The Geiger-Müller Tube and Complex Radioactive Decay

Nate Schulz

Partner: Tim Struble
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1 Introduction

The dawn of nuclear physics stems from the discovery of radioactivity in 1896 by a French physicist named Antoine Henri Becquerel, who was awarded the Nobel Prize in Physics in 1903 for his discovery. Becquerel was not alone in the early study of radioactivity. Physicists, Pierre and Marie Curie, were also working in the field of radioactivity at the turn of the century. Marie, who coined the term "radioactivity" was instrumental in the development of the field. Her husband, Pierre, and their children were all involved in the study of the growing fields of physics and chemistry.

Another physicist by the name of Ernest Rutherford, a native of New Zealand, was involved in the area of radioactivity from his position as the chair of physics at a University in Montreal, Canada in the late 1890s. His interest in radioactivity studies arose from his involvement in the Chemistry community, causing him to approach the field as a method of determining an atomic structure that describe many of the odd characteristics of various elements he and many other had seen. Some elements were known to mutate into other configurations including those of nearby elements. This was the puzzle to be solved around the turn of the century.

The combined work of these and other physicists from around the world including Faraday, Boltzmann, Einstein, Planck, Kirchhoff, Bohr, and others, form the foundation for the era of modern physics. The discovery of radioactivity served as a catalyst for others to bring their individual specialties together and work toward a better understanding of matter at the atomic and subatomic level.

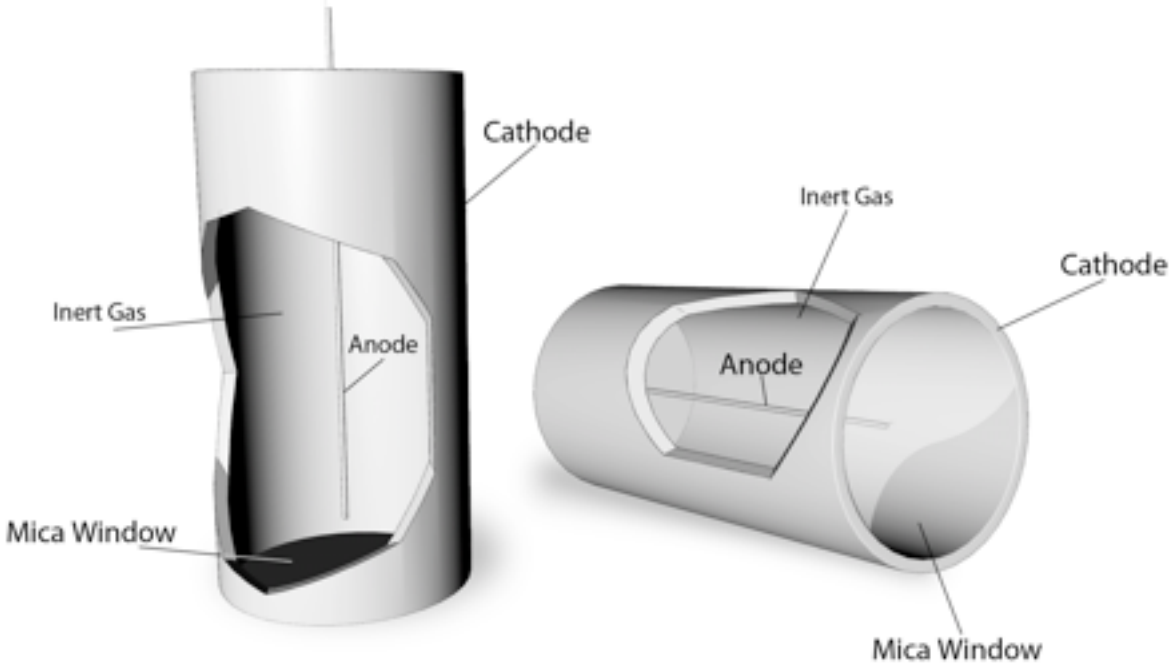
In this experiment, we will be examining the emissions of two primary sources, Cesium-137, a Gamma emitter, and Cobalt-60, a Gamma and Beta emitter. We will determine strength of emission over distance, through lead and silver, and measure the decay rate in Cesium-137. In order to examine these sources, we require a device that is capable of alerting us to the emissions as they leave the samples. For this we use a Geiger-Müller tube or G-M Tube.

A G-M Tube is a fairly simple apparatus which is capable of detecting the emissions from radioactive substances. Invented by Hans Geiger, a German physicist, in 1908, who later refined the device with the assistance of Walther Müller, also a German physicist, the G-M Tube is widely used to detect the presence of ionizing radiation. The G-M Tube is continued to be used today and will be our primary method of investigating radioactivity in this experiment.

2 Theory

Radioactive decay is the result of an unstable atom attempting to revert to a more stable state. During this transformation, the unstable nucleus of the atom can lose neutrons, electrions or positrons, as is the case for beta decay, or emit high energy

photons on the order of 10^{20} Hz and higher, as is the case for gamma emission. The device known as a Geiger-Müller tube is used to detect these types of emissions by detecting the ionization of a normally inert gas inside its chamber caused by the passing of radioactive emissions. This G-M Tube will be the primary instrument for gather data in this experiment.

