Radioactivity

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Radioactive materials differ from other forms of matter in that their atomic structure is inherently unstable. Over time radioactive materials gradually decay by emission of energy in the form of ionizing particles. Properties such as type of decay, frequency of emission, and range of particles, can vary widely for many different materials. In addition to these, there are systematic difficulties unique to the apparatus that arise. Proper analysis of the theory requires that these complications, specifically resolving time and percent efficiency, be assessed for the specific setup used. Here, the emitter materials are tested to understand the properties of the physical particles they emit. Specifically the range and energy are calculated and supported for Alpha and Beta particles. As well, the effect of the inverse square law on radiation is observed and verified.

I. INTRODUCTION

In general, radioactivity is a fairly common phenomenon throughout the universe. Any energy that is emitted from an atom without a physical medium is radiation. Light waves are perhaps the most obvious form of radiation but atoms can also release energy in the form of ions.The emission of a particle from a radioactive nucleus is called ionizing radiation, and it behaves quite differently from electromagnetic radiation. This means that in order to investigate the theory of radioactivity, a specialized tool must be used, called a Geiger-Muller tube.

The GM tube allows for the physical counting of ionizing particles. The issue with this method of detection however is that the GM tube is sensitive to many sources of error. In order to properly assess the radioactivity of materials it is first essential to determine the resolving time of the counter as well as the prevalence of background radiation. This is a required step in order to calculate an accurate ion count from the values measured by thecounter. Understanding how the count of particles in the tube can be accurately determined from the source is crucial to the investigation of radioactive materials, as well as the behavior and characteristics of particles themselves.

II. Experimental Setup

The primary apparatus for measuring radioactivity is a Geiger-Muller counter. For our investigations,, a Geiger-Muller tube was set up inside a compact housing that held it in place on its vertical axis. The detection window of the GM tube faced downwards at a series of “shelves.” These shelves are stacked vertically inside the housing underneath the GM tube.They are equally spaced, at intervals of 1 cm. The emission sources to be used throughout the experiment would be placed on these shelves so as to face the detector.

The Geiger-Muller tube itself is simply a long tube filled tightly with a gas that is easily ionized. At one end of the tube is an easily permeable material that particles can enter through. Once a particle enters the tube it ionizes the gas, and electrons are emitted. Along the central axis of the tube is a conducting rod that acts as an anode, and the shell of the tube acts as a cathode.

For our Geiger counter to work it is connected to a circuit with a counter module. This circuit maintains a high potential gap between the anode and cathode. This high voltage causes the electrons from the ionized gas to gravitate towards the anode. In the process of doing so the electrons ionize the gas again, starting a chain reaction that results in a rapid multiplication of electrons inside the tube, called an “avalanche.” An avalanche generates a current in the tube such that the voltage in the circuit drops. This voltage drop is what signals a count to be made.

The bulk of our trials consisted of placing a source underneath the detector and turning the counter on for a set number of seconds to measure the particles emitted during a run.

III. Procedure & Theory

For our analysis of radioactivity, the data to test our particular theories of interest were collected through 9 different configurations of the setup, as well as 1 initial run to determine the operating voltage of the GM tube.

For the counter to work properly, the voltage gap held between the anode and cathode must be sufficiently high. It must pass the so-called “knee,” to allow an electron avalanche to occur. This voltage is determined through examination of the counters results across it’s full range of voltages. Too low a voltage, and the counter will not detect particles; Too high, and the counter will become overly sensitive, which will distort the data and potentially damage the GM tube. An expected operating voltage should fall somewhere in the 800-900 V range where the results “plateau.” 880 V was the selected operating voltage for our GM tube.

Our first trial was to determine the statistical accuracy of the counter. That is, it should provide data that is consistent with the probability of decay, and hence, detection. If analyzed, the data should reflect a probability distribution that can be approximated by a standard poisson or gaussian distribution. Those distributions are respectively given as follows:

$$P(n) = \frac{m^n}{n!}e^{-m} \tag{1}$$

$$P(n) = \frac{1}{\sigma\sqrt{2pi}}e^{-\frac{(x-m)^2}{2\sigma^2}} \tag{2}$$

For n objects, mean m, and standard deviation σ. Moving forward, background radiation would be measured and compared with the detected particles from a source (Sr-90) so that the degree of the background noise could be determined and then corrected for. This correction is simply the background count rate subtracted from the measured count rate of the source.

