Radioactivity

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Contents

Abstract

The prime objective of this experiment was to detect the radio-active properties of the two radioactive sample: Americium 241 and the meta-stable state of Barium 137m. Using the sample Americium 241, we determined the distance dependence of radiation (alpha, beta, and gamma ray) and its penetration effect on different materials whereas using Barium 137m and plotting the graph of count rate over time, we measured its half life. The range for the alpha particle from Americium 241 was found to be 20$\pm$2 mm which slightly differs from the literature value of 17 mm. Since the distance between the Geiger-Müller tube and the sample was measured manually using hands, and the sample might not be aligned parallel to the tube, they might be the reasons for the variance of the value from the literature one. From the further experiment, it was found that higher the density of the materials, higher the radiation absorption capacity. Similarly, the half life of Barium-137m was found to be (154.69 $\pm$ 2.9) seconds which is quite closer to the literature value of 151 second.

1 Introduction and Theory

1.1 Atomic Structure

There are some of the basic fundamentals of atom that we must know before thinking about the radioactivity. An atom consists of proton, neutron in its nuclei, and electron on the outer orbit called "shell". Among them, proton is considered as the most fundamental aspect of an atom which determines its chemical nature. An atom with 'Z' protons or electrons, 'N' neutrons, and 'A' atomic mass is related as:

$$A = Z + N$$

An addition or subtraction of one or more electrons in an atom comparing to its number of protons results in the formation of ions. On the other hand difference in the number of neutrons results in the formation of isotopes of an atom despite the fact that they have same number of protons and electrons.

Instability in the the atom causes the decay of its nuclei and formation of other nuclides by emitting particles or electromagnetic radiation. Among 2500 of the known atomic nuclei, about 90% of them undergo radioactive decay. The particles emitted during this decay are known as α particles, β particles, and γ rays. It was first discovered by Antoine Becquerel and isolated by Marie and Pierre Curie.

1.2 Types of radiation and radioactive decay

α particle is a positively charged Helium nuclei consisting two protons and two neutrons. In this atomic decay, the atomic number of an atom is reduced by two and mass number is reduced by four. α decays mostly occur with atoms with more than 82 protons because the electrostatic force of repulsion among the nuclei overcome the nuclear force of attraction. Thus, the nuclear force can not hold the nuclei together. The α decay occurs as:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

β particle is either an electron that consists of negative charge -e or a positron that consists of positive charge $+e$. In this decay, a neutron gets converted into proton during the course of electron emission. This results in the increment of the proton number of the daughter nuclei by 1. However, we should note that the emitted electron is the one which is formed during the decay rather than the orbital electron. The beta decay occurs as:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-}$$

γ rays are the high energy electromagnetic radiation which are formed during the change in the structure and energy levels of the excited atomic nucleus. It is also formed during the electron-positron annihilation. It is very difficult to shield gamma rays since they can travel longer distance than α and β particles.

An example of gamma decay is shown below.

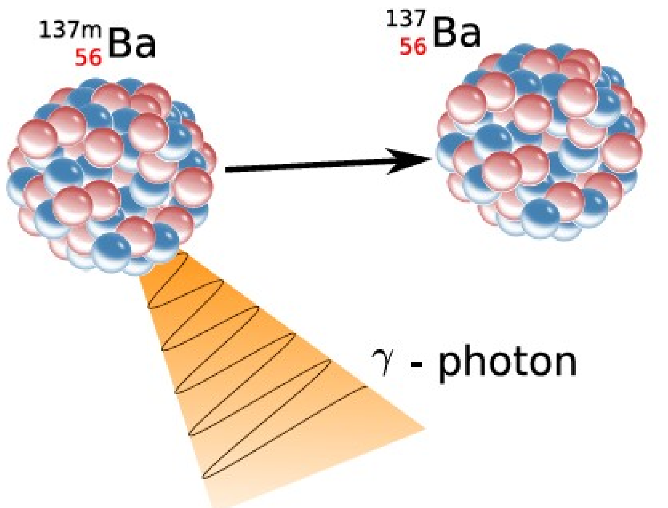

Figure 1: Example of γ decay

α particle is the one with high ionizing power as they have sufficient amount of charge. Thus, they can travel few cm in air due to the loss of energy while ionizing. However, β particle are partially absorbed in air which makes it travel for the longer distance. With regard to γ radiation, its absorption in air is negligible, however, due to its low intensity, it gets scattered in the air. Thus, we can conclude that α particle has the shortest range.

