Radiation Protection and The Safety of Radiation Sources

Supervisor:
Dr. Said AbouElazm

From:
Hazem Said Nasr Elsayed
Faculty of Engineering – Alexandria University

INTErnational **RE**mote **S**tudent **T**raining

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Abstract

With the growing use of radioactive sources in various fields, radiation protection has become increasingly important. To support this, a range of radiation detectors have been developed. The project mostly focuses on resolution and energy calibration—key aspects in evaluating detector performance and identifying unknown isotopes.

A comparative study was conducted on the resolution of two scintillator detectors (BGO and NaI) and one semiconductor detector (CdTe). Energy calibration equations were derived from known sources and applied to unknown samples.

The work extended to measuring attenuation coefficients for Al and Cu, and tracking alpha particles in air using Monte Carlo simulations. Various software tools were employed throughout the project, including ROOT, OriginPro, DppMCA, and SRIM.

Key words: Resolution, Energy Calibration, BGO Detector, NaI(Tl) Detector, Cd(Te) Detector, Attenuation Coefficient, Alpha range.

Acknowledgement

I would like to express my sincere gratitude to **Dr. Said AbouElazm** for his invaluable teaching, patient guidance, and dedicated support throughout the duration of wave 12. It was such a privilege to learn from him.

I am also grateful to the **INTEREST team** for accepting me into their interesting **INTEREST** community and giving me the opportunity to participate in Wave 12, and I look forward to being part of future waves.

Pre-Tasks: Introduction to Radiation

Introduction: Radioactivity

Radioactivity is the release of energy from the decay of some atomic nuclei. This energy travels as **waves or particles** and comes in different forms with varying effects.

Types of Radiation

Non-ionizing radiation

It has enough energy to move atoms in a molecule around or cause them to vibrate, but not enough to remove electrons.

Examples: Microwaves, radio waves, cell phones, Earth's magnetic field.

Ionizing Radiation

It has sufficient energy to remove electrons from atoms, leading to **ionization**. This can damage living cells and DNA.

- Some Types of Ionizing Radiation:

Alpha (α): 2 protons + 2 neutrons, heavy and positively charged. Stopped by paper.

Beta (β): Fast-moving electrons, much lighter than alpha, stopped by plastic.

Gamma (γ): High-energy waves with no mass or charge, penetrates deeply; blocked by lead or concrete.

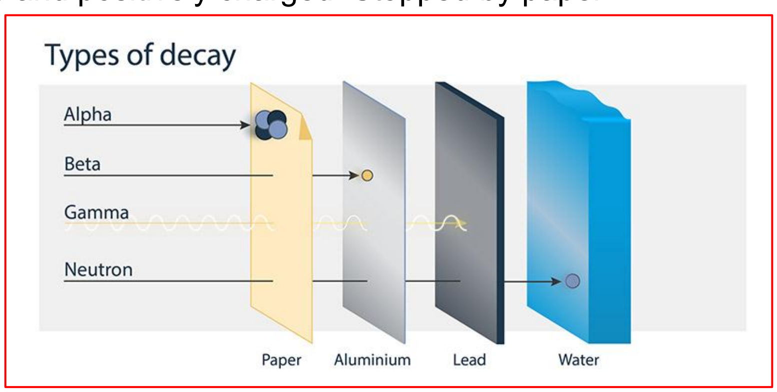

Figure 1 The Penetrating Power of Radiation Types

X-rays: Like gamma, but usually man-made.

Neutrons: Ejected during nuclear reactions, best blocked by hydrogen-rich materials like water.

Radiation Protection

To minimize the harmful effects of ionizing radiation, three guiding principles must be followed:

Justification: Radiation use must do more good than harm.

Optimization: Keep doses as low as reasonably achievable **(ALARA).**

Limitation: Prevent excess exposure to individuals.

Radiation Dose

Radiation dose is a measure of the amount of exposure to radiation. There are three kinds of dose in radiological protection.

Absorbed Dose: Energy deposited in unit mass of material. It is expressed in grays (Gy), or, more frequently milligrays (mGy).

Equivalent Dose: Absorbed dose adjusted for **radiation type**.

Effective Dose: Sum of equivalent doses, adjusted for **organ sensitivity.**

Absorbed dose is a measurable, physical quantity, while equivalent dose and effective dose are specifically for **radiological protection** purposes, both expressed in sieverts (Sv), or, more frequently, millisieverts (mSv).

Radiation Detectors

Radiation is invisible and needs special instruments for detection. Detectors measure the **physical effects** of radiation, such as ionization or light emission. i.e., converting radiation energy into **measurable effects** (e.g., light, electric signals, stored energy).

- Some of the media used are:

- Gases (e.g., Ion chamber, Proportional counter, GM counter)
- Scintillators (NaI (Tl), BGO, etc.)
- Solid state detectors (Semiconductors, Thermo-luminescent dosimeters etc.)

- Detector selection depends on:

- Type & energy of radiation
- Intensity level
- Cost, size, electronics, etc.

Scintillator properties of crystals

Scintillator	Light output	Decay (ns)	Wavelength (nm) max	Density (g/cm2)	Hygroscopic
Na(Tl)	100	250	415	3.67	yes
CsI	5	16	315	4.51	slightly
BGO	20	300	480	7.13	no
BaF2(f/s)	3/16	0.7/630	220/310	4.88	slightly
CaF2	50	940	435	3.18	no
CdWO4	40	14000	475	7.9	no
LaBr3(Ce)	165	16	380	5.29	yes
LYSO	75	41	420	7.1	no
YAG(Ce)	15	70	550	4.57	no

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Figure 2 Scintillation Detectors Properties

Task 1.1. Resolution vs. Applied Voltage for BGO Detector

Overview - BGO

BGO is an inorganic scintillator made from **Bismuth Oxide** and **Germanium Oxide** and is widely used in radiation detection and medical imaging.

Figure 3 BGO detector configuration

- Advantages:

High density, high effective atomic number, and high stopping power for gamma rays.

- Main drawback: Its poor energy resolution

Energy Resolution

It's the extent to which a detector can distinguish two close-lying energies. It's usually given in terms of the **full width at half maximum (FWHM)** of a peak.

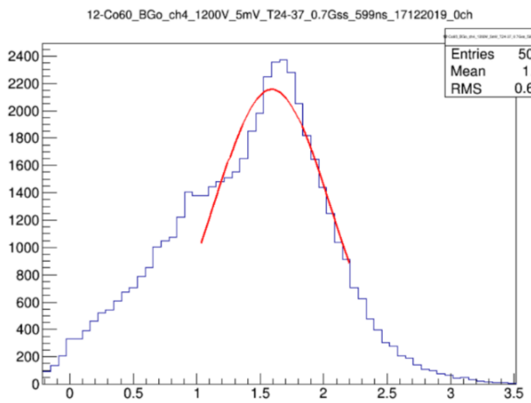
Lower FWHM (better resolution) means peaks are more distinct and identifiable.

