Radioactivity

Khalifa Salem Almatrooshi

Department of Physics, American University of Sharjah, Sharjah

United Arab Emirates, PO Box: 26666

Abstract

This experiment was designed to explore the fundamental principles of radioactivity through a series of measurements and observations using a Geiger-Müller (GM) tube. The objectives included the investigation of the inverse square law for radiation intensity, the absorption of beta and gamma radiation, and the determination of the half-life of a radioactive isotope. The experiment underscored the stochastic nature of radioactive decay and provided insights into the practical applications of radioactivity in medical, industrial, and research settings. Significant findings were the confirmation of the inverse square law for beta/gamma radiation from a Cs-137 source and the calculation of the half-life of Ba-137m. Discrepancies in the expected and observed values were analyzed, attributing potential causes to experimental setup and measurement techniques.

Keywords: *Radioactivity, Geiger-Müller tube, Inverse Square Law, Half-life.*

1 Introduction

Radioactivity involves the spontaneous emission of particles or electromagnetic waves from the unstable nuclei of certain atoms. These emissions, known as radiation, are a natural byproduct of unstable isotopes seeking stability through processes such as alpha decay, beta decay, and gamma emission. Radiation can be detected and quantified using instruments such as the Geiger-Müller (GM) tube, a device designed to measure ionizing radiation types including alpha particles, beta particles, and gamma rays.

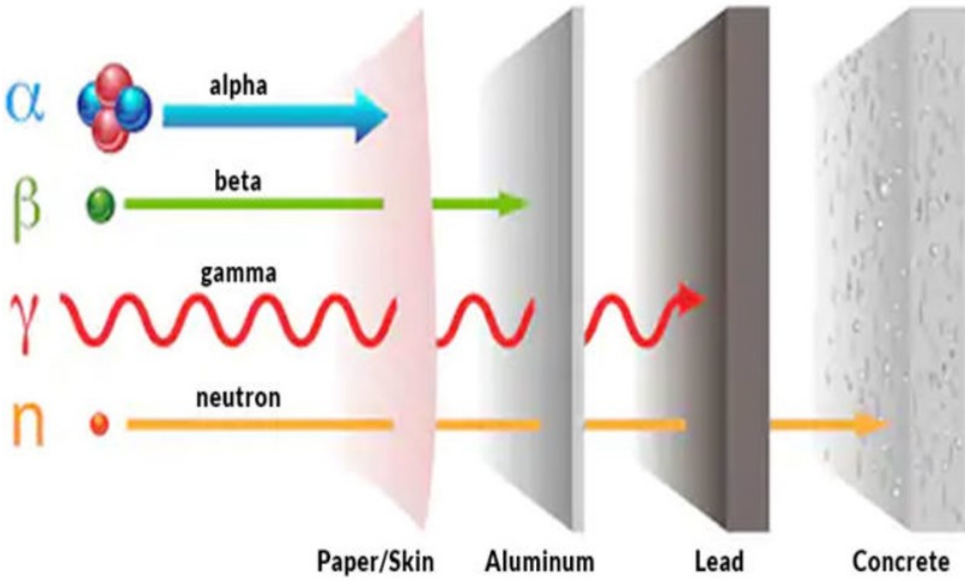

Figure 1: Radiation types

Radioactivity is quantified in two principal units: the Becquerel (Bq) and the Curie (Ci) [2].

- Becquerel (Bq): The Becquerel is the SI unit of radioactivity. One Becquerel is defined as one disintegration per second. This unit directly measures the rate at which an unstable atomic nucleus transforms, emitting radiation in the process.
- Curie (Ci): The Curie is an older, non-SI unit of radioactivity, still commonly used in some contexts, particularly within the United States. One Curie is approximately equal to 3.7×10^{10} disintegrations per second, defined historically based on the activity of one gram of radium-226.

The GM tube operates by using a gas-filled metal cylinder with a thin mica window that allows radiation to enter. Inside the tube, a high voltage is applied between the outer metal cylinder (cathode) and a central wire (anode). When radiation penetrates the tube, it ionizes the gas, creating ions and electrons. The electrons are attracted towards the anode, creating an ionization current that is detected as a count.

This process is instrumental in understanding the intensity and type of radiation being measured. The efficiency of the GM tube is affected by factors such as the type of gas used, the pressure within the tube, and the voltage applied across the electrodes.

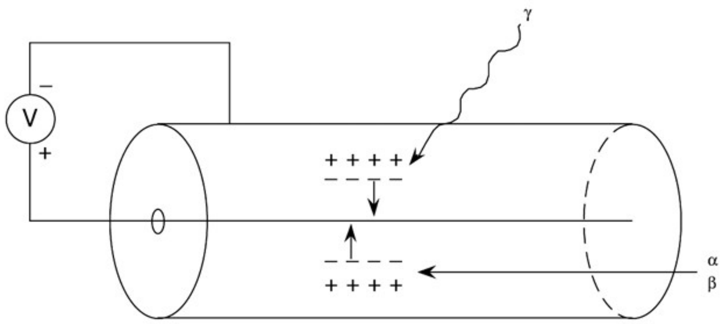

Figure 2: Schematic of gas-filled detector operated with a varying voltage applied between the chamber wall (cathode) and a central collecting electrode (anode) [1]

The interaction of radiation with matter is fundamentally probabilistic, described by exponential decay laws. The activity A of a radioactive sample, measured in disintegrations per second (or Becquerels), follows the equation:

$$A = A_0 e^{-\lambda t} \tag{1}$$

where: A_0 is the initial activity, λ is the decay constant, t is the time elapsed. This is also equivalent to the number of radioactive atoms N.

In this lab report, we explore several aspects of radioactivity and its detection:

1. **Background Radiation Measurement**: Understanding and measuring the omnipresent background radiation is crucial for accurate radiation measurement.
2. **Resolving Time**: This part examines the time after each detection during which the detector is 'blind' to further incoming radiation.
3. **Geiger Tube Efficiency**: We investigate how efficiently the GM tube detects different types of radiation.
4. **Inverse Square Law**: This part validates the principle that the intensity of radiation observed from a point source decreases inversely with the square of the distance from the source.
5. **Range and Absorption**: We explore how different materials absorb or attenuate different types of radiation, providing insights into shielding and radiation protection.

