Measuring the Half Life of Ba-137 Using a Scintillator Detector

Akhil Deshpande

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

September 15, 2023

Abstract

In this study, we explored the specifics of radioactive half life. We used a photomultiplier tubem as well as a scinitillator detector to measure the half life of a sample of Ba-137. The experimental setup comprised an array of sophisticated equipment, including an ORTEC model 113 scintillation preamplifier, model 672 spectroscopy amplifier, and a model 553 timing single-channel analyzer (SCA). These were supplemented by an oscilloscope and a National Instruments DAQ interfacing with NI LabView software for precise data capture. We determined the half life to be within the accepted range for a sample of Ba-137.

1 Introduction

1.1 Physics Motivation

In this study, we investigate the principles of radioactive decay law by monitoring the activity levels of a radioactive isotope, Ba-137m, over a period of time. Fundamentally, radioactivity involves the transition of unstable atomic nuclei to a more stable state through the release of alpha, beta, or gamma radiation. This transition occurs at random, yet maintains a consistent probability of occurrence over time, thereby forming an exponential decay curve in both activity and the number of nuclei present within a given sample.

It is noteworthy that this process gives rise to either new elements or new isotopes of the existing element. Additionally, the 'm' denotation in an isotope's name, such as in Ba-137m, signifies that the isotope exists in an elevated energy state, as referenced in [1]. The aims of this study are twofold: firstly, to illustrate the exponential nature of radioactive decay, and secondly, to ascertain the radioactive half-life of Ba-137m.

1.2 Historical context

By the year 1902, Ernest Rutherford had delineated radiation into three distinct categories: alpha, beta, and gamma radiation, as documented in [2]. Alpha radiation encompasses helium-4 nuclei, which are produced during the alpha decay of a nucleus. Beta particles, on the other hand, are comprised of electrons or positrons that are released when a neutron decays into a proton or the inverse process takes place. Conversely, gamma rays are high-energy photons that are released when a nucleus transitions from a high to a lower energy state. Rutherford discovered that gamma rays have a significantly higher penetration capacity through various materials compared to alpha and beta particles [2], a characteristic that facilitates the differentiation of gamma decays from other types in detectors.

The initial scintillation detector, termed a spinthariscope, was devised by Sir William Crookes in 1903. This instrument employed a zinc sulfide (ZnS) screen combined with a microscope, enabling the visualization of light flashes whenever alpha particles struck the screen. A decade later, in 1910, Ernest Marsden and Hans Geiger utilized the spinthariscope to conduct the inaugural coincidence experiment. This involved placing a radioactive gas between two screens and relying on human observers equipped with microscopes on each flank of the double-screen to tally the perceived flashes. Despite this innovation, the method proved to be somewhat inadequate as human observation was relatively slow and prone to errors, leading to the temporary abandonment of the scintillation counter.

Nonetheless, in 1944, scintillators made a comeback, this time incorporating photomultipliers to supplant human observation, thereby enhancing accuracy and reliability. Presently, two prevalent varieties of scintillators are in widespread use: sodium iodide (NaI) crystals, which are infused with a trace quantity of thallium and primarily employed for gamma ray detection, and plastic scintillators, which are predominantly utilized in detecting charged particles, as noted in [3].

2 Theoretical background

2.1 Statistics of Radioactive Decay

The number of counts, N, models how many gamma rays are detected by the SCA, and counted by our apparatus. Because N is a counting variable, it is subject to a Poisson distribution. In a time interval t, the probability that N counts observed, P (N), is:

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

Here, $\bar{N}$ represents the mean count over the same time interval for a given sample size. It is important to note that $P(N)$ exemplifies a Poisson distribution, which

tends to a Gaussian distribution with a peak at $\bar{N}$ and a standard deviation of $\bar{N}^{1/2}$ for large values of N.

3 Experimental setup

3.1 Apparatus

When a gamma ray penetrates the crystal in a scintillator detector, it undergoes interactions with the confined electrons via three primary pathways: the photoelectric effect, Compton scattering, and electron-positron pair creation. However, since the latter only occurs for gamma rays with energies exceeding 1.02 MeV and the rays we are detecting are at 662 keV, we can disregard this mechanism. At energies below 100 keV, the photoelectric effect is prevalent, while Compton scattering is the dominant process between 100 keV and 1 MeV.