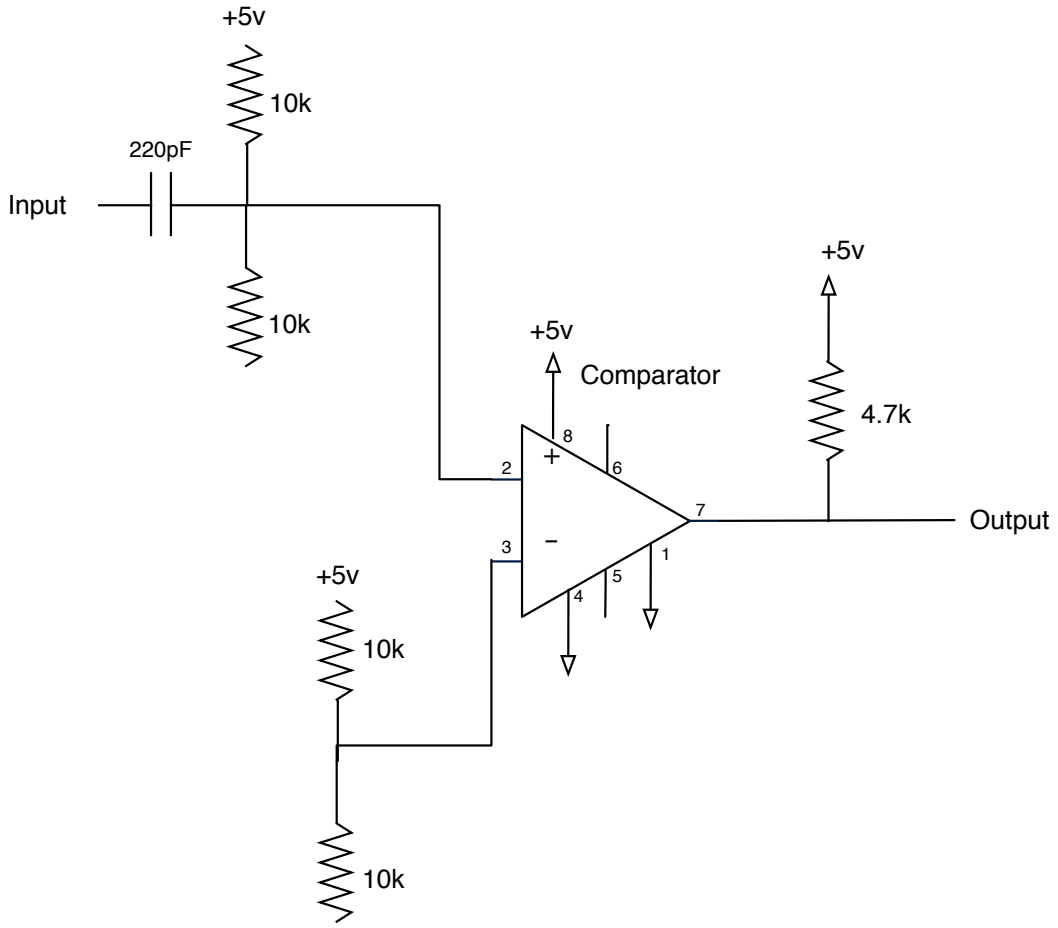


The G-M Tube consists of a low-pressure gas filled chamber which contains high voltage electrodes. The inside of the tube is typically lined with some type of metal to serve as the cathode, or positively charged surface. At the center of the tube, is a thin, negatively charged wire or anode. The high voltage between the cathode and anode is usually on the order of a few hundred to a few thousand volts, depending on the type of tube. There is no current flow between the two points, instead the voltage serves to create an electric field which will drive charged particles toward the anode.

Molecules in the normally inert gas filling the tube become ionized when under the influence of ionizing radiation from a radioactive source. This process of ionization creates positively charged ions and electrons (or positrons) and these ions are attracted to the central, negatively charged wire down the center of the tube. When they meet, a shower of ionizing energy further ionizes the gas and causes a cascading effect which

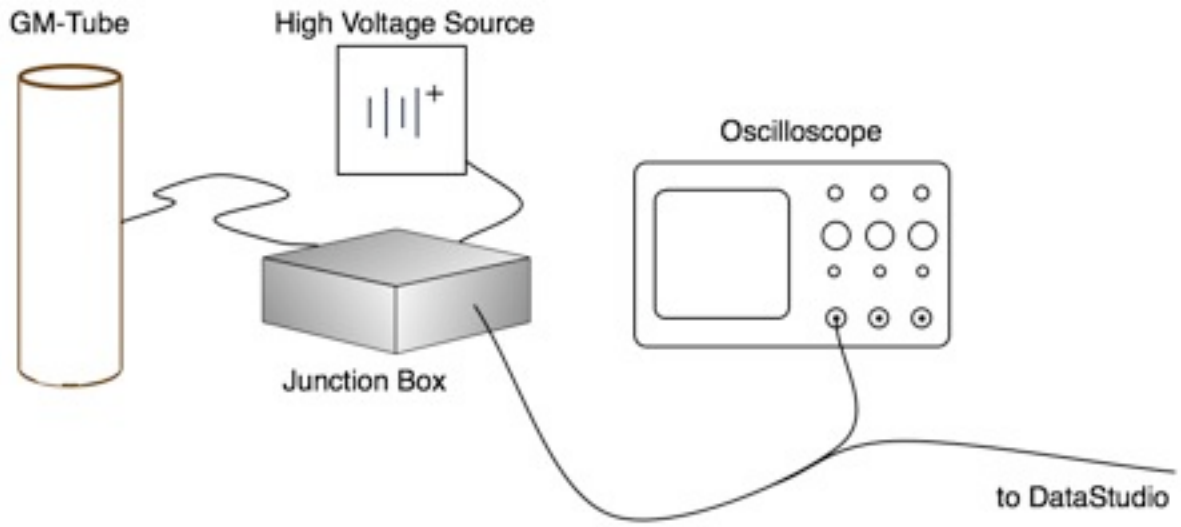
results in a short burst of current to flow between the anode and cathode. This burst, registers as a short pulse and with the use of an amplifying RC circuit, whose design can be seen below, can be read on an oscilloscope and in computer software like DataStudio through the use of a digitizing experiment box.