This lab report is vital for several reasons. First, it enhances understanding of the fundamental principles of radioactivity and the practical application of radiation detection methods, particularly through the use of the Geiger-Müller (GM) tube. Such knowledge is crucial for fields ranging from medical diagnostics, where radioactive tracers are used in imaging, to environmental science, which often involves monitoring natural and anthropogenic radioactive sources.

Second, this report contributes to safety in handling and using radioactive materials. By measuring background radiation and understanding the behavior of different radioactive sources under various conditions, we can better manage and mitigate the risks associated with radiation exposure. The manual's discussion on exposure to radiation highlights the omnipresent nature of background radiation and the importance of quantifying this exposure accurately, especially in occupational settings such as nuclear plants and hospitals.

Third, the experiments detailed in this report serve as practical examples of the inverse square law and radiation absorption principles, which are not only foundational concepts in physics but also critical in designing shielding and safety protocols to protect against harmful radiation.

To sum up, the insights provided by this report have profound implications for health, safety, and the practical use of radiation in various technological and medical applications.

2 Experimental Details

This section details the procedure for each method and the expected results according to the lab manuals and the relevant equations. We use Microsoft Excel for data analysis. Sources and absorber kit are in the appendix.

Figure 3: Setup for ST360 with sources and absorber kit. [2]

2.1 Plotting a GM Plateau

This subsection details the procedure for determining plateau and optimal operating voltage of a Geiger-Müller Counter.

- **Setup the GM Tube:**
  1. Ensure the power supply is disconnected before setup.
  2. Remove the protective end cap from the GM tube very carefully to avoid damaging the thin window.
  3. Place the GM tube into the shelf stand with the window facing down and the BNC connector facing upwards.
  4. Connect the BNC cable from the GM tube to the GM input on the control unit.
- **Initial Configuration:**
  1. Connect the power supply to the control unit and then to a standard electricity outlet.
  2. Switch on the power at the back of the unit and observe any startup indications.

- **Voltage Setup:**
  1. Start with the initial voltage set to 700 Volts.
  2. Incrementally increase the voltage in steps of 20 Volts up to a maximum as required by your experimental setup. Take note that the maximum allowable voltage should not exceed 1200 Volts for the tube.
- **Manual Count Recording:**
  1. Record counts manually for each voltage step.
  2. Observe the count rate stabilization and identify the plateau region where the count rate changes minimally with increases in voltage.
  3. Note the voltage where the plateau begins and where it ends, signifying the discharge region.
- **Data Recording:**
  1. Document all readings and voltage settings.
  2. Use the recorded data to plot the count rate against the voltage to visualize the Geiger plateau.
- **Conclusion of Experiment:**
  1. Determine the optimal operating voltage based on the mid-region of the plateau, favoring the lower half closer to the knee to prolong tube life and avoid continuous discharge.

2.2 Background

This subsection outlines the procedure for investigating and measuring background radiation using a Geiger-Müller Counter.

- **Setup and Initial Configuration:**
  1. Follow steps in the *Plotting a GM Plateau* subsection for the initial setup and configuration of the GM tube.
  2. Set the GM tube to its optimal operating voltage as determined from the plateau experiment. This ensures that the tube is operating within its most efficient range.
- **Background Radiation Counting:**
  1. Ensure no radioactive source is placed near the GM tube to only measure ambient background radiation.
  2. Record the count rate over a predetermined time interval to establish a baseline measure-

ment of background radiation.

- **Data Recording and Analysis:**
  1. Document the background count rate along with environmental conditions that may affect it, such as electronic devices or building materials.
  2. Analyze the significance of the background radiation level in relation to total radiation measurements performed in other experiments.
- **Conclusion of Experiment:**
  1. Evaluate the necessity of background radiation correction for subsequent experiments involving radioactive sources.
  2. Assess any potential health risks or safety concerns based on the measured background radiation levels.

2.3 Resolving Time

This subsection details the procedure for determining the resolving time of a Geiger-Müller Counter, which is crucial for understanding the temporal limitations of radiation detection by the GM tube.

- **Setup and Initial Configuration:**
  1. Follow steps in the *Plotting a GM Plateau* subsection for the initial setup and configuration of the GM tube.
  2. Set the GM tube to its optimal operating voltage as determined from the plateau experiment. This ensures that the tube is operating within its most efficient range.
- **Voltage Setup:**
  1. Set the GM tube to its optimal operating voltage as determined from the plateau experiment.
- **Resolving Time Measurement:**
  1. Prepare a test setup with two identical radioactive sources of known activity.
  2. Place one source at a time in the detection range of the GM tube and record the count rates separately for each source as r_1 and r_2.
  3. Place both sources simultaneously in the detection range and record the combined count rate as r_3.
  4. Use these measurements to calculate the resolving time T of the GM tube using the

formula:

$$T = \frac{r_1 + r_2 - r_3}{2r_1 r_2}$$

- **Data Recording and Analysis:**
  1. Document all individual and combined count rates.
  2. Analyze the effect of coincidences on the count rates and calculate the GM tube's resolving time.
- **Conclusion of Experiment:**
  1. Determine the suitability of the GM tube's resolving time for various types of radiation experiments.
  2. Assess how the resolving time might impact the accuracy and reliability of radiation measurements in high radiation fields.

2.4 Geiger Tube Efficiency

This subsection outlines the procedure for determining the efficiency of a Geiger-Müller Counter in detecting various types of radiation to assess the performance characteristics of the GM tube.

- **Setup and Initial Configuration:**
  1. Follow steps in the *Plotting a GM Plateau* subsection for the initial setup and configuration of the GM tube.
  2. Set the GM tube to its optimal operating voltage as determined from the plateau experiment. This ensures that the tube is operating within its most efficient range.
- **Efficiency Measurement:**
  1. Select radioactive sources with known activities and types of radiation (e.g., alpha, beta, gamma).
  2. For each type of radiation, position the source at a fixed distance from the GM tube to ensure consistent measurement conditions.
  3. Record the count rate for a set period, ensuring each type of radiation is measured under identical settings.
  4. Calculate the efficiency of the GM tube for each type of radiation by comparing the observed count rates to the known activities of the sources.
- **Data Recording and Analysis:**
  1. Document the type of radiation, source activity, observed count rates, and calculated

efficiencies.