The goal of the fourth procedure was to determine the Resolving Time of the GM tube used. A GM counter is only able to count a single particle during a given time window. The electron avalanche is not instantaneous, and since only a single count can be made per avalanche, it is possible that additional particles enter the tube during this brief time and are unaccounted for. This time window is referred to as the “Resolving Time” and it is unique to the counter. It must be determined so that the true number of counts can be adjusted for the probability that a few additional particles went unnoticed by the counter.

Given a resolving time T, the true count rate R, is given by:

$$R = \frac{r}{(1-rT)} \tag{3}$$

Where r is the measured count rate. For this procedure, two half-sources were used in addition to the whole source Altogether our measured count rates should satisfy:

$$r_1+r_2 = r_3+b \tag{4}$$

Where r_1 and r_2 are the rates of the half-sources, and r_3 the whole source. They can then be adjusted for the resolving time, by the method for R in equation (3) above. Then T can be determined from those rates by:

$$T = \frac{r_1+r_2-r_3}{2r_1r_2} \tag{5}$$

The next procedure was to determine the efficiency of the Geiger tube. Since radioactive sources emit ions spherically in all directions, and the area of the counter’s detection window only occupies a fraction of that sphere, it must be determined what percentage of the expected disintegration rate is actually detected by the counter. This is referred to as the counter’s “Percent Efficiency” and is given by:

$$Efficiency = \frac{r(100)}{CK} \tag{6}$$

Where r is the measured count rate, K is the conversion factor, and C is the disintegration rate or “activity” of the source, given in microCuries.

Next was to determine the “Shelf Ratio” of the apparatus. Each shelf constitutes a 1 cm increase in the distance of the source from the tube. As this distance goes up, the detected counts will decrease, since the detection window will occupy less and less of the area of emission from the source. The Shelf Ratio is simply the number of counts at each shelf divided by the counts from the 2nd shelf. Each shelf below the second will yield only a fraction of the 2nd shelf’s counts.This fraction is the shelf ratio.

With the shelf ratio for each level below the tube determined, the application of the inverse square law to this procedure can be tested by first calculating ($1/d^2$) for each shelf, where d is the distance of the source from the tube in cm. Then comparing those values to the number of counts detected at each distance.

The next procedure was to determine the “Range” of alpha particles (emitted from Po-210), and then use it to find the energy. The range is the distance a particle is able to travel through a material. Radioactive particles have a certain kinetic energy which as they permeate through matter, will inevitably be absorbed by collisions in the medium until they are depleted of energy and stop. The range for alpha particles in air was found by placing the source as close as possible to the tube, so that counts are detected, and then increasing the distance between the source and tube until the counts approximately match that of the background. Whatever distance this occurs at is the range of the alpha particles.

Knowing the range, R, we can then find an approximate value for the kinetic energy of alpha particles by:

$$E \square R+1.5 \qquad (7)$$

The next procedure, similar to the previous one,, is to determine the properties of beta particles. Unlike alpha decay, beta decay, which is an electron emitted from the nucleus of an atom, is not restricted to a single value for energy. Beta particles can have anywhere from 0 MeV spanning all the way up to the maximum energy of the isotope from which the particle originated. This means that the range of beta particles can not be determined simply by examining the count.

So instead, an absorber is placed in between the beta emitter (sr-90), and the counter. By measuring the count rate for different thicknesses of absorber, a range value for beta particles can be extrapolated. For alpha particles it was necessary to find the distance at which the count matched the background. For beta particles, it is about finding the absorber thickness that causes this instead. By plotting the counts against thickness, it can be found where the beta activity matches the background. Wherever the line-of-best-fit intercepts the X axis will give us the range of the particles, this time in units of thickness.

The final testing procedure is to extrapolate a value for the energy of beta particles using the range value that was previously determined. This is accomplished using a similar method to finding the range. Absorbers of varying thickness separated the emitter from the GM tube. After determining the counts for each run, the common logarithm was taken for each count rate, and then plotted against thickness. Like the previous test, a best-fit line is made, and the slope used to extrapolate an X intercept. This value is the expected range, in units of thickness. Then with a value for R, the Energy of the beta particles was approximated according to the following:

$$E_{\beta}=1.84R+.212 \qquad (8)$$

IV. Results

To find a reliable operating voltage for the GM tube, background counts were taken for incremental voltages until the counter began to plateau. These counts are plotted vs voltage as shown in figure 1.

