Proximity and Protection: An In-Depth Study of Absorber Materials and Spatial Dynamics in Radiation Safety

PHYC11 - Lab 3

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Abstract

This study aimed to investigate how spatial parameters, such as distance, and shielding of absorber materials with varying thicknesses, impact health and safety when discussing radiation. To measure counts per second (cps) of radioactive sources, a Geiger-Müller counter and an ST360 Radiation Counter by Spectrum Techniques were utilised. The radioactive sources used in this study were Polonium-210 (alpha emission), Thallium-204 (beta emission) and Cobalt-60 (beta and gamma emission). The collected data indicated that the radioactivity of all radioactive types decreased as the distance to the GM detector increased, following an inverse square law pattern. Furthermore, the study revealed that the plastic, aluminium, and lead absorbers were the most effective at shielding Thallium-204, with an increasing pattern proportional to the mass thickness. For Cobalt-60, the lead absorber was found to be the most effective and additionally at higher mass thicknesses. However, it's worth noting that measurement errors arose from non-corrections of the air medium through which the radioactivity passed and Polonium-210 half-life.

1. INTRODUCTION

When the term "radiation" is mentioned, it often evokes feelings of fear and danger. While it is true that radiation can be harmful to humans in general, there are many factors to consider when assessing its severity and potential threat. It is also crucial to realise that everyone is subjected to radiation in some form throughout their lifetime. While many assume that artificial sources such as medical and dental procedures, consumer products, and nuclear reactors are the primary culprits, natural sources of radiation on Earth also expose the human population. According to Shahbazi-Gahrouei et al. (2013), approximately 82% of human-absorbed radiation doses come from natural sources. These natural sources include radon gas, terrestrial sources, and cosmic radiation. Unfortunately, it is impossible to avoid radiation entirely as natural radioactivity exists in every part of the world. However, it is crucial to understand the genuine danger that radiation poses to human health and how to avoid significant doses. It is worth noting that not all forms of radiation are harmful to humans. Light, for instance, is radiation, and it is essential to be aware of our surroundings. Radiation is also sometimes employed in the medical field as a treatment for patients.

1.1. Radiation Types and Safety

The International Atomic Energy Agency (IAEA) defines radiation as energy that is transported in a form that can be described as particles or waves (Galindo, 2023). As explained before, radiation can be used in certain treatments and benefit many. However, radiation can also do intensive harm to the human body. Thus, a good overview of radiation and radiation types must be explained in detail for clarity.

Radiation can be grouped into two main types: *non-ionising* and *ionising* radiation. As the name implies, non-ionising radiation does not possess sufficient energy to detach electrons from atoms or molecules (Galindo, 2023). However, its energy is enough to vibrate molecules and produce heat, which is the concept behind microwaves in modern households. Other than heat production, non-ionising radiation does not pose a risk to one's health. On the other hand, ionising radiation does have sufficient energy to detach electrons from atoms or molecules which can cause changes at the atomic level. This type of radiation can damage living organisms and involve the production of ions. High doses of this type of radiation can cause serious damage to cells and organs and can be fatal. However, it is worth mentioning that in controlled amounts and with protective measures considered, ionising radiation can be used beneficially. For instance, this type of radiation is often used for energy production and in cancer treatments. From this point on, this paper will shift the attention to ionising radiation only as it is the radioactive type that is the focus of this study.

Ionising radiation can be further broken down into three different types of radioactive decay. These types include alpha, beta and gamma radiation. In alpha radiation, a positively charged helium-4 nucleus is released from the decaying nuclei. The particle released is also called an alpha particle. Due to the particle's size, it cannot penetrate most materials. Fortunately, alpha particles cannot penetrate through human skin or even a thin piece of paper (Galindo, 2023). However, this does not mean that they are not dangerous. If alpha-emitting substances are within the body, say through consumption, so that alpha particles can interact with organs and internal tissues, they can cause serious damage.