2. Analyze how the GM tube's efficiency varies with different types of radiation, considering factors such as the energy and penetration power of each radiation type.

- **Conclusion of Experiment:**
  1. Assess the overall performance of the GM tube across different radiation types and identify any potential limitations.
  2. Provide recommendations for the use of the GM tube in various practical applications based on its efficiency characteristics.

2.5 Inverse Square Law

This subsection explains the procedure for verifying the Inverse Square Law with a Geiger-Müller Counter, which is fundamental for understanding the relationship between distance and radiation intensity.

- **Setup and Initial Configuration:**
  1. Follow the *Setup and Initial Configuration* steps from the *Plotting a GM Plateau* subsection for the initial setup and configuration of the GM tube.
  2. Ensure the GM tube is set to its optimal operating voltage as determined from the plateau experiment, ensuring accuracy in measurement.
- **Testing the Inverse Square Law:**
  1. Place a radioactive source (preferably one with a strong and easily detectable emission such as Cs-137) at a measured initial distance from the GM tube.
  2. Record the count rate at this initial distance.
  3. Incrementally increase the distance between the source and the GM tube, doubling the initial distance successively (e.g., 1cm, 2cm, 4cm, etc.).
  4. Record the count rates at each distance.
  5. Plot these distances against the corresponding count rates on a log-log graph to visually assess the inverse square relationship.
- **Data Recording and Analysis:**
  1. Document each distance and the corresponding count rate.
  2. Use the data to calculate the intensity of radiation as a function of distance, ideally fitting a curve to verify the inverse square proportionality: $I \propto \frac{1}{d^2}$ where I is intensity and d is distance.

3. Analyze any deviations from the ideal inverse square law which may be influenced by factors such as air absorption or scatter.

- **Conclusion of Experiment:**
  1. Summarize the findings and confirm whether the experimental data supports the Inverse Square Law.
  2. Discuss the implications of the results for practical applications where understanding radiation intensity and distance is important, such as in medical radiography, nuclear safety, and radiation shielding.

2.6 Range of Alpha Particles

This subsection details the procedure for determining the range of alpha particles using a Geiger-Müller Counter, an essential step for understanding the penetration power of alpha radiation and its interaction with matter.

- **Setup and Initial Configuration:**
  1. Refer to the *Setup and Initial Configuration* steps from the *Plotting a GM Plateau* subsection for the initial setup and configuration of the GM tube.
  2. Set the GM tube to its optimal operating voltage as determined from the plateau experiment, ensuring accurate measurements.
- **Measuring Alpha Particle Range:**
  1. Place an alpha-emitting radioactive source, such as Po-210, at a very close distance (a few centimeters) from the GM tube to maximize detection efficiency.
  2. Record the count rate at this initial position.
  3. Gradually increase the distance between the source and the GM tube in small increments, such as 0.5 cm, noting the count rate at each step.
  4. Continue adjusting the distance until the count rate falls to background levels, indicating that alpha particles no longer reach the detector.
  5. Measure and document the maximum distance at which alpha particles are detected, known as the range of the alpha particles in air.
- **Data Recording and Analysis:**
  1. Record the distances and corresponding count rates.
  2. Plot these values to visually depict the decrease in alpha particle intensity with increased

distance.

3. Analyze the range where the count rate significantly drops to near-background levels, establishing the practical range of alpha particles in air.

- **Conclusion of Experiment:**
  1. Evaluate the implications of the alpha particle range for safety and material design, particularly in scenarios involving radioactive materials.
  2. Discuss the relationship between alpha particle energy and penetration range, highlighting how this experiment helps in understanding alpha radiation shielding requirements.

2.7 Absorption of Beta Particles

This subsection describes the procedure for examining the absorption characteristics of beta particles using a Geiger-Müller Counter. This experiment is fundamental for understanding the interaction between beta radiation and matter, specifically how different materials can attenuate beta radiation.

- **Setup and Initial Configuration:**
  1. Follow the *Setup and Initial Configuration* steps from the *Plotting a GM Plateau* subsection to prepare the GM tube.
  2. Ensure the GM tube is set to the optimal operating voltage as determined from previous experiments, to ensure accurate and reliable measurements.
- **Measuring Beta Particle Absorption:**
  1. Select a beta-emitting radioactive source, such as Sr-90.
  2. Place the source at a fixed distance from the GM tube. Begin without any absorber to record the baseline count rate.
  3. Introduce absorbers of varying thicknesses and materials between the source and the GM tube. Common materials include aluminum, lead, and plastic.
  4. For each absorber, record the count rate. Note how the count rate changes as the thickness or type of the absorber changes.
  5. Incrementally increase the thickness of the absorber and observe the attenuation of beta particles until the count rate approaches background levels.
- **Data Recording and Analysis:**
  1. Document each type and thickness of the absorber used along with the corresponding count rates.

2. Plot the count rates against the thickness or type of the absorber to illustrate the absorption curve of beta particles.
3. Analyze how the absorption characteristics vary with different materials and thicknesses, and calculate the half-value layer for each type of absorber if applicable.

- **Conclusion of Experiment:**
  1. Summarize how effectively different materials can shield against beta radiation.
  2. Discuss the practical applications of this knowledge in designing safety measures and protective gear for environments where beta radiation is present.

2.8 Beta Decay Energy

This subsection describes the methodology for determining the energy spectrum of beta particles emitted by a radioactive source using a Geiger-Müller Counter. This experiment is essential for exploring the energetic properties of beta decay and its implications for nuclear physics and radiation protection.