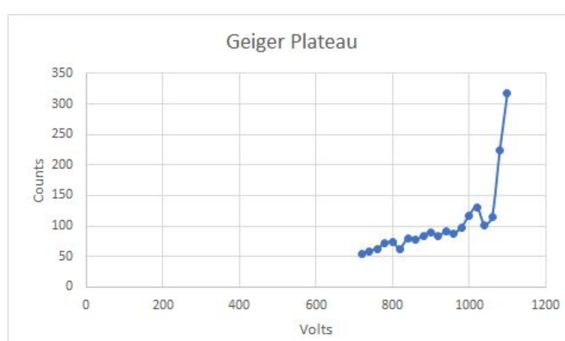

Figure 1

It is best to select a voltage in the plateau range, perhaps just off center. Using this chart, an operating voltage of 880 V was selected for the rest of testing.

The second procedure was to verify the statistical accuracy of the counter. This was done by measuring background radiation counts for 151 runs and comparing that data to the probabilities of decay for the given number of counts in each run. This would confirm that the counter is performing as expected based on the probabilities of decay. In figure 2 below, the frequency of count values is plotted alongside a poisson and gaussian distribution of the collected data.

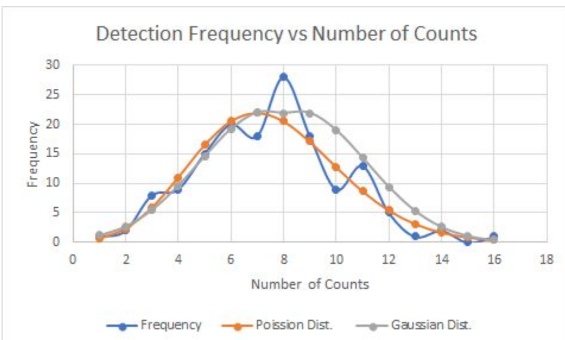

Figure 2

As shown, the detector did verify that background radiation occurs with frequencies that are well approximated by Poisson and Gaussian probability distributions. Thus, our measurements reflect the expected results. The plot is symmetric about the mean of 7.48, with a standard deviation of 2.67

Next the background radiation was measured to determine its impact on the counts from the GM tube.. Knowing this is how the true count rates can be determined when an emitter is actually measured. So 3, 5 minute runs were performed with no source present and then again with a Sr-90 source. The results of these runs were both averaged so that there was an average for the counts from the emitter, and an average for the counts from the background. The difference was taken to find the true number of counts. For the Sr-90 emitter, the determined true count rate was 103368 counts per 5 minutes, or 20673.3 cpm

For the resolving time calculation, following equations (4) and (5) with r_1 = 73446 cpm, r_2= 70687 cpm, and r_3 = 107693 cpm, we have that T=0.000211 seconds. With the resolving time known, and the background radiation levels approximated, it is now possible to adjust our data to the correct values for the sources tested.

Finally, before moving to testing the physical properties of the emitted particles, the efficiency of the Geiger tube needs to be determined. The formula is given by equation (6) in the previous section, and a percent efficiency was found for 3 different emitters. For Po-210 this percentage was exceptionally low, .007%. This is consistent though, when considering the counts for this source were in the neighborhood of the counts received from the background. The efficiency found for Sr-90 was 4.78%, and for Co-60 it was 6.32%.

Following this, the next two procedures were to determine the impact of distance between the source and counter on the measured counts. Specifically, the “shelf ratio” for each incremental distance further from the counter was determined. The ratios are given in the following table.

Shelf	Ratio of Counts
2	1
3	.63742
4	.436051
5	.320473
6	.248541
7	.193126
8	.147367
9	.136456
10	.108692

Using the same data, the Inverse Square law can also be observed. The activity detected by the counter is measured as the source’s distance from the tube is increased. Figure 3 below shows the graph of the corrected counts plotted against (1/d^2) for the distance d in meters from the Geiger tube.