When the pulse signal leaves the G-M Tube it still has a relatively small amplitude and requires amplification to register on electronic devices such as an oscilloscope or a digitizing box connected to DataStudio. The following RC circuit is used to feed the pulse signal through an electronic amplifier which then passes the amplified signal to the rest of our laboratory equipment.



The amplifier is represented by the triangle in this diagram, and is connected to its own power source to enable it to increase the amplitude of the input signal waveform. After passing through the initial RC filter, the raw signal gets amplified and then passed back out of the circuit from left to right in the above diagram. The result is a signal with an amplitude that can be detected by counting equipment and the oscilloscope. This circuit is enclosed in a project box and attached by several coaxial cable connectors which complete the Junction Box apparatus for the lab setup, as seen in the next section.

3 Apparatus and Procedures

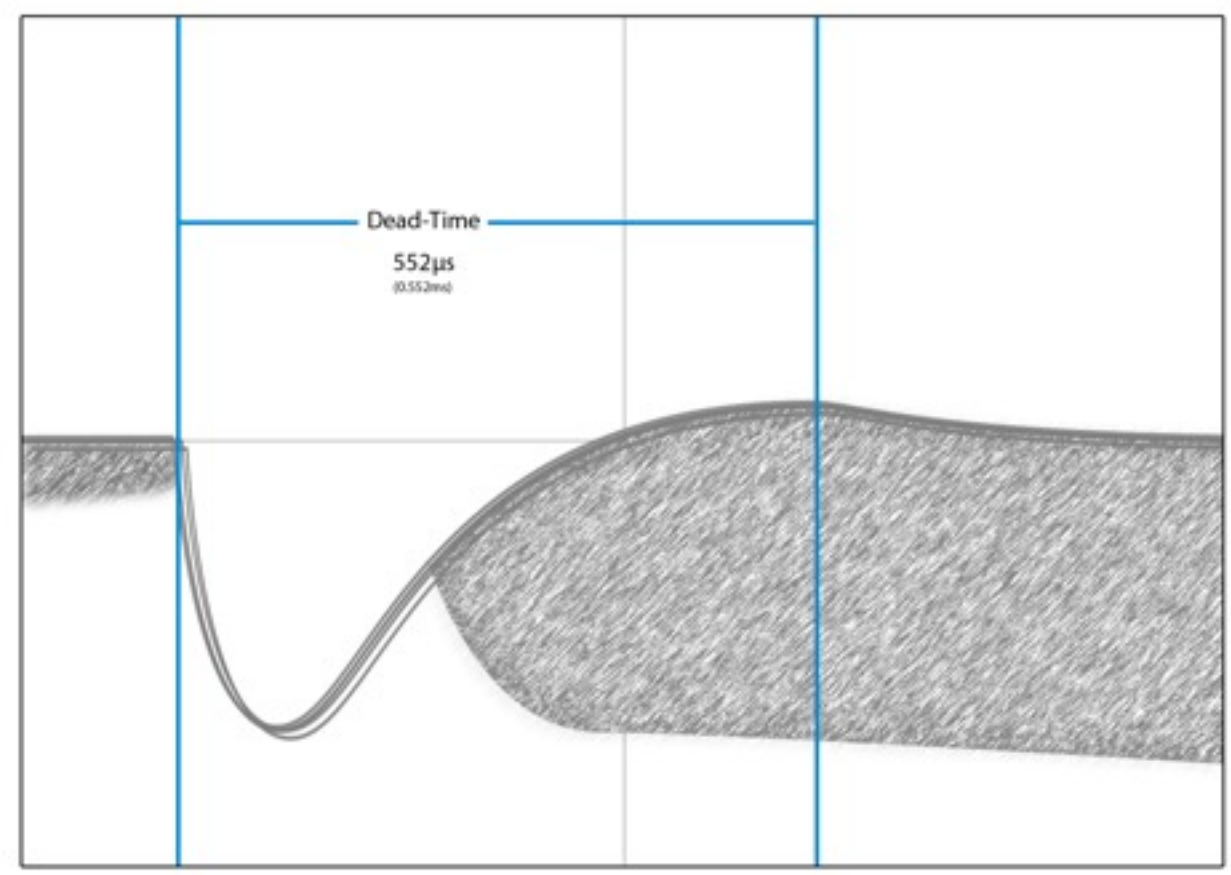


The standard G-M Tube readout setup is shown above. The G-M Tube is connected through the junction box containing the previously described RC circuit, to a high voltage power supply. It is from this power source that the high voltage is applied to the electrodes on the inside of the G-M Tube. The output of the RC amplification circuit is connected to an oscilloscope for an analog representation of the electrical pulses, and to a digital converter box to allow the pulse to be counted by the DataStudio software program.

To begin the experiment, we need to determine the amount of voltage required to detect emissions with the G-M Tube. We know that we should expect this voltage, or Geiger plateau, to be in the range of 1300 V, therefore we start below this voltage to find the base of the plateau and start at 1200V. We use the Cesium-137 source to locate this plateau voltage.

