Joint Institute for Nuclear Research

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Radiation Protection And the Safety of Radiation Sources

FINAL REPORT ON THE INTEREST PROGRAMME

Supervisor:

Dr. Said Abou El-Azm

Participant:

Soumyajit Ganguly

Jadavpur University, Kolkata,

West Bengal, India

Participation Period:

October 20 - November 30, Wave 13

CONTENT

1 Abstract

Radiation protection plays a crucial role in environments where ionizing radiation is present, aiming to minimize exposure, limit biological risk, and promote safe handling of radioactive materials. Understanding radiation types, dose quantities, shielding principles, and detector behaviour is essential for applying these safety measures effectively. In this work, both theoretical concepts and practical analysis techniques were explored to study how radiation interacts with matter and how different detectors respond to gamma and alpha radiation.

Using ROOT, Origin, Excel, MATLAB, and SRIM, experimental data were processed to examine scintillation detector performance, build calibration curves, and identify unknown sources from their energy spectra. The study analyses the features of BGO and NaI detectors, pointing out that NaI has superior energy resolution and that each type of detector has its own strengths. Attenuation coefficients for aluminium and copper were determined using Cs-137 data, and the range of alpha particles in air was evaluated using several detection methods and Monte Carlo simulations.

Overall the study combines radiation protection principles with hands-on data analysis to give a clear picture of how detectors work, how materials block radiation, and how to find sources. These are all important for safely and effectively using ionizing radiation.

2 Introduction

Radiation is the emission or transfer of energy in the form of waves or particles. It is classified into ionizing and non-ionizing radiation based on its ability to penetrate and interact with matter. Ionizing radiation, such as alpha, beta, gamma rays, neutrons, and X-rays, has enough energy to remove electrons from atoms and can cause damage to cells or molecules. Non-ionizing radiation, like microwave, ultraviolet, radio, and infrared radiation, has lower energy and mainly produces molecular vibrations and heat.

Despite its risks, radiation plays an important role in many fields, including medicine, industry, energy production, agriculture, and research. When used within safety limits, ionizing radiation supports important uses such as diagnostic imaging, radiotherapy, industrial testing, and scientific experiments. However, its benefits come with the responsibility to manage exposure and ensure protection for workers, patients, and the environment.

Radiation protection is the science of keeping people and the environment safe from the harmful effects of ionizing radiation while allowing its beneficial use. It focuses on reducing exposure, maintaining safety standards, and raising awareness of radiological hazards. International organizations like the IAEA, ICRP, and UNSCEAR set guidelines, exposure limits, and best practices to ensure consistent radiation safety worldwide.

In healthcare, radiation protection ensures the safety of patients and professionals during imaging and therapy. In the nuclear and industrial sectors, it reduces risks in power plants, laboratories, and when handling radioactive materials. Environmental monitoring also applies these principles to control both natural and artificial sources of radiation.

The goal of this project is to build a strong foundation in radiation protection and the safe handling of radiation sources. It aims to improve understanding of radiation-matter interaction, dosimetry, and shielding, and to develop essential skills for applying radiation safety practices in scientific and industrial settings.

3: Tasks

3.1 Task 1: Relation between Resolution and Applied Voltage for BGO

Resolution of BGO detectors is its ability to accurately determine the energy of the incoming radiation and separate it between adjacent energy peaks. It is calculated from the peak at full width half maximum (FWHM) divided by the location of the peak centroid.

