SCHOOL OF PHYSICS
UNIVERSITI SAINS MALAYSIA

ZCT191/192 PHYSICS PRACTICAL I/II
1MP1 RADIOACTIVITY

Lab Manual

OBJECTIVES

1. *To determine the operating voltage for a Geiger-Müller (G-M) tube;*
2. *To show that the standard deviation (σ) for a single count rate (R) can be estimated as $\sqrt{R/t}$ within 68% confidence for nuclear decay with high count rates; and*
3. *To determine the range of β particles.*

THEORY

Introduction

This radioactive experiment is designed in such a way that some basic aspects on radioactivity and its detection can be described and verified. Students should be familiar with error analysis, the role of statistics in physical measurements (especially in radioactive measurements) and have sufficient background knowledge on radioactivity. Students could also refer to the reading materials listed in the references for more information.

The only significant danger you will face in this experiment is if you ingest (eat or swallow) the sources. You will probably not intentionally eat any of the radioactive sources, but there is a small possibility that one of the seals may leak, and this could ultimately contaminate something that you eat. Thus, you should wash your hands after handling any radioactive source. Do not handle the sources with your fingers: it is safer to use the supplied tweezers.

Radioactivity

Our present state of knowledge indicates that an atom is composed of a central core (the *nucleus*) and various groupings of electrons in rapid motion around it. The *nuclei* consist of neutrons and protons, it can exist only in certain definite energy states. Transitions from higher to lower energy states are accompanied by the emission of either electromagnetic radiation or subatomic particles. This phenomenon called *radioactivity*, and when exhibited by naturally occurring isotopes (e.g. uranium, radium or polonium) it is termed *natural radioactivity*.

Artificial radioactivity is related to man-made isotopes. In this experiment, we shall consider the three most important modes of radioactive disintegration, characterised according to the emission as either *alpha*, *beta* or *gamma decay*.

Alpha decay. The alpha particle is identical with the helium nucleus (^{4}He). When ejecting an alpha particle, the original nucleus loses four unit masses (two protons, two neurons) and two units of charge. Hence, the resulting daughter nucleus is that of a different element. This new isotope may also be radioactive, and may decay again via the emission of an alpha or beta particle. Alpha particles are highly ionising, and they lose energy over a short distance, thus they cannot travel far in most medium. Alpha particles are commonly emitted by the larger radioactive nuclei such as polonium-210, radon-222, radium-226 and americium-241.

Beta decay. Beta particles may be either negative (electrons, e^-) or positive (positrons, e^+), the former being by far the more common type. The daughter isotopes will have the same mass number as the parent (since the mass of the ejected beta particle is negligible in comparison with the mass of the nucleus). Emitted simultaneously with the beta particle is an electrically neutral particle of negligible rest mass called a *neutrino*. Beta particles have the moderate penetrating and ionising power. Although the beta particles given off by different radioactive materials vary in energy, most beta particles can be stopped by a few millimetres of aluminium. Examples of radioactive materials that give off beta particles are hydrogen-3 (tritium), carbon-14, phosphorus-32, sulfur-35 and strontium-90.

Gamma decay. Transitions from higher to lower nuclear energy states of the same isotope are accompanied by the emission of *gamma rays*. These rays are similar in nature with X-rays, radio waves and other electromagnetic radiation, but are of much higher energy. These waves can travel a considerable range in air and have greater penetrating power (can travel further) than either alpha or beta particles. Gamma rays are generally blocked by thick blocks of lead or other heavy materials. Examples of common radionuclides that emit gamma rays are technetium-99m, iodine-125, iodine-131, cobalt-57 and cesium-137.

Absorption of Radiation

The absorption of beta and gamma radiation may be described by an exponential equation,

$$R = R_0 e^{-\mu x}, \tag{1}$$

where R is the *radiation intensity*, R_0 the radiation intensity without an absorber, μ the *linear absorption coefficient* and x the absorber's thickness. μ is dependent on the material of which the absorber is made and has a dimension of $[L^{-1}]$.

Equation 1 is most frequently written in the form of

$$R = R_0 e^{-\frac{\mu}{\rho}\rho x} = R_0 e^{-\mu_m \rho x}, \tag{2}$$

where ρ is the *density* of the absorber. μ_m is the *mass absorption coefficient* with dimension $[L^2 M^{-1}]$, and ρx is the *mass area density*. This expression has an advantage such that μ_m is practically independent of the nature of the absorber.