With the voltage plateau identified for our G-M Tube at 1325±5V, we continue with our experiment by placing a Cobalt-60 beta source beneath the G-M Tube and examine the electrical single output on the oscilloscope. The Cobalt-60 source is used only for its lower emission flux, or lower counts/second, making it easier to locate the pattern on the scope. Each ion causes a sharp burst of current for a split second and then

the circuit requires some amount of time, known as “dead-time” to regain its polarization and ability to detect additional ions. Fortunately, this time is on the order of microseconds or 10^{-6} seconds. We enable image persistence on the oscilloscope to force it to retain the signal on the screen for one to two seconds, causing the signals to overlap and clearly define our area of dead-time. Below is a rendering of the scope output and our method of measuring dead-time.



After obtaining a value by this method of observation on the oscilloscope, we remove the Cobalt-60 source and replace it with the first of two half-disk sources. We experimentally determine the counting rate of three different half-disk combinations: half-disk #1 alone, both half-disks together forming a full disk, and finally remove the first half-disk without moving the second. This leaves just the second half-disk beneath the G-M Tube to measure its individual count rate. Using the method of dead-time estimation described in Melissinos, we find the following count rates.

$$R_1' = 2132.3$$
$$R_{12}' = 2913.0$$
$$R_2' = 1518.2$$

Here the values are listed with primes as they are the observed count rates, and have not been corrected to account for circuit dead-time. Melissinos shows us how to estimate the dead-time τ, using the following equation.

$$\tau = \frac{1 \pm \sqrt{1 - \frac{R'_{12}(R'_1 + R'_2 - R'_{12})}{R'_1 R'_2}}}{R'_{12}}$$

Simply plugging in our count values provides an approximate value for τ.

$$\tau = 0.542ms = 542\mu s$$

This value is within 2% of our observed value on the oscilloscope. (see Results and Analysis section for more details.)

With our dead-time determined, we continue the experiment by measuring the counting rate as a function of the distance between the Cesium-137 source and the window of the G-M Tube. To do this, we set up the tube so that it is immediately above the source and take count rate data for 25 seconds before increasing the distance. We repeat this as many times as possible until the tube can not be raised any further or we determine that we are merely measuring the background count. We have data for a distance range from what we consider to be 0 cm to 29.8cm. For each distance point, we have an average count rate in counts per second taken over 20-25 seconds. Given this information, we determine our standard deviation as follows,

$$\sigma = \frac{\sqrt{N}}{t}$$

where N is the total number of counts collected in time t, which was approximately 25 seconds for each run. The calculated values can be seen in column 3 of the data table.

Using computer plotting software, Origin by OriginLab, we compute an estimate of sensitive volume inside the tube. We know that the emission flux falls off like $1/r^2$ but we also want to determine an arbitrary value above the measured distance which will represent the distance inside the tube to the sensitive volume. To do this we utilize Origin's powerful non-linear fitting tools to perform a simultaneous, three parameter fit of the following form.

$$I = I_0\left(\frac{1}{(x+a)^2}\right) + B$$

Where I_0 is the count rate at x = 0 from the source, B is the background count rate, and a is the arbitrary fit parameter which represents the distance from the base of the tube to the sensitive volume, or the part of the tube which handles the majority of detection.

Following the sensitive volume determination, we proceed to the next part of the lab which is to use a source and thin sheets of aluminum and lead to determine the total absorption coefficient for both materials. In order to take the necessary data we determine that we will record data for each sample for 15 seconds. We create a data table and record a row for each aluminum sheet of different thickness and repeat the process for the 4 lead sheets. Once the data is collected, we enter the data tables into Origin and plot an exponential fit function of the following form.

$$y = ae^{bx} + c$$

Where a is the full intensity emission value with no absorbing material between the source and the G-M Tube, y_0 is the background count value, and b is the absorption coefficient of the material.

With the absorption coefficients determined, we begin the last data collection activity of the lab. We place a thin silver foil in the neutron source for at least 25 minutes. While we wait, we monitor background radiation levels and take a good count average over time to maximize background accuracy. After 25 minutes, remove the foil from the neutron source and then as quickly as possible, place the foil beneath the G-M Tube and record count rate data in 10-15 second intervals until the count rate has returned to background levels. This should take about 5-8 minutes.
Once the data is collected, we enter the data tables into Origin and plot an exponential decay fit of 1st order for silver and second order for Rhodium.

$$y = y_0 + A_1 e^{-x/t_1}$$

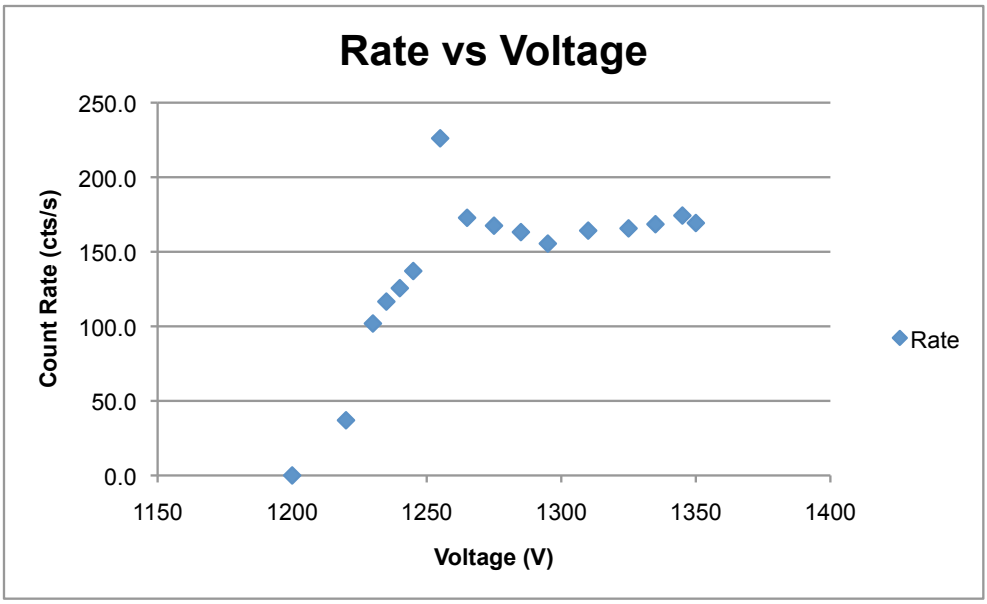
$$y = y_0 + A_1 e^{-x/t_1} + A_2 e^{-x/t_2}$$

4 Results and Analysis

Voltage data points for determining the Geiger plateau.