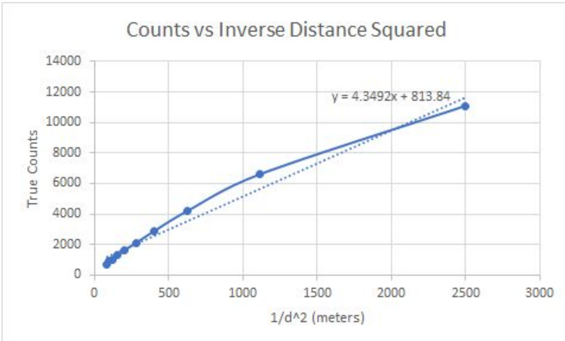

Figure 3

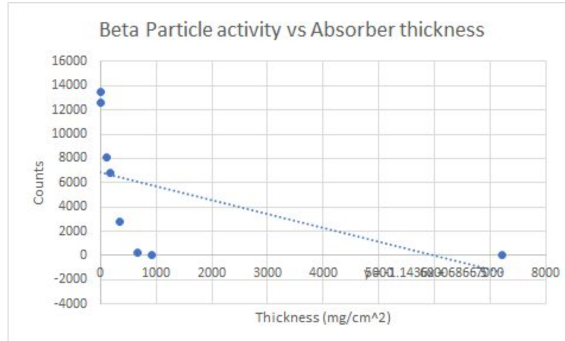

Figure 4

The best fit line approximates the data fairly well and it seems as though the Inverse Square Law holds unaffected in this setup. The measured counts at the tube decrease at twice the rate of the increase in distance.

To find the range of alpha particles, a polonium source was placed in the top shelf under the counter, where the corrected count averaged over 3 runs was 47.40605 cpm. 3 more runs were taken and averaged for the source on the second shelf, where the count dropped to 2.034636 cpm. Beyond this distance the averaged counts per minute match that of the background levels. This means the counter is outside the range of the alpha particles when the emitter is on the 3rd shelf. So the second shelf lies at just about the right distance from the tube to match the range of the alpha particles. The distance here is 4 cm. So plugged into equation (7) for energy given in the previous section, We have that alpha particles have kinetic energy of E= 5.5 MeV.

The next data set is to determine the range of beta particles as was done with alpha particles. Here however, distance is not useful for finding the range because beta particles can have a wide range of energies. Instead, the counts are measured after contacting absorbers of increasing thickness. Figure 4 shows the corrected counts graphed against thickness of absorber:

The best fit line doesn't fit the data particularly well here, but that's not necessarily important. The thickness value for the range lies somewhere between the final two points, and the slope of the line is how a value can be extrapolated. The X intercept is the range that was determined for beta particles. R = 6004.28 (mg/cm^2)

Finally, a value of Energy for beta particles can be determined. To do so a Sr-90 emitter was tested for a large range of absorbers and instead of using the counts to determine the range, the common logarithm of the activity was used instead. The resulting plot is as follows:

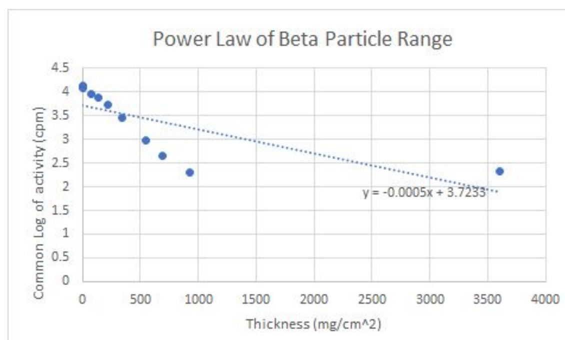

Figure 5

Here it is seen that Beta particle energies follow a power law. The best fit line works better for this set because we took the logarithm of the count rate. The range here, using the x-intercept, is R= 7.4466 g/cm^2.

With this value for R, the Energy for beta particles can be calculated from equation (8) given in the previous section. The energy was found to be E_B=13.91374 MeV.

V. Summarization and Conclusion

The operating voltage selected was 880 V. It was selected because it was within the plateau range, close to the center. Different GM tubes have different materials, sizes, and tolerances, and so can have different ideal voltages, which is why this first trial was necessary. The quenching gas in our GM tube was non-organic and so likely would not cause an issue in our counters ideal voltage even after a long time of use. However, if the quenching gas is organic and has undergone a large number of counts this could affect the ability of the electrons to gravitate towards the anode. The ideal voltage could differ slightly after an extended period. The slope percent of the Geiger plateau is 1.68, and so this indicates that it is a true plateau and our operating voltage is valid.