- **Setup and Initial Configuration:**
  1. Implement the *Setup and Initial Configuration* steps from the *Plotting a GM Plateau* subsection for setting up the GM tube.
  2. Adjust the GM tube to the optimal operating voltage established from the plateau experiment, ensuring the detector operates within its effective range for accurate energy measurements.
- **Measuring Beta Particle Energy:**
  1. Use a beta-emitting radioactive source known for a specific energy spectrum, such as Sr-90 or P-32.
  2. Position the source a consistent distance from the GM tube to standardize measurement conditions.
  3. Employ a series of absorbers with precisely known thicknesses to progressively attenuate the beta particles.
  4. Record the count rate as each absorber is introduced, noting the decrease in count rate corresponding to increased absorber thickness.
  5. Use the count rates and known absorber properties to calculate the maximum energy of the beta particles using absorption data and range-energy relationships.
- **Data Recording and Analysis:**

1. Log each absorber's material, thickness, and the associated count rates.
2. Analyze how the count rates decrease as the beta particles' energy is absorbed by the material, plotting energy absorption curves.
3. Determine the endpoint energy of the beta spectrum from the absorption data, which reflects the maximum energy that beta particles can carry.

- **Conclusion of Experiment:**
  1. Interpret the findings in the context of beta decay theory and discuss the energy spectrum of the utilized beta source.
  2. Evaluate how the measured beta energies relate to theoretical predictions and their implications for applications in medical imaging, radiation therapy, and nuclear safety.

2.9 Absorption of Gamma Rays

This subsection outlines the procedure for studying the absorption characteristics of gamma rays through different materials using a Geiger-Müller Counter. Understanding gamma ray absorption is vital for applications in medical diagnostics, nuclear power management, and radiation shielding.

- **Setup and Initial Configuration:**
  1. Follow the *Setup and Initial Configuration* steps from the *Plotting a GM Plateau* subsection for preparing the GM tube.
  2. Ensure the GM tube is set to its optimal operating voltage, as identified from the plateau experiment, to accurately measure gamma radiation.
- **Measuring Gamma Ray Absorption:**
  1. Select a gamma-emitting radioactive source, such as Co-60 or Cs-137, known for their penetrating gamma rays.
  2. Place the source at a fixed distance from the GM tube. Record the baseline count rate without any absorber to measure the unattenuated intensity.
  3. Introduce different materials as absorbers between the source and the GM tube, starting with lighter materials like aluminum and progressing to denser materials like lead.
  4. Record the count rate for each absorber, noting the attenuation of gamma rays as the absorber thickness or density increases.
  5. Continuously adjust the thickness of each material to determine the half-value thickness, where the original intensity is reduced by half.

- **Data Recording and Analysis:**
  1. Document each absorber's material, thickness, and the corresponding count rates.
  2. Plot these values to illustrate the relationship between absorber density/thickness and gamma ray attenuation.
  3. Analyze the effectiveness of each material in shielding against gamma radiation, calculating the half-value layer for each type of absorber.
- **Conclusion of Experiment:**
  1. Summarize the results and assess the efficiency of different materials in absorbing gamma rays.
  2. Discuss the implications of the findings for designing radiation protection measures and the safe handling of gamma-emitting sources.

2.10 Half-Life Measurement

This subsection explains the procedure for measuring the half-life of a radioactive isotope, a key experiment for understanding the decay characteristics and stability of nuclear materials.

- **Setup and Initial Configuration:**
  1. Implement the *Setup and Initial Configuration* steps from the *Plotting a GM Plateau* subsection to prepare the GM tube.
  2. Set the GM tube to the optimal operating voltage as determined from previous experiments to ensure accurate decay rate measurements.
- **Measuring Half-Life:**
  1. Choose a radioactive source with a known or suspected half-life that is practical for the duration of the laboratory session, such as Ba-137m.
  2. Start with the source in close proximity to the GM tube to record the initial activity (count rate).
  3. Record the activity at regular intervals over a period that includes several expected half-lives of the isotope. For isotopes with very short half-lives, measurements may need to be taken every few seconds or minutes; for longer half-lives, hourly measurements may suffice.
  4. Continue recording until the activity decreases to a point where it approaches the background radiation level, or until enough data has been collected to clearly define the decay

curve.

- **Data Recording and Analysis:**
  1. Document the time and corresponding count rate at each interval.
  2. Plot the natural logarithm of the count rate against time to produce a decay curve. The slope of this line will provide the decay constant (λ), from which the half-life ($T_{1/2}$) can be calculated using the relationship $T_{1/2} = \frac{\ln 2}{\lambda}$.
  3. Analyze the data to confirm the exponential nature of the decay process and to accurately determine the half-life.
- **Conclusion of Experiment:**
  1. Evaluate the calculated half-life against known values (if available) to validate the experimental approach and the accuracy of the measurements.
  2. Discuss the implications of the findings for practical applications, such as radioactive dating, medical diagnostics, and nuclear power generation.

3 Results and Discussion

The following subsections contains our results for each section with tables and graphs. This is accompanied by a discussion that includes interpretations of the results and error analysis.

3.1 Plotting a GM Plateau

Table 1: Voltage (V) vs Counts (30s) for Sr-90 Beta Radiation

Voltage (V)	Counts (30 s)			
	Trials			Average
	1	2	3	
700	1668	1659	1643	1657
720	1762	1793	1765	1773
740	1904	1917	1939	1920
760	1968	2013	2000	1994
780	2038	2072	2050	2053
800	2038	2197	2181	2139
820	2135	2129	2134	2133
840	2223	2199	2210	2211
860	2179	2236	2245	2220
880	2357	2320	2359	2345
900	2278	2305	2299	2294
920	2287	2362	2325	2325
940	2323	2340	2345	2336
960	2544	2453	2482	2493
980	2629	2484	2565	2559
1000	3055	3081	3020	3052
1020	4387	4364	4455	4402

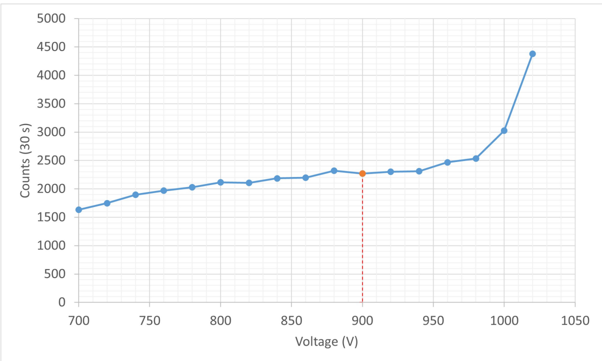

Figure 4: Voltage (V) vs Counts (30s) for Sr-90 Beta Radiation

The above graph does show a plateau around 875 V and 925 V, we went with the average which gives 900 V. This is the best operating voltage for this specific tube and so we use it for further experiments.