Voltage (V ± 5V)	Rate (cts/s average over 30 sec)
1200	0
1220	37
1230	101.9
1235	116.6

Voltage (V ± 5V)	Rate (cts/s average over 30 sec)
1240	125.6
1245	137.1
1255	226.1
1265	172.8
1275	167.5
1285	163.2
1295	155.5
1310	164.2
1325	165.7
1335	168.5
1345	174.3
1350	169.3



This data-set clearly shows a plateau around 1275-1300. For the remainder of the experiment we use a voltage of 1325V ± 5V on the G-M Tube.
Our observational method of determining dead-time revealed an approximate dead-time of 0.552ms.

$$\tau = \frac{1 \pm \sqrt{1 - \frac{R'_{12}(R'_1 + R'_2 - R'_{12})}{R'_1 R'_2}}}{R'_{12}} \qquad \begin{aligned} R'_1 &= 2132.3 \\ R'_{12} &= 2913.0 \\ R'_2 &= 1518.2 \end{aligned}$$

$$\tau = \frac{1 \pm \sqrt{1 - \frac{2913.0(2132.3 + 1518.2 - 2913.0)}{2132.3 * 1518.2}}}{2913.0}$$

$$\tau = 0.542ms = 542\mu s$$

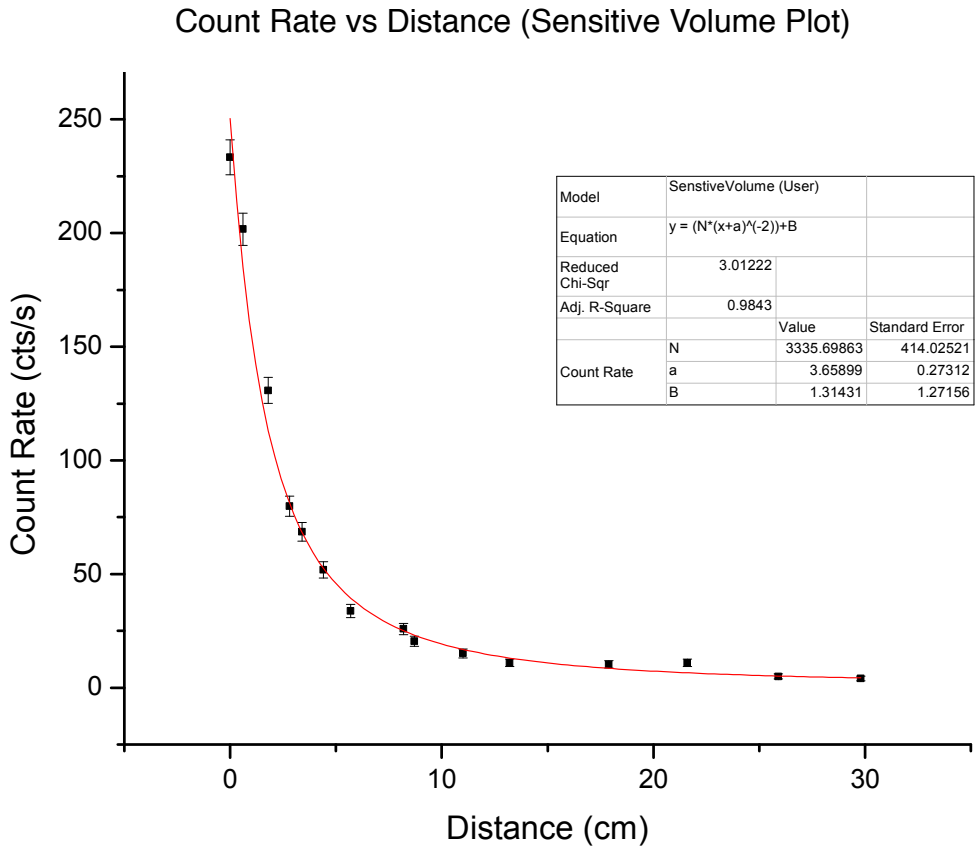
$$\frac{|552\mu s - 542\mu s|}{542\mu s} \times 100\% = 1.845\% diff$$

The method described in Melissinos agrees with our observed value within 2% difference.

The data table and plot for the sensitive volume calculation can be seen below.

