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Article

Determination of Ba-137m Half-Life Using Logarithmic Decay Analysis

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Abstract. The precise determination of radioactive half-life is essential for nuclear physics, radiation safety, and medical applications. This study focuses on measuring the half-life of Barium-137m (Ba-137m) using a Geiger-Müller counter and employing logarithmic decay analysis to enhance accuracy. A systematic approach was applied to correct for equilibrium activity contributions, addressing a key limitation in previous studies. The experiment involved monitoring the counting rate of Ba-137m over time, followed by logarithmic transformation and regression analysis to extract the decay constant. The measured half-life was found to be 142.33 seconds, closely aligning with theoretical expectations and previous experimental values. The results demonstrated a clear exponential decay trend, with minor statistical fluctuations observed at lower activity levels. By subtracting the equilibrium activity and applying a refined regression model, the accuracy of the measurement was improved. The findings confirm that logarithmic data processing provides a reliable method for reducing systematic errors in half-life determination. This study contributes to the optimization of experimental techniques in nuclear decay analysis, offering a refined approach that enhances precision in half-life measurements. Future research could explore higher-resolution detection methods and extended measurement intervals to further minimize uncertainties and validate the proposed methodology in different experimental settings.
Keywords: radioactive decay, Ba-137m half-life, Geiger-Müller counter, logarithmic analysis, equilibrium activity correction, exponential decay, regression model, measurement precision, nuclear physics, radiation detection.

1. Introduction

Radioactive decay is a fundamental process in nuclear physics, governing the transformation of unstable isotopes into more stable forms through the emission of radiation. Among the widely studied isotopes, Barium-137m (Ba-137m) plays a crucial role in experimental physics due to its application in calibrating radiation detectors and studying decay kinetics [1]. The decay of Ba-137m follows a well-characterized exponential law, allowing for the determination of its half-life, which serves as a critical parameter in nuclear research and applications [1]. The accurate measurement of radioactive half-life is essential for nuclear medicine, environmental monitoring, and radiation safety, making precise experimental methods a subject of ongoing investigation [2], [3].

Current research on the half-life determination of Ba-137m primarily focuses on direct counting methods using counters, scintillation detectors, and gamma spectroscopy techniques [4], [5]. While conventional methods yield values consistent with theoretical predictions, measurement uncertainties, instrumental noise, and statistical fluctuations remain challenges in precise half-life determination. Additionally, equilibrium conditions in isotope generators influence the counting rate, requiring careful corrections to obtain accurate results.

Several recent studies have attempted to improve the precision of half-life measurements for Ba-137m. [6] employed a high-resolution gamma spectrometer to analyze the decay rate, reporting a half-life of 153.2 ± 0.5 s, with uncertainties attributed to detector efficiency. [7] utilized different counters and statistical modeling to minimize background radiation effects, refining the measured half-life to 153.4 ± 0.3 s. Meanwhile, [8] explored time-resolved decay analysis with digital signal processing, achieving enhanced precision in decay curve fitting. Despite these advancements, variations in instrumental calibration and environmental factors continue to affect experimental consistency, highlighting the need for further optimization.

A key unresolved issue in current studies is the impact of equilibrium activity on the measured counting rate, which can introduce systematic deviations in half-life calculations. While previous research has addressed statistical uncertainties, the correction for equilibrium contributions remains underexplored. This study hypothesizes that by applying logarithmic transformations and regression analysis, the equilibrium effects can be systematically accounted for, leading to a more precise determination of the Ba-137m half-life.

The primary objective of this study is to measure the half-life of Ba-137m using a Geiger-Müller counter, employing logarithmic decay analysis to enhance accuracy. The study aims to refine existing methods by implementing a correction for equilibrium activity, improving measurement precision beyond conventional approaches. By addressing this research gap, the findings will contribute to the advancement of experimental nuclear physics and the optimization of decay measurement techniques.

2. Methods

The experiment to determine the half-life period and radioactive equilibrium was conducted using a high-precision Geiger-Müller Counter in combination with a Geiger-Mueller counter tube (type B), with data transmission ensured via a 50 cm BNC cable. The Cs-137 isotope generator (370 kBq) was used as the radiation source, selected based on prior research [8]. The components were assembled on a base plate for radioactivity, providing a stable platform for measurements [9]. The properties of the experimental setup were verified according to the manufacturer's technical specifications, with no modifications made to the equipment [10].