Let $\rho x = X$. In logarithmic form, **Equation 2** becomes

$$\ln R = \ln R_0 - \mu_m X. \tag{3}$$

Thus, by plotting $\ln R$ vs. X, we will obtain a straight line with a slope of $-\mu_m$ and a y-intercept of $\ln R_0$.

When passing through matter, charged particles ionise and thus lose energy in many steps, until their energy is (almost) zero. The distance to this point is called the *range* (r) of the particle. The range depends on the type of particle, its initial energy, and on the material through which it passes. The extrapolated range is the point where the absorption curve meets the background, as shown in **Figure 1**.

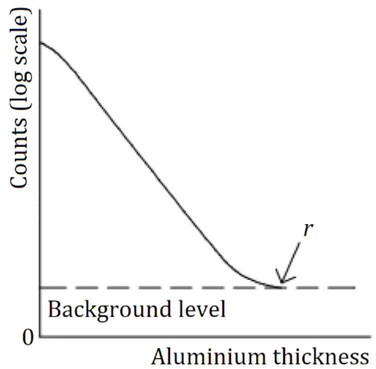

Figure 1: Beta decay absorption curve.

A useful measure of the penetrating power is the *half-value thickness* $X_{1/2}$ defined as the thickness of the absorber necessary to reduce the radiation intensity by a factor of two ($R/R_0 = 1/2$). Thus, from **Equation 3**,

$$\ln\left(\frac{R_0}{2}\right) = \ln R_0 - \mu_m X_{\frac{1}{2}} \tag{4}$$

$$X_{1/2} = -\frac{\ln\left(\frac{1}{2}\right)}{\mu_m}. \tag{5}$$

In fact, only gamma radiation actually obeys the above relationship exactly, provided that all secondary radiation is excluded from a beam arriving at the detector. However, you will find in this experiment that the equations provide quite a good quantitative description of the total absorption of the beta radiation as well.

Uncertainty in the Count Rate

Radioactive decay and most other nuclear reactions are *random events*; therefore they must be described quantitatively in statistical terms. Not only is there a continuous change in the activity within a specific measurement (due to the half-life of the radionuclide), but there is also a fluctuation in the decay rate between measurements due to the random nature of radioactive decay. Thus the *radiation count* N from a single measurement can be expressed as

$$N \pm \sigma = N \pm \sqrt{N}, \tag{6}$$

where $\sigma = \sqrt{N}$ represents one standard deviation using *Poisson statistics*. Since a sample is counted for a specified period of time (t), the results are reported in units of inverse time, i.e. *counts per minute* (cpm) or *counts per second* (cps). Thus, the equation for count rate is

$$\frac{N}{t} \pm \frac{\sqrt{N}}{t} = R \pm \sqrt{\frac{R}{t}}, \tag{7}$$

where $R = N/t$ is the count rate, or counts per unit time.

The range of values $N \pm \sigma$ will contain the true mean N_{mean} within 68% probability. We can also say that the interval $N_{\text{mean}} \pm \sigma_{\text{mean}}$ has 68% probability of containing our single measurement N. Thus, we can interchange N_{mean} and N in the statement.

Geiger-Müller Tube

A *Geiger-Müller* (G-M) tube is a device used for the detection and measurement of all types of radiation: alpha, beta and gamma radiation. Basically, it consists of a pair of electrodes surrounded by a gas, usually helium or argon. The electrodes have high voltages across them. When radiation enters the tube, it ionises the gas, the ions and electrons are then attracted to the electrodes and an electric current is produced. A scaler counts the current pulses, and one obtains a count whenever radiation ionises the gas. **Figure 2** shows a simplified detector circuit with a G-M tube.