Resolution Formula

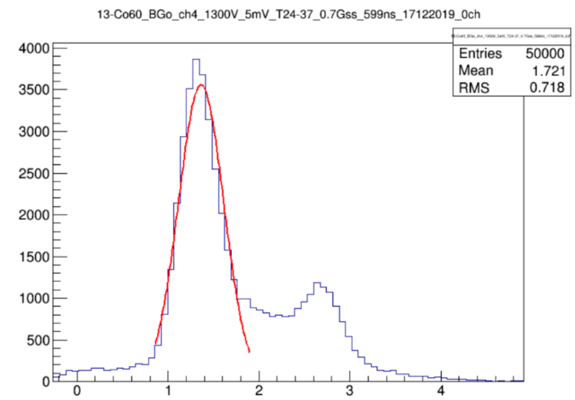
The resolution can be calculated as:

$$\boxed{\text{Resolution } \% = \frac{\sigma}{\text{mean}} \times 2.355 \times 100\%}$$

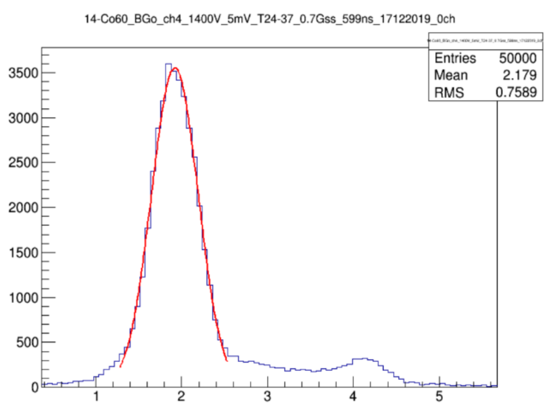
Plots of Channel Number vs. Counts



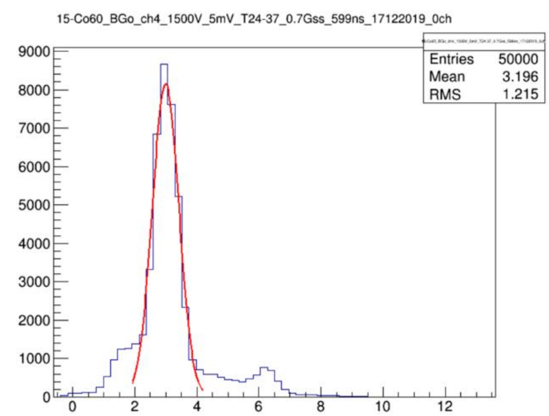
(a) 1200 V



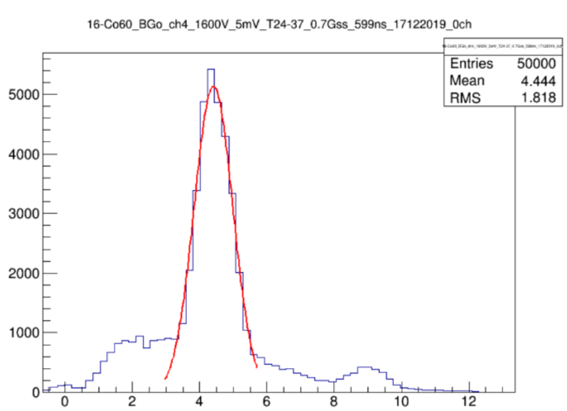
(b) 1300 V



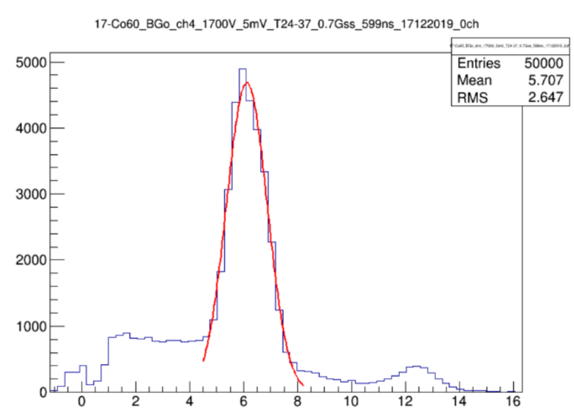
(c) 1400 V



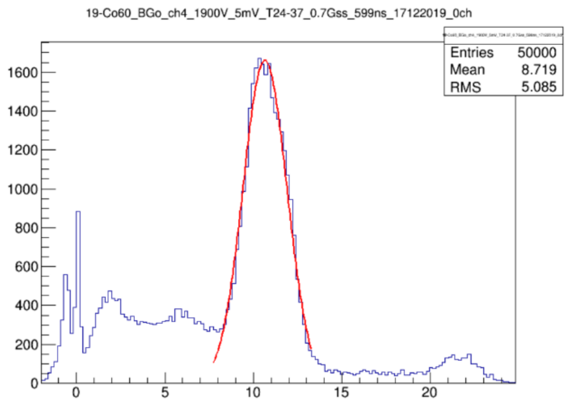
(d) 1500 V



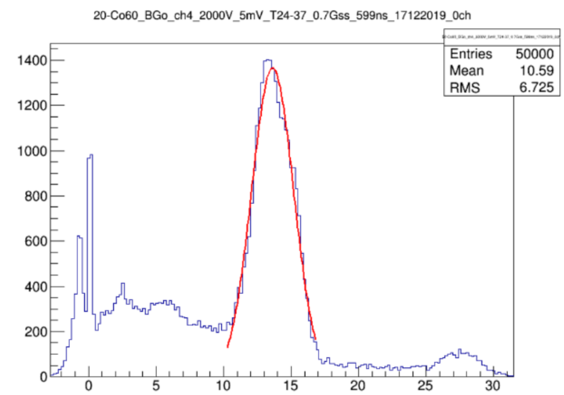
(e) 1600 V



(f) 1700 V



(g) 1900 V



(h) 2000 V

Figure 4 Intensity Curves for BGO detector at different operating voltages

Plot of Resolution vs. Applied voltage

The resolution variation with applied voltage, obtained from fitting intensity curves at different voltages, is summarized in the following table:

Table 1 Applied voltage vs. resolution for BGO detector

Applied voltage (V)	Resolution %
1200	68
1300	42.76
1400	33.26
1500	33.7
1600	30.8
1700	29
1900	27.4
2000	26.73