Where, $$Resolution = \frac{FWHM}{Mean}$$

And $$FWHM = \sigma * 2.35$$

Therefore, $$Resolution = \frac{\sigma}{Mean} * 2.35$$

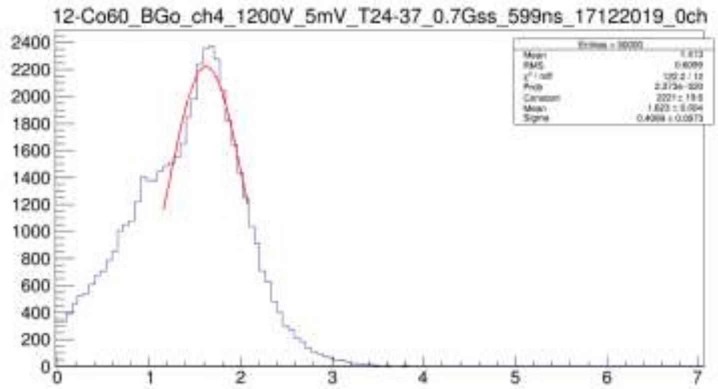


Fig1: 1200V Applied

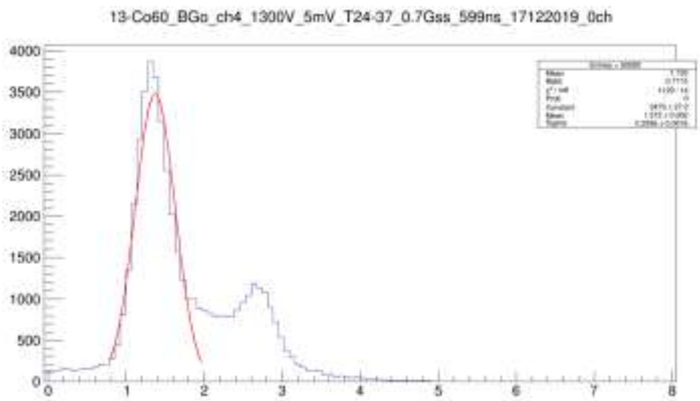


Fig2: 1300V Applied

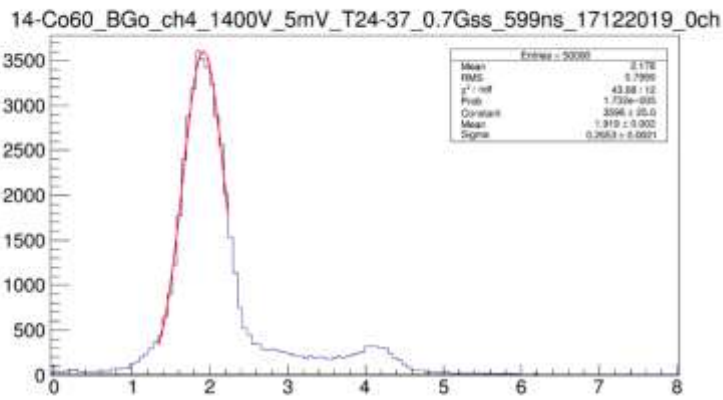


Fig3: 1400V Applied

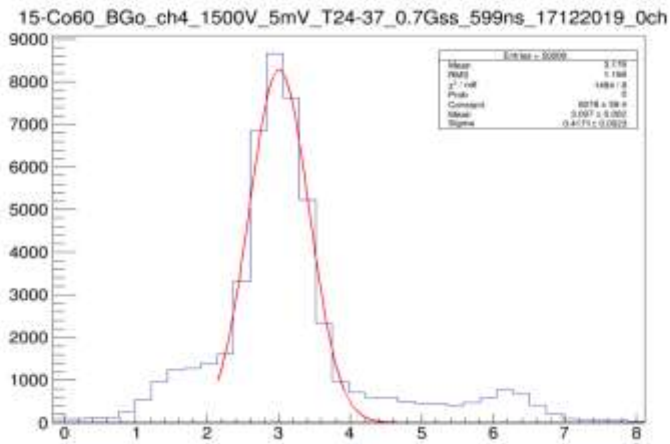


Fig4: 1500V Applied

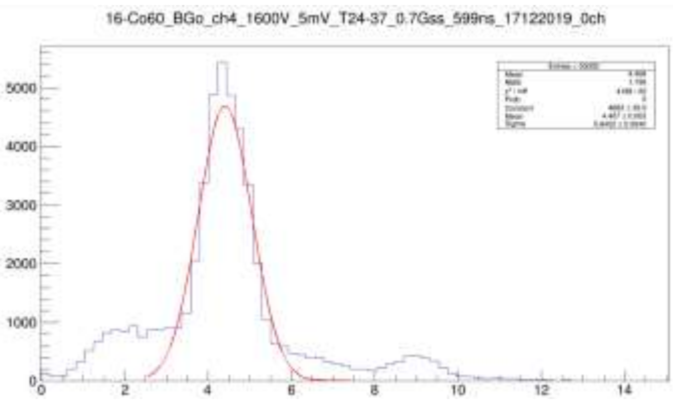


Fig5: 1600V Applied

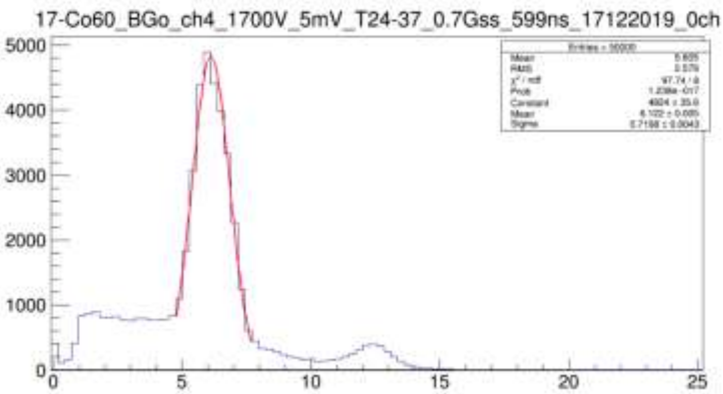


Fig6: 1700V Applied

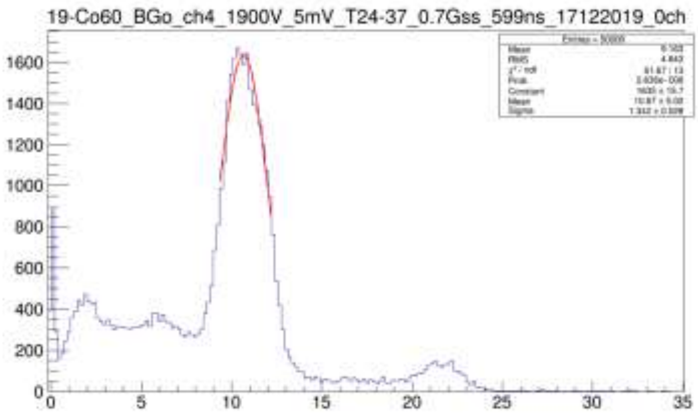


Fig7: 1900V Applied

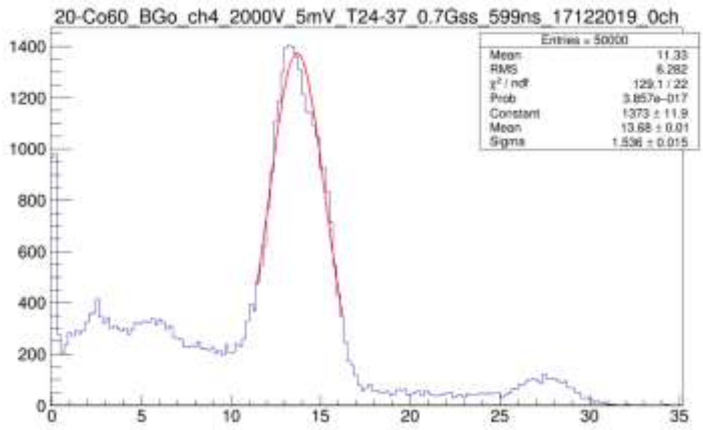


Fig8: 2000V Applied

Results:

Applied voltage(V)	σ	Mean	Resolution
1200	0.4009	1.623	58.0
1300	0.2556	1.372	43.8
1400	0.2653	1.919	32.5
1500	0.4171	3.007	32.6
1600	0.6452	4.407	34.4
1700	0.7198	6.122	27.6
1900	1.342	10.67	29.6
2000	1.536	13.68	26.3

Table 1: Resolution (%) of BGO detector corresponding to the applied voltage

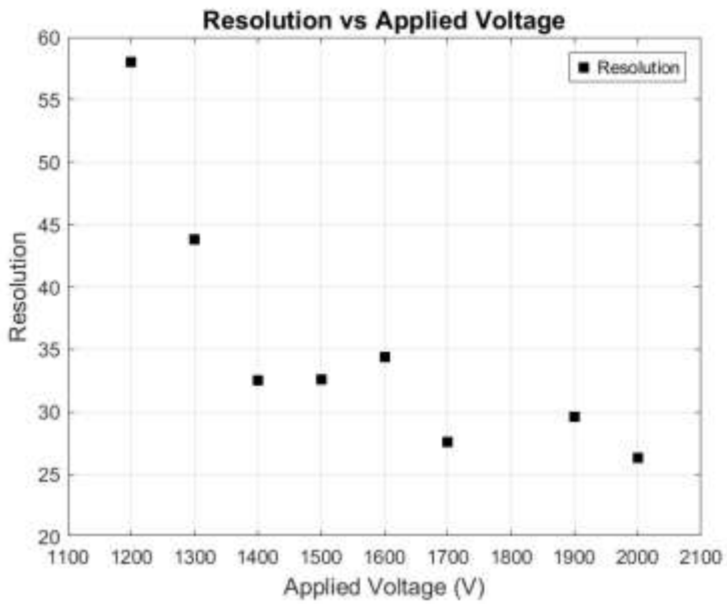


Fig9: The relation between resolution and applied voltage for BGO detector

3.2 Task 2: Energy Calibration of BGO Detectors

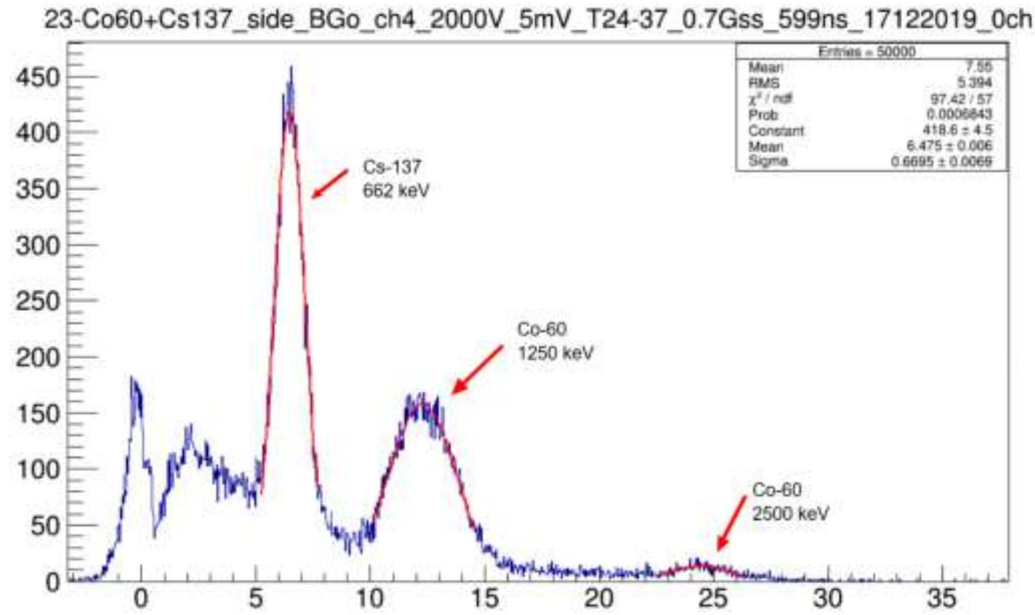


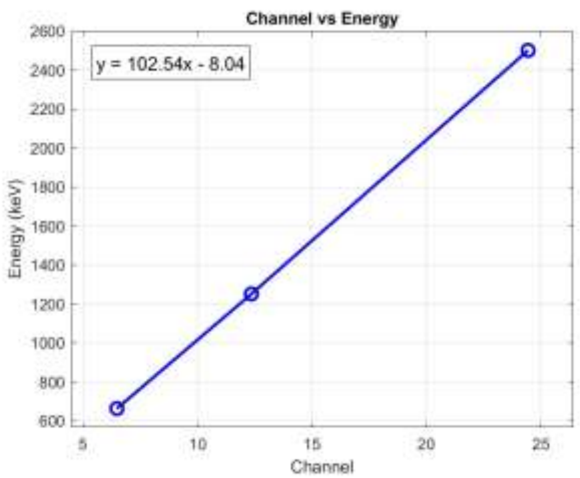
Fig10: The energy spectrum of Cs-137 and Co-60 from BGO detector measurements at 2000V

Calibration results in a relationship between the number of a given channel (mean) and its corresponding energy. Therefore, to obtain the relation, a source of known energy peaks (in this case, Cobalt and Cesium) will be used.

