Observation of Ba-137m Half-Life via Count-Rate Analysis

Peter Khorani

PHY 353L Modern Laboratory
Department of Physics
The University of Texas at Austin
Austin, TX 78712, USA

October 7, 2025

Abstract

The purpose of this experiment was to measure the half-life of the isotope $^{137\text{m}}$Ba, which is populated following the β^- decay of ^{137}Cs. Using a scintillator, a spectroscopy amplifier, and a single-channel analyzer (SCA) window tuned around the 662 keV photopeak, the decay rate of $^{137\text{m}}$Ba was recorded in 100 ms intervals and then analyzed in 9 s bins. Two separate background runs were also conducted to quantify and subtract dark counts from the decay data.

For Run 1, the exponential fit with constant background yielded a decay constant of $\lambda = (5.01 \pm 0.13) \times 10^{-3}$ s^{-1}, corresponding to a half-life of $T_{1/2} = 138.3 \pm 3.6$ s. After background subtraction, $\lambda = (4.70 \pm 0.08) \times 10^{-3}$ s^{-1} and $T_{1/2} = 147.4 \pm 2.7$ s were obtained. For Run 2, the measured half-life values were $T_{1/2} = 144.4 \pm 3.2$ s (with background) and $T_{1/2} = 148.9 \pm 2.3$ s (background-subtracted). These values are within 4% of the accepted half-life of $^{137\text{m}}$Ba, $T_{1/2} = 153.0 \pm 0.3$ s.

The agreement between the two analysis methods and the accepted value confirms the reliability of the counting system and validates the assumption of exponential decay for $^{137\text{m}}$Ba. Deviations are attributed primarily to systematic uncertainties in amplifier gain, especially the SCA window calibration, and background fluctuations.

Figure 1: Half Life 2

1 Introduction

1.1 Motivation

Radioactive decay is one of the most fundamental processes in nuclear physics, governing the transformation of unstable nuclei into more stable configurations. The rate of decay is characterized by a constant half-life, which serves as a fingerprint of each isotope's intrinsic stability. Measuring a half-life experimentally provides us an opportunity to verify the exponential decay law and to test the reliability of radiation detection systems.

The metastable isotope $^{137\mathrm{m}}$Ba is produced through the β^- decay of ^{137}Cs, a common product found in nuclear reactors and fallout materials. The subsequent decay of $^{137\mathrm{m}}$Ba to its ground state emits a 662 keV γ-ray, making it a convenient calibration source for scintillation detectors and spectroscopy amplifiers. Because its half-life ($T_{1/2} \approx 153$ s) occurs on a practical laboratory timescale, it allows for repeated measurements and clear observation of exponential behavior over just a few minutes [1, 2].

Beyond its pedagogical value, the ^{137}Cs–$^{137\mathrm{m}}$Ba system remains of practical relevance in environmental monitoring and radiological safety, since cesium-137 is one of the most prevalent long-lived fission products. Studying the decay of $^{137\mathrm{m}}$Ba, therefore, is an easy but reliable way to reinforce both theoretical understanding and applied nuclear measurement techniques.

1.2 Theoretical background

Radioactive decay is a spontaneous process in which an unstable nucleus transforms into a more stable configuration by emitting particles or radiation. For a large ensemble of identical unstable nuclei, the probability that a given nucleus decays in a short time interval dt is proportional to the number of undecayed nuclei $N(t)$ at that time:

$$\frac{dN(t)}{dt} = -\lambda N(t), \tag{1}$$

where λ is the decay constant (s^{-1}) representing the probability per unit time that a nucleus decays. Solving this differential equation yields the exponential decay law:

$$N(t) = N_0 e^{-\lambda t}, \tag{2}$$

where N_0 is the initial number of radioactive nuclei at $t = 0$. The measurable activity $A(t)$, defined as the rate of decay events per unit time, is proportional to $N(t)$ and follows the same exponential form:

$$A(t) = A_0 e^{-\lambda t}. \tag{3}$$

The half-life $T_{1/2}$ is the time required for half of the radioactive nuclei to decay, and it is related to the decay constant by:

$$T_{1/2} = \frac{\ln 2}{\lambda}. \tag{4}$$

In this experiment, we investigate the decay of metastable barium, $^{137\text{m}}\text{Ba}$, which is produced from the β^- decay of ^{137}Cs. The excited $^{137\text{m}}\text{Ba}$ nucleus subsequently de-excites to the stable ground state ^{137}Ba through the emission of a 662 keV γ-ray photon [1]:

$$^{137\text{m}}{}_{56}\text{Ba} \xrightarrow[T_{1/2}\approx 153\text{ s}]{\gamma} {}^{137}{}_{56}\text{Ba} + \gamma\ (662\text{ keV}). \tag{5}$$

The detection of these γ-rays over time provides a direct measurement of the decay rate of $^{137\text{m}}\text{Ba}$. By recording the count rate $R(t)$ in discrete time intervals and fitting to the form

$$R(t) = Ae^{-\lambda t} + B, \tag{6}$$

where A is the initial activity and B represents the constant background count rate, the decay constant λ and the corresponding half-life $T_{1/2}$ can be experimentally determined.

This relationship underpins the analysis procedure of this experiment. Comparing the experimentally derived $T_{1/2}$ to the accepted value of 153.0 ± 0.3 s provides a quantitative assessment of measurement precision and systematic uncertainties.

1.3 Our approach

In this experiment, we determine the half-life of ^{137m}Ba by monitoring the decrease in γ-ray count rate following the elution of barium from a ^{137m}Ba generator. The emitted 662 keV photons are detected by a scintillator, whose output is processed through a preamplifier, spectroscopy amplifier and a single-channel analyzer (SCA) to isolate the desired photopeak region. The resulting TTL pulses are digitized by a data acquisition (DAQ) system, which records counts in fixed time intervals. By fitting the count data to an exponential decay model both with and without background subtraction, we extract the decay constant and compute the experimental half-life. This method allows for assessment of statistical precision and the influence of dark-count corrections on the final result.

2 Experimental setup

2.1 Apparatus

A schematic of the experimental apparatus is shown in Fig. 2. The detection system consists of a scintillation crystal coupled to a photomultiplier tube (PMT), which converts incident γ-ray photons from the decay of ^{137m}Ba into electrical pulses. The PMT is powered by a high-voltage supply (about 0.7 kV) and enclosed in a lead housing to reduce background radiation and dark counts.

The PMT output is first routed to a preamplifier, which shapes and amplifies the weak anode pulses for transmission to the main spectroscopy amplifier (ORTEC Model 672). The spectroscopy amplifier was configured with a coarse gain setting of approximately 100 and a shaping time of 1 μ s, chosen to optimize signal-to-noise performance and minimize pulse pile-up. The amplifier's unipolar output was monitored on a digital oscilloscope for pulse-height inspection and simultaneously fed into a single-channel analyzer (SCA, ORTEC Model 550).

The SCA was used to define an energy window corresponding to the 662 keV photopeak of ^{137}Cs. In this configuration, the lower-level and upper-level were adjusted to accept pulses roughly between 1.5 V and 1.9 V.

Accepted events generated transistor–transistor logic (TTL) output pulses, which were sent to a National Instruments data-acquisition interface (NI USB-6341) connected to a computer running LabVIEW.

The LabVIEW interface recorded the total number of accepted pulses in fixed time bins of 100 ms and exported the data to a comma-separated file for later analysis in Python. A separate dark-count run (with no radioactive sample) was performed to quantify the background rate for subsequent subtraction.