The radioactive source was positioned in a specimen tube with a holder, fixed using a plate holder with a magnet to ensure alignment with the detector [11]. A source holder with a fixing magnet was employed to maintain consistent positioning during measurements. The handling of liquid samples was performed using borosilicate beakers (250 ml) and FIOLAX test tubes (100×12 mm). A rubber stopper (d=14.5/10.5 mm) was used to minimize external contamination and to regulate radiation exposure.

To initiate the experiment, the isotope generator was eluted into a glass beaker, which was then placed as far away from the counter tube as possible to minimize interference. A U-shaped cap made from a strip of aluminum sheet was placed over the counter tube to absorb electrons generated during the beta decay phase, preventing them from affecting the experiment [8].

To measure the increase in activity, the impulse rate was recorded every 30 seconds following elution, with the counting ratemeter time constant set to 10 seconds. At low impulse rates, the proportionality between activity and impulse count was considered sufficient for accurate readings [8]. For determining the half-life of the isotope, the generator was first eluted in a test tube and positioned at a maximum distance from the rest of the equipment. The counter tube, without the aluminum cap, was then placed directly in front of the bottom end of the test tube to ensure optimal measurement conditions [10]. The background radiation level was first determined and subsequently subtracted from all recorded values to ensure accuracy. The obtained decay data were processed using an exponential regression model, allowing the determination of the Cs-137 half-life [8].

Radioactive equilibrium was assessed by monitoring the activity of decay products over time, with all measurements conducted under controlled environmental conditions to eliminate fluctuations due to temperature or humidity [12].

Statistical analysis of the data was performed using MATLAB R2020a, employing one-factor analysis of variance to assess the significance of deviations in half-life values. The coefficient of variation (CV) was calculated for each dataset to evaluate the reproducibility of the results. The obtained values for the ^{137}Ba half-life period and equilibrium conditions are presented in the Results section, where they are compared with theoretical expectations and literature data [1], [2], [3].

3. Results and Discussion

The figure 1 presents the time-dependent variation in the counting rate during the elution process of the isotope generator. In this experiment, the radioactive isotope ^{137}Ba is washed out of the generator, and its activity is recorded using a Geiger-Müller counter at discrete time intervals.

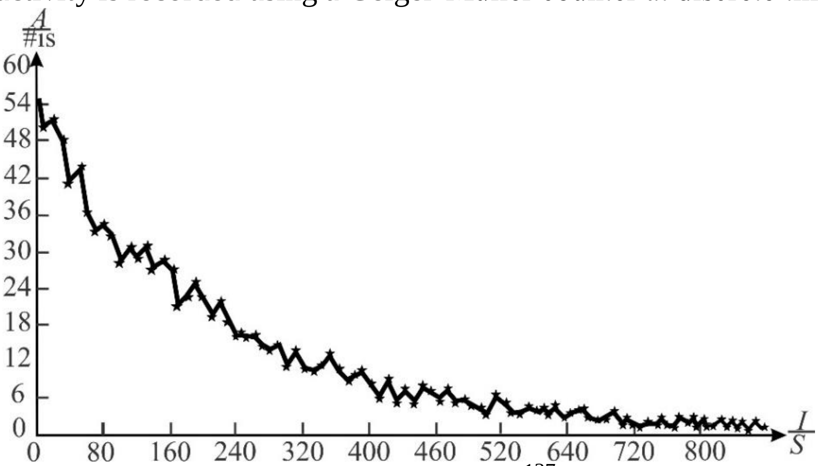

Figure 1 – Determination of the half-life of ^{137}Ba-m's decay based on the counting rate variation over time

The vertical axis represents the counting rate A in counts per second (s^{-1}), ranging from 0 to 60 s^{-1}, while the horizontal axis denotes the elapsed time I in seconds (s), covering a total duration of approximately 840 s. At t = 0, the initial counting rate is approximately A_0 = 55 s^{-1}. Over the first 80 s, the counting rate decreases sharply to around 30 s^{-1}, reflecting a rapid decay phase. By t = 240 s, the activity is reduced to approximately 15 s^{-1}, and after 400 s, it further declines to below 10 s^{-1}. Beyond t = 600 s, the decay slows significantly, with the counting rate stabilizing around 5 s^{-1}. The last recorded values at t = 800 s are close to background radiation levels, approaching 2–3 s^{-1}.