- The first peak on the spectrum is noise that originated due to the resolution of the detector, so it's not a peak of energy from either element.
- Cesium-137 has one energy peak, which is the first from the left. While Cobalt-60 has two peaks

Isotope	Mean	Energy(keV)
Cs-137	6.478	662
Co-60	12.352	1250
	24.431	2500

Table2: Mean and energy of Cs-137 and Co-60 peaks from a BGO detector



The equation of the energy calibration line for BGO detector is:

$$y = 102.54x - 8.04$$

Where:

x = channel number (mean)

y = energy of the peaks (in keV)

Fig11: Energy calibration function for Cs-137 and Co-60 spectrum from BGO detector measurements.

3.3 Task 3: Identification of Unknown Sources

For the identification of the energy spectrum and its unknown sources, the following steps can be applied:

i. Using the ROOT software, a Gauss function is fitted individually into the spectrum of the unknown energy, and the channel number (mean) is obtained
ii. From the equation of the calibration line of the BGO detector (from Task 3.2), the channel number can be converted to energy
iii. The unknown source of the calculated energy can be determined using the Nuclide Datasheet

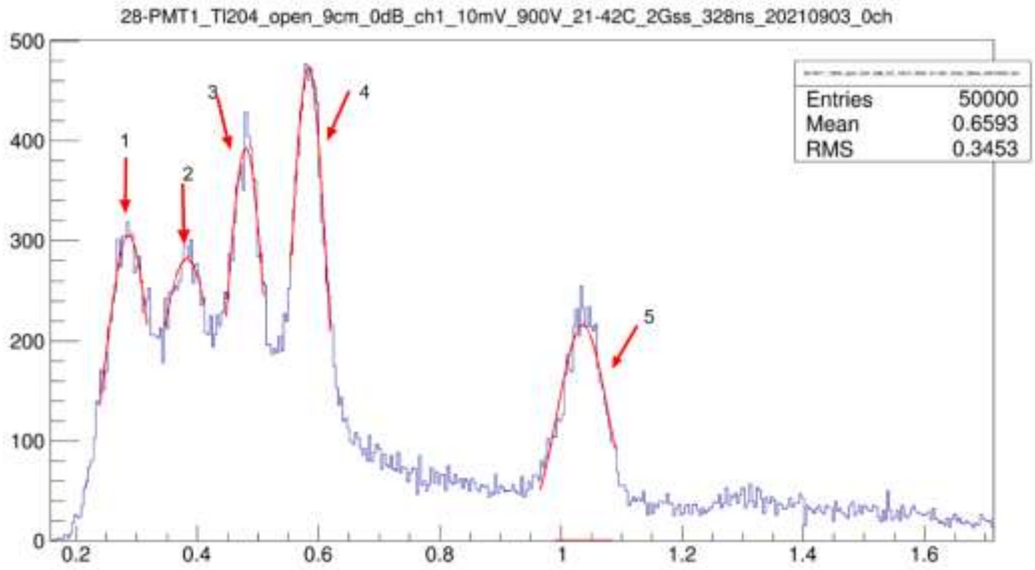


Fig12: Energy spectrum of the unknown sources from BGO detector measurements at 900V

Sample Calculation for Unknown Source Peak ID 1:

When the Gauss function is fitted the channel(mean) = 0.2866

The equation of the energy calibration line for BGO detector is: $y = 102.54x - 8.04$

Putting x = 0.2866 we get $y = (102.54 * 0.2866) - 8.04 = 21.347\ keV$

Unknown Source Peak ID	Channel (mean)	Energy (keV)	Energy (MeV)	Unknown Source
1	0.2866	21.347	0.021347	Sm-151
2	0.3827	31.2020	0.0312020	Mg-28
3	0.4792	41.097	0.041097	
4	0.583	51.740	0.051740	Rh-104m or Te-132
5	1.036	98.191	0.098191	Au-145

Table 3: Energy, channel, and peak ID of the unknown sources identified using the Nuclide Datasheet.

3.4 Task 4: Relation of Resolution Against Applied Voltage for NaI Detector

The Sodium Iodide (NaI) detector operates on the principle of scintillation, where incident radiation interacts with the crystal to produce light flashes that are then converted into electrical signals by a photomultiplier tube and the connected electronics. In comparison to the BGO detector, the NaI detector provides better energy resolution and can more distinctly separate adjacent spectral peaks. However, both detectors are limited to a maximum resolution of around 23%, making it difficult to completely resolve the two closely spaced gamma peaks of Cobalt-60. The resolution of the NaI detector thus indicates its capability to precisely measure the energy of incoming radiation and distinguish between nearby energy levels.

