. When it does so, the direction of its path may be deflected. This deflection is known as scattering. Most particles undergo multiple scattering passing through matter. Beta particles especially may be scattered through large angles.

Radiation scattered through approximately 1800 is said to be backscattered. For Geiger counters, the fraction of radiation emitted away from the GM tube that strikes the material supporting the sample. It is deflected toward the tube window and is counted.

A beta particle entering matter undergoes a series of collisions with mostly nuclei and sometimes orbital electrons. A collision between particles does not occur in the same manner we picture them in the macroscopic world. There are very little contact collisions, but instead the term, collision, refers to any interaction, coulombic or otherwise. (A coulombic interaction is an electrical attraction or repulsion that changes the path of the particle's motion.) A collision may be elastic or inelastic, but in either 50 case the result is not only a change in direction but usually a decrease in the energy of the beta particle as well (inelastic). In the first part of the experiment, we will investigate the effect of the size of the nucleus on backscattering since this would seem most likely effect the number of backscattered beta particles. This can be determined by using absorbers as backing materials. Even though the metal pieces you will use are called absorbers, in this experiment, they will also be used to deflect radiation upward into the GM tube. To eliminate any other effects, the absorbers will be the same thickness but different atomic number (and thus different sized nuclei). In the second part of the experiment, you will use absorbers of the same material (atomic number) and different thickness.

This is a common experimental technique, fixing one variable and varying another to investigate each one individually Normally when we think of thickness, we think of linear thickness that can be measured in a linear unit such as inches or centimeters. However, in nuclear and particle physics, thickness refers to areal thickness. This is the thickness of the absorbers in mg/cm$^2$. The absorptive power of a material is dependent on its density and thickness, so the product of these two quantities is given as the total absorber thickness, or areal thickness. We determine areal thickness with the equation:

Density (mg/cm$^3$) x thickness (cm) = Absorber thickness (mg/cm$^2$). You will determine the dependence that absorber thickness has on backscattering.

**Procedure:**

**Part I – Atomic Number Dependence**

1. Setup the Geiger counter as you have in the previous experiments. Set the Voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the Preset menu, set Runs to zero and set Preset Time to 60.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the second shelf from the top and take data.
5. Place an absorber piece, or disk, in the source holder and place the source directly on top of it.
6. Repeat this for all of the various absorbers (different materials) including the unknown.

(Plastic is poly-carbonate** – Z = 6, Aluminum – Z = 13, Copper – Z = 29, Tin – Z =50, and Lead – Z = 82)

7. Record the data to a file on disk or into a data table.

**Part I – Thickness Dependence**

8. Repeat 1-5 Setup the Geiger counter as you have in the previous experiments.

9. Place the source on a different thickness of the absorber and insert into the second shelf.

10. Repeat for at least three other absorber thicknesses and record the data to a file.

**Data Sheet for Backscattering Lab**

Date time: ……………………… Run duration: …………

| **Element (Z)** | **Counts Corr.** | **Counts %** | **Backscattering** % |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

Date time: ……………………… Run duration: …………

| **Thickness** ($mg/cm^2$) | **Counts Corr.** | **Counts %** | **Backscattering** % |
|---|---|---|---|
| | | | |
| | | | |
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What is your conclusion about the dependence of backscattering on atomic number? How about on thickness?

## 5. Experiments 6

### Inverse square relationship between the distance and intensity of radiation

As a source is moved away from the detector, the intensity, or amount of detected radiation, decreases. You may have observed this effect in a previous experiment. If not, you have observed a similar effect in your life. The farther you move away from a friend, the harder it is to hear them. Or the farther you move away from a light source, the harder it is to see. Basically, nature provides many examples (including light, sound, and radiation) that follow an inverse square law. What an inverse square law says is that as you double the distance between source and detector, intensity goes down by a factor of four. If you triple the distance, intensity would decrease by a factor of nine. If you quadruple the distance, the intensity would decrease by a factor of 16, and so on and so on. As a result, if you move to a distance *d* away from the window of the GM counter, then the intensity of radiation decreases by a factor $1/d^2$.