1.3 Quantifying radioactivity

There are several useful quantities for analyzing the radio-activity that we need to understand. The most simple and the basic is ***activity*** which can be mathematically represented as:

$$Activity = \frac{Number\ of\ decays\ in\ a\ sample}{Time}$$

Its SI unit is Becquerel which is equivalent to disintegration per second.

Another important quantifying factor is ***exposure*** or ***absorbed dose*** which can be mathematically represented as:

$$Absorbed\ dose = \frac{Amount\ of\ energy\ absorbed\ by\ a\ material}{Mass\ of\ the\ material}$$

Its SI unit is Gray(Gy) which is equivalent to 1 J/Kg = 100 rad. The absorbed dose depends upon the energy per particle of the radiation, number of particles absorbed per time, and the type of the absorbing material.

In order to characterize the type of absorbing material, a quantity called ***equivalent dose*** of ***effective dose*** is used which relates to the degree of biological effect of radiation with a type of the ionizing material that produces similar biological damage. If H is the equivalent dose, D is the absorbed dose, and w_r is the quality factor, then we have the relation as:

$$H = w_r \cdot D$$

Since some of the radiation are biologically more damaging by nature and also equivalent dose depends on the type of organs exposed, quality factor w_r is used. The SI unit of equivalent dose is Sievert. It is quantified that a normal human being should not be exposed to more than 5 **mSv** per year. It is also estimated for the people exposed to radiation in hospital to stay below 20 **mSv** per year.

1.4 Shielding of radiation by materials

The impact of radiation on material depends upon the major factors such as kind and energy of the radiation, atomic number of the absorber, time of exposure of the material, distance of material from the source, and the shielding (thickness of the walls (d) and density of material). The shielding of radiation by a material is described by the ***distance law of radiation*** as:

$$N(d) = N_o \cdot e^{-\mu \cdot d} \tag{1}$$

where N_o is the count rate for the absorber during *d=0* thickness, N(d) is the count rate during d thickness, and μ is the attenuation coefficient. Thus, it can be concluded that shielding effect increases with increase in the density of the material. From the above equation (1), it can also be derived that:

$$d_{1/2} = \frac{\ln 2}{\mu} \tag{2}$$

where $d_{1/2}$ is the half thickness of the material. This equation shows that half the thickness of the material decrease the effect of radiation by the factor of two.

Another similar quantifier to analyze the shielding of the radiation by the material is ***air equivalent absorption***. It is the thickness of the air equivalent to the same attenuation of the radiation caused by the material.

1.5 Radioactive decay and half-life

Although it is quite unpredictable to determine the decay of the material, the probabilistic theory can be helpful to predict the decay of a nuclei over a given time. If *N(t)* is the number of the number of radioactive sample in the given time t, and $\frac{d(N)}{dt}$ is the rate of change of the sample over time, then the activity is given by:

$$-\frac{d(N)}{dt} = \lambda \cdot N(t) \tag{3}$$

where λ is the decay constant and negative sign indicates the reduction in the quantity of the sample. Similarly, we also have the decay law which shows the remaining quantity of radioactive sample *N(t)* after disintegration as:

$$N(t) = N_o \cdot e^{-\lambda \cdot t} \tag{4}$$

where N_o is the original quantity of the radioactive sample.

The time required to decay the half of the radioactive sample is known as half life. When we replace t in the equation (4) with $t_{1/2}$, we get the equation as:

$$t_{1/2} = \frac{\ln 2}{\lambda} \tag{5}$$

1.6 Radioactive sample

Two two radioactive samples used for this experiment was Americium 241 and Barium 137m. Since Americium 241 was a closed source and Barium 137m has the short half life of some minutes and can be properly disposed, they were used for the experiment.