Beta radiation involves the emission of electrons, also called beta particles, during radioactive decay. Because beta particles are much smaller, they can travel farther and penetrate further compared to alpha particles. Similar to that of alpha particles, beta particles are most harmful if ingested (Fore, 2021). However, according to the United States Environmental Protection Agency (EPA), they are less damaging to DNA and tissue because their ionisations are more widely spaced as opposed to alpha particles (*Radiation Basics* 2023). Even though they are more penetrating than alpha particles, they can actually be stopped by a layer of clothing. If contact with skin is made, beta particles are capable of penetrating the skin and causing damage through skin burns.

Lastly, gamma radiation involves the emission of gamma rays. Unlike alpha and beta radiation, the emission of gamma rays is pure energy (*Radiation Basics* 2023). The packets of energy transported in gamma rays are known as photons. Gamma rays have much further penetration power as compared to the previous radiation types and can sometimes pierce through the human body undisturbed. However, gamma rays can also cause ionisation as they pass through damaging DNA and tissue. During the emission of gamma rays, they are often paired with alpha or beta radiation during decay.

Now knowing the radiation types and their effects, radiation safety must be discussed. According to the Centers for Disease Control and Prevention (CDC), the risks of radiation can be reduced when following three principles: time, distance and shielding (Hawes, 2024). The time spent near the radioactive source should always be kept at a minimum. This helps reduce the total dosage one would receive near a radioactive source. The distance between the person and the radioactive source should be large to lessen the exposure. Finally, shielding can help reduce exposure to radioactive sources. Shielding means having a material between a person and the source. However, the effectiveness of shielding can be a result of many factors such as the source of radiation, the shielding material and the shielding thickness. This paper aims to study the effectiveness of distance and shielding with the three types of ionising radiation.

1.2. Distance and Shielding

Some important theories of radionuclides and their relationship to distance and interactions with shielding should be understood. The activity of a radioactive source is typically measured in disintegrations per unit of time, such as seconds (dps), through a detector. However, this study utilises counts, which are disintegrations as measured by a detector. To measure this quantity, a Geiger-Müller (GM) counter (or tube) is used, which will be further explained in the method section. When a radioactive source is placed at a distance h away from the (GM) counter, radiation is emitted not only towards the device but in all directions. As illustrated in Figure 1, the source has a sphere of radiation emitted away from it, and only a small amount enters the GM counter. As the source is moved away, the activity

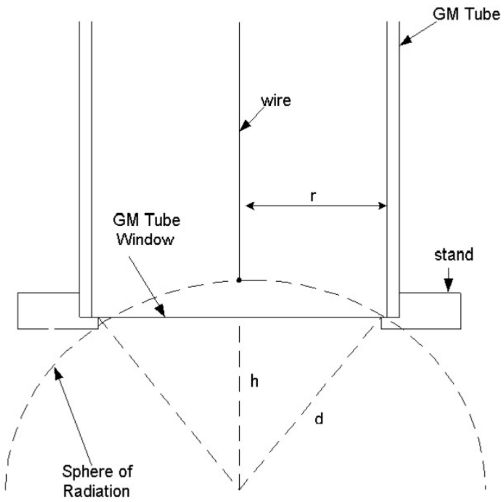

Fig. 1: Diagram showing the sphere of radiation emitting away from the source placed a distance h away from the GM tube (*Spectrum Techniques Student Lab Manual* 2014).

decreases following the *inverse square law*. Consequently, the activity of the source drops proportionally to the square of the distance from the detector. This effect will be studied using different sources of radiation that emit different radioactive particles.

As mentioned earlier, alpha particles are helium nuclei and so they are considered heavy particles when compared to the other forms of radiation. As alpha radiation passes through matter, it comes into close contact with atoms of the material (*Spectrum Techniques Student Lab Manual* 2014). The positive charge of the alpha particle attracts valence electrons of the atoms in the material, sometimes ionising the atom. If ionised, it must transfer some energy to the freed electron. Aside from inelastic collisions in material, this is the only true interaction that the alpha particle has while passing through matter. Its energy loss as it passes through the material can be calculated using the Bethe-Bloch equation,

$$-\frac{dE}{dx} = K\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2v^2W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right] \tag{1}$$