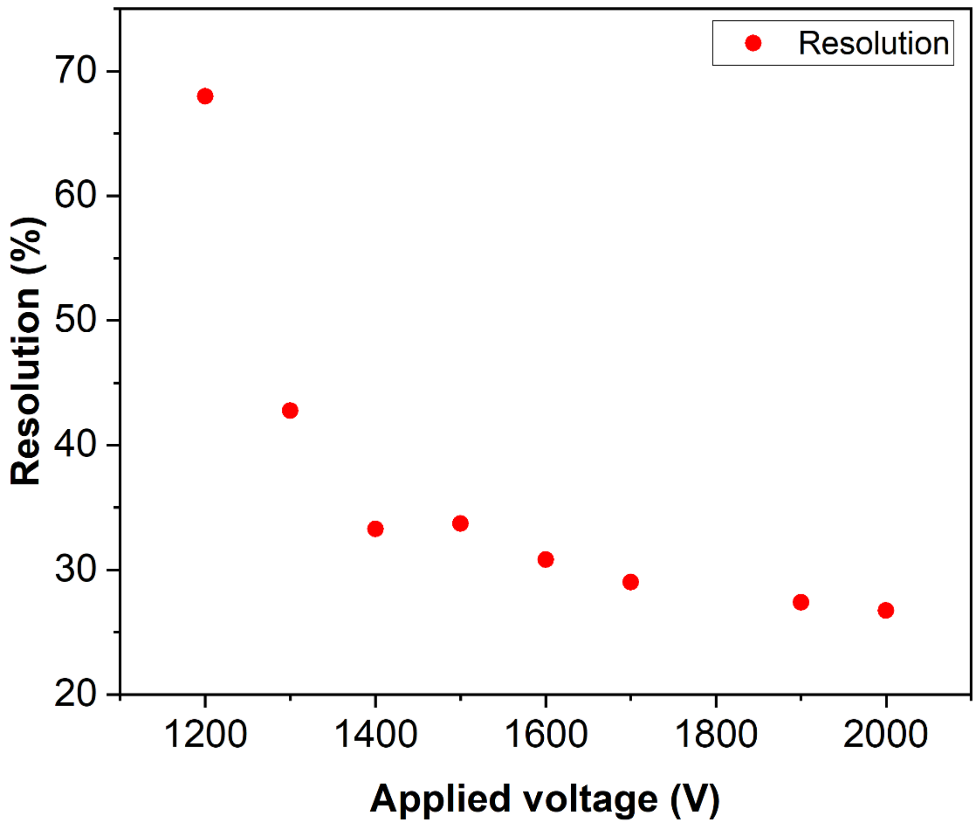


Figure 5 Plot of applied voltage vs. resolution for BGO detector

Observation

- BGO scintillator detectors exhibit **poor resolution**.
- Increasing the applied voltage **improves resolution** and signal amplitude, but may cause **nonlinearity** in energy response, complicating calibration and peak fitting. Thus, the operating voltage must be optimized to balance resolution and calibration accuracy.

<u>Task 1.2.</u> Energy Calibration for BGO Using Co-60 and Cs-137

Energy calibration means evaluating a relationship between the energy of the emitted particle and the channel number of the peak. i.e., to identify the energy associated with each photopeak in the gamma-ray spectra.

- Once the energy calibration is known, it is easy to find the energy of unknown source.
- The energy is **proportional** to the channel number of the peak.
- The channel number of each peak was determined using ROOT's Gaussian fittings.

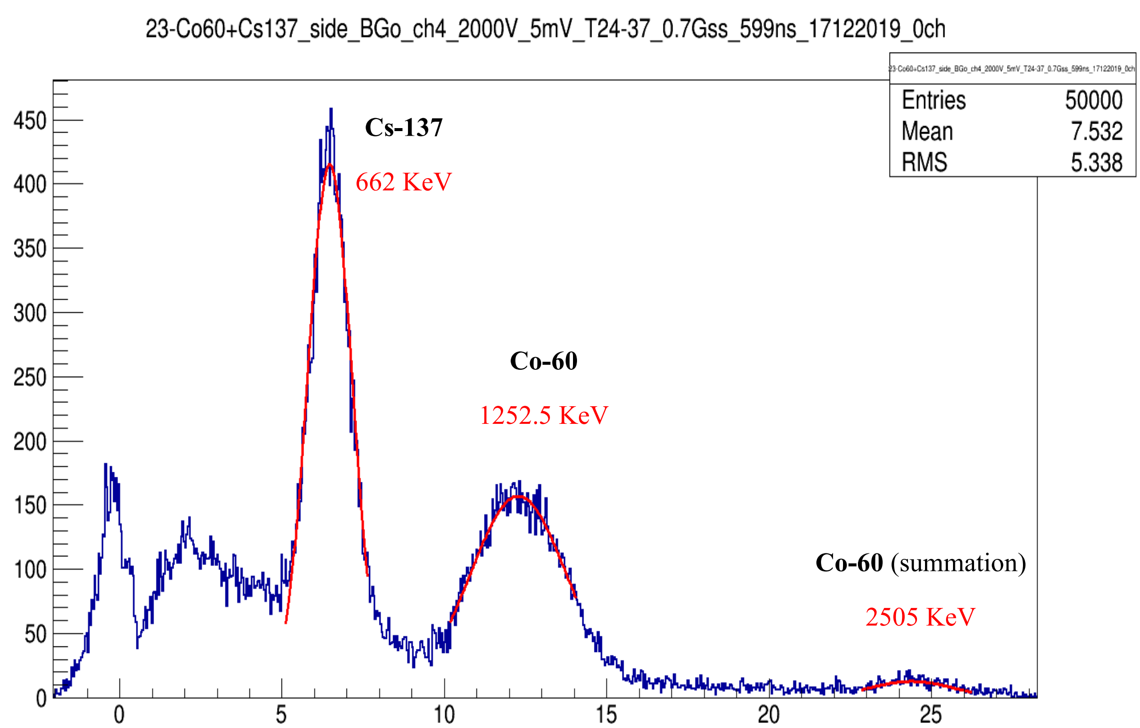


Figure 6 Gamma-ray spectrum of Cs-137 and Co-60 using BGO at 2000 V

- The results are summarized in the following table:

Table 2 Channel number vs. energy for BGO detector

Element	Channel number	Energy (KeV)
Cs-137	6.476	662
Co-60 (1st Peak)	12.25	1252.5
Co-60 (summation)	24.42	2505

- A graph showing the relationship between channel number and energy can be generated using OriginPro software.