1.7 Radiation detection - the Geiger Müller tube

The basic effect of radioactive sample on the material is ionizing the material. The Geiger Müller Tube is based on the same principle that helps to detect the radioactive sample. As shown below in the figure, it consists of a metal tube, acting as cathode, filled with halogen and noble gas. A horizontal wire through the tube acts as anode. The radiation coming from the radioactive sample nearby enters the tube ionizing the noble gas inside it due to collisions. When the potential difference is applied across the tube, the charges from the ionization events get accelerated producing the avalanche of charges. All the charges being negatively charged moves towards the anode, the counting wire, and are recorded as an impulse by the electronic counter. The suitable voltage between the tube is selected in such a way that it can avoid self-discharge, gives measurable pulse, and do not miss the particles as well. The pulse detected by a detector operating at working voltage is known as background voltage. Therefore, in order to get the correct reading of the pulse, the background activity is subtracted.

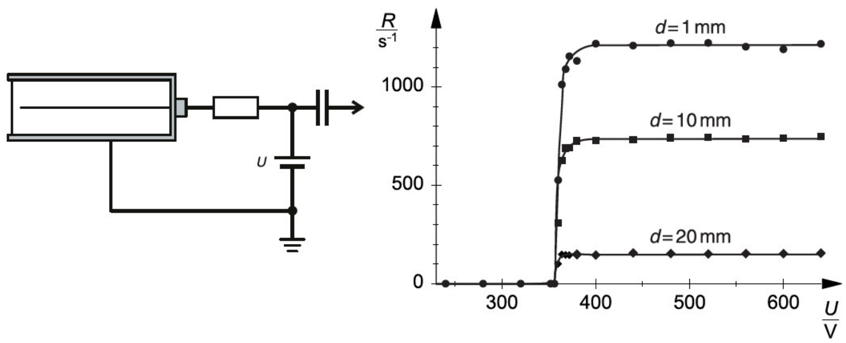

Figure 2: Left: Assembly diagram of the Geiger Müller Tube. Right: GM characteristics. Count rate R versus counter voltage U for different distances

The plot between the number of pulses recorded per time and the applied voltage gives the characteristic of a Geiger-Müller tube.This characteristic is obtained at a plateau region where change in applied voltage does not change the pulse number. Also, a "dead time" is used in detector systems to record the events between the time interval so that the electronic counter could not record other incoming events.

1.8 Decay Statistics

As radioactive decay is probabilistic, repetition of the experiment will create variance in the numbers. However, this fluctuations occur at definite average rate. Using the statistics, the fluctuations can be described and errors can be calculated. A so-called Poisson distribution can be used to describe the count distribution in the radioactive decay. To avoid repeating the measurement several times, the standard deviation can be calculated, which can simply be given by the square root of the mean count. The result can be analyzed as $\overline{N} \pm \sqrt{\overline{N}}$. in order to get the proper count rate, we have to divide the mean and the standard deviation by gate time. Consequently, a bell shaped Gaussian distributions can be obtained for a continuous distributions of values.

2 Experimental Set-up and Procedure

2.1 Using the Geiger-Müller Tube

As shown below in the figure, the experiment was set up.

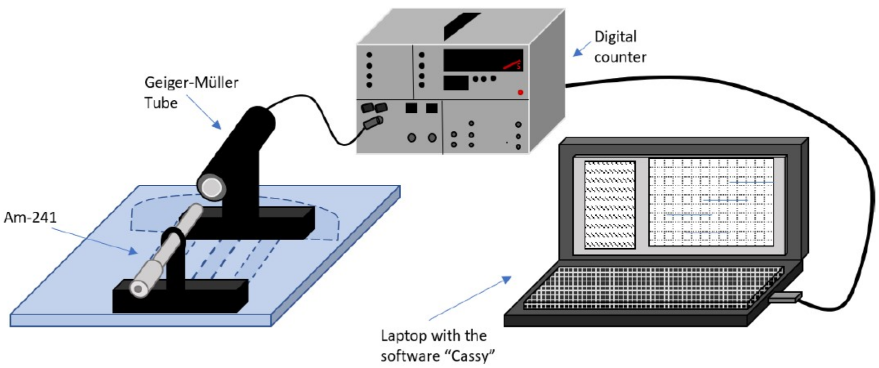

Figure 3: Experimental Setup for Using Geiger Müller tube to detect the range of α particle and its penetration effect effect on materials