Sensitive Volume Calculation Data Table

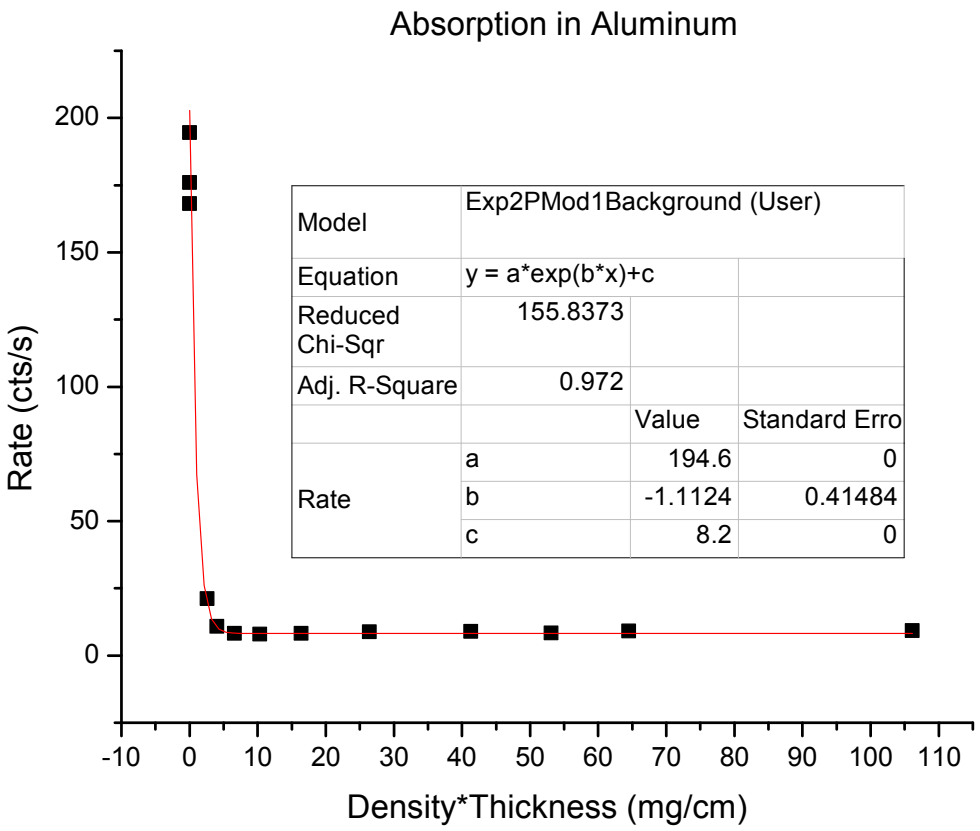
Distance (cm) ±0.2	Count Rate (cts/s)	Count Rate (σ)
0.0	233.3	± 7.637
0.6	201.7	± 7.101
1.8	130.8	± 5.718
2.8	79.8	± 4.467
3.4	68.6	± 4.141
4.4	51.9	± 3.602
5.7	33.7	± 2.903
8.2	25.8	± 2.540
8.7	20.4	± 2.258
11.0	15.1	± 1.943
13.2	10.9	± 1.651
17.9	10.2	± 1.597
21.6	10.9	± 1.651
25.9	4.9	± 1.107
29.8	4.1	± 1.012



The three parameter fit suggests that the sensitive region is approximately 3.65 cm from the bottom of the G-M Tube. The count rate σ is the standard deviation for each data point as determined by the equation,

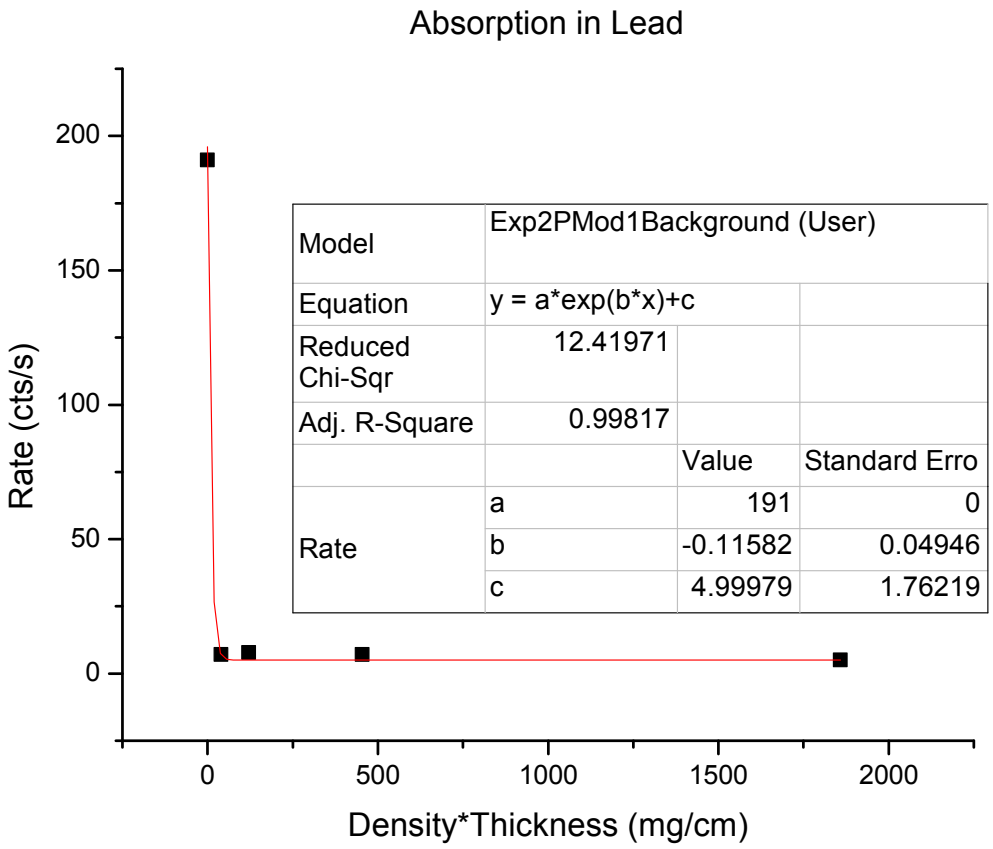
$$\sigma = \frac{\sqrt{N}}{t}$$

where N is the total number of counts in the observation time t.