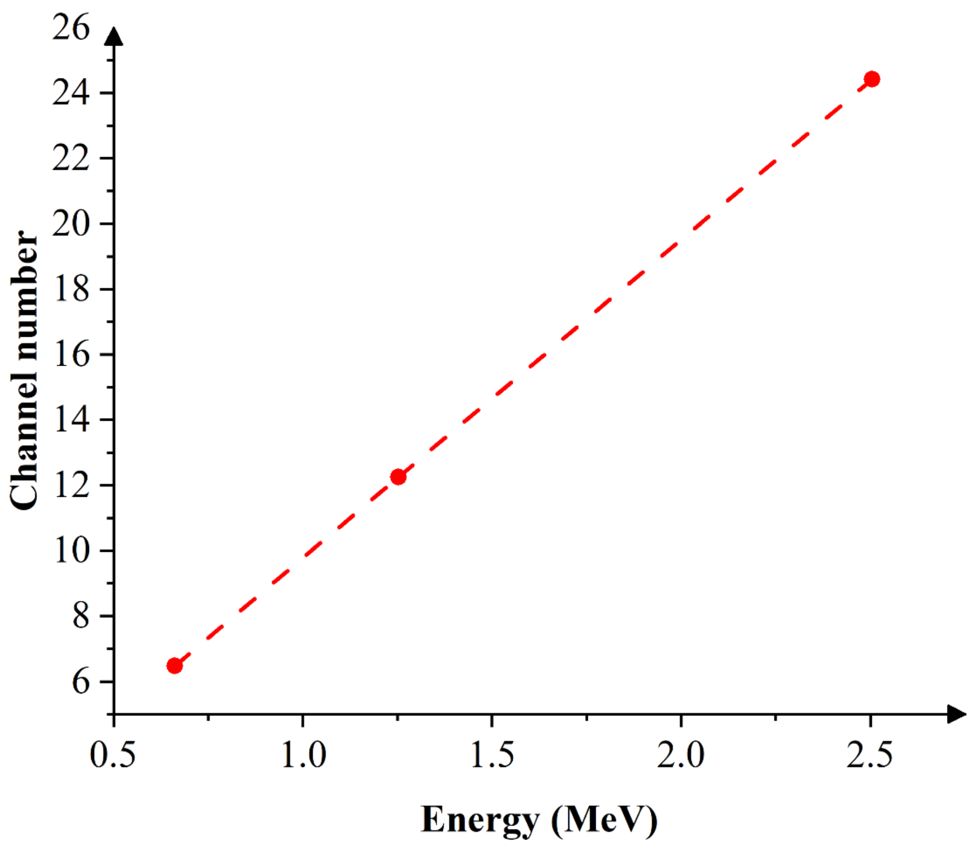


Figure 7 Energy calibration for BGO detector

- As observed, there is a **linear relationship** between the channel number and energy. The calibration equation, determined using OriginPro, is

$$\boxed{\mathrm{Ch.}\,\# = 9.73\ \times \mathrm{Energy} + 0.0433}$$

Task 1.3. Identification of Unknown Source Using BGO Detector

Unknown elements can be identified by determining their energy using the **calibration equation** obtained by OriginPro.

Using ROOT fittings to obtain the channel number of each peak, the corresponding energy values can be determined by substituting these values into the calibration equation, as shown in the table 3.

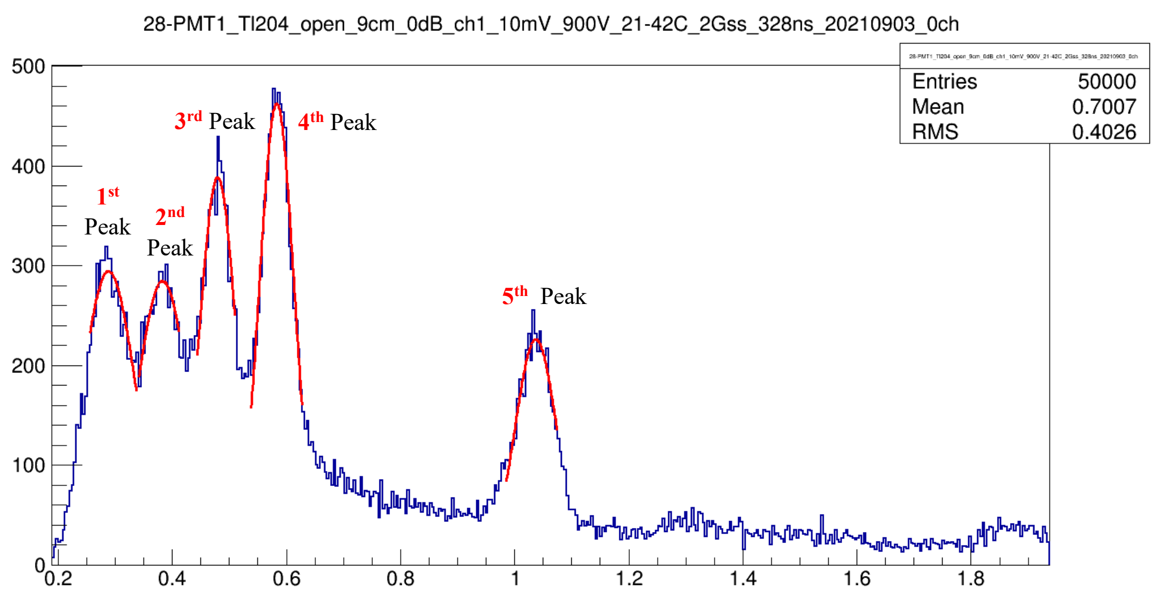


Figure 8 Gamma ray spectrum of an unknown source

Table 3 Energy values of an unknown source using BGO calibration

Peak no.	Channel number	Energy (KeV)
1st	0.2855	25
2nd	0.3848	35.1
3rd	0.4804	45
4th	0.5833	55.5
5th	1.0377	102.2

Task 2.1. Resolution vs. Applied Voltage for NaI Detector

Overview - NaI

Sodium Iodide doped with thallium, NaI(TI), scintillation detector is the **most commonly used** scintillator in experimental physics for the measurement of the gamma-ray activity.

- Advantages:

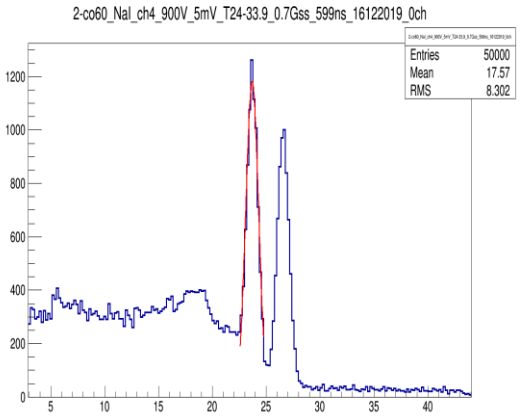
It has a relatively high density and high atomic number combined with a large volume of very high efficiency.

- Applications:

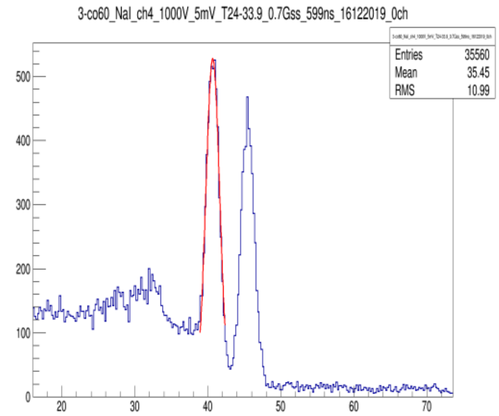
Although semiconductor detectors have a better energy resolution, many researchers cannot replace the NaI (TI) in experiments where large detector volumes are needed.