With careful attention while handling the GM tube, the inlet A was connected to the digital counter and the protective cover of the tube was then removed. As shown in the figure, the Americium 241 sample was carefully placed next to the mouth of GM tube allingned parallel to tube at 15cm. The digital counter was connected to the laptop and the "Digital Counter" software was started. The digital counter was switched on and the button A was pushed. Also the loud speaker was turned on and the gate time was selected to 10 second. The Voltage in the digital counter was set to 100 V and it was raised slowly until the count from the loud speaker was heard. Then again the voltage was decreased by 50 V and the count in independence of the voltage was recorded. As the gate time of 10 sec was passed, the count rate was recorded with corresponding voltage. The voltage was raised then simultaneously, smaller in the beginning and larger at the end, and the readings were taken till 500 V.

2.2 Determining the half-life of Ba-137m

As shown below in the figure, the following experimental set up was introduced in the beginning.

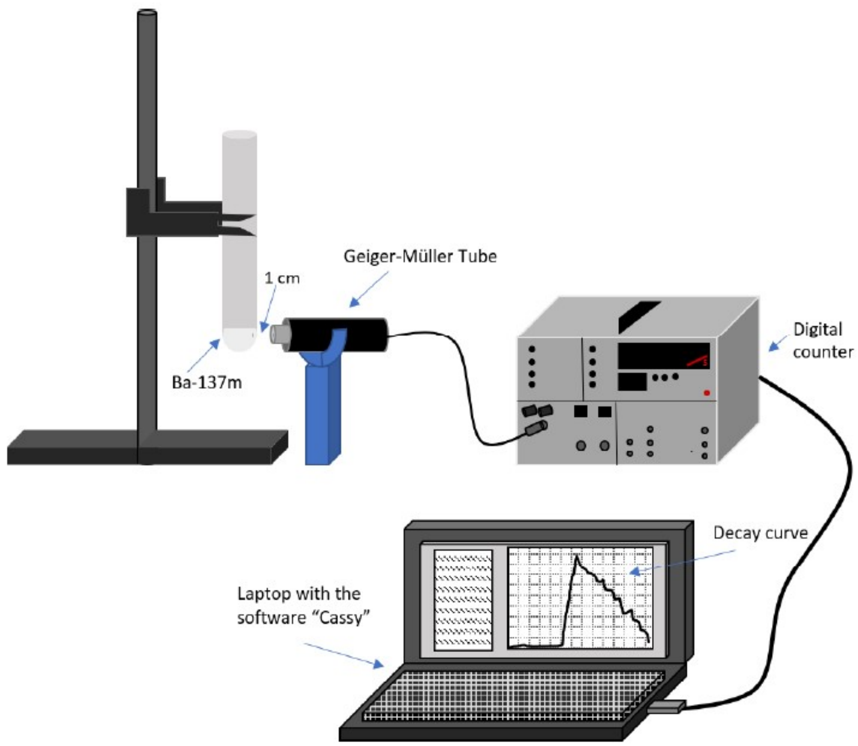

Figure 4: Experimental setup for recording the decay curve of the meta-stable Ba-137m

The instructor prepared the Ba-137m and it was kept in the reaction tube. The GM tube was then clipped close to the reaction tube at the bottom as shown in the figure. Finally, the GM tube was connected to the digital counter which was again connected to the laptop. The recording was done longer than 5 minutes.

3 Results and Data Analysis

As per the procedures explained above, the experiment was performed and the raw findings were used in in order to obtain the following meaningful results.