Where $K = 0.1535MeVcm^2/g$, Z is the atomic number, ρ is the density of the absorbing material, A is the atomic mass of the absorbing material, z is the charge of the incident particle, $\beta = v/c$ for the particle, I is the mean ionisation energy, δ is the density correction and W_{max} is the maximum energy transfer in a single collision. Although the derivation of the equation is quite complex and will not be covered in this paper, it's worth noting that a close analysis of the equation reveals some important results. Specifically, there are two notable correction terms in the Beth-Bloche equation that account for density and shell effects. The density effects are due to the fact the atoms in the material become polarised by the electric field as the alpha particle passes by. Consequently, electrons on the far side of the atom will be shielded from interactions with the alpha particle; this effect reduces the possible interactions. The shell effect arises when the velocity of the alpha particle is equal to or less than the orbital speed of the electron, removing the assumption that electrons are stationary. The Bethe-Bloch equation predicts that higher material density is correlated with greater energy loss, a relationship that seems to hold true for the atomic number as well.

Beta particles also follow a similar ionisation energy loss that is predicted by the Beth-Bloch equation (*Spectrum Techniques Student Lab Manual* 2014). However, a significant difference is that the beta particles are much less massive than the alpha particles. This results in beta particles being able to be largely scattered in the material. There is also an effect known as *bremsstrahlung*. Bremsstrahlung results from a beta particle passing closely to the nucleus of an atom. The electromagnetic interactions slow the beta particle down and cause it to change directions. So unlike alpha particles that will traverse in relatively straight paths due to their mass, the beta particle follows a more complex path of a "zigzag" pattern as it passes through matter.

Lastly, gamma rays can interact with matter in three different ways. These are the Photoelectric effect, Compton scattering, and Pair production (*Spectrum Techniques Student Lab Manual* 2014). The *photoelectric effect* occurs when a photon is absorbed by an electron which causes the ejection of an electron from the atom. The ejected electron can obtain a maximum energy given by,

$$KE_{max} = E_\gamma - \Phi \tag{2}$$

Compton scattering describes the scattering of photons on electrons. If the photon has sufficient energy, it will experience an inelastic collision with the electron giving some of its energy to the electron. The photon incident on the electron has energy hv where v is the frequency of the electron and h is Planck's constant. The photon scattered leaves with a new energy hv'. This value can be calculated using equation 3 if the scattering angle of the photon, θ, is known.

$$hv' = \frac{hv}{1 + \gamma(1 - \cos\theta)} \tag{3}$$

Pair production is the transformation of a photon into an electron-positron pair. Due to momentum conservation, this only occurs when the photon is close to the nucleus of the atom in the material. The photon only requires the energy equivalent to that of the mass of an electron-positron pair, which is $1.022 MeV$. However, it rarely occurs for photon energies less than $1.5 MeV$, since the electron-positron pair usually have kinetic energy. Usually, the photoelectric effect dominates for photon energies between $4eV$ to $0.5 MeV$. Compton scattering dominates up to $2 MeV$. Pair production dominates above $10 MeV$.

1.3. Objectives

This paper aims to examine the effects of distance and shielding on the three ionising radiation types - alpha, beta and gamma. The motivation behind this study is to explore the techniques and materials required to mitigate the effects of radiation exposure in a setting characterised by significant radioactivity.

2. METHOD

The counts of radioactivity of the three sources of radiation were measured using an apparatus designed and manufactured by Spectrum Techniques. The apparatus included a Geiger-Müller counter and a ST360 Radiation Counter.

2.1. Apparatus

The setup of the apparatus is shown in Figure 2. In the figure, we can see the Geiger-Müller Counter (GM) on the right side and it is connected to the ST360 Radiation Counter. Once the GM counter detects a disintegration, registered as a count, it sends the information to the ST360 to process the information. The ST360 is connected to the PC where software is used to log the data of counts. The GM tube works by taking advantage of the ionisation properties of the radioactive source. Within the GM tube, it contains a gas that can be easily ionised. The gas is a neon, argon and halogen mixture. On one end of the GM tube, it contains a thin window known as a mica window which allows the entrance of alpha particles. A wire inside runs along the centre axis of the GM tube and acts as an anode, while the tube acts as the cathode. The wire and tube are connected to an electric circuit to maintain a high voltage.