This three parameter fit reveals an approximate value for the coefficient of absorption in aluminum. The value represented here by the parameter b, is 1.112 cm/mg, which implies a ray penetration of approximately 0.028 cm at a density of 206 mg/cm^2 which is consistent with our data shown in the plot. After the first thickness which is thicker than 0.025 cm, the emission flux levels off to what appears to be a background level.

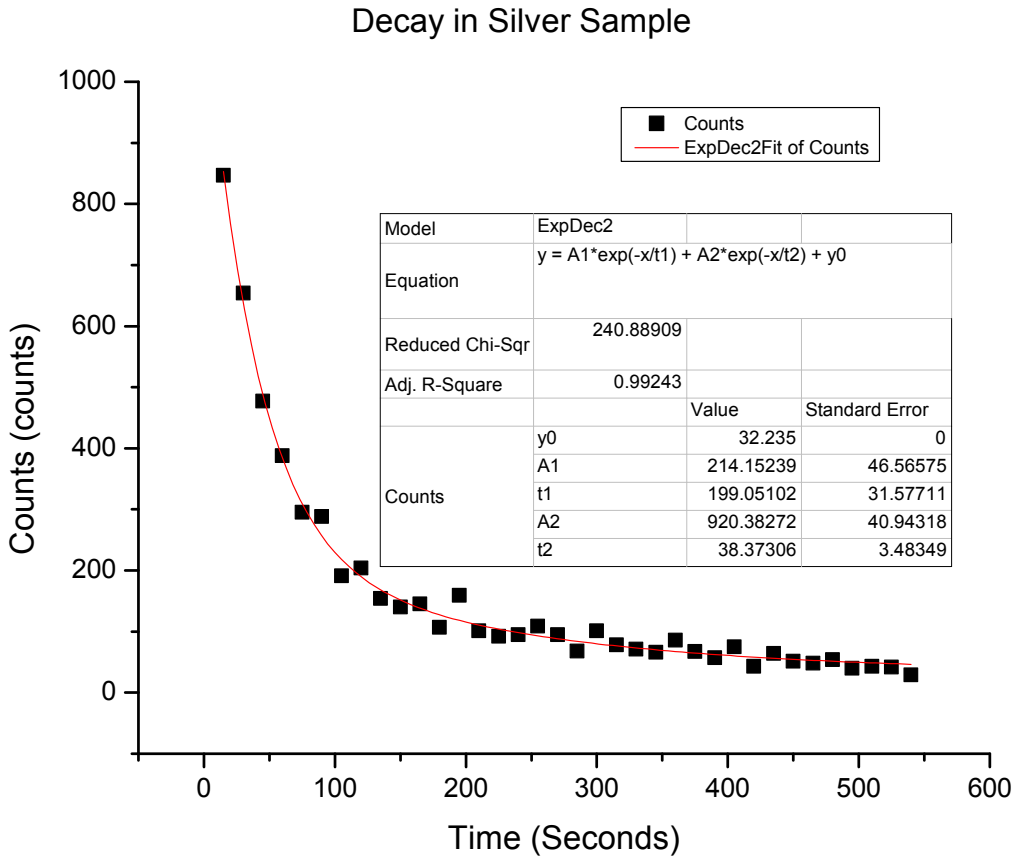
Material Code	Thickness (cm)	Density (mg/cm^2)	Count Rate (cts/s)	Count Rate (±σ)
None	0.0000	0	194.6	3.60
A	0.0007	4.5	175.9	3.42
B	0.0010	6.5	168.1	3.35
G	0.0200	129	21.1	1.19
H	0.0250	161	10.9	0.85
I	0.0320	206	8.2	0.74
J	0.0400	258	8.0	0.73
K	0.0500	328	8.2	0.74
L	0.0630	419	8.8	0.77
M	0.0800	516	9.0	0.77
N	0.090	590	9.3	0.79
O	0.100	645	9.1	0.78
P	0.125	849	9.2	0.78



Similar to the process for determining absorption in lead, this three parameter fit reveals an approximate value for the coefficient of absorption in lead. The value represented here by the parameter b, is 0.116 cm/mg, which implies a gamma ray penetration of approximately 0.007 cm at a density of 1230 mg/cm^2 which is consistent with the data shown in our plot. After the first thickness which is thicker than 0.007 cm, the emission flux falls to nearly the background count.

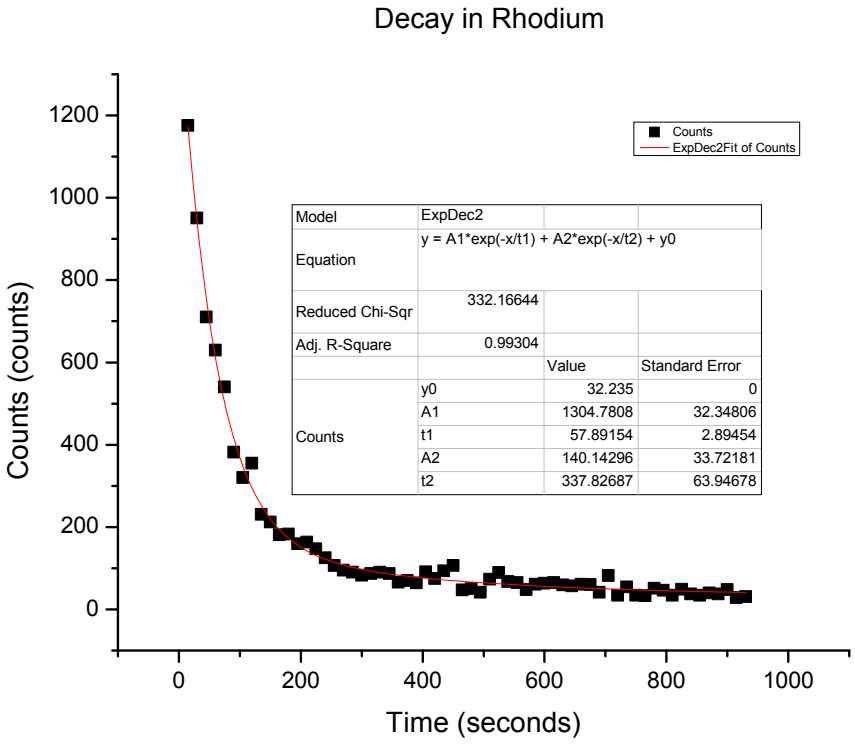
Material Code	Thickness (cm)	Density (mg/cm^2)	Count Rate (cts/s)	Count Rate (σ)
None	0.000	0	191.0	±2.91
Q	0.032	1230	7.0	±0.56
R	0.064	1890	7.8	±0.59
S	0.125	3632	7.1	±0.56
T	0.250	7435	5.1	±0.48