3.2 Background

Table 2: Background Radiation

Voltage (V)	Counts (30 s)			
	Trials			Average
	1	2	3	
900	26	21	27	25

The measurements for some experiments were collated at different times, so this measurement for the background is not always used. This confirms the statistical variation of background radiation.

3.3 Resolving Time

This subsection was done at different times so the background radiation will be different. The resolving time is found using

$$T = \frac{r_1 + r_2 - r_3}{2r_1r_2}.$$

Also the True cpm is found by

$$R = \frac{r}{1 - rT}.$$

% Counts added is found by

$$\% = \left(\frac{|New - Corrected|}{Corrected}\right).$$

Table 3: First Trial for Ti-204 Beta Radiation

Half-sources	cpm	Corrected cpm	True cpm	% Counts Added
r1	84702	84544	137243	62.03%
r2	84900	84742	137766	62.27%
r3	104365	104207	197845	89.57%
Background cpm	158			
Resolving Time (s)	4.54181E-06			

Table 4: Second Trial for Ti-204 Beta Radiation

Half-sources	cpm	Corrected cpm	True cpm	% Counts Added
r1	53949	53920	71407	32.36%
r2	55928	55899	74920	33.96%
r3	82970	82941	133068	60.38%
Background cpm	29			
Resolving Time (s)	4.45875E-06			

The average resolving time for this tube is 4.50028×10^{-6} s, and it falls withing the accepted 1 µs to 100 µs range. This value is used for further experiments wherever True cpm is calculated. The percent of correction is not the same for all values, ideally it should be consistent but because of inherent errors in the experiment the percentage varies. Some errors include

- **Random Nature of Decay**: Radioactive decay is a stochastic process, meaning it is random by nature. The time between decay events is exponentially distributed, which can lead to variability in the number of disintegrations observed over a fixed time interval, even under identical experimental conditions.

- **Detector Efficiency Variability**: Geiger-Müller tubes can have slight variations in sensitivity and efficiency, even among tubes of the same model and make. These variations can affect how many events the tube detects, particularly during periods of high activity when multiple decays occur close together in time.
- **Experimental Setup**: Small differences in how the experiment is set up each time can influence results. This includes variations in source placement, environmental conditions (like temperature and humidity), and background radiation levels, all of which can affect the count rate.
- **Dead Time of the Detector**: The dead time (Resolving time) can vary slightly depending on the specific characteristics of the tube and the operating voltage. If the count rates are high, even small variations in dead time can significantly impact the percentage of counts added.

3.4 Geiger Tube Efficiency

Table 5: Efficiency Table

Trials	cpm	Corrected cpm	True cpm	Expected cpm	Efficiency
1	53720	53720	70848	445778820	0.02%
2	53436	53436	70355	445778820	0.02%
3	53530	53530	70518	445778820	0.02%

Table 6: Cs-137 Relevant Information

Dead Time (s)	4.50028E-06
Initial Activity (Ci)	5.00E-06
Half-life (yrs)	30.2
Manufacturing Date	1 11 2006
Current Date	29 04 2024
Time since MD (yrs)	17.49
Today Activity (Ci)	3.34647E-06
Ci to Bq	3.70E+10
Today Activity (Bq)	7429173

The efficiency is very low indicating that not all the expected counts were counted. This is a given due to many factors: the activity of the sample decaying over time, the placement of the sample in the holder, environmental fluctuations, etc. The main factor is the expected cpm accounts for all the radiation emitting from a sample, not the fraction detected by the GM tube.

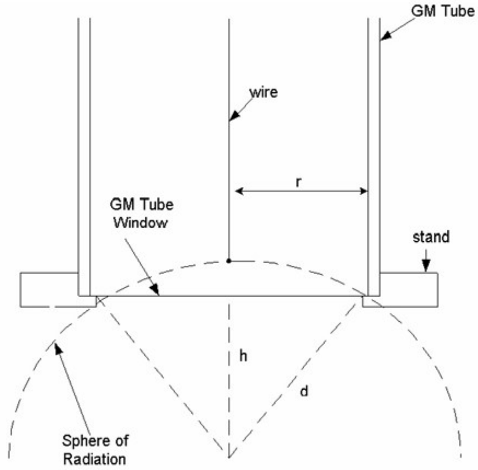

Figure 5: Sphere of radiation

Comparing the surface area of a sphere 3 cm from the source to the area of the GM tube's window (ST360: 35 mm OD).

$$\frac{\pi(\frac{3.5\,\mathrm{cm}}{2})^2}{4\pi(3\,\mathrm{cm})^2} = 0.0851$$

Multiplying this ratio by the expected cpm gives 37935777, which is still far from the True cpm.

3.5 Inverse Square Law

Table 7: Distance d (cm) vs Counts (cpm) for Cs-137 Beta/Gamma Radiation

d (cm)	$1/d^2$ (cm^{-2})	Counts (cpm)					
		Trials			Average	Corrected Average	True Average
		1	2	3			
2	0.25	53640	53336	53516	53497	53473	70418
3	0.11	34358	34722	34497	34526	34501	40842
4	0.06	23032	22858	23049	22980	22955	25600
5	0.04	15941	15638	16057	15879	15854	17072
6	0.03	11760	11533	11592	11628	11604	12243
7	0.02	8877	8903	8832	8871	8846	9213
8	0.02	6958	7031	6992	6994	6969	7195
9	0.01	5603	5659	5587	5616	5592	5736
10	0.01	4638	4622	4643	4634	4610	4707
11	0.01	3963	4012	3931	3969	3944	4015