Figure 9 NaI detector configuration

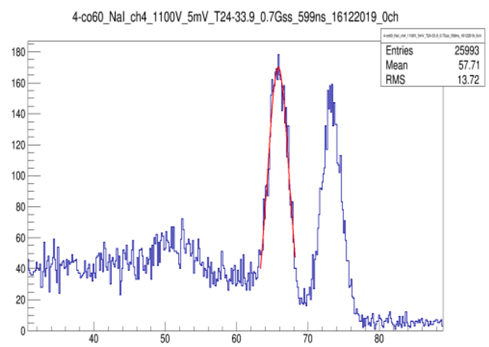
Plots of Channel Number vs. Counts



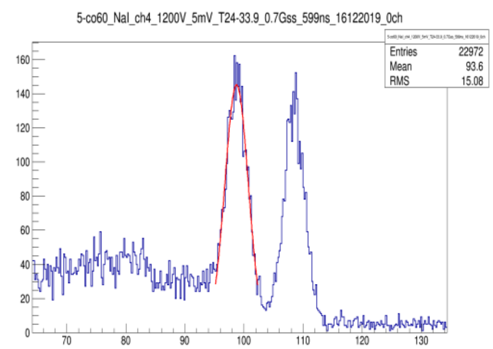
(a) 900 V



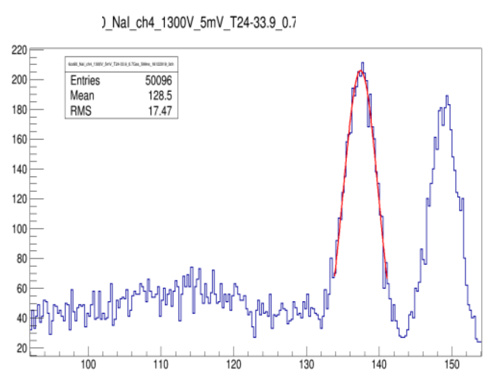
(b) 1000 V



(c) 1100 V



(d) 1200 V



(e) 1300 V

Figure 10 Intensity curves for NaI detector at different operating voltages

Plot of Resolution vs. Applied Voltage

Table 4 Applied voltage vs. resolution for NaI detector

Applied voltage (V)	Resolution %
900	5.8
1000	5.47
1100	5.29
1200	4.69
1300	4.13

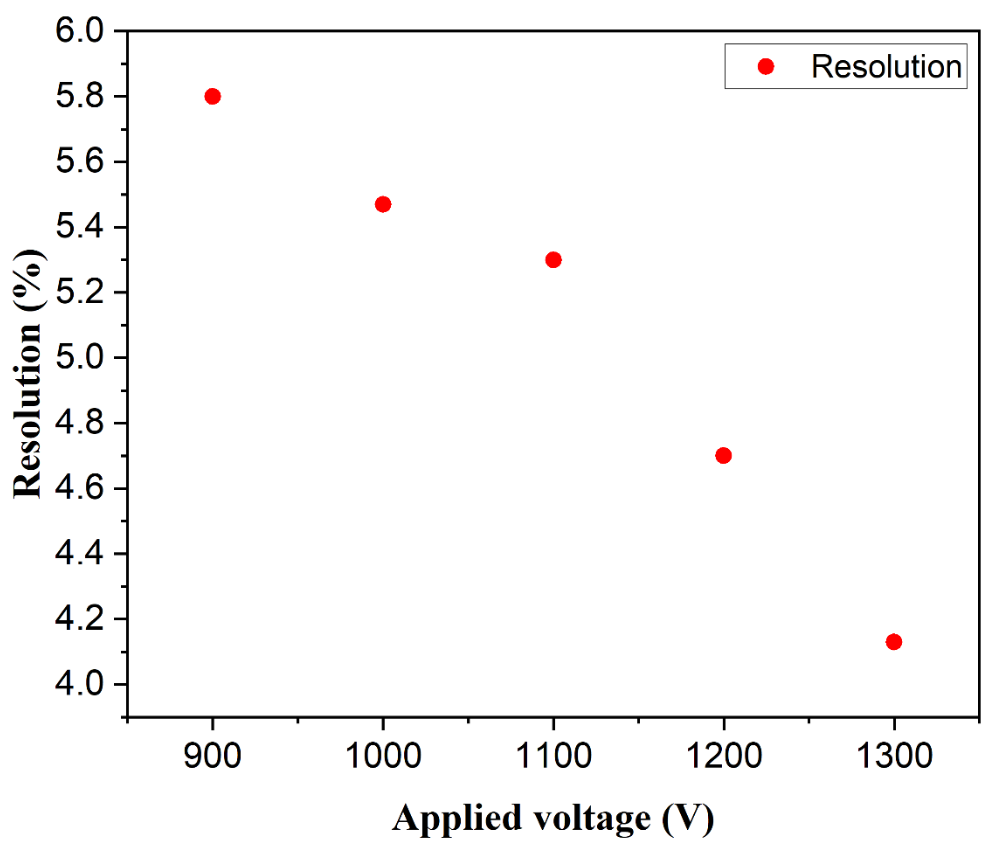


Figure 11 Plot of applied voltage vs. resolution for NaI detector

Observation

- NaI detector demonstrates **superior resolution** compared to BGO detector.