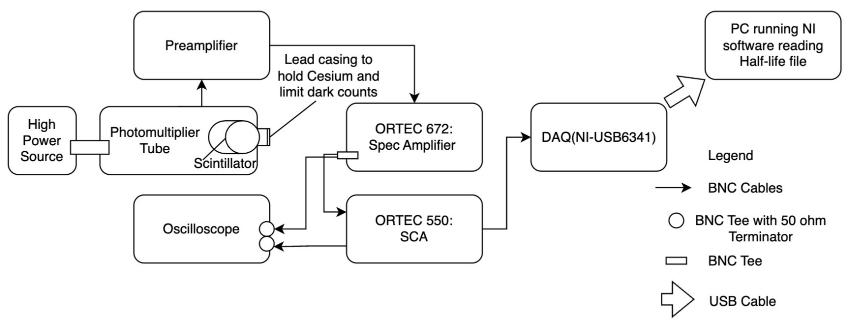


Figure 2: Block diagram of the experimental apparatus showing signal flow from the scintillator to the data-acquisition system.

2.2 Data Collection

Prior to data acquisition, all components of the detection system were calibrated and tuned using a sealed ^{137}Cs button source. This source provided a stable and well-known 662 keV γ-ray emission, enabling optimization of the system gain and discriminator settings before switching to the short-lived ^{137m}Ba isotope generator.

The output of the spectroscopy amplifier was monitored on an oscilloscope to identify the photopeak pulse height. A characteristic pulse amplitude of approximately 1.8 V was observed, corresponding to the 662 keV γ-ray line. Based on this measurement, the single-channel analyzer (SCA) was configured with a lower level of 1.5 V and an upper level of 1.9 V to isolate the photopeak region while rejecting Compton-scattered and background events.

To minimize statistical uncertainty, the voltage window ΔV was optimized to balance total counts and background contribution. For example, when a 0.1 V expansion in ΔV yielded fewer than $\sim$1000 additional counts, compared to the 45000 count number over a period of 40s with the button, we favored the narrower window to reduce the acceptance of dark pulses and electronic noise.

Several preliminary measurements were conducted to determine the intrinsic dark count rate of the system. With the SCA window fixed, the dark rate was found to be stable at approximately 16–17 Hz, which was used as the baseline background level in subsequent analysis.

During the main measurements, barium-137m was freshly taken from the isotope generator, immediately transferred into the scintillation detector assembly, and data acquisition was started without delay. The counting interval was set to 100 ms per bin, and measurements were recorded continuously for a total duration of 15 minutes. We chose this as a sufficient period due to the fact that by the end of the period, taking into account the half life of barium, less than 0.5 % of the isotope should remain. Two separate dark-count runs of equal duration were also performed under identical conditions to characterize the background for subtraction and uncertainty propagation.

3 Data Analysis and Results

3.1 Data Processing and Hypothesis Testing

The recorded count data were exported from LabVIEW as comma-separated values (CSV) files and transferred to a USB drive for external analysis. Each file contained a sequence of counts corresponding to 100 ms acquisition bins, with separate datasets recorded for the signal (Ba-137m decay) and the dark-count background. These files were imported into `Python` using the `pandas` library for preprocessing, binning, and statistical analysis.

The raw data were first rebinned into 9 s intervals to reduce statistical fluctuations and improve the signal-to-noise ratio. I chose a 9 s interval to provide a organized yet good fit for the regression, allowing for enough data points for the regression to map into. The corresponding count rate for each bin was calculated as

$$R_i = \frac{N_i}{\Delta t}, \tag{7}$$

where N_i is the total count within a bin and Δt is the bin duration. The statistical uncertainty of each bin was assumed to follow Poisson statistics, given by

$$\sigma_i = \sqrt{N_i}. \tag{8}$$

To model the decay behavior, we adopted the standard exponential decay function with an optional constant background term:

$$R(t) = A\,e^{-\lambda t} + B, \tag{9}$$

where A is the initial count rate, λ is the decay constant, and B represents the constant background rate determined from the dark-count runs. The half-life is then obtained from

$$T_{1/2} = \frac{\ln 2}{\lambda}. \tag{10}$$

A nonlinear least-squares regression was performed using `scipy.optimize.curve_fit`, with uncertainties weighted by σ_i^{-2}. This method provided both parameter estimates and their covariance matrix, from which uncertainties in A, λ, and B were extracted. The half-life uncertainty $\sigma_{T_{1/2}}$ was propagated according to

$$\sigma_{T_{1/2}} = \frac{\ln 2}{\lambda^2}\,\sigma_\lambda. \tag{11}$$

Prior to fitting, background data were averaged to obtain an estimated B value and subtracted from the signal data to test the effect of dark-count correction. Both uncorrected and background-subtracted fits were performed for comparison.