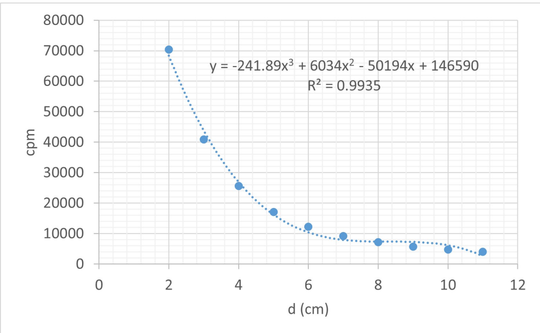

Figure 6: Distance (cm) vs Counts (cpm) for Cs-137 Beta/Gamma Radiation

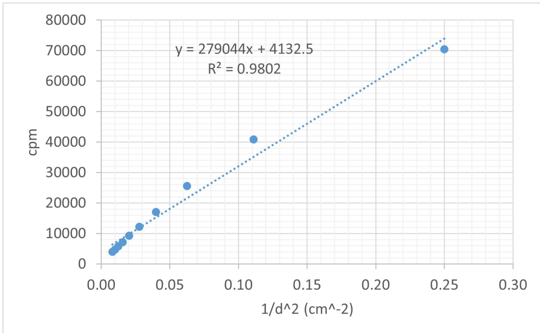

Figure 7: 1/Distance^2 (cm^{-2}) vs Counts (cpm) for Cs-137 Beta/Gamma Radiation

Figure 5 shows the asymptotic behavior of radiation intensity of source with varying distance, and Figure 6 verifies the inverse square law by Intensity $\propto 1/d^2$. An R^2 value of 0.9802 indicates a strong correlation.

3.6 Range of Alpha Particles

Table 8: Distance d (cm) vs Counts (cpm) for Am-241 Alpha Radiation

Distance (cm)	Counts (cpm)						
	Trials			Average	Corrected Average	True Average	I/I_0
	1	2	3				
1.5	11958	11782	11679	11806	11806	12469	1
2	11098	11165	11207	11157	11132	11719	0.93985
2.5	8274	8270	8243	8262	8262	8581	0.68819
3	138	144	137	140	140	140	0.01123
4	72	74	68	71	71	71	0.00569

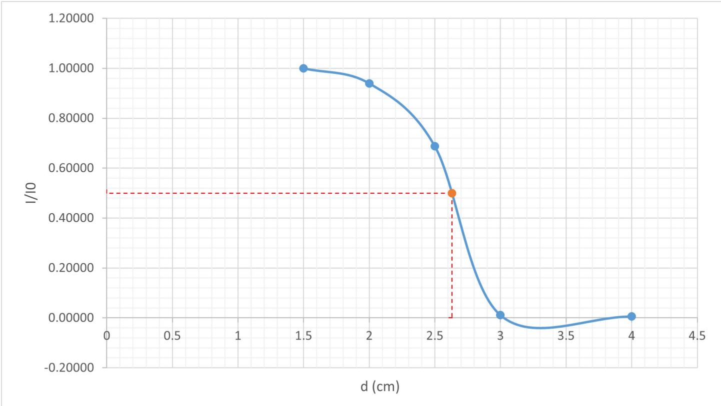

Figure 8: Distance d (cm) vs Counts (cpm) for Am-241 Alpha Radiation

We were able to take some reading less than 2 cm and this allows us to see the curve slope down over a certain interval of distances towards zero. This range indicates that not every identical particle will have identical energy loss because every particles goes through a different number of collisions. This phenomenon is called *range straggling* and the mean range $\bar{R}$ can be used to approximate the energy of an alpha particle. The energy is approximated by $E \approx R + 1.5$, where E is in MeV and R is in cm.

Table 9: Energy Calculation and Error

Mean Range (cm)	Approximated Energy (J)	Expected Energy (J)	% error
2.63	4.13	5.34	29%

The percent error is high indicating some inherent error in the experiment. Main source of error would be misalignment of the source and detector especially with this sample since alpha particles have very short range in air, any deviation can introduce error. The air density can fluctuate from temperature or pressure changes from nearby objects like humans, GM Tube, computers.

3.7 Absorption of Beta Particles

Table 10: Mass Thickness vs ln(True cpm)

Material	Thickness (mm)	Mass Thickness ($\mathrm{mg\,cm^{-2}}$)	cpm	True cpm	ln(New cpm)
no absorber	0	0	8047	8279	3.918
Al foil A	0.7 mil	4.5	7561	7827	3.894
Al foil B	1 mil	6.5	7507	7769	3.890
Poly C	5 mil	14.1	7444	7702	3.887
Poly D	10 mil	28.1	6813	7028	3.847
Plastic E	0.03	59.1	5062	5180	3.714
Plastic F	0.04	102	4925	5037	3.702
Al G	0.02	129	4464	4556	3.659
Al H	0.025	161	3910	3980	3.600
Al I	0.032	206	3426	3480	3.542
Al J	0.04	258	2720	2754	3.440
Al K	0.05	328	1924	1941	3.288
Al L	0.063	419	1176	1182	3.073
Al M	0.08	516	617	619	2.792
Al N	0.09	590	363	364	2.561
Al O	0.1	645	272	272	2.435
Al P	0.125	849	108	108	2.033
Lead Q	0.032	1230	71	71	1.851
Lead R	0.064	1890	72	72	1.857
Lead S	0.125	3632	71	71	1.851
Lead T	0.25	7435	68	68	1.833

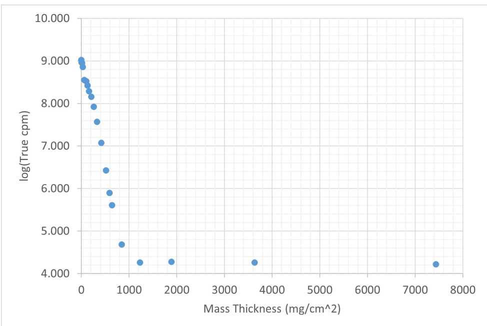

Figure 9: Mass Thickness vs ln(True cpm) with background

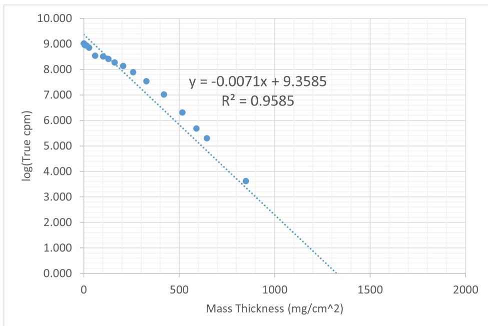

Figure 10: Mass Thickness vs ln(True cpm) without background

For Figure 8, the drop-off in cpm is sharp initially and then flattens out, which is due to background radiation. Figure 9 is constructed by subtracting the average of the background from Lead and removing those reading, now it depicts a clear linear decay trend of ln(True cpm) with mass thickness, which is more consistent with the theoretical expectation for beta particle absorption. The linear trend line with a negative slope and a high R^2 value suggests a good fit to an exponential decay model, implying that the intensity of beta radiation decreases exponentially with the mass thickness of the absorber.