Task 2.2. Energy Calibration for NaI Using Co-60 and Cs-137

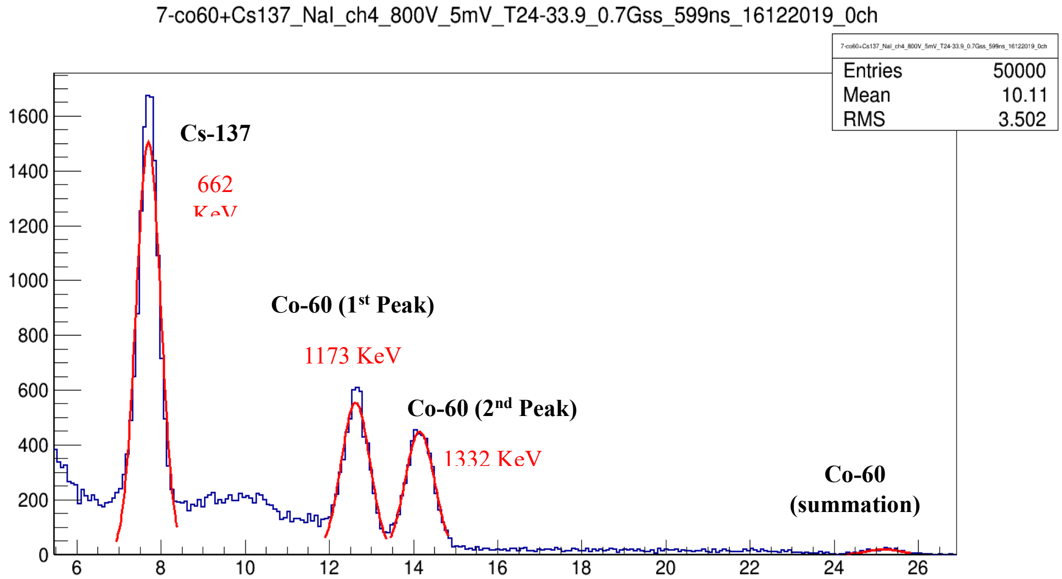


Figure 12 Gamma-ray spectrum for NaI detector at 800 V

Table 5 Channel number vs. energy for NaI detector

Element	Channel number	Energy (KeV)
Cs-137	7.71	662
Co-60 (1st Peak)	12.63	1173
Co-60 (2nd Peak)	14.15	1332
Co-60 (Summation)	25.19	2505

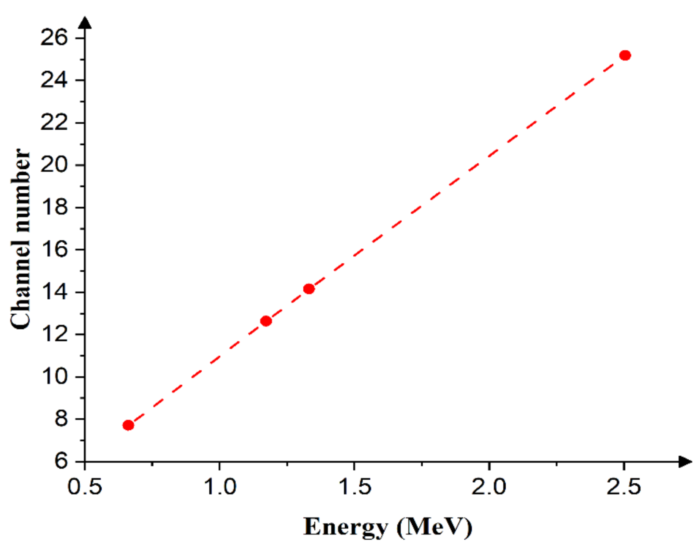


Figure 13 Energy calibration for NaI detector

Task 2.3. Identification of Unknown Source Using NaI Detector

Now, we can utilize the energy calibration to identify unknown elements, as previously done with the BGO detector. The **calibration equation** obtained using OriginPro is:

$$\boxed{\mathrm{Ch.\#} = 0.00947 \times \mathrm{Energy} + 1.49}$$

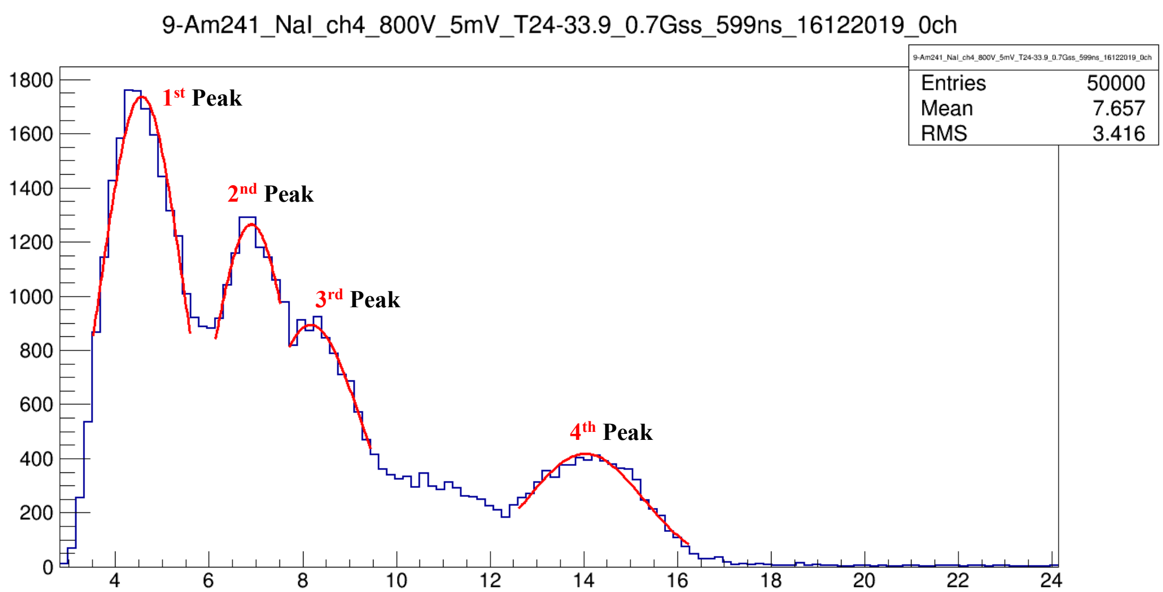


Figure 14 Gamma-ray spectrum of an unknown source

Using ROOT fittings to obtain the channel number of each peak, the corresponding energy values can be determined by substituting these values into the calibration equation, as shown in the table 6

Table 6 Energy values of an unknown source using NaI calibration

Peak no.	Channel number	Energy (KeV)
1st	4.54	322
2nd	6.914	572.76
3rd	8.178	706.23
4th	14	1321

<u>Task 3.1.</u> Energy Calibration of CdTe Detector

CdTe - Overview

The **CdTe detector** is a compact, thermoelectrically cooled detector. CdTe is considered a very appealing material that has been studied since 1960s for the development of high-resolution x-ray and gamma ray detectors.