$$Resolution = \frac{\sigma}{Mean} * 2.35$$

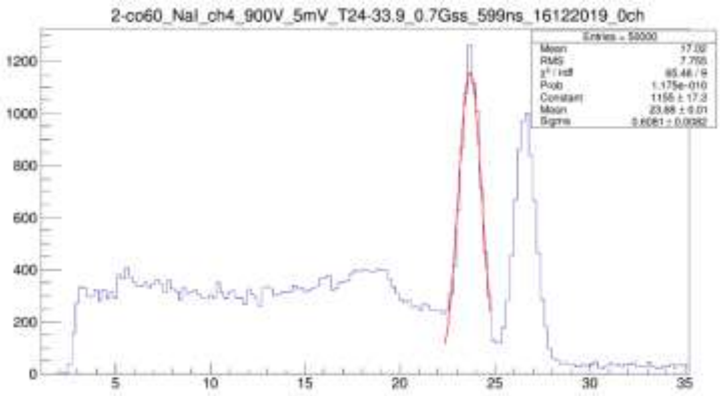


Fig13: 900V Applied

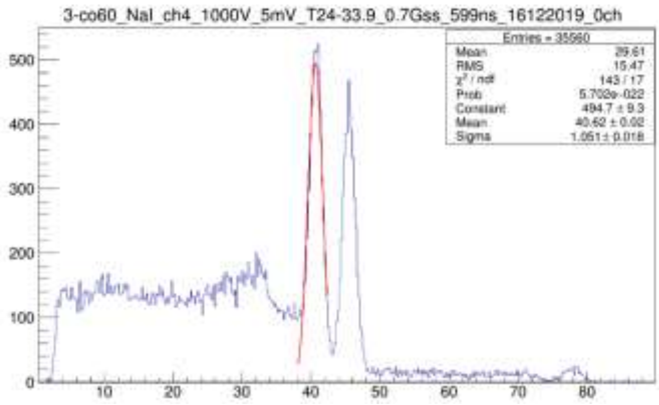


Fig14: 1000V Applied

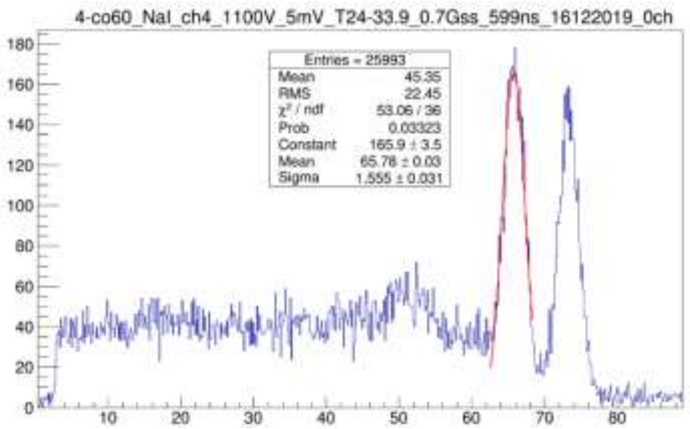


Fig15: 1100V Applied

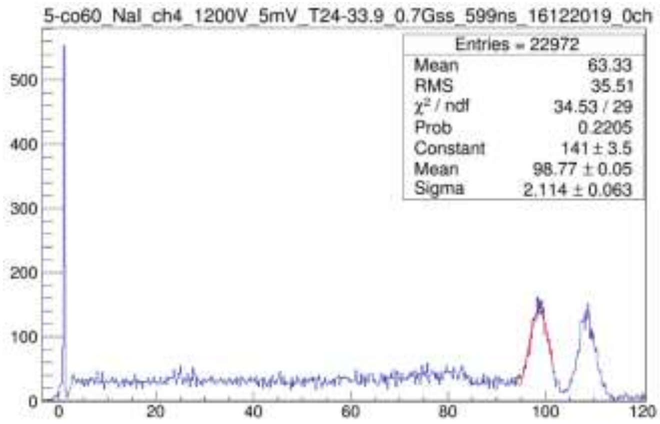


Fig16: 1200V Applied

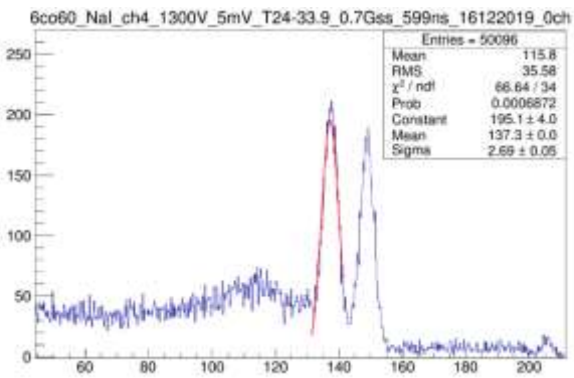


Fig17: 1300V Applied

Results

Applied voltage (V)	σ	Mean	Resolution (%)
900	0.6081	23.68	6.034
1000	1.051	40.62	6.08
1100	1.555	65.78	5.55
1200	2.114	98.77	5.029
1300	2.69	137.3	4.60

Table 4: Resolution (%) of NaI detector corresponding to the applied voltage

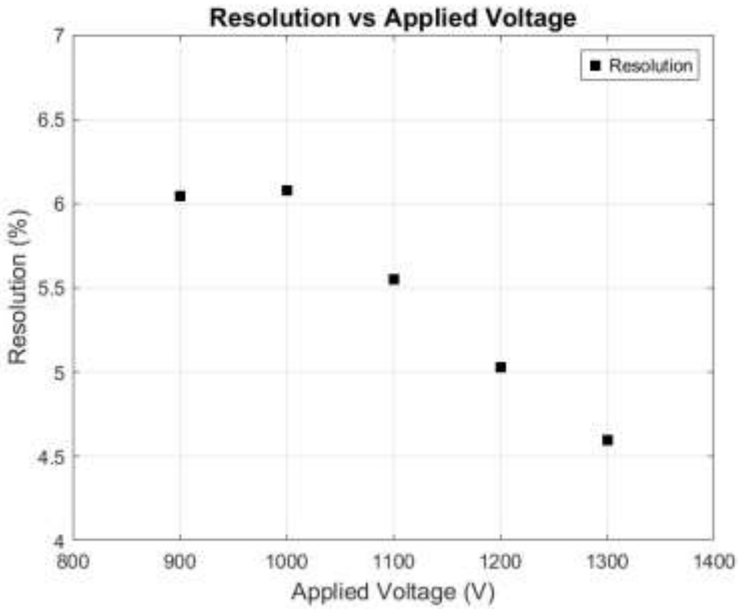


Fig18: The relation between resolution and applied voltage for NAI detector

3.5 Task 5: Energy Calibration of NaI detectors at 800V

A NaI detector produces a stronger light signal compared to a BGO detector, giving it roughly twice the energy resolution. Because of this higher resolution, it can clearly distinguish the two close gamma peaks of Co-60 at about 1170 keV and 1330 keV. As a result, instead of seeing three merged peaks as in the BGO spectrum, four distinct peaks appear in the spectrum.

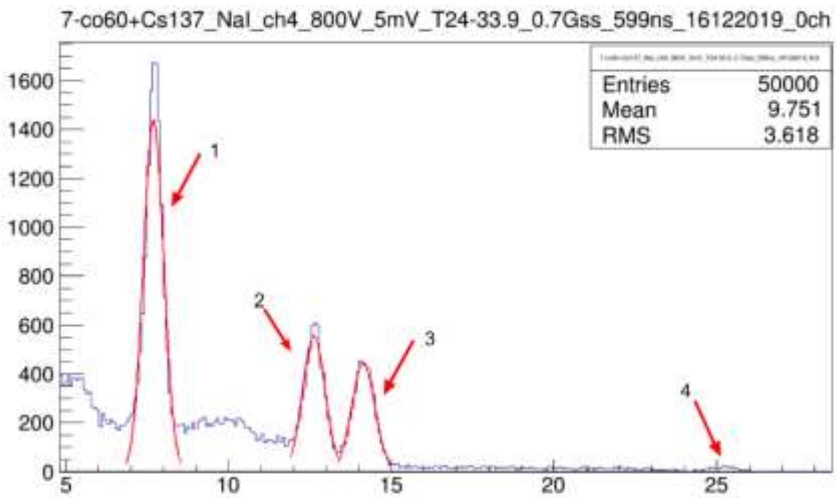


Fig19: The energy spectrum of Cs-137 and Co-60 from NaI detector measurements at 800V

Isotope	Channel (Mean)	Energy(keV)
Cs-137	7.697	662
Co-60	12.64	1170
	14.14	1330
	25.2	2500

Table 5 Mean and energy of Cs-137 and Co-60 peaks from a NaI detector

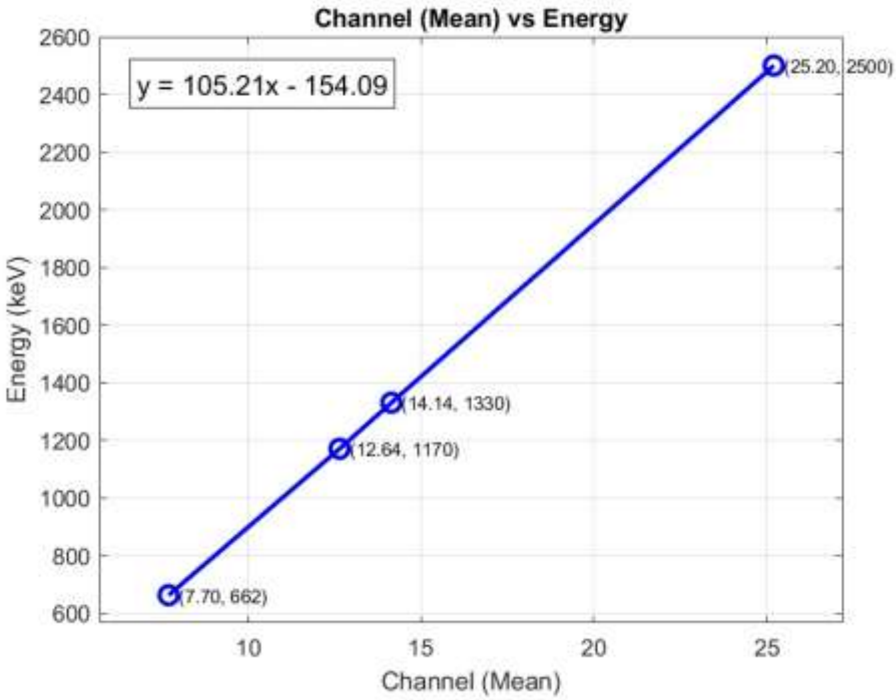


Fig20: Energy calibration function for Cs-137 and Co-60 spectrum from NaI detector measurements