3.8 Beta Decay Energy

Table 11: Mass Thickness vs log(True cpm)

Material	Thickness (mm)	Mass Thickness ($mg\,cm^{-2}$)	cpm	True cpm	log(New cpm)
no absorber	0	0	8047	8279	3.918
Al foil A	0.7 mil	4.5	7561	7757	3.890
Al foil B	1 mil	6.5	7507	7699	3.886
Poly C	5 mil	14.1	7444	7632	3.883
Poly D	10 mil	28.1	6813	6958	3.842
Plastic E	0.03	59.1	5062	5110	3.708
Plastic F	0.04	102	4925	4967	3.696
Al G	0.02	129	4464	4486	3.652
Al H	0.025	161	3910	3910	3.592
Al I	0.032	206	3426	3410	3.533
Al J	0.04	258	2720	2684	3.429
Al K	0.05	328	1924	1871	3.272
Al L	0.063	419	1176	1112	3.046
Al M	0.08	516	617	549	2.740
Al N	0.09	590	363	294	2.468
Al O	0.1	645	272	202	2.305
Al P	0.125	849	108	38	1.580
Lead Q	0.032	1230	71	1	0.000
Lead R	0.064	1890	72	2	0.301
Lead S	0.125	3632	71	1	0.000
Lead T	0.25	7435	68	-2	0.000

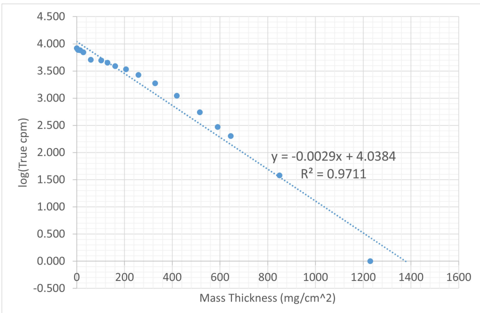

Figure 11: Mass Thickness vs log(True cpm) without background

The maximum energy of the beta particles is 0.546 MeV, the experimental measurement is found by setting the equation of the line to 0 and finding x. $x = 1.3926 \times 10^3\,mg\,cm^{-2}$. Dividing this by 1000 to convert it to suitable units and inserting it into $E = 1.84R + 0.212$, where R is in $g\,cm^{-2}$. $E = 2.7743\,MeV$. Clearly this is too far from the real value and this can be attributed to range strangling. I attempted to remove range straggling by not counting the lead readings from the graph. Even so, this indicates that range strangling occurs for aluminum, meaning the x-intercept must be between $129\,gram/cm^2$ and $849\,mg\,cm^{-2}$.

3.9 Absorption of Gamma Rays

Table 12: Mass Thickness vs $\ln(I/I_0)$

Material	Thickness (mm)	Mass Thickness ($\mathrm{mg\,cm^{-2}}$)	cpm	True cpm	$\ln(I/I_0)$
no absorber	0	0	265	265	0.000
Al foil A	0.7 mil	4.5	264	264	-0.004
Al foil B	1 mil	6.5	276	276	0.041
Poly C	5 mil	14.1	284	284	0.069
Poly D	10 mil	28.1	286	286	0.076
Plastic E	0.03	59.1	254	254	-0.042
Plastic F	0.04	102	234	234	-0.124
Al G	0.02	129	229	229	-0.146
Al H	0.025	161	260	260	-0.019
Al I	0.032	206	262	262	-0.011
Al J	0.04	258	243	243	-0.087
Al K	0.05	328	239	239	-0.103
Al L	0.063	419	253	253	-0.046
Al M	0.08	516	256	256	-0.035
Al N	0.09	590	273	273	0.030
Al O	0.1	645	300	300	0.124
Al P	0.125	849	231	231	-0.137
Lead Q	0.032	1230	242	242	-0.091
Lead R	0.064	1890	266	266	0.004
Lead S	0.125	3632	205	205	-0.257
Lead T	0.25	7435	179	179	-0.392

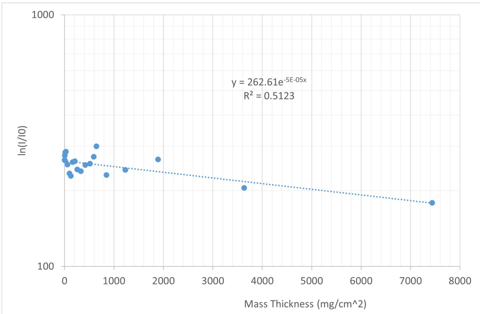

Figure 12: Mass Thickness vs $\ln(I/I_0)$

The best fit line indicates the exponential nature of attenuation, where $I = I_0 e^{-\mu X}$, $\mu = 5 \times 10^{-5}$. With that we can find the half mass thickness $X_{1/2}$ by $I_0/2 = I_0 e^{-\mu X_{1/2}}$.

$$X_{1/2} = \frac{\ln(2)}{5 \times 10^{-5}} = 13\,863\,\mathrm{mg\,cm^{-2}}$$

This is consistent with our data as no absorber has 265 cpm, half of that is 133 cpm and our readings reach 179 cpm, so there is still more shielding needed to half the original cpm.