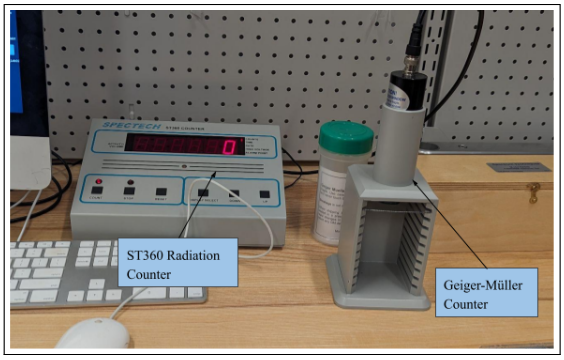

Fig. 2: Picture taken of apparatus used in study. On the right side is the Geiger-Müller Counter and the left side is the ST360 Radiation Counter.

As radiation enters through the mica window, it ionises some atoms in the gas. Due to the high voltage maintained inside the tube, the ions and electrons are accelerated toward the cathode (tube) and anode (wire) respectively as illustrated in Figure 3. However, usually, the electrons ionise other atoms

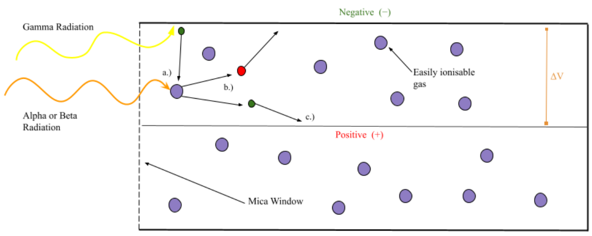

Fig. 3: Illustration of how the Geiger-Müller counter detects radiation. Part a.) shows the ionisation process of the gas within the GM tube. Part b.) shows the creation of positive ions and negative electrons (gas multiplication is not displayed) that are accelerated towards the cathode and anode respectively. In part c.), the electrons reach the anode and cause a electric discharge dropping voltage, dedicating a detection.

as they travel to the anode producing a cascade of more electrons. This process is known as gas multiplication or a Townsend avalanche. The discharge current from the electrons causes the voltage to drop. This voltage drop is detected via the ST360 Radiation Counter and is recognized as a signal of a particle and measures a count. Once measured, the data is sent to the PC where it is logged using software provided by Spectrum Techniques.

2.2. Research Procedure

The apparatus was used to conduct two separate experiments, measuring different properties of radiation. The first experiment focused on the relationship between the source of radiation and its distance from the GM tube, while the second experiment examined the effects of the source of radiation on different absorber types and their respective thicknesses. The experiments used Polonium-210 (alpha emission), Thallium-204 (beta emission), and Cobalt-60 (beta and gamma emission), each of which is depicted in Figure 4. Prior to conducting

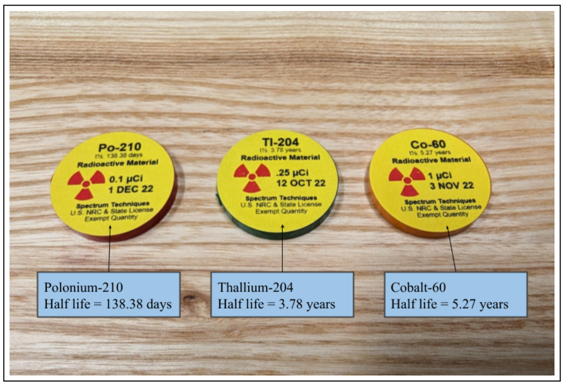

Fig. 4: Image displaying radioactive sources used in the study. The left is Polonium-210 (alpha emission), center is Thallium-204 (beta emission) and on right of the image is Cobalt-60 (beta and gamma emission).

the experiments, the GM plateau was measured and plotted to determine the optimal operating voltage. A value of $900V$, slightly left of the middle of the plateau, was chosen for best performance. The GM apparatus also features shelves spaced approximately 2 centimetres apart underneath the GM tube.