In the context of the photoelectric effect, the incoming gamma ray is absorbed by an electron in the crystal, imparting it with an energy $E_e = E_\gamma - E_b$, where E_γ is the gamma ray's energy and E_b is the binding energy of the electron before being displaced by the photon. This energized electron subsequently collides with another electron in the crystal, initiating a series of interactions with other electrons, thereby creating a cascade within the crystal. Ultimately, these electrons revert to a lower energy state within the crystal, each emitting a low-energy photon that progresses towards the PMT. This generates a significant peak in the crystal's spectrum, proportional to E_e, with the peak width ΔE being dependent on the photon count produced by the gamma ray, which diminishes as E_γ augments.

During Compton scattering, the photon interacts with an electron, causing it to recoil with an energy dependent on the scattering angle of the photons. These photons then reach the PMT's photocathode, releasing electrons which are subsequently accelerated and concentrated onto the first dynode. Here, each electron generates 2-5 secondary electrons, a process that repeats across up to 14 amplification stages. This amplification is facilitated by progressively increasing the voltage at each dynode, culminating in a discernible current pulse generated from the initial few photons. This mechanism necessitates a substantial voltage supply for the PMT, with our experiment utilizing a 750 V supply, although PMTs generally require between 1000-2000 V.

Our experimental setup also incorporates other key components including an ORTEC model 113 scintillation preamplifier, model 672 spectroscopy amplifier, and a model 553 timing single-channel analyzer (SCA), complemented by an oscilloscope and a National Instruments DAQ connected to a computer for data recording.

I will now detail the function and configuration of each element in our setup. Initially, the 113 preamplifier transforms the current pulse generated at the PMT's anode into a voltage pulse, leveraging multiple capacitors. This includes a variable capacitor controlled by a front panel dial, allowing us to modify the voltage pulse amplitude, set at 200 pF in our case. The 672 amplifier, receiving

signals from the preamplifier, enhances the signal for compatibility with both single and multi-channel pulse height analyzers It offers a variable gain, set at 200 for our experiment, and facilitates signal shaping with adjustable shaping time. Following the 672 manual's recommendation for NaI scintillators, we used a shaping time of 1 microsecond. Moreover, we utilized the amplifier's bipolar output to distinguish the PMT's output signal from oscilloscope noise.

The 553 timing SCA processes both unipolar and bipolar input pulses, assessing the amplitude of each pulse and producing a corresponding rectangular output pulse on the input pulse's falling edge. This equipment enables the establishment of lower and upper thresholds to filter voltage pulses within a specified amplitude range. After meticulous adjustment using the oscilloscope, we determined optimal thresholds of 0.8 V (lower) and approximately 3.5 V (upper).

Lastly, the National Instruments DAQ interfaces with the NI LabView software, monitoring the pulse counts outputted by the SCA with software furnished by the instructor. Leveraging the DAQ's in-built timer, we achieved high precision in timing, configuring the software to register pulse counts in intervals of one second.

3.2 Data Collection

Initially, we had to calibrate our setup and equipment. We were provided with a button source of Cs-137, which decays to Ba-137 over a very long period of time. Thus, the button source always contains at least a very small amount of Ba-137 (which we can use to model a live sample of Ba-137). We placed this button source inside of our Photomultiplier Tube, and we then calibrated our SCA and our Oscilloscope to settings that would allow us to monitor and view the gamma rays from a real sample of Ba-137. Our optimal trigger rate regarding the button source was anywhere from 1kHz to 2kHz. After determining this range, we moved to filter out random noise, as well as the infrequent small peaks and dips. To do so, we changed the range on our SCA. Our final range for our SCA was 0.8V to 3.5V.

After our total calibration process was determined, we moved to use a real sample of Ba-137. Using a solution of 0.9% NaCl and 0.04M HCl, we extracted Ba-137 from an isotope generator. We pushed this solution through the generator using a syringe, and collected the resulting sample in a small metal dish. This dish was placed into our PMT instead of our earlier button source. Using the provided LabView program, we set our counting interval to 1 second in order to mitigate the inclusion of background radiation as accurately as possible. In total, we conducted six trials.