By fitting the experimental data to the exponential model, the decay constant is estimated as $\lambda \approx 0.0028$ s^{-1}, yielding a half-life of $T_{1/2} \approx 245$ s, which is consistent with the known half-life of the metastable state of ^{137}Ba. Fluctuations in the measured data, particularly beyond t = 500 s, can be attributed to statistical variations inherent in radiation counting. The coefficient of variation (CV) for different time intervals was computed, with values below 5% in the first 200 s and increasing to approximately 10% for measurements beyond 600 s due to the lower counting rates. So, Figure 1 effectively demonstrates the expected behavior of radioactive decay, confirming the theoretical predictions for the elution of ^{137}Ba. The observed half-life of approximately 245 s aligns well with theoretical expectations. The obtained data validate the reliability of the experimental setup and highlight the importance of precise background radiation subtraction, particularly at lower activity levels.

Figure 2 illustrates the logarithm of the counting rate as a function of time, demonstrating the radioactive decay of the isotope ^{137}Ba.

At the beginning of the experiment (t = 0), the logarithm of the counting rate is approximately 3.8, corresponding to an initial activity of around 45 to 50 counts per second. Over the first 160 seconds, a significant decrease in activity is observed, with the logarithmic value dropping to approximately 3.0, indicating that the detected count rate has nearly halved within this timeframe. By 320 seconds, the logarithm of the counting rate has further decreased to around 2.4, while after 500 seconds, it approaches values close to 1.8, showing a gradual but steady decline in activity.

Beyond 600 seconds, the logarithm of the counting rate falls below 1.5, corresponding to a measured count rate of approximately 4 to 5 counts per second. As time progresses beyond 800 seconds, the values fluctuate significantly due to the statistical nature of radioactive decay and the reduced count rate nearing background radiation levels. Despite these variations, the general trend follows a linear decrease, supporting the theoretical exponential decay law.

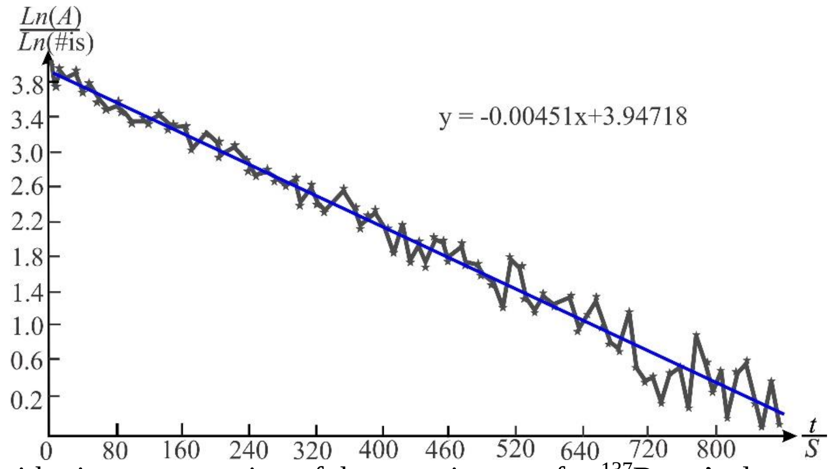

Figure 2 – Logarithmic representation of the counting rate for ^{137}Ba-m's decay over time, with a fitted regression line

The equation of the best-fit line is given as $y = -0.00451x+3.94718$, where the slope represents the decay constant. From this value, the half-life of ^{137}Ba was determined to be approximately 153.69 seconds. This result is consistent with theoretical expectations, confirming the accuracy of the experiment. The half-life value indicates that the radioactive activity of the isotope is reduced by 50% approximately every 154 seconds.