In the first experiment, the operating voltage was set to $900V$ and the data collection time for measuring counts was set to 30 seconds. The first run for all radioactive sources was done without any radioactive source in the GM apparatus to measure the background level for corrections. Next, the source was placed on the first shelf ($2cm$ from the GM tube). For subsequent measurements, the source was placed on the next shelf below for each run until the final shelf was reached ($20cm$).

In the second experiment, the operating voltage was set to $900V$ and the data collection time for measuring counts was set to 60 seconds. The absorber materials used in the experiment are summarised in Table 1 and absorber types are shown in Figure 5. Also listed in Table 1, is the mass thickness which is representative of how much matter is being passed through by the radiation source. The identifier labels are used to differentiate the absorbers of the same type by mass thickness. Absorbers C and D, which were thinner plastic sheets, were not used in this study as they were determined to display similar results to absorbers E and F. The initial run for all radioactive sources was done without any of them in the GM apparatus to measure the background level for corrections when analysing data. Then, the source was placed on the second shelf ($4cm$ from the GM tube) without any absorber material between the source and the GM tube. After this test, an absorber was placed on the first shelf ($2cm$ from the GM tube) above the radioactive source. Subsequent measurements made were with absorbers of the same type but with higher mass thickness.

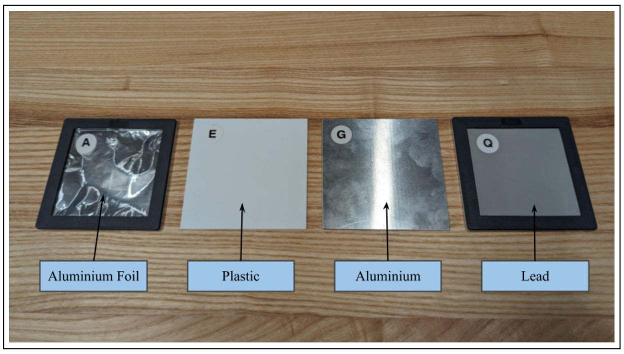

Fig. 5: Absorber materials used in the study. In the image, the absorbers presented are aluminium foil, plastic, aluminium and lead.

3. RESULTS

The first set of data from the first experiment examining the effects of distance from the GM tube for each radioactive source is shown in Figure 6. In the graphs, the counts per second (cps) measured by the GM counter are shown on the y-axis and the changing distance from the GM counter is displayed on the x-axis in their respective units. Also included in the graphs, is a best-fit line restricted to an inverse square power only in the form,

$$f(x) = ax^{-2} + b$$

The inverse square law best-fit line demonstrates the pattern of the counts per second detected diminishing as the distance to the source increases. The uncertainty in the counts of radioactivity measured was calculated using the square-root rule for counting experiments (Taylor, 1996). Uncertainties to the measured distances were assessed using half values of increments to the next shelf. Thus, uncertainties in

Identifier	**Absorber Type**	**Mass Thickness** (mg/cm^2)
A	Aluminium Foil	4.5
B	Aluminium Foil	6.5
E	Plastic	76.4
F	Plastic	104.1
G	Aluminium	130.7
H	Aluminium	163.9
I	Aluminium	206.7
J	Aluminium	261.4
K	Aluminium	323.5
L	Aluminium	415.1
M	Aluminium	531.5
N	Aluminium	601
O	Aluminium	669.6
P	Aluminium	814
Q	Lead	1031.3
R	Lead	1878.3
S	Lead	3721.8
T	Lead	7413.8

Table 1: Table of absorber materials used in this study. The identifier labels are used to differentiate the asborber's of the same type by mass thickness.