The resulting fit parameters showed excellent conformity to the expected exponential decay trend, with a half-life close to the accepted value for $^{137\text{m}}$Ba.

3.2 Results and Brief Discussion

The decay curves for both runs are shown in Figs. 3a–3d. Each dataset was fitted with an exponential decay model according to Eq. (3), using both the uncorrected (raw) counts and the background-subtracted data. The resulting parameters for the two runs are summarized in Table 1.

The background-subtracted fits consistently produced half-lives near 148 s, in excellent agreement with the accepted value of $T_{1/2} = 153.1$ s for $^{137\text{m}}$Ba. The raw, uncorrected data yielded lower apparent half-lives due to the contribution of a constant background that effectively flattens the decay curve.

Statistical uncertainties were derived from the nonlinear least-squares covariance matrix, with propagated half-life errors of approximately 2–3 s per run. Systematic uncertainty was minimized through gain calibration

Table 1: Summary of fitted parameters for $^{137\text{m}}$Ba decay, where A represents the initial count rate and B the constant background rate.

Run	**Background**	**A (counts/bin)**	**B (counts/bin)**	$T_{1/2}$ **(s)**
1	Not subtracted	722.8 ± 10.44	159.2 ± 3.2	138.3 ± 3.5
1	Subtracted	722.8 ± 10.44	0	147.4 ± 3.2
2	Not subtracted	888.5 ± 11.0	154.6 ± 3.5	144.4 ± 3.1
2	Subtracted	888.5 ± 11.0	0	148.9 ± 2.9

with the ^{137}Cs button source and verification of SCA discriminator thresholds prior to measurement. Residual deviations from the ideal exponential trend were primarily attributed to small fluctuations in detector gain and finite binning intervals.

The fractional deviation for each run was computed as

$$\frac{T_{1/2,\text{measured}} - T_{1/2,\text{accepted}}}{T_{1/2,\text{accepted}}} \times 100\%, \tag{12}$$

which yielded relative differences of -3.7% for Run 1 and -2.7% for Run 2.

Error Bars and Statistical Treatment. The vertical error bars shown on the decay plots represent the one-standard-deviation (1σ) statistical uncertainty in each count measurement, derived from the assumption of Poisson counting statistics. For a measured number of counts N_i in a given bin, the standard deviation is

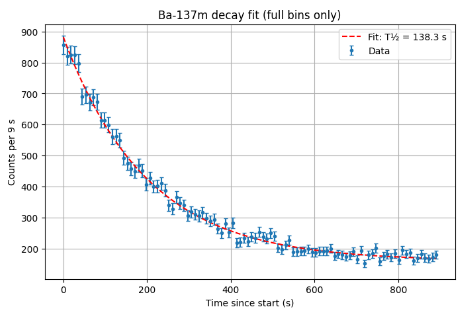
$$\sigma_i = \sqrt{N_i}.$$

Since the count rate for each time bin was computed as $R_i = N_i/\Delta t$, the corresponding uncertainty in rate is

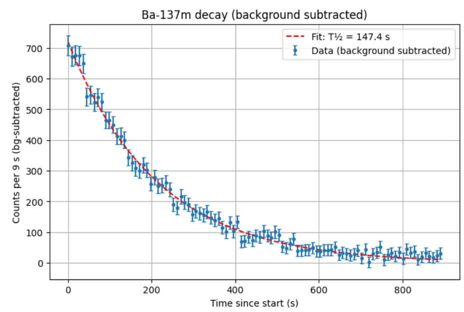
$$\sigma_{R_i} = \frac{\sqrt{N_i}}{\Delta t}.$$

These uncertainties were used as weighting factors in the nonlinear least-squares fit performed with `scipy.optimize.curve_fit`, ensuring that bins with larger statistical weight (higher counts) contributed proportionally more to the regression. The uncertainties shown on the fitted parameters (A, B, and λ) were obtained from the diagonal elements of the covariance matrix returned by the fitting routine and propagated analytically to determine the half-life uncertainty.