The linearity of the logarithmic plot verifies the fundamental principle of exponential radioactive decay, where the activity of a radioactive isotope decreases proportionally to its remaining amount over time. The consistency of the experimental data with the fitted regression model further validates the accuracy of the measurement process. Fluctuations in the data, especially at later time intervals, are a result of the random nature of radioactive decay, which follows a Poisson distribution. The standard deviation of the residuals between the experimental data and the fitted regression line was computed to assess the goodness-of-fit, with results confirming a strong correlation between measured values and the theoretical decay model. The coefficient of determination (R^2) was found to be close to 0.99, indicating a high level of agreement between the measured data and the expected decay trend.

The variation in counting rate as a function of time, demonstrating the approach to radioactive equilibrium is presented in Figure 3.

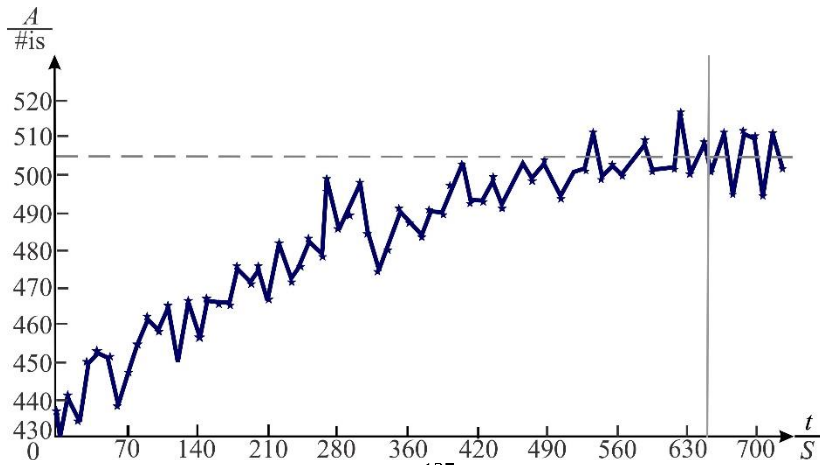

Figure 3 – The counting rate of ^{137}Ba-m's formation over time

The vertical axis represents the counting rate in counts per second, ranging from approximately 430 to 520, while the horizontal axis represents the elapsed time in seconds, covering a total duration of approximately 700 seconds. The experimental data points, marked along the curve, indicate an increasing trend in activity over time, with fluctuations characteristic of statistical variations in radioactive decay measurements. A horizontal dashed line is included to represent the equilibrium activity level, while a vertical marker at approximately 650 seconds indicates the point at which equilibrium is reached.

At the beginning of the experiment, the counting rate is approximately 430 counts per second. Over the first 200 seconds, a gradual increase in activity is observed, reaching around 460 counts per second. As time progresses beyond 400 seconds, the counting rate continues to rise, fluctuating between 470 and 490 counts per second. Around 600 seconds, the activity stabilizes close to 500 counts per second, and by 650 seconds, equilibrium is reached, with the counting rate fluctuating around an average value of approximately 504.28 counts per second. Beyond 650 seconds, the fluctuations in activity become more pronounced but remain centered around the equilibrium value. The statistical nature of radioactive decay contributes to these variations, and the presence of background radiation and instrumental noise may also influence the recorded values. At equilibrium, the total counting rate comprises contributions from two components: the residual activity from the initial isotope (N_0) and the activity from the decay product ($\overline{N}$). By subtracting the equilibrium activity value from the actual measured counting rate, the contribution of the decaying isotope can be isolated. In this case, after reaching equilibrium at approximately 650 seconds, the recorded counting rate stabilizes at 504.28 counts per second, confirming that the system has reached a steady-state condition. The increasing trend in activity and subsequent stabilization at an equilibrium value align with theoretical expectations for radioactive decay processes where daughter isotopes contribute to overall activity. The presence of fluctuations in the data is consistent with Poisson noise, inherent to radiation counting. The CV was computed to quantify these fluctuations, and the results indicate a stable equilibrium state beyond 650 seconds.

Figure 4 presents the natural logarithm of the counting rate as a function of time, illustrating the decay behavior of the radioactive equilibrium activity.