Both the coefficient for lead and the coefficient for aluminum appear to be on the correct order of the accepted values provided.



Irradiated Silver Foil Decay

Placing the silver foil in the neutron source for 25 minutes irradiated it causing it to temporarily become an active source. Once removed from the neutron source the foil displays a second order exponential decay in emission counts over a time period of about 9 minutes. Again, using Origin to fit the data, the decay constant t_1=199.05 seconds ±31.58 and t_2=38.37 ± 3.48 seconds. Looking these values up in a list of silver isotopes gives an approximate value for what appears to be ^{108}Ag and ^{107m}Ag where m stands for meta-stable. ^{107}Ag is stable in its natural form but after gaining a few addition neutrons from the neutron source, it becomes unstable and has a half-life listed above.



Irradiated Rhodium Decay

Placing the Rhodium sample in the neutron source for 25 minutes irradiated it similar to the silver foil, causing it to temporarily become an active source. Once removed from the neutron source the sample count rate produces an exponential decay over a time period of about 15 minutes. Again, using Origin to fit the data, the decay constant t_1=57.89±2.89 seconds and t_2=337.83±63.95 seconds. Looking these values up in a list of Rhodium isotopes implies that we are seeing the decay of ^{104}Rh and ^{104m}Rh respectively. Rhodium is stable in its ^{103}Rh isotope.

5 Discussion and Conclusions

Over a century after the discovery of radioactivity, we are performing similar experiments in a lab course as undergraduates. The work that Becquerel, Curie, and Rutherford has had a lasting effect on the field of Physics in the form of a a new area of study called Radioactivity. This lab familiarized us with the concepts behind radioactivity studies at the subatomic level and informed us how to use the G-M Tube apparatus, which is used to detect radioactive phenomena, at a level beyond simply pulling one fully assembled and enclosed out of a box. While we were not required to build the complete amplification circuit, we were required to do some experimenting of

our own to determine which voltage would be ideal for data taking. This lab challenged us to do research of our own to understand some of the decays and fits with which our data-sets presented us.

One fit in-particular that stands out is the sensitive volume fit. We have used fit lines in the past to help identify various constants and values, and even performed a similar fit in our 223 lab course, but it was not until I was presented with the challenge of performing this fit in this lab that I understood the process behind fitting with three parameters. This may not be the most profound thing, but I feel that rendering all of the plots in this lab taught me how to use some of the advanced fitting features of origin. All of the plots use error bars representing the standard deviation in each value as determined by,

$$\sigma = \frac{\sqrt{N}}{t},$$

where N is the total number of counts observed in the observation time, t. There was a a moment of clarity associated with the second or third plot that I felt began to draw from the all of the lecture material and previous lab exercises in this course that combined to allow me to both understand Origin, and a good deal of the statistics behind the plots.

I feel that this is our best lab yet in terms of data taking. While it may not have seemed that way while taking the data and later how we organized the raw data files out of DataStudio, our numbers tend to line up fairly well with known values an we can also make a logical guess as to which isotopes we are present in the decays at the end of the lab based on our exponential decay fit lines.

One thing did confuse me in this lab. We were asked to determine the half-lives of ^{107}Ag and ^{109}Ag, both of which are considered to be stable isotopes of silver. However, with the addition of extra neutrons fro the neutron source, the ^{108}Ag and ^{107m}Ag isotopes became the emitting isotopes that we observed in the decay.

As we approach the end of the course and semester, there are many best practices and what-not-to-dos I will be able to take with me. The first of which is that it is indeed far more efficient to plot any data we take as we go to help us identify any inconsistencies early on and most likely before we are preparing the formal lab write-up. Not that I doubted this when we were told several times that plotting data would be beneficial, but I got to see for myself why it is so important. In this lab, this method of data taking helped us identify an inconsistency in how Tim and I were measuring distance between the source and the G-M Tube for the sensitive volume data. We were able to catch this difference early enough to make the correction on the spot and continue taking data. This is not evident in this report, but is evident in my lab notebook.

Another thing I will take away from this course, is the importance of a neat and organized lab notebook. This report was one of the first reports where I had completed

the lab in my lab notebook before starting this write-up. I never started with a blank notebook in the past, but this time I took the time to carefully notate each procedure as we went next to the data tables in the log book. This makes the report process much easier when most of the hard work is already completed and the majority of this paper is just typing up what is in the log book.

I know that I will take these experiences and more with me in my future course-work and career. I also expect to have my most organized report to be our last report of the semester, which will be on the Millikan Oil Drop experiment.

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