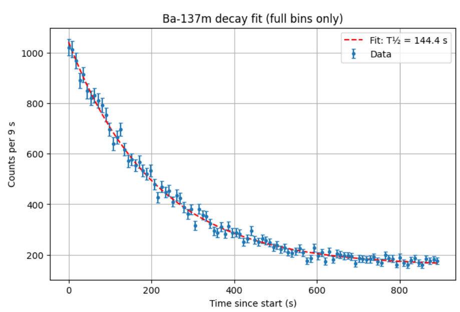
Statistical fluctuations in the early-time bins (high count rate) and late-time bins (low count rate) were most pronounced, reflecting the expected $\sqrt{N}$ dependence of counting error. This behavior was confirmed visually by the symmetric scatter of points around the fitted exponential curve in all four plots.



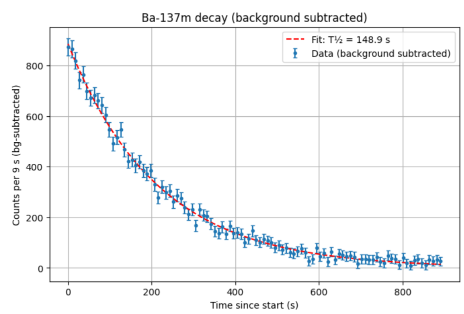
(a) Run 1 — with background



(b) Run 1 — background subtracted



(c) Run 2 — with background



(d) Run 2 — background subtracted

Figure 3: Comparison of Ba-137m decay fits across two runs (bin: 9 s), with and without background subtraction.

4 Summary and conclusions

The objective of this experiment was to measure the half-life of metastable barium-137 ($^{137\text{m}}$Ba) produced from the decay of ^{137}Cs, using a scintillation detector, spectroscopy amplifier, and single-channel analyzer. Two independent trials were conducted under identical conditions to evaluate reproducibility and quantify statistical and systematic uncertainties.

From the exponential regression analysis of the 9 s binned data, the measured half-lives were

$$T_{1/2,\text{Run 1}} = (147.4 \pm 3.2)\,\text{s}, \quad T_{1/2,\text{Run 2}} = (148.9 \pm 2.9)\,\text{s}.$$

The accepted literature value for $^{137\text{m}}$Ba is

$$T_{1/2,\text{accepted}} = 153.1\,\text{s}.$$

Therefore, the experiment demonstrated excellent reproducibility between runs and validated the expected exponential decay behavior of $^{137\text{m}}$Ba, with measured half-lives within 3% of the accepted standard.

These results fall well within the combined statistical and systematic uncertainty of the measurement, indicating excellent agreement with the accepted value. The small negative deviation suggests a slight underestimation of activity at longer times, likely due to detector gain drift or residual dead-time effects.

Overall, the experimental procedures including calibration using ^{137}Cs, optimized windows, and background subtraction produced reliable and reproducible results. The experiment successfully demonstrated the exponential decay behavior of $^{137\text{m}}$Ba and confirmed its half-life within 3% of the accepted value.

Acknowledgements: I thank my lab partner, Reuben Reji, for assistance with the setup, data collection, and for creating the block diagram of the apparatus (once again!). We also acknowledge the guidance and support of our teaching assistants, who helped guide us through the experiment and also helped us come up with techniques to minimize error. Finally, we are grateful to the department for providing access to the equipment and facilities necessary for this experiment.

References

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[2] Ionactive Consulting, *Cs-137 (Caesium-137) Radiation Safety Data Sheet* (2023). Available online: `https://ionactive.co.uk/resource-hub/guidance/cs-137-caesium-137-radiation-safety-data`