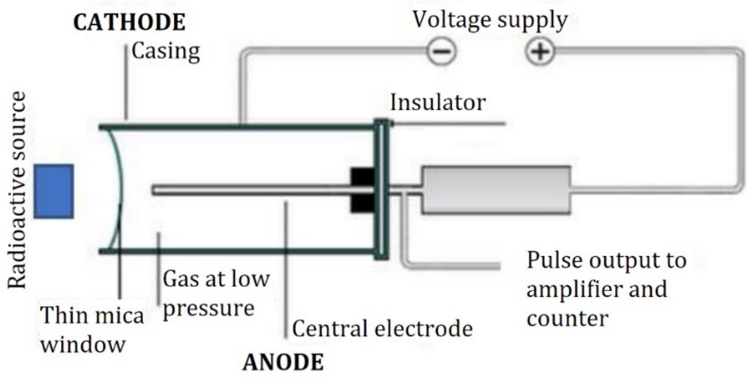

Figure 2: A simplified detector circuit with a G-M tube.

The characteristic curve of a G-M tube is obtained by plotting the count rate as a function of supply voltage in a constant radiation field. The main features of these characteristics are given below in **Figure 3** below.

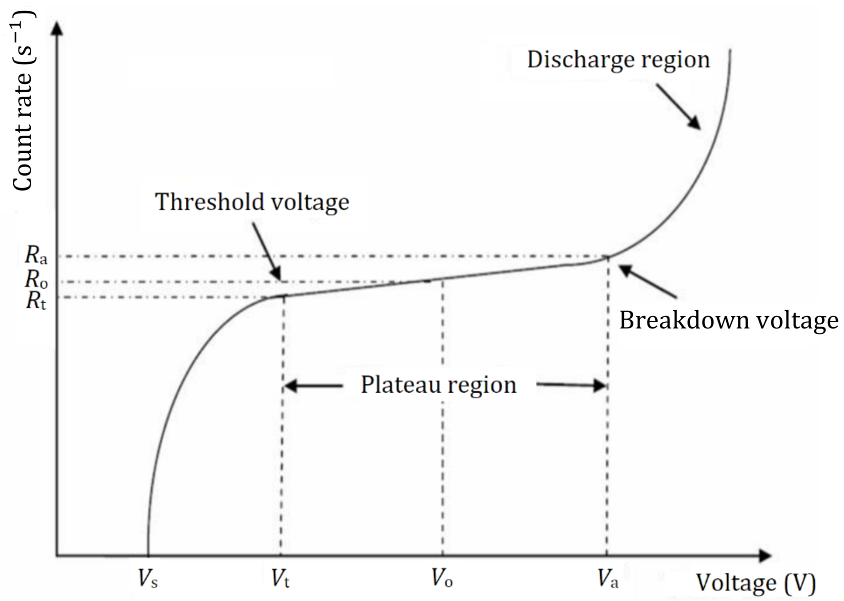

Figure 3: The characteristic curve of a Geiger-Müller tube.

At a very low voltage, the count rate is insignificant, so the tubes cannot generally be operated usefully in this region. The *starting voltage* (V_s) is defined as the lowest voltage applied to a counter tube at which pulses can be detected. Above the starting voltage, the count rate increases rapidly until it reaches the *threshold voltage* (V_t), which marks the beginning of the G-M tube *plateau region* (or *Geiger region*) for the conditions under which the circuit should be operating.

Beyond the threshold, further increase in voltage will result in a negligible increase in the count rate. An *operating voltage* (V_o) is selected to be used within this plateau. If the voltage is increased further past the plateau, another rapid rise in count rate takes place. This region is called the *discharge region*, where the voltage is large enough to cause the atoms to self-ionise. Operating a G-M tube in this region will quickly ruin the tube.

In this experiment, we will investigate the operating principles of the Geiger-Müller tube, validate the uncertainty analysis for a radioactive decay experiment and study some characteristics of β particles.

EQUIPMENT

1. Geiger-Müller tube
2. Radioactive source (β) ^{90}Sr
3. Counter
4. Absorber (aluminium foil)

PROCEDURE

Part A: Operating Voltage for a Geiger-Müller Tube

Measurement

1. Switch on the counter, and wait for a few minutes for it to warm up.
2. Place the radioactive source at a suitable distance from the window of the G-M tube (see **Figure 2**).
3. Slowly increase the applied voltage by ~20 steps a time, until radiation counts just began to be detected (R_o). Record this starting voltage (V_s).
4. Increase the count rate by ~20 steps each time, and record the count rate at each increment (take multiple readings). Note that the count rate should be set to ~10^3 by varying the distance between the G-M tube and the source. Once this distance is set, this arrangement should be maintained throughout the experiment (redo **Step 3** if needed).
5. Determine the standard deviation for each measurement.
6. When you reach the plateau region, record the threshold voltage (V_t, the beginning of the plateau) and its corresponding count rate (R_t). After this point, the rate should remain fairly constant over a range of applied voltage and then increase rapidly as it enters the discharge region.
7. Record the breakdown voltage (V_a) and its corresponding count rate (R_a). Do not continue to operate the tube in the discharge region (limit the applied voltage to 1200 V).