- Calculation of actual activity of radioactive element AM-241.

As per the data provided on the sample, the calibrated value of Americium-241 was 370 KBq. With regard to the date mentioned on the sample, the time difference of Am-241 was found to be 18 years, 7 months, 20 days, and 15 minutes which is equal to 587520900 seconds.

From the previous equation (4), we have:

$$N(t) = N_o \cdot e^{-\lambda \cdot t}$$

Also, from equation (5), we have;

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Therefore, using these two equations and the given half life of the sample, the value of λ was calculated to be;

$$\lambda = 5.09 \cdot 10^{-11} s^{-1}$$

Therefore,

$$N(t) = 359.099\ KBq$$

- Characteristics of the GM tube

In order to determine the optimal voltage for the proper functioning of GM tube, the following measurements were taken for 18 times as tabulated below.

VOLTAGE [V]	COUNT RATE [1/S]
336	0
340	0
348	22
352	24
364	25
372	26
400	27
428	26
432	26
440	26
448	26
452	26
460	26
464	25
472	26
480	25
492	25
500	26

Table 1: Count rate of the digital counter corresponding to the given voltage

Then after, the count rate versus voltage graph was plotted in order to obtain the threshold and operating voltage of the GM tube between 336 and 500 volts.

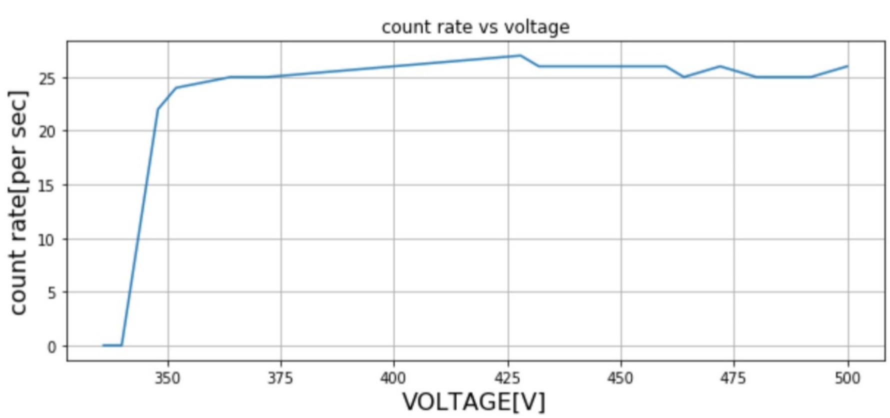

Figure 5: Graph of count rate versus voltage to determine the operating voltage for the GM tube

Studying the graph above, the stable voltage was found to be from 380 volts.

Thus, after analyzing the graph carefully, we were determined to use 472 Volt as our operating voltage.

From the graph, threshold voltage can be determine as 348 volts.

- Random decays and Statistics

The GM tube was setup at the distance of 8 cm from the source and the frequency of different count rates was observed using the voltage of 472 V, and the gate time of 1 second.

COUNT RATE [1/SEC]	FREQUENCY
0	48
1	106
2	144
3	650
4	86
5	48
6	28
7	11
8	6
9	1

Table 2: Frequency of the count rate

Using the above data, the histogram was plotted, so called as as Poisson distribution.