3.10 Half-Life of Ba-137m

Table 13: Half-life readings for Ba-137m

Time	cpm	Corrected cpm	New cpm	ln(New cpm)
(Background Count)	31			
30	3205	3174	3220	8.08
60	2749	2718	2752	7.92
90	2329	2298	2322	7.75
120	2079	2048	2067	7.63
150	1842	1811	1826	7.51
180	1627	1596	1608	7.38
210	1376	1345	1353	7.21
240	1186	1155	1161	7.06
270	1051	1020	1025	6.93
300	835	804	807	6.69
330	825	794	797	6.68
360	736	705	707	6.56
390	624	593	595	6.39
420	546	515	516	6.25
450	488	457	458	6.13
480	426	395	396	5.98
510	373	342	343	5.84
540	356	325	325	5.78
570	271	240	240	5.48
600	254	223	223	5.41
630	221	190	190	5.25
660	191	160	160	5.08
690	157	126	126	4.84
720	150	119	119	4.78

Table 14: Half-life Error Analysis

Data	lambda	$t_{1/2}$	Standard Error $t_{1/2}$	$\sigma_{t_{1/2}}$	# of σ's
First Half	0.00469	147.69612	3.45404	11.96516	0.44328
Second Half	0.00501	138.23978	3.88492	13.45775	1.09678
Whole	0.00472	146.74856	1.50594	7.37758	0.84736

The standard error comes from the regression analysis tables, and the standard deviations σ are found by $SE = \frac{\sigma}{\sqrt{n}}$ where n is the number of observations for that run. The real value of Ba-137m $t_{1/2}$ is 153 s and the # of σ's is found by $\frac{|Experimental - Real|}{\sigma_{t_{1/2}}}$. The best result from the three is the first half with a percent error of 3.47%. Initially one would think the whole data would give the best result but this indicates some inherent errors in the experiment. The relationship is exponential meaning that linear regression is not the best model. Also the inherent statistical variation of radiation is a major factor.

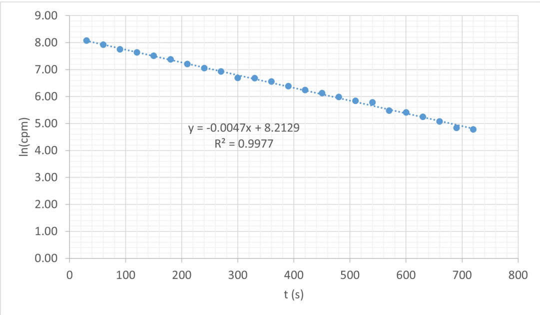

Figure 13: Time (s) vs ln(cpm)

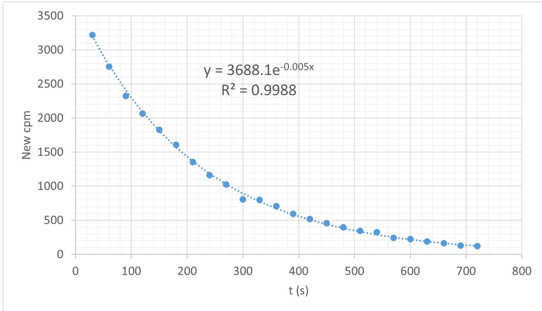

Figure 14: Time (s) vs True cpm

Table 15: First Half Data Regression Analysis

Regression Statistics	
Multiple R	0.997
R Square	0.995
Adjusted R Square	0.994
Standard Error	0.039
Observations	12.000

	Coefficients	*Standard Error*
Intercept	8.199	0.024
X Variable 1	-0.005	0.000

Table 16: Second Half Data Regression Analysis

Regression Statistics	
Multiple R	0.996
R Square	0.992
Adjusted R Square	0.991
Standard Error	0.051
Observations	12.000

	Coefficients	*Standard Error*
Intercept	8.382	0.080
X Variable 1	-0.005	0.000

Table 17: Whole Data Regression Analysis

Regression Statistics	
Multiple R	0.999
R Square	0.998
Adjusted R Square	0.998
Standard Error	0.049
Observations	24.000

	Coefficients	*Standard Error*
Intercept	8.213	0.021
X Variable 1	-0.005	0.000

4 Applications

Radioactivity has a wide range of applications across various fields. Some of the key applications include:

- **Medical Applications:**
  - *Diagnostic Imaging:* Radioactive tracers are used in nuclear medicine to diagnose ailments. Techniques like Positron Emission Tomography (PET) scans use radioisotopes to visualize and measure metabolic processes in the body.
  - *Radiation Therapy:* Radioisotopes are used to treat certain types of cancer. Targeted radiation can destroy malignant cells, minimizing damage to healthy tissue.
- **Industrial Applications:**
  - *Material Testing:* Radioactive sources are used in non-destructive testing to inspect metal parts and welds for defects.
  - *Radiation Processing:* Radiation is used to sterilize medical products and food items, as well as to improve the properties of materials like polymers.
- **Scientific Research:**
  - *Radiometric Dating:* Radioactive isotopes are used to date ancient materials, such as archaeological artifacts and geological formations, based on their decay rates.
  - *Tracer Studies:* Radioisotopes are used as tracers in environmental and biological research to track the movement and chemical reactions of substances.
- **Energy Production:**
  - *Nuclear Power:* Radioactive materials, such as uranium, are used as fuel in nuclear reactors to generate electricity through controlled nuclear fission reactions.
- **National Security:**
  - *Border Security:* Radioactive sources are used in detection systems to prevent the illegal transport of radioactive materials across borders.
  - *Nuclear Forensics:* Techniques that involve the analysis of radioactive materials can help in investigating nuclear smuggling and terrorism.

5 Conclusion

The series of experiments conducted provided a comprehensive understanding of several phenomena associated with radioactivity. The inverse square law was confirmed within an acceptable margin of error, demonstrating the predictable nature of radiation intensity as a function of distance from a source. The experiments involving the absorption of beta and gamma rays yielded results that were consistent with established physical laws, although the beta particle energy measurements indicated a need for further refinement in experimental technique.

The half-life measurement for Ba-137m, while not entirely within the expected range, offered a practical exercise in the challenges of radiometric data collection and analysis. The observed percent error prompted a review of the data collection process, leading to improvements in both methodology and analytical precision.

In summary, the experiments successfully demonstrated the core principles of radioactivity and its measurement, reinforcing theoretical knowledge with empirical data. The experience has shown the importance of experimental design and has provided valuable lessons in the interpretation of radiometric data.

References

[1] James E. Martin. *Physics for radiation protection: a handbook*. 2nd ed., completely rev. and enlarged. OCLC: 912414275. New York: John Wiley & Sons, 2006. 822 pp. ISBN: 978-3-527-40611-1.

[2] LLC Spectrum Techniques. *Spectrum Techniques. Lab Manual*. Version Student. 119 pp. URL: www.SpectrumTechniques.com.

6 Appendix

Figure 15: Sources

Figure 16: Absorbers kit