Analysis

1. Plot a graph of count rate vs. the applied voltage. Show error bars for each point in the graph. Explain how the error bars are obtained.
2. Determine the Geiger region, the region between R_t and R_a corresponding to the voltages V_t and V_a respectively.
3. Compute the slope of the plateau of the G-M tube. The slope should be 10% per 100 V, defined by

$$\text{Slope} = \frac{R_\mathrm{a} - R_\mathrm{t}}{0.5(R_\mathrm{a} + R_\mathrm{t})}\frac{1}{V_\mathrm{a} - V_\mathrm{t}} \times 100\% \quad (\%\ \text{per volt}) \tag{8}$$

Part B: Standard Deviation of Count Rate

Measurement
1. Set the applied voltage to the operating voltage obtained in **Part A**.
2. Take 20 measurements of the count rate, record these count rates and the total time taken to take these measurements.

Analysis
1. Calculate the standard deviation (σ) for this measurement.
2. Compare this value with $\sqrt{R/t}$ and calculate the percentage discrepancy.
3. At what condition does the Poisson distribution approaches a Gaussian distribution?

Part C: The Range of β Particles

Measurement
1. Set the applied voltage to the operating voltage obtained in **Part A**.
2. Remove the absorber, determine the background count rate and its standard deviation.
3. Arrange the experimental set up as illustrated in **Figure 4** below.

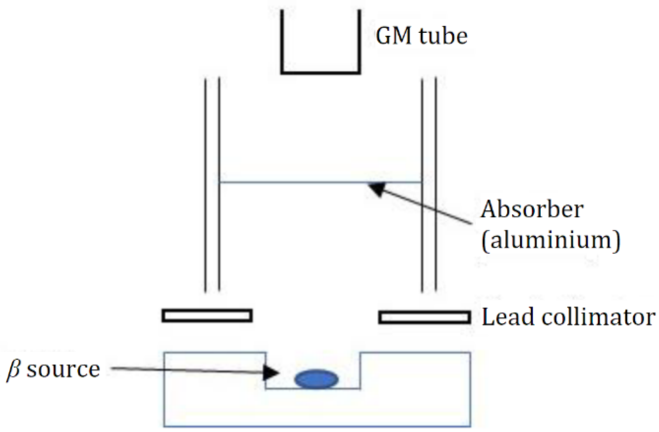

Figure 4: Experimental setup for measuring the range of β radiation.

4. Place an aluminium foil between the source (^{90}Sr) and the G-M tube.
5. Measure the activity for 30 s, and record the counts.
6. Add layers of aluminium in pairs, and repeat **Step 5**, until the activity drops to that the background radiation level.

Analysis

7. Plot the count rate (R) vs. the thickness of the absorber (X) with the background count rate included.
8. From the graph of R vs. X, determine the range of the β particles in aluminium.
9. Plot the log of the count rate vs. the thickness of the absorber ($\ln R$ vs. X) with the background count rate included.
10. From the graph of $\ln R$ vs. X, determine the range of the β particles in aluminium and its absorption coefficient (μ_m).
11. Compare the two values of the range of β particles obtained from the different graph.
12. Does the count rate R from β particles satisfy the equation $R = R_0 e^{-\mu m X}$? R_0 is the count rate without an absorber, and X the thickness of the absorber is measured in mg cm^{-2}.
13. Compute the half-thickness value ($X_{1/2}$) for β particles in the aluminium absorber. The value of $X_{1/2}$ can be obtained by setting $R/R_0 = 1$.

REFERENCES

1. Turner, J. E. (2008). *Atoms, Radiation and Radiation Protection* (3rd ed.). John Wiley & Sons.
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