- <u>Characteristics:</u>

- Structurally, it crystallizes in a cubic zincblende form and is composed of cadmium (Z = 48) and tellurium (Z = 52).
- Small size, and low cost
- Its ability to operate at room temperature, thanks to its wide band gap (1.44–1.47 eV).
- High resolution

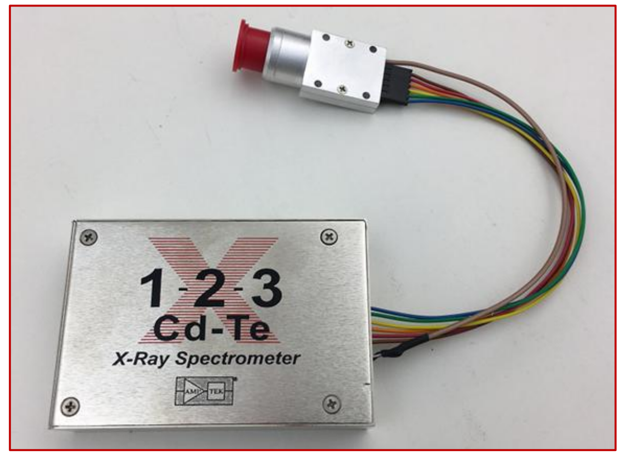
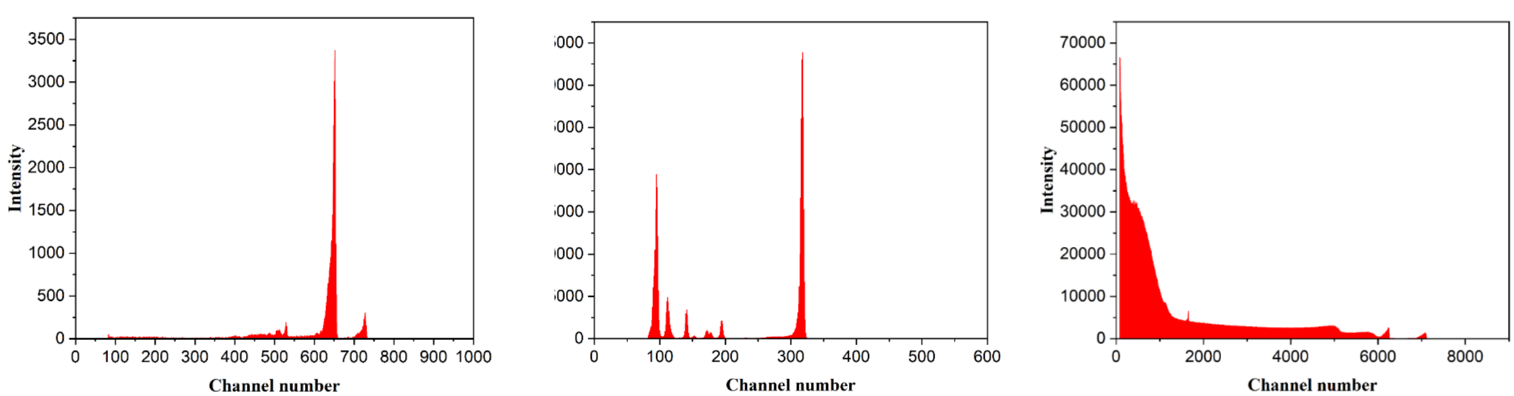


Figure 15 CdTe detector configuration

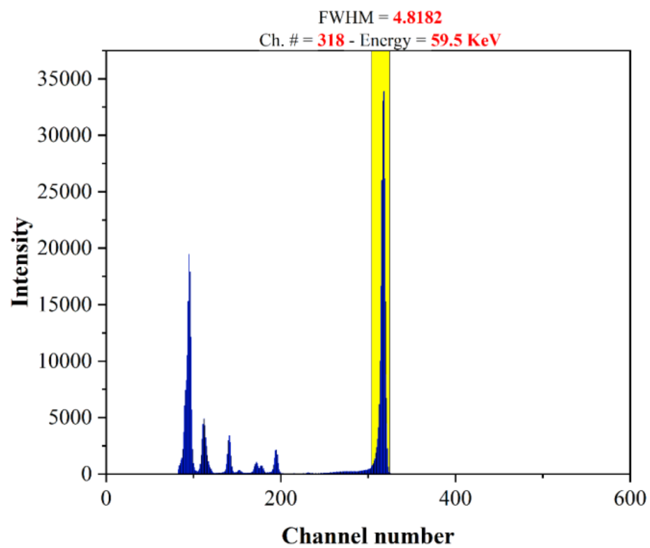
Plots of Intensity vs. Channel Number



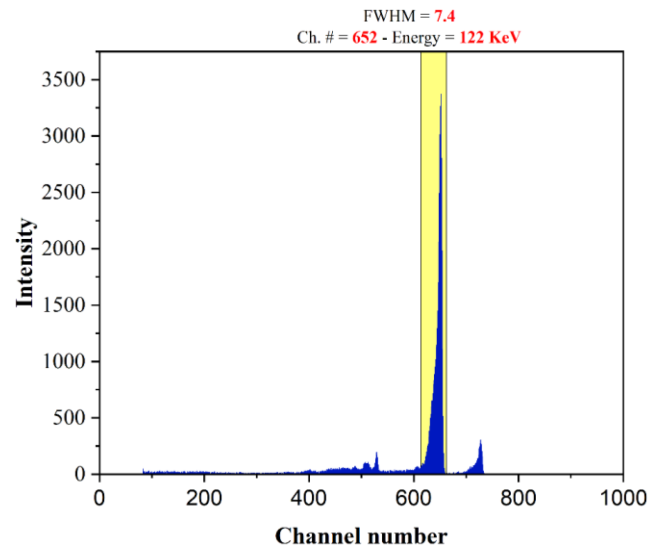
(a) Co-57 (b) Am-241 (C) Co-60

Figure 16 Intensity curves for different elements using CdTe detector

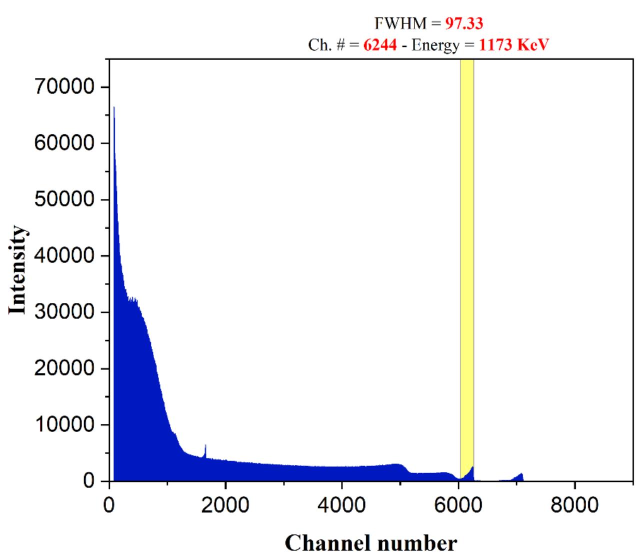
Plot of gamma peaks' integration of different elements



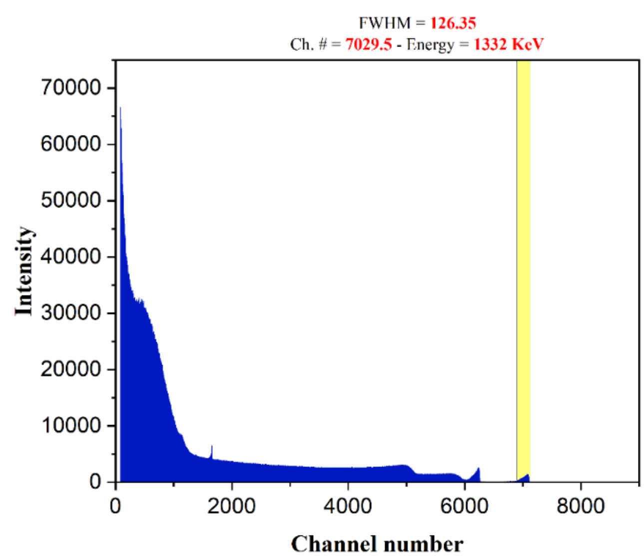
(a) Am-241



(b) Co-57



(c) Co-60 (1st peak)