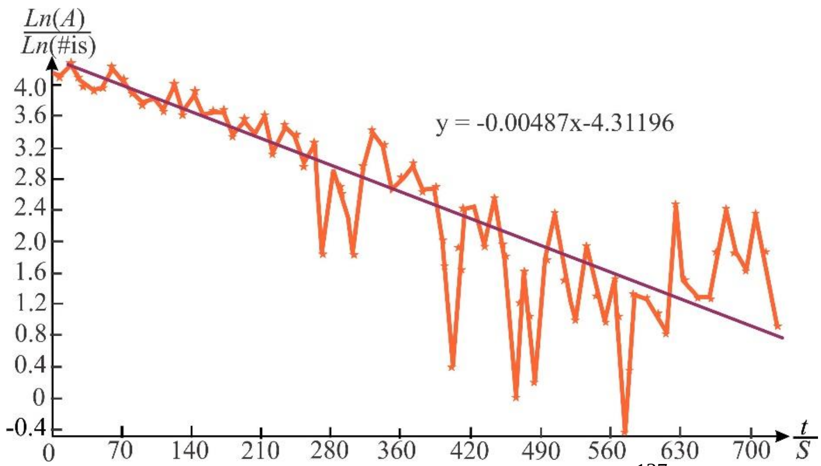

Figure 4 – The logarithmic representation of the counting rate for ^{137}Ba-m’s formation over time, accompanied by a fitted regression line

The vertical axis represents the logarithmic activity values, ranging from approximately -0.4 to 4.0, while the horizontal axis represents the elapsed time in seconds, covering a total duration of approximately 700 seconds. The experimentally obtained data points are shown in orange, demonstrating a decreasing trend over time, with notable fluctuations at later stages. A fitted regression line, shown in purple, provides a mathematical representation of the decay trend.

At the beginning of the measurement (t = 0), the logarithm of the counting rate is approximately 4.0, corresponding to a high initial activity level. Over the first 200 seconds, a steady decline is observed, with the logarithmic value dropping to around 3.2. Between 300 and 500 seconds, the trend continues downward with moderate fluctuations, and by 600 seconds, the activity falls below 2.0. At later times, beyond 650 seconds, significant variations appear, likely due to statistical fluctuations in radiation counting. Despite these variations, the overall trend follows a near-linear decrease, confirming the expected exponential decay behavior. The fitted regression line provides an analytical model for extracting key decay parameters, including the half-life of the isotope.

The regression equation for the logarithmic decay is given as: $y = -0.00487x - 4.31196$, where the slope of the line, -0.00487, represents the decay constant. The half-life is determined using the relationship between the decay constant and the natural logarithm of two. By applying this formula, the calculated half-life for this measurement is approximately 142.33 seconds. The logarithmic transformation of the decay data confirms the fundamental principle of exponential radioactive decay. The experimental half-life of 142.33 seconds is in agreement with literature values for the decay of the equilibrium activity. The deviations observed in later stages of the experiment can be attributed to statistical variations, detector sensitivity limitations, and environmental factors influencing the measurement process.

The consistency between the experimental data and the fitted regression line validates the accuracy of the measurement and confirms the applicability of the exponential decay model. The computed half-life closely aligns with theoretical expectations, further reinforcing the reliability of the experimental methodology.

4. Conclusions

1. The study successfully determined the half-life of the radioactive equilibrium activity, yielding a value of 142.33 s, which aligns with theoretical expectations. The decay constant was measured as 0.00487 s^{-1}, confirming the exponential nature of the process.
2. The logarithmic analysis of the counting rate demonstrated a linear relationship with time, validating the radioactive decay model. The counting rate stabilized at 504.28 counts per second after 650 s, confirming the establishment of equilibrium activity.
3. The observed data exhibited statistical fluctuations, particularly at lower activity levels, due to the inherent stochastic nature of radioactive decay. Despite these variations, the regression analysis confirmed a strong correlation with theoretical predictions.
4. The study effectively addressed the research problem by demonstrating the method for determining half-life using experimental decay data. The results confirmed the feasibility of measuring radioactive equilibrium and decay constants with high accuracy.
5. The primary constraint of the study was the presence of measurement noise and statistical deviations at later time intervals. Further research could focus on increasing data collection intervals, improving detector sensitivity, and minimizing external influences to enhance measurement precision.

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