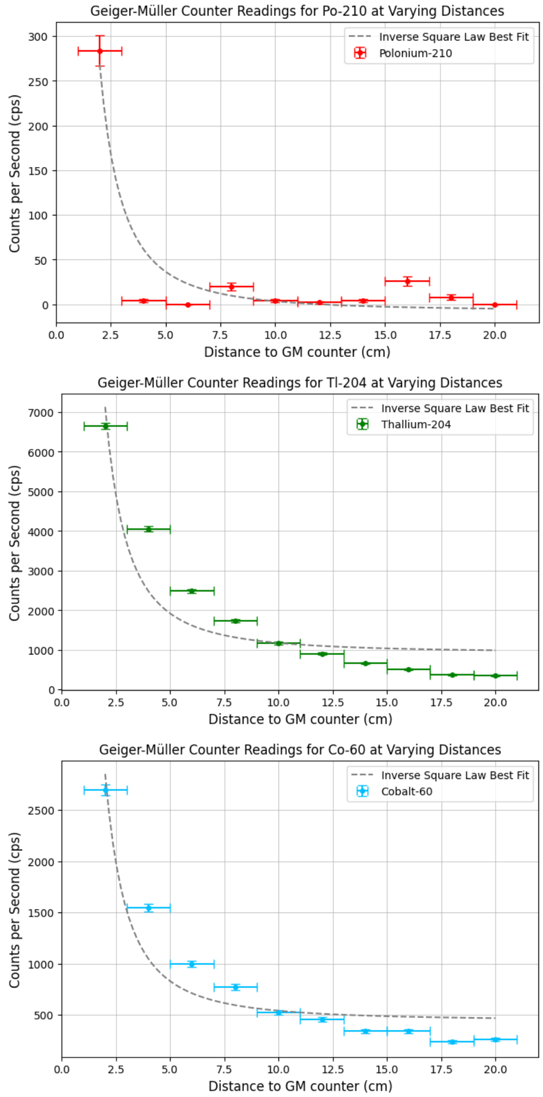

Fig. 6: Experiment 1 data measuring the effects of distance on counts per second detected by GM Counter. Data is shown for each radioactive source: Polonium-210 (red), Thallium-204 (green) and Cobalt-60 (blue).

distance measurements were $\pm 1cm$. It was observed that Polonium-210, the alpha emission source, experienced a significant drop in counts from the first shelf ($2cm$) to the second shelf ($4cm$) and levelled off for the remainder of the measurements. The following sources, Thallium-204 and Cobalt-60, followed a relatively similar pattern that seemed to align with the inverse square law best fit.

The second set of data from the second experiment analysing the effects of absorber types and their respective thickness for each radioactive source is shown in Figure 7. Similar to the first experiment, the counts per second (cps) measured by the GM counter are shown on the y-axis. However, the x-axis now displays the mass thickness of the absorber type. The absorber type is shown at the top of each graph as well as in the legend associated with each graph for clarity. There are few notable observations made in the set of data for each radioactive source. Firstly, Polonium-210 was shown to fluctuate at low count values for all absorber types. Thus, it is difficult to draw any conclusions or other observations from the radioactive source. Secondly, Thallium-204 activity seemed to be most reduced using plastic, aluminium and lead absorbers. It is worth noting aluminium foil did block a considerable amount of activity with the highest count reduction being 714 ± 119.8 cps. The plastic absorber was able to reduce counts significantly to a maximum of 3610 ± 81.5 cps. It was observed that at $206 mg/cm^2$ mass thickness of aluminium, counts of Thallium-204 fluctuate at low count values. A similar observation was made with the lead absorber which occurred at the mass thickness of $1031.3 mg/cm^2$, which was the thinnest lead absorber available. Finally, it was observed that Cobalt-60 activity was most reduced by the lead absorber. Additionally, there were