The equation of the energy calibration line for BGO detector is:

$$y = 105.21x - 154.09$$

Where:

x = channel number (mean)

y = energy of the peaks (in keV)

3.6 Task 6: Identification of Unknown Source by NaI Detector

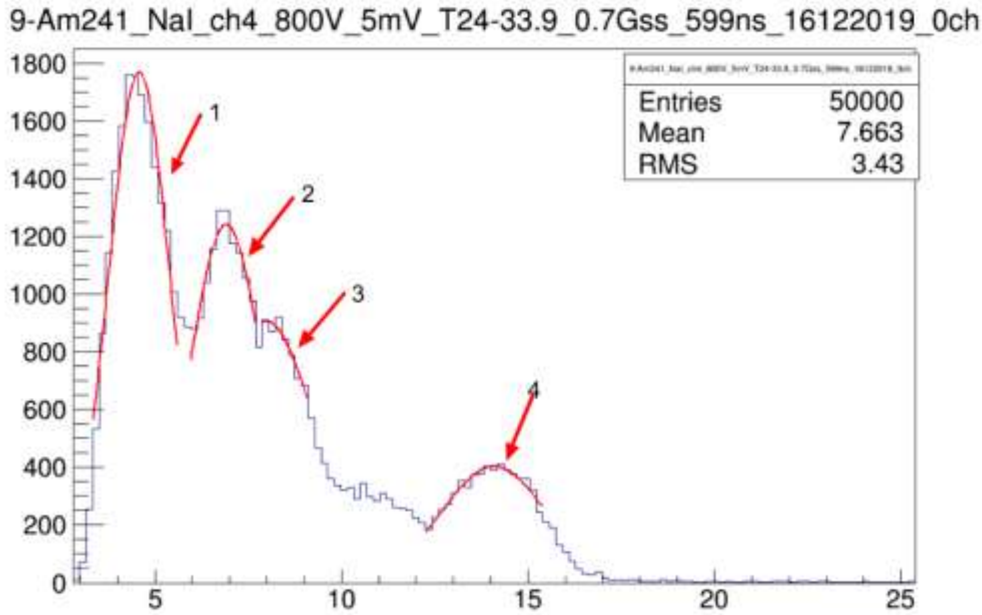


Fig21: Energy spectrum of the unknown sources from NaI detector measurements at 800V

Unknown Source Peak ID	Channel (mean)	Energy (keV)	Unknown Source
1	4.593	329.139	Ir-194
2	6.915	573.437	Bi-207
3	7.792	665.706	Tc-129m
4	14.16	1335.683	Ca-47

Table 6: Energy, channel, and peak ID of the unknown sources identified using the Nuclide Datasheet.

Sample Calculation for Unknown Source Peak ID 1:

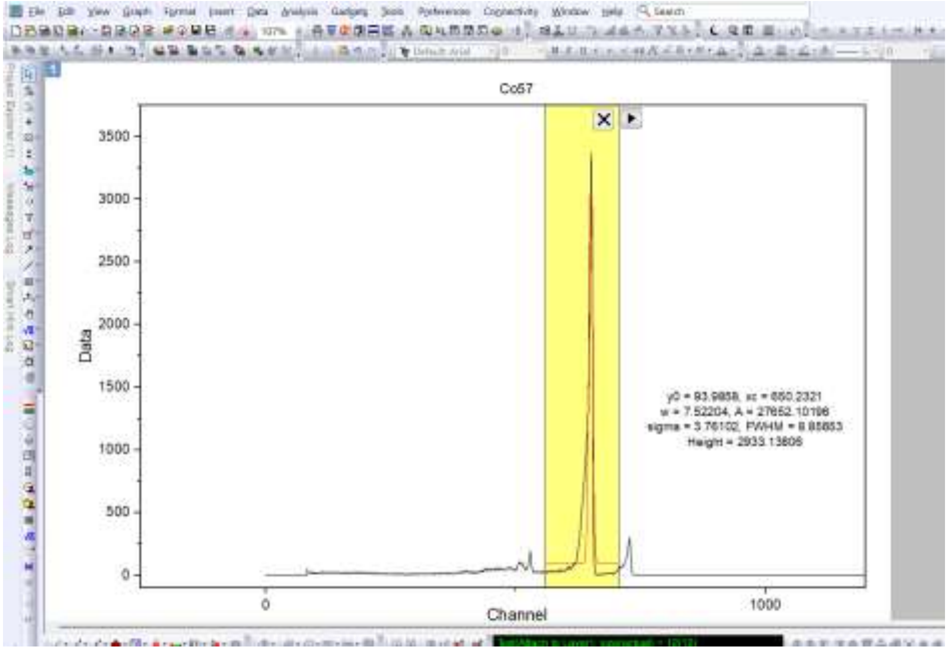
When the Gauss function is fitted the channel(mean) = 4.593

The equation of the energy calibration line for BGO detector is:

$$y = 105.21x - 154.09$$

Putting x = 0.2866 we get $y = (105.21 * 4.593) - 154.09 = 329.139\ keV$

3.7 Task 7: Resolution Of Semiconductor Cd-Te 1,2,3

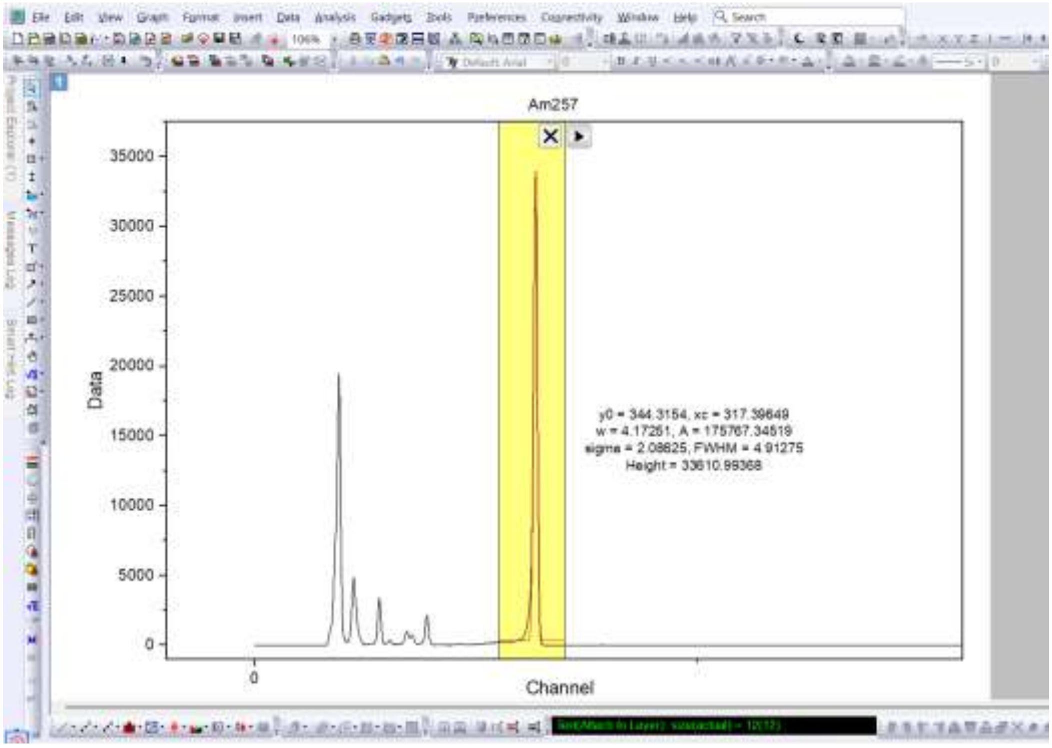


Resolution of cadmium telluride detector using Co-57

Resolution =(FWHM/Mean)*100

FWHM = 8.856   MEAN= 650.2321

Resolution = 1.361

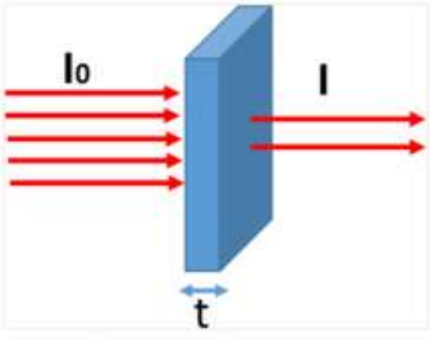


Resolution of cadmium telluride detector using Am-257

FWHM = 4.912   MEAN= 317.396

Resolution = 1.547

3.8 Task 8: Attenuation of γ radiation coefficient



The attenuation coefficient describes how quickly gamma rays lose intensity as they travel through a material. It essentially tells us how strongly a substance can weaken or absorb gamma radiation. This reduction in intensity depends mainly on the material's density, atomic number, and the energy of the incoming photons.

The behaviour of gamma-ray attenuation follows an exponential pattern, expressed as:

$$I = I_0 e^{-\mu x}$$

where

- I is the remaining intensity after the radiation passes through the material,
- I_0 is the original intensity,
- μ is the linear attenuation coefficient, and
- x is the thickness of the absorber.

The coefficient μ indicates how effectively the material can attenuate radiation per unit thickness. A higher value means the material reduces gamma intensity more rapidly. Rearranging the exponential law gives a convenient expression for calculating μ:

$$\mu = \frac{\ln (I_0/I)}{x}$$

In practice, materials with high density and large atomic numbers—such as lead or thick concrete—show strong attenuation because they interact more frequently with gamma photons. This is why they are commonly used for radiation shielding and protection in environments where gamma rays are present.

Experimental Setup

- Detector: BGO scintillation detector
- Applied Voltage: 2000 V
- Gamma Source: Cs-137 (primary gamma energy = 662 keV)
- Attenuation Materials: Aluminum and Copper

Procedure for Determining the Attenuation Coefficient

1. Record the Initial Intensity I_0
   Begin by measuring the gamma-ray intensity from the Cs-137 source without placing any material in the beam path. This gives the reference intensity I_0.

2. Measure the Transmitted Intensity I
   Place the chosen attenuating material (Al or Cu) between the source and the detector. Measure the new intensity I, which represents the radiation that successfully passed through the material.

3. Determine the Material Thickness x
   Measure the physical thickness of the attenuating sample through which the gamma rays travel.

4. Calculate the Linear Attenuation Coefficient
   Use the attenuation formula to compute the coefficient:

$$\mu = \frac{\ln{(I_0/I)}}{x}$$

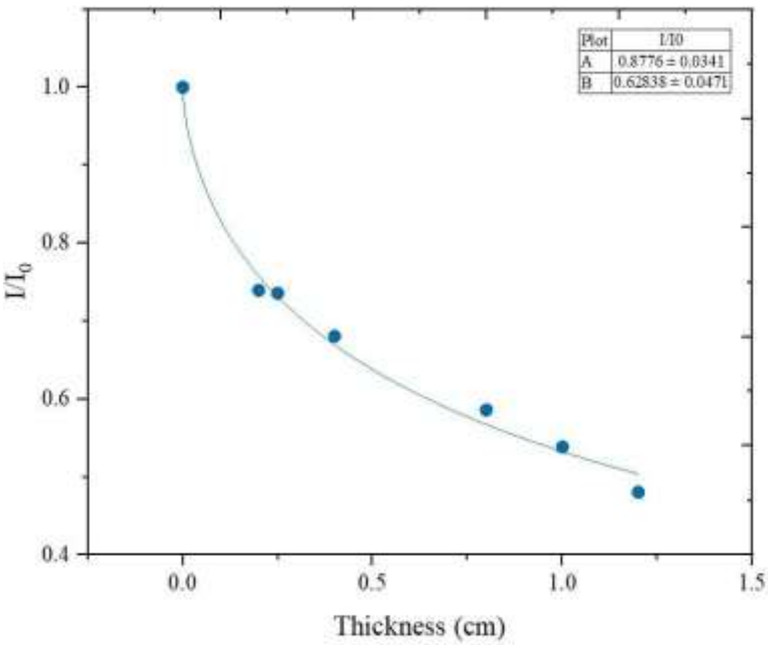
This value indicates how strongly the material reduces gamma-ray intensity per unit thickness

Attenuation coefficient for

(a) Copper

Table 7: Thickness vs (I/I_0) for Copper

Thickness (cm)	$\boldsymbol{\frac{I}{I_0}}$
0	1
0.1	0.73931
0.25	0.7357
0.4	0.68065
0.8	0.58611
1	0.53827
1.2	0.48042



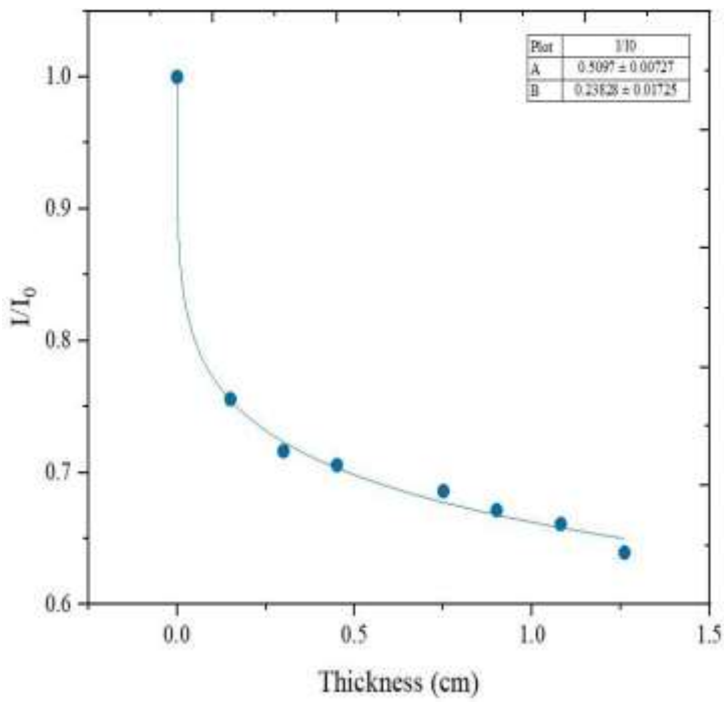
Therefore, μ for copper = 0.628 cm^{-1}

Fig21 : Determination of attenuation coefficient for Cu using BGO scintillation detector and the radiation source 137Cs (661 keV)

(b) Aluminium

Table 8: Thickness vs (I/I_0) for Aluminum

Thickness (cm)	$\frac{I}{I_0}$
0	1
0.15	0.75573
0.3	0.71623
0.45	0.70569
0.75	0.68596
0.9	0.67155
1.08	0.66103
1.26	0.63939



Therefore, μ for Aluminium = 0.238 cm^{-1}

Fig22: Determination of attenuation coefficient for Al using BGO scintillation detector and the radiation source 137Cs (661 keV)