For the background data counts, it would seem that the Gaussian Distribution matched the values a bit better than the Poisson distribution. Since Poisson is a special case of the binomial theorem, this seems sensible. Radioactive decay, even though it is a binary occurrence, is better represented using a Gaussian probability distribution, because it can handle continuous variables. The Poisson method however, is easier for calculating the standard deviation.

Background radiation is an unavoidable systemic complication. It must be calculated and adjusted for in any scenario where a Geiger counter is involved. Radioactive ions are simply too common in the universe to be effectively ignored. So common in fact, that even the human body should expect to receive around 129,254 counts of background radiation per day. And 47,177,856 counts per year. There are of course discrepancies between each of the individual counts. Background radiation is not uniform, but it is also possible that there is systematic interference. This could include the direction of the detection window, if it faces easily permeable matter, or towards directions containing different activity levels. As well, the resolving time of the tube was not taken into account for this measurement.

The calculated resolving time came to be .000211 seconds, which falls on the expected order of 100 microseconds. The percent of added counts when adjusted to the resolving time all fall within a low but consistent range. It is unlikely the resolving time would ever cause any one run of counts to deviate too dramatically from the true value, though it does not seem impossible.

When determining the efficiency of the Geiger tube, we found that all values for the isotopes fell within the range of 0-10 percent; this is about what we would expect given the area of the detector compared to the area and activity of some of the isotopes. The efficiency values are specific to each isotope. Different isotopes can have different activities which affects the efficiency of the tube. Were the sources to be placed at a different distance from the counter then the efficiency would be changed. This is due to the varying size of the detection window as a segment of the total area for the emission range. For a source in the 3rd shelf, 3 cm from the detection window, the ratio of areas is 38.48/113.1 = .34 so the counters window is positioned to occupy about 1 third of the area spanned by the source emission. This confirms the intuition that efficiency is primarily a matter of surface area. Although activity of the source matters as well.

The shelf ratios were determined in the lab using a Ti-204 emitter. If another beta source was used, the ratios should be fairly similar. Though the ratios could differ more heavily between source materials that emit a different form of particle. Different particles have different ranges and energies, so if a gamma emitter was used, I would expect the ratios to be higher across all the shelves. On the other hand, I'd expect the ratios to be lower in the case of an alpha emitter.The reason the 2nd shelf was used as the reference point, instead of the 1st shelf is because resolving time is too significant of a factor at that short of a distance to the source.

The data acquired for the inverse square relationship for distance and particle counts follows the best fit line on the graph quite well. The linearity between the two rates seems to confirm the inverse square law’s effect on emitted particles; That the energy becomes sparser logarithmically as distance increases.

Alpha particles are helium nuclei emitted from atoms. As such, though they have a lot of ionizing potential, they lack the high energy states that other forms of decay can occupy. This means that they tend not to travel too far, having their kinetic energy rapidly absorbed by surrounding matter. The highest energy alpha particles have only about 8 MeV of energy. To avoid being hit by them, one would need only stand a distance greater than 6.5 cm from the source of the emission.

When finding the range of the alpha particles, the percent error for the measured energy value at 3 cm was around 2%. This is pleasing, as it suggests the data is quite reliable. This indicates that the true range of Alpha particles is quite close to the 4 cm that was experimentally observed.

The Beta particles had to be analyzed using absorbers, rather than just distance. This is because of the vast range of energies that beta particles can have. Thus, finding the range is trickier. The curve showing the counts of the particles as they encounter thicker absorbers is not linear, but logarithmic. So to determine the range, it is advised to take the common logarithm of the particle counts in order to make the data slope linearly, or to use a line of best fit. The data from the results section has a slope of -1.1436. This was obtained from the best fit line however, which does not fit the data well. A value for the range of beta particles could still be found however. It seems that for R=6004.8 (mg/cm^2) no beta particles would feasibly exist beyond such a range.

For determining the energy of beta particles, the data used was “linearized” by taking the logarithm. This allowed the best fit line to represent the data much more accurately. The data does have some outlier values that skew the slope a good bit past 1400 (mg/cm^2). This unfortunately is likely to give us a higher value for the range than is expected, which also happened in the previous section. The issue here though, is that to find the energy for beta decay, the range being so far skewed causes the energy calculations to be considerably off track as well. The calculated energy for beta particles was E=13.91374 for Sr-90. When compared to the accepted value for E, the percent error comes out to 2,448%. The theoretical value for E is indeed quite a bit lower, at .546 MeV.