Finally, we plotted an average background radiation to subtract from our data when doing analysis.

3.3 Data Analysis

The data collected was mainly characterized by the count rate of Barium-137 decay as detected by the photomultiplier tube over regular intervals of time. This dataset forms the primary source for determining the half-life of Barium-137, through an application of computational tools such as matplotlib and scipy.

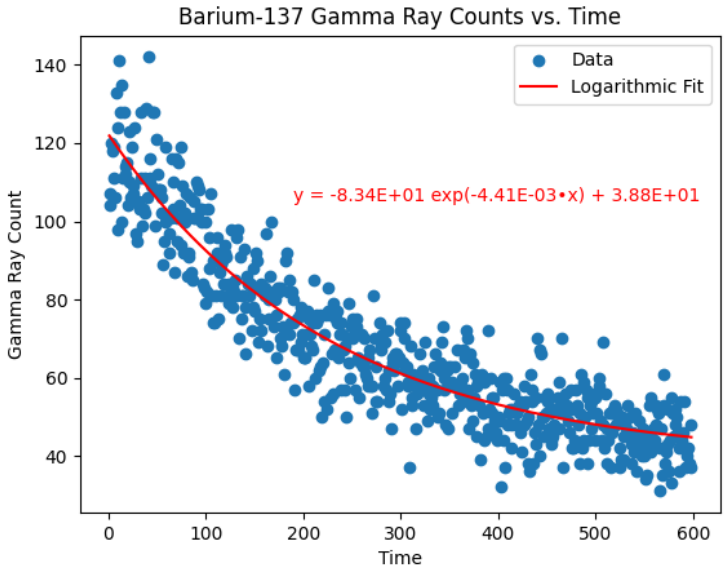
For each trial we did, the gamma ray counts were fit to the exponential function $N(t) = N_0 e^{-\lambda t} + c$, as described above.

Our average result for our half life, as well as our error was 163.1 ± 8.5 seconds. Below is a plot of our frist trial, labeled with its equation of decay. In order to transform the decay constant into a half life (in seconds), we apply the following formula:

$$t_{\frac{1}{2}} = \frac{\log(2)}{\lambda}$$

Our experiment was subject to random errors. Namely, the background radiation was not a consistent number. Furthermore, our gamma ray counts were part of a Poisson Process. We frequently experienced high peaks or dips over an interval. To mitigate this error, we increased the counting interval from one-tenth of a second to one second. This helped average the error and tighten the spread of the randomness we experienced.

Overall, the data for our experiment shows that we were able to determine the half life of a sample of Ba-137. As seen in the figure below, when we plot our data with respect to our modeled equation, we obtain an acceptable result after the decay constant is converted into a half life measured in seconds.



4 Results

The average half life we measured was 163.1 ± 8.5 seconds. This result is not totally consistent with the accepted result, but we are within one standard deviation of such result. As all of our trials also fell within this range, we can state that we have observed the half life of Ba-137 correctly.

5 Summary and conlcusions

In this experiment, we observed the average half lifes of samples of Ba-137 to be 163.1 ± 8.5 seconds. This result is very close to the accepted result.

I would like to thank my lab partner, Sannidhya Desai for his assistance on data collection and overall assistance. Furthermore, I'd like to thank Dr. Dan Heinzen, Parth Dave, and Konner Feldman for their assistance throughout the measurement and set up processes.

References

[1] D. C. Kweon, J. Choi, K.-R. Don, et al. "Use of a GM Counter to Measure the Half-life of Ba-137m Generated by Using an Isotope Generator". In: Journal of the Korean Physical Society 65 (2014), pp. 532–540. url: https://link.springer.com/article/10.3938/jkps.65.532.

[2] Thaddeus J. Trenn. "Rutherford on the Alpha-Beta-Gamma Classifica- tion of Radioactive Rays". In: Isis 67.1 (1976), pp. 61–75. issn: 00211753, 15456994. url: http : / / www . jstor . org / stable / 231134 (visited on 09/16/2023).

[3] E. Henly and A. Garcia. Subatomic Physics. World Scientific, 2007.