3.9 Task 9: The Range of α-Particles in Air Using SRIM

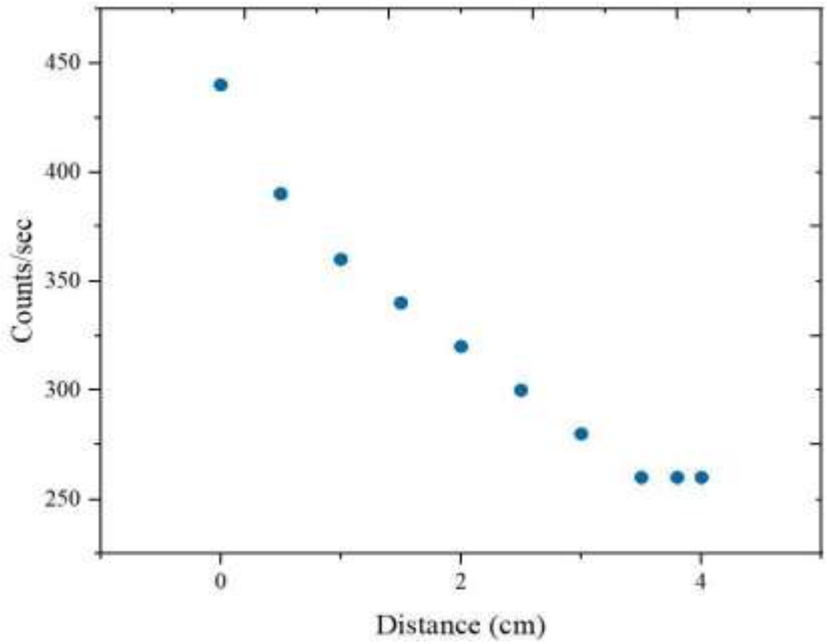
Range is characterized as the path length that a particle travels from its source through the matter before it is stopped. It is influenced by the type of particle, its original kinetic energy, and the medium through which it travels. The range is especially important for charged particles, like electrons and alpha particles. Alpha particles particularly travel in almost straight lines because they are thousands of times heavier than atomic electrons, to which they lose energy slowly. Their range is usually measured in a straight line from the source to the point where ionization stops.

In this experiment, a plastic detector is used instead of a BGO detector. This is because the BGO detector has a thin aluminium foil layer and shielding can occur, leading to energy loss and inaccurate measurements

Experimental Equipment:

- Radioactive Source: Pu-239
- Energy of He: 5.5 MeV
- Detector: Plastic Detector
- Voltage: 2000V

Distance (cm)	Counts/sec
0	440
0.5	390
1	360
1.5	340
2	320
2.5	300
3	280
3.5	260
3.8	260
4	260



From the table and the plot, it can be observed that the counts per second decreases as the distance increases, until reaching a point where the number of counts is constant. It means that there is no more signal detected. Therefore, the range of alpha particles in air is about 3.5 cm^{-1}

Range of Alpha Particles in Air by SRIM Simulation (Monte Carlo)

Using the SRIM software, it is possible to observe the simulation of the total path length traveled by alpha particles in the air. Two plots are obtained: the depth vs. y-axis and the ionization (Bragg peak/curve) of the alpha particles. The Bragg curve represents the energy loss rate as a function of the distance through a stopping medium. The Bragg peak is the maximum, and beyond that, the energy deposition drops sharply

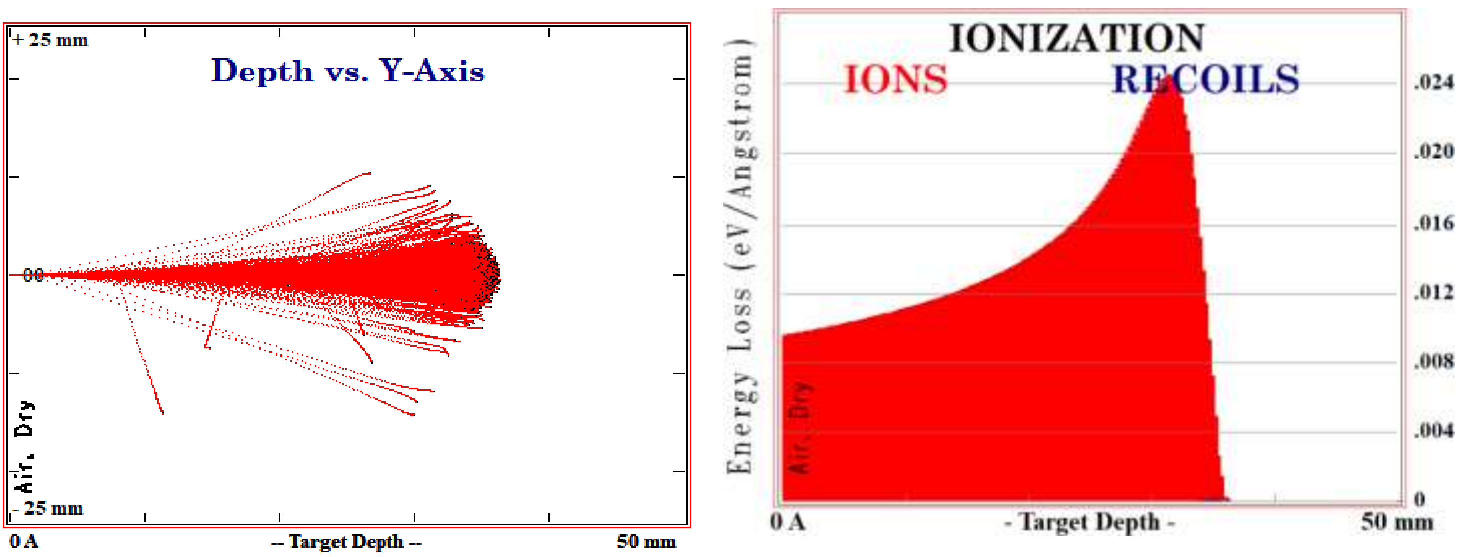


Fig23; Depth and Bragg curve of alpha particles in 5 cm

From the two plots, it can be denoted that the intensity of alpha particles decreases when the distance increases. Alpha particles lose their energy when they interact with the particles present in the air. Here, the range of the alpha particles in air is around 3.5 to 4 cm. The Bragg peak is about 4.3 cm and beyond that, the energy decreases sharply until no more signal is detected.