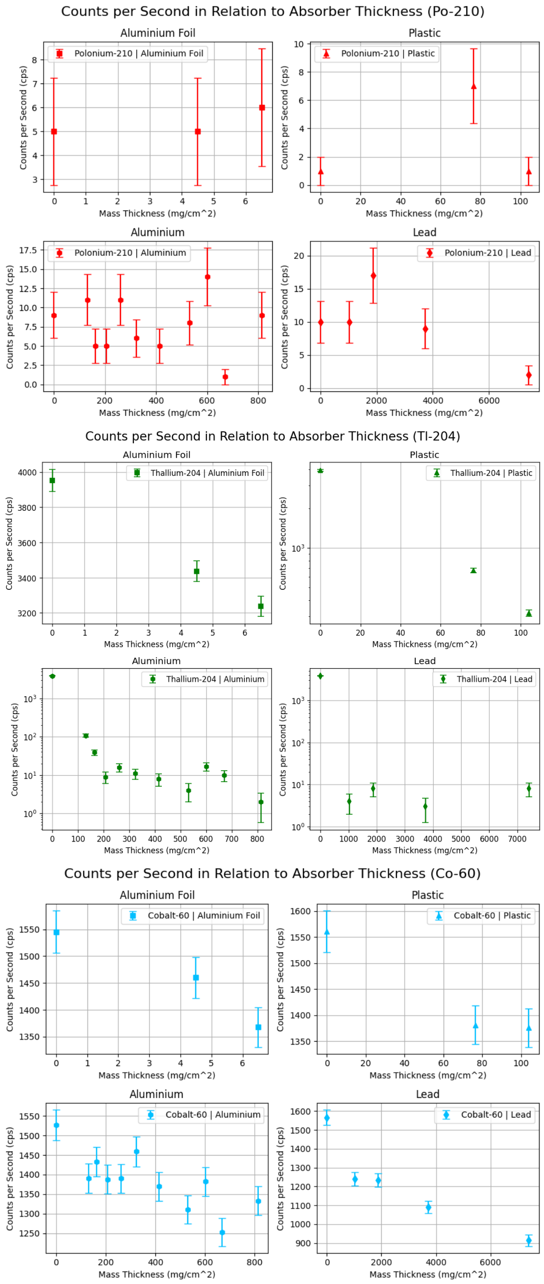

Fig. 7: Experiment 2 data measuring the effects of absorber type and mass thickness on counts per second detected by GM Counter. Data is shown for each radioactive source: Polonium-210 (red), Thallium-204 (green) and Cobalt-60 (blue). The shape of data points illustrate the absorber type: Aluminium foil (square), plastic (triangle), aluminium (hexagon) and lead (diamond).

some considerable reductions in counts detected with the other absorbers with the most significant being the aluminium absorber with a count reduction of 273 ± 74.46 cps. However, the lead absorber was the most effective absorber with a maximum count reduction of 654 ± 69.8 cps at a mass thickness of $7413.8mg/cm^2$.

4. DISCUSSION

This study was able to make some significant findings on radioactivity detection and its diminishing pattern with increasing distance as well as increasing absorber thickness of varying types. The initial dataset, illustrated in Figure 6, revealed a similar trend in the counts per second detected by radioactive sources across varying distances. However, Polonium-210 experienced a drastic reduction in radioactivity of 280 ± 19 cps when the source was moved from the first shelf ($2cm$) to the second shelf ($4cm$). Subsequently, the measured counts fluctuated insignificantly, indicating that most radioactivity is undetectable. The data collected from the other sources, Thallium-204 and Cobalt-60, displayed a reasonably good fit with the inverse square law, as shown in the graphs in Figure 6. For both sources, significant counts per second were still detected at a maximum distance of $20cm$. However, the general trend suggested that radioactivity decreases with increasing distance, eventually approaching an insignificant count.

In the second dataset, the measured counts per second detected by the radioactive sources when passed through absorbers of varying mass thickness were analysed. An intriguing observation from this experiment was that Polonium-210 showed markedly low measured counts of radioactivity for all absorbers. As such, no direct conclusions could be drawn on the effect of absorber material on Polonium-210's radioactivity. More information on this finding will be provided in the error analysis section.

It was found that Thallium-204 radioactivity was most significantly affected by the plastic, aluminium and lead absorbers. However, it is worth mentioning that aluminium foil did considerably reduce the counts per second detected of a maximum value of 714 ± 119.8 cps. The plastic absorber was able to significantly reduce the counts per second measured by a maximum value of 3610 ± 80.5 cps at $104mg/cm^2$ mass thickness. The aluminium absorber was observed to be a very effective absorber of radioactivity from Thallium-204 when then the mass thickness was $206.2mg/cm^2$ or greater. Measurements after this value fluctuate around insignificant counts per second. Similarly, the lead absorber was also an effective absorber of radioactivity from Thallium-204 when the mass thickness was $1031.3 mg/cm^2$, which was the thinnest lead absorber available for the study. Measurements with increasing mass thickness of lead absorbers showed no significant counts per second detected. The general trend in the data aligns well with predictions made by the Bethe-Bloch equation. In reference to equation 1, it is shown that the energy loss as the beta particle moves within the matter is proportional to the density of the material.