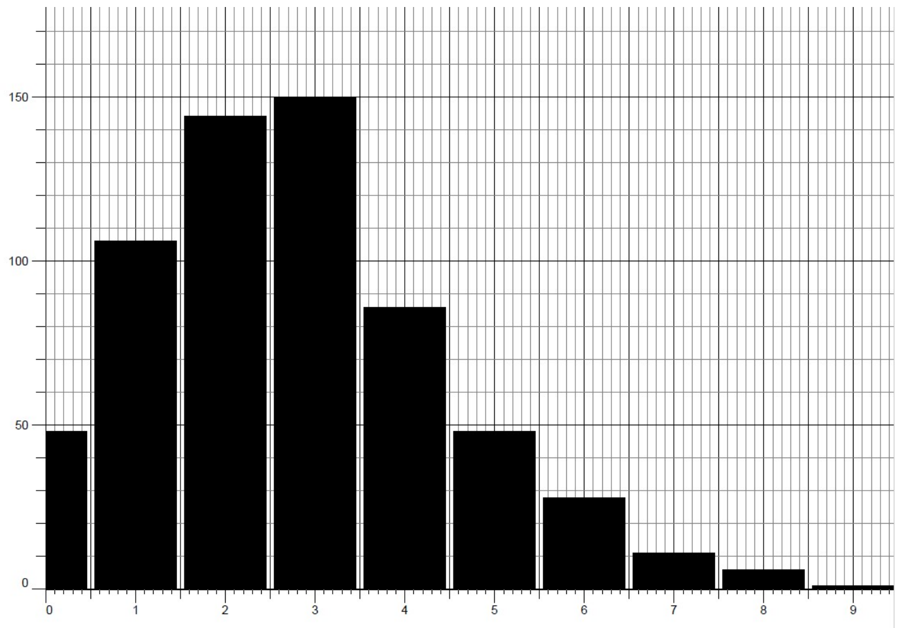

Figure 6: Poisson Distribution

From the above histogram, we get:

$$\overline{X} = \frac{\Sigma f x}{f} = 3.28\ s^{-1}$$

And the statistical error of the Poisson distribution can be determined by,

$$\sqrt{\overline{X}} = 1.81\ s^{-1}$$

Therefore, mean count rate is (3.28$\pm$1.81) s^{-1}

- Range of radiation of Am-241 sample in air

In order to determine the range of radiation of AM-241 sample, the graph was plotted for logarithm of count rate as a function of distance from the GM tube. The measurement was done without any physical shield, and then with paper. The following data were collected.

Without paper		With paper	
Distance mm	Count rate 1/s	Distance mm	Count rate 1/s
5	59592	5	1235
6	59832	6	1039
7	58775	7	853
8	56927	8	837
9	52808	9	704
10	48703	10	629
11	43775	11	547
12	38274	12	544
14	23702	14	437
16	8899	16	370
18	1599	18	293
20	375	20	262
22	315	22	257
25	220	25	181
30	156	30	159
40	102	40	85
50	75	50	71
60	45	60	51
70	27	70	30
80	30	80	30
90	24	90	22
100	14	100	17

Table 3: Count rate as a function of distance with and without paper

From the above data, following graph was obtained.

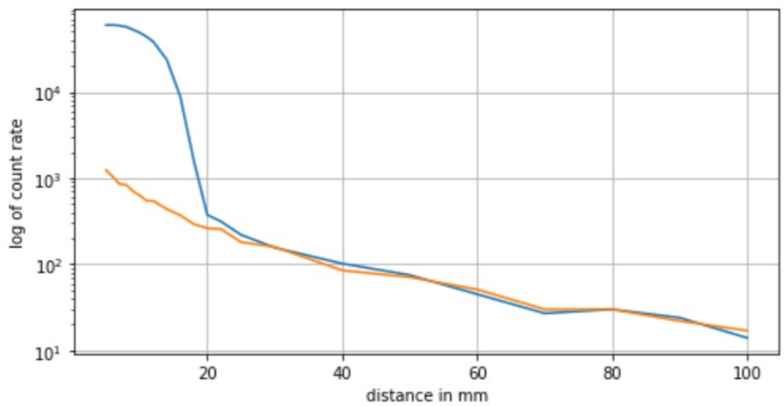

Figure 7: Logarithm of count rate over distance

According to the graph above, the blue line gives the data without any physical interference, and the second one gives the count rate when paper was placed between GM tube and source. The curve l started aligning from 20 mm. Therefore, we concluded that the range for alpha particle was found to be 20 mm. Also, while measuring the distance from the GM tube, the reduction of range for alpha radiation was given in the manual 1.4 cm and instrumental error was of 2 mm while calculating the larger distances. Hence, including the whole error, the range of alpha particle was found to be:

$$Range = 20 \pm 2\ mm$$

- Absorption of γ radiation by different materials

By placing different materials like Pb, Fe ,Al, Hard paper, and Plexi glass between the GM tube and source of radiation, the absorption of gamma radiation was determined. Distance of 2.5 cm was used between source Am-241 and GM tube. The ratio of decrease in count rate from the initial count was calculated and the following results were obtained.

Count rate 1/s	Density g/cm^3	$\frac{N_O - N_{mat}}{N_0}$	Materials
3.5	11.41	0.98	Pb
28	8.1	0.87	Fe
126.4	2.68	0.39	Al
172.5	1.39	0.17	Hard paper
184	1.12	0.12	Plexi Glass

Table 4: Absorption level of the different materials with various densities.

Using the tabulated data above, the graph of $\frac{N_o - N_{mat}}{N_o}$ versus density was plotted.

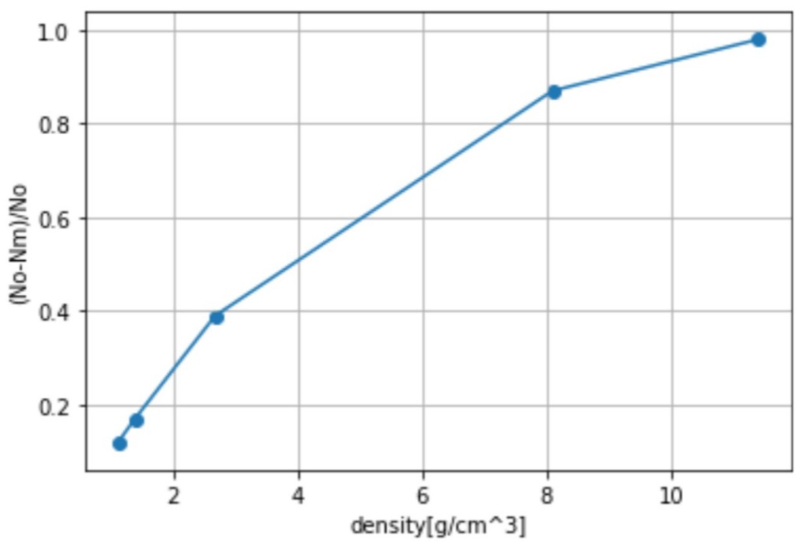

Figure 8: Absorption level of material versus densities

From the graph above, we concluded that the number of penetrated radiations decrease or the absorption of gamma radiation increase with the increase in density of the material. We can see that count rate is decreasing with the increase of density. It can clearly observed from a graph that almost every gamma radiation are absorbed by the material with density of about 11.5 g cm^{-3}. Also, it was analyzed that increase in the atomic number increases the absorption capacity of material up to certain number (as it would remain constant then after).

- Determination of the half-life of Ba-137m

In order to determine the half-life of Ba-137, the count rate was calculated every 10 seconds and the respective value of $\ln \frac{N(t)}{N_o}$ was determined. The graph was plotted for of $\ln \frac{N(t)}{N_o}$ as a function of time and the best fit line was determined from the plot. From the linear equation of that line, the value of λ was determined.

As we have:

$$\lambda t = \ln\left(\frac{N_o}{N(t)}\right)$$

The following data were calculated from the the count rate using the formula above.

Time (s)	ln (N_o/N(t)
10	0
20.1	0.152137
30	0.200223
40	0.197763
50	0.232766
60	0.220124
70.1	0.419679
80	0.428924
90	0.509482
100	0.615589
110	0.597104
120.1	0.669242
130	0.673186
140.1	0.709408
150	0.817504
160	0.864242
170	0.845284
180	1.002569
190.1	0.854718
200	1.195941
210	1.053284
220	1.137672
230	1.131402
240.1	1.250749
250	1.346764
260	1.354546
270	1.362389
280	1.189296
290.1	1.293921
300	1.524445
310.1	1.591455
320	1.506096
330	1.524445
340	1.591455
350	1.673976
360.1	1.611456
370	1.611456
380	1.479188
390	1.812127
400	1.799857
410.1	1.943896
420	2.047693
430	2.032189
440	2.001883
450	2.079442
460.1	2.314756
470	2.016921
480.1	2.095702
490	2.377935
500	2.335375
510	2.595658
520	2.56899
530.1	2.623057
540	2.56899
550	2.377935
560	2.710068
570	2.468906
580.1	2.543014

Table 5: Calculated value of $\ln\left(\frac{N_o}{N(t)}\right)$ and Time

According to the results obtained in the table, a graph of maximum voltage produced as a function of frequency was drawn, which is shown below.

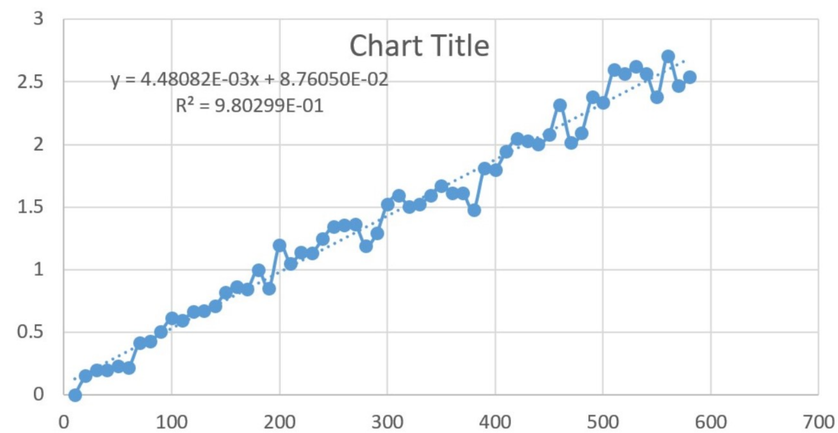

Figure 9: $\ln\left(\frac{N_o}{N(t)}\right)$as a function of time

From the equation of line in the graph we get:

$$Slope\ (m) = 4.48 \cdot 10^{-3}$$

As we have λ = m = 0.00448;

$$t_{1/2} = \frac{\ln 2}{\lambda} = 154.69\ seconds$$

For the calculation of error in slope, we get from the graph: $R^2 = 0.98$.

$$\frac{\Delta m}{m} = \sqrt{\frac{1-R^2}{(n-2)R^2}}$$

Therefore, Δm = 2.93

Thus, half life period was found to be (154.69 $\pm$2.9) s^{-1}.

4 Error Analysis

The instrumental and mathematical error is already discussed in the results and data analysis part. According to the Poisson distribution, the error in the mean count rate is determined by $\sqrt{\overline{X}}$ and was found to be 1.81 s^{-1}. While calculating the range of alpha particle, the reduction of range for alpha radiation was mentioned in the lab manual as 1.4 cm or 14 mm. Similarly, while calculating the distance there was instrumental error of 2 mm and the error in the half life period of Ba-137 was found to be 2.9 seconds. However, both of the values were close to the literature value.

5 Discussion and Conclusion

The main objective of this experiment were to determine the range of radiation of Am-241 radioactive sample in air, absorption of gamma radiation by different materials and determine the half life of Ba-37m. The range of alpha radiation was found to be 20$\pm$2 mm which is near to the literature value of 17 mm .By penetrating the gamma radiation through different materials, it was found that the absorption capacity of material would increase with increase in density of the material which would eventually provide better shield from radiation. Moreover, the half life of Ba-137m was found to be (154.69$\pm$2.9) seconds which is almost equal to literature value of 156 seconds. Due to higher half-life of Am-241, the decrement in the activity was only of about 2.95% in the span of about 18.5 years. It verifies that the sample can be stored for a long period of time.

6 References

- Modern Physics Lab Manual CH-141-B fall 2020 (Prof. Dr. Jürgen Fritz and Dr. Vladislav Jovanov).
- Error analysis booklet for physics teaching lab at Jacobs university
- University Physics by Young and Freedman
- Wikipedia