3.10 Task 10: Determination of the range of Alpha particles with (241Am) energy about 4 MeV in air using pixel detector

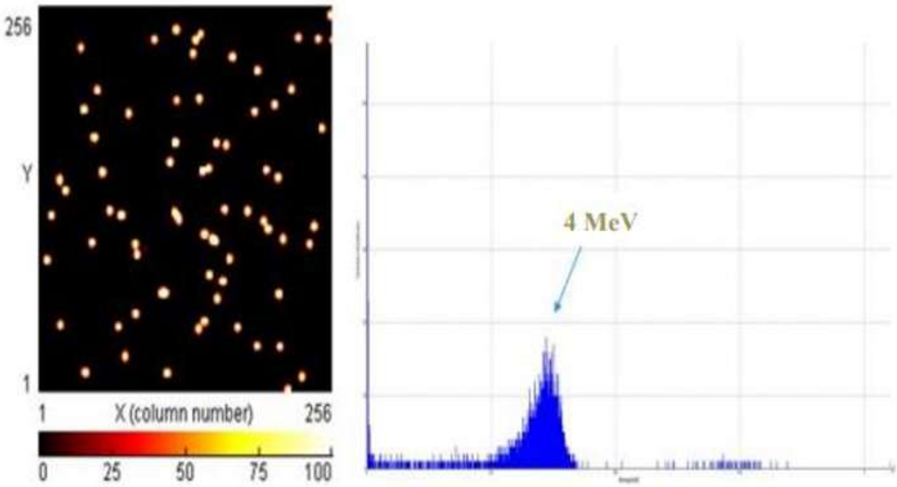


Fig24: Absorption of αparticle energy at 0 cm in the

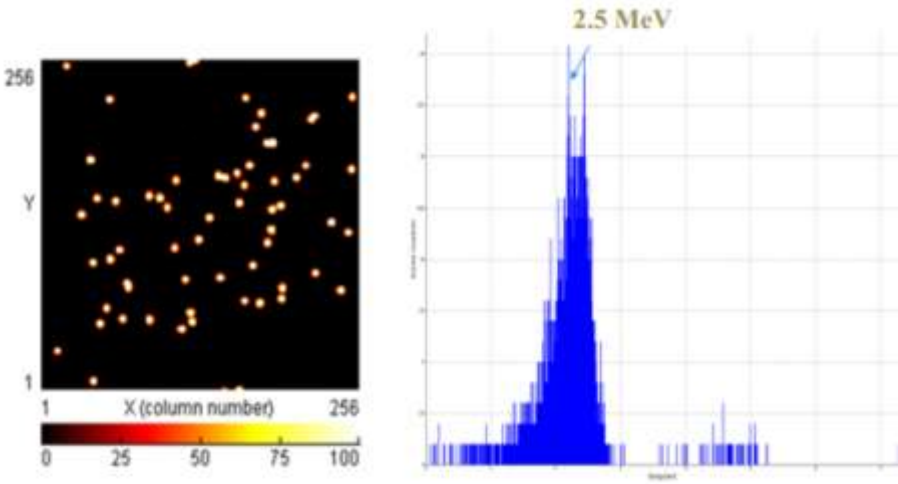


Fig25: Absorption of αparticle energy at 1 cm in the

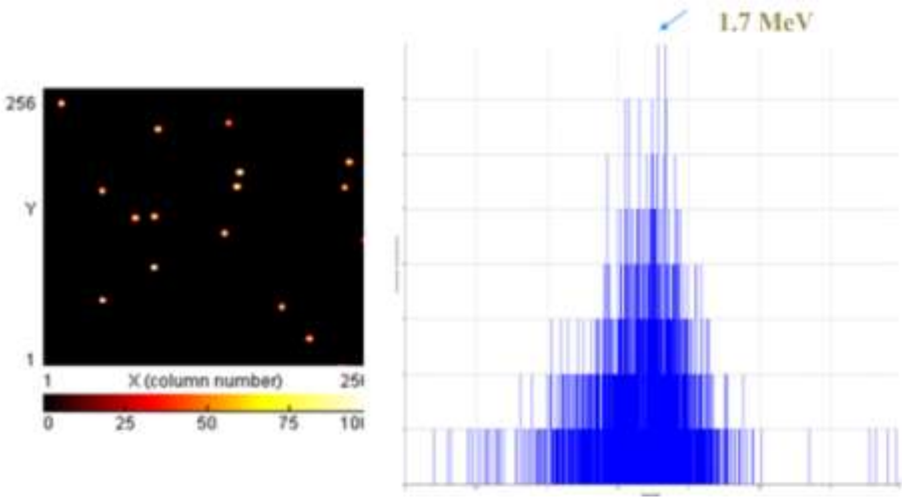


Fig26: Absorption of αparticle energy at 2 cm in the

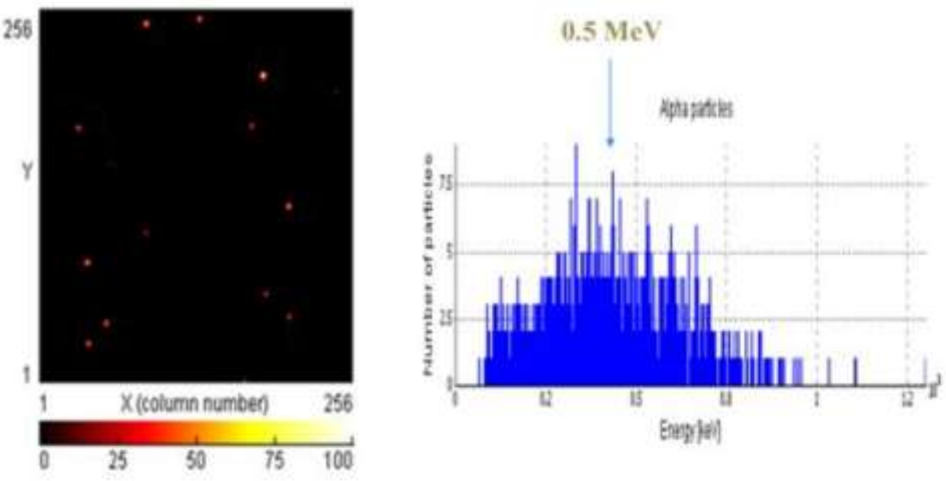


Fig27: Absorption of αparticle energy at 2.5 cm in the

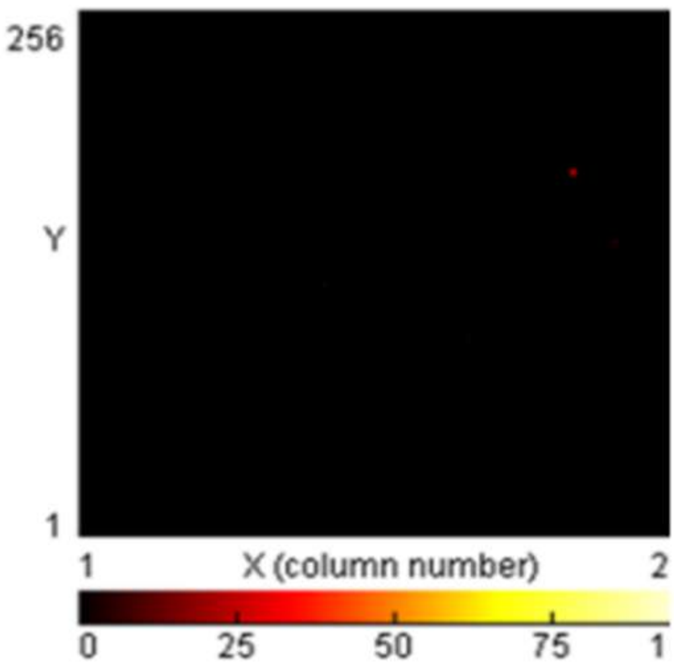


Fig28: No α-particles are detected which means maximum of α-particle range is 3 cm in this case

Result

At a 3 cm distance from the source, there are no alpha particles detected. Therefore, the maximum range of alpha particles in air as measured by a pixel detector is about 3 cm.

4 Conclusion

This project offered a broad and practical understanding of radiation protection and the behaviour of different types of radiation and detectors. Through a mix of theory, software analysis, and experimental measurements, several key aspects of radiation detection were explored — including peak identification, energy calibration, attenuation studies, and the range of alpha particles. Tools such as ROOT, Origin, Excel, and SRIM were used throughout, which helped in analysing spectra, performing Gaussian fits, and estimating particle ranges.

A comparison between the BGO and NaI scintillation detectors showed clear differences in performance. The NaI detector demonstrated better resolution, allowing it to distinguish closely spaced gamma peaks more effectively, while the BGO detector was still useful for higher-energy measurements and attenuation studies. Using the calibration line, the energy of an unknown source was estimated and compared with reference values, keeping in mind that small fitting errors can affect the final result.

The attenuation coefficients of aluminium and copper were determined using the BGO detector at 2000 V with Cs-137 as the source. As expected, copper showed a higher attenuation coefficient due to its greater density and atomic number, making it a more efficient shielding material. The study also included determining the range of alpha particles in air using different detectors and SRIM simulation; the measured range was around 3 to 4 cm, with no alpha particles detected beyond roughly 3 cm in the pixel detector setup.

Overall, the project brought together multiple ideas — from understanding radiation interaction and safety principles to practically measuring detector response and material attenuation. It reinforces the importance of accurate measurement, proper shielding, and responsible handling of radioactive sources, all of which are central to the field of radiation protection.

5 References

[1] Knoll, G. F., Radiation detection and measurement, 4th Edition, Wiley (2010).

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