(d) Co-60 (2nd peak)

Figure 17 Integration of gamma peaks for different elements using CdTe

Table 7 Channel number vs. energy for CdTe detector

Element	Channel number	Energy (KeV)
Am-241	318	59.5
Co-57	652	122
Co-60 (1st Peak)	6244	1173
Co-60 (2nd Peak)	7029.5	1332

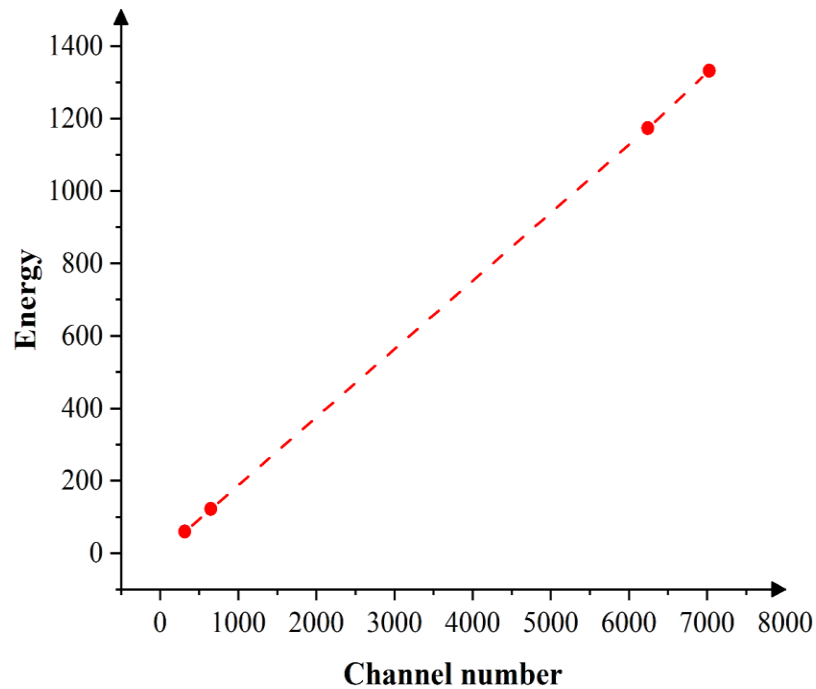


Figure 18 Energy calibration of CdTe detector

Task 3.2. Evaluating CdTe Resolution

Table 8 Energy resolution values of CdTe detector

Element	FWHM	Mean	Resolution (%)
Am-241	4.8182	318	1.5
Co-57	7.4	652	1.135
Co-60 (1st Peak)	97.33	6244	1.56
Co-60 (2nd Peak)	126.35	7029.5	1.8

Observation

- As observed and expected, the CdTe detector exhibits **better resolution** compared to scintillator detectors.

Task 4. Determining The Attenuation Coefficients of Al and Cu

Overview

The attenuation coefficient is a measure of how much the incident energy beam is **weakened** by the material it is passing through.

There are two types of attenuation coefficients:

- linear attenuation coefficient (μ)
- mass attenuation coefficient (μ/ρ)

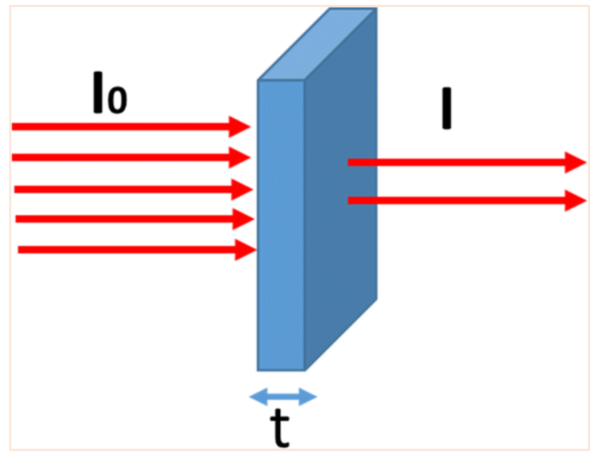


Figure 19 Illustration of radiation attenuation

- ### Linear Attenuation Coefficient

The intensity of the beam at distance x (cm) within a material is calculated using the Beer-Lambert Law:

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

Where $I(x)$ is the intensity at depth of x, I_0 is the original intensity, and μ is the linear attenuation coefficient.

- ### Mass Attenuation Coefficient

The mass attenuation coefficient is a **normalization** of the linear attenuation coefficient per unit density of a material producing a value that is constant for a given element.

It is expressed in cm^2/g.

Attenuation Coefficient of Al

Table 9 Variation of intensity with Al thickness

Thickness (cm)	I/I_0
0	1
0.11	0.9224
0.16	0.865
0.3	0.7872
0.5	0.68
0.8	0.5268
1.6	0.287
2.897	0.119
3.397	0.0668
4.374	0.0438
5.174	0.01767

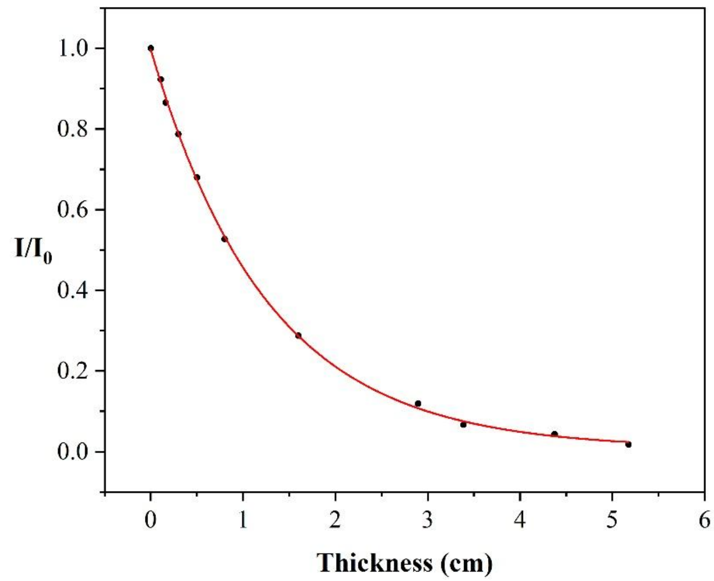


Figure 20 Attenuation curve