**Procedure**:

1. Setup the Geiger counter as you have in the previous experiments. Set the voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the Preset menu, set Runs to zero and set Preset Time to 30.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the top shelf and begin taking data. In this position, the source is 2 cm from the GM tube's actual detector components.
5. Move the source down one shelf each time and take another run. You should see the data accumulating in the Data window. After all ten shelves have been used, save the data onto disk or record in a data table. Remember that the first run is a background number.

**Data Sheet**

Date time: ……………………… Run duration: ………….

| **Counts** | **Corr.** | **Counts** | **Distance 1/d2** |
|---|---|---|---|
| | | | |
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Use your graph to determine if the data does indeed obey inverse square law.

## 6. Experiments 7

### Absorption of beta particles

Beta particles are electrons that are emitted from an atom when a neutron decays by the weak force. The neutron (n) becomes a proton (p), an electron (e-), and an anti-neutrino (v′). When an electron originates in the nucleus, it is called a beta particle.

$$n \rightarrow p + e^- + \nu'$$

Unlike alpha particles which are emitted from the nucleus with the same energy (~5 MeV), beta particles are emitted with a range of energies lying between 0 MeV and the maximum energy for a given radioactive isotope. The velocity of a beta particle is dependent on its energy, and velocities range from zero to about 2.9 x $10^8$ m/s, nearly the speed of light. So the beta particles do not all have the same kinetic energy and thus they do not all have the same range. When the range varies over different values, this is called range straggling. It represents the different energy losses all of the beta particles have given their different initial values. Figure 6 shows a typical absorption curve for beta particles, which illustrates the range straggling.

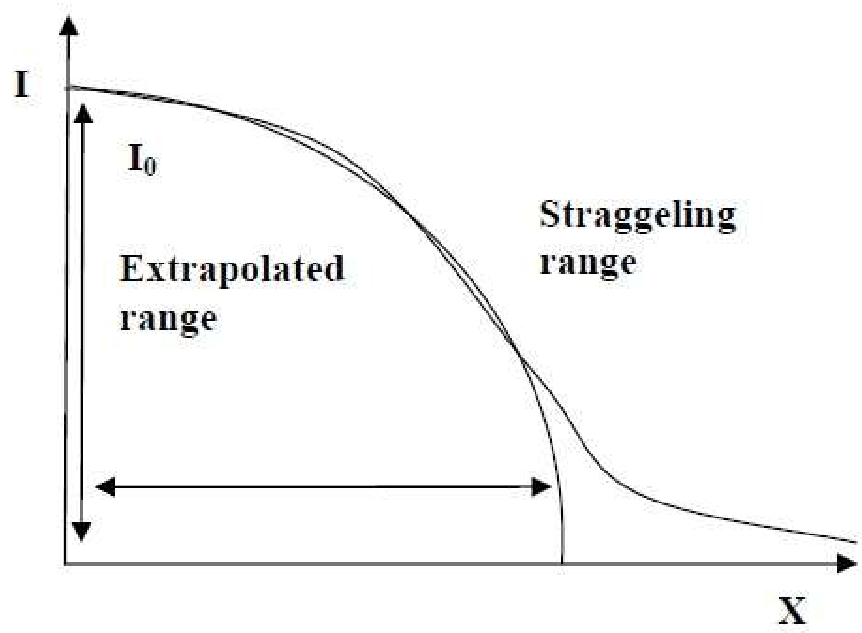


Figure: Typical absorption curve for beta particles. Plot is of intensity (activity) vs. absorber thickness (x).

**Procedure**:

1. Setup the Geiger counter as you have in previous experiments. Set the Voltage of the GM tube to its optimal operating voltage, which should be around 900 Volts.
2. From the Preset menu, set Runs to zero and set Preset Time to 60.
3. First do a run without a radioactive source to determine your background level.
4. Next, place the radioactive source in the second shelf from the top and begin taking data.
5. Place an absorber piece in the top shelf and take another run of data.
6. Repeat this minimum of 5 more times with absorbers of increasing thickness.

**Data Sheet**

Date time: ………………………    Run duration: ………….

| **Counts** | **Corr. Counts** | **Thickness** | **In (Counts)** |
|---|---|---|---|
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You should be able to characterize the relationship between beta particle activity and absorber thicknesses.