Finally, Cobalt-60 radioactivity was most significantly affected by the lead absorber. It was observed that the lead absorber significantly reduced the measured counts per second to a maximum of 654 ± 69.8 cps at mass thickness $7413.8 mg/cm^2$. However, the aluminium absorber did have notable effects on Cobalt-60's radioactivity in a measured reduction of 273 ± 74.46 cps at $669.6 mg/cm^2$ mass thickness.

4.1. Error Analysis

The reason for noticeable errors or anomalies can be explained by many factors. As explained previously, it was shown in the first experiment that all radioactive sources deviated from the inverse square law best fit in Figure 6. However, it was not taken into account that the radioactivity emitted from the sources travelled through the air before being detected by the GM counter. Thus, it must undergo interactions with air molecules before reaching the detector. These interactions alter the measured counts per second and can result in deviations from the expected inverse square law relationship. An additional source of error worth mentioning discusses the interesting observations made of Polonium-210. In the second experiment, it was found that no direct conclusions could be made on Polonium-210 and the absorber's effectiveness on its radioactivity fluctuated at insignificant values even when the absorber was not present. However, this is seen in the first experiment when Polonium-210 becomes almost undetectable on the second shelf at a distance of $4cm$. Thus, when it was placed on the second shelf for all measurements in the second experiment, it was almost undetectable as well. The reason for this anomaly is because of Polonium-210's half-life. In figure 4, it is shown that the Polonium used in this study has a half-life of 138.38 days and it was created on December 1st, 2022. That means, it has experienced approximately 3.5 half-lives. Thus the Polonium used in this study is roughly an eighth of the amount it was when it was first manufactured. Consequently, Polonium-210 showed much less radioactivity and provided data that didn't align well with the inverse square law best fit and was found to be almost undetectable in the second experiment.

4.2. Further Research

Interesting further research into this topic may include investigations of backscattering. Although the data shown in this study effectively demonstrates the importance of distance and shielding when it comes to radiation safety, the effects of backscattering are not mentioned nor studied. Further investigation into this study could provide meaningful data on methods with shielding to minimise backscattering when necessary. Additionally, this study did not investigate varying amounts of radioactive sources. The amount of radioactive material is a significant factor in the amount of radioactivity it will emit. Thus, it is an important aspect to consider when discussing health and safety around radiation.

5. CONCLUSION

In consideration of all the data presented in this study, conclusions on the effects of distance and absorber type and thickness can be made. The results demonstrate that regardless of the type of radioactive source - alpha, beta, or gamma radiation - increasing the distance between the source and the detector decreases the measured radioactivity. When graphed, the data shows a clear inverse square law relationship. Additionally, interesting findings on effective absorbers for radioactive types were observed for beta and gamma emitters. For Thallium-204, it was found that the most effective absorbers were plastic, aluminium and lead. Increasing the mass thickness of any of these absorbers resulted in reduced radioactivity. For Cobalt-60, the most effective absorber was lead, with increasing mass thickness resulting in reduced radioactivity. However, the aluminium absorber also considerably reduced radioactivity at higher mass thicknesses.

The error in measurement in this study was a result of a few factors. The interactions with air molecules was not taken into account when measuring the radioactivity over varying distances for each of the sources. This had caused deviations from the inverse square law trend. Additionally, due to Polonium-210's relatively short half-life, its detection in this study was minimal and no conclusions could be drawn from the second experiment.

Nonetheless, this study has revealed intriguing correlations between radioactivity, spatial parameters, and the shielding effectiveness of various absorber materials and thicknesses. The data presented offers valuable insights for promoting health and safety in environments where hazardous levels of radioactivity are present. It serves as a reminder of the tremendous impact that research can have on our lives and the world we inhabit. By investing in scientific exploration, we can push the boundaries of knowledge and make significant strides towards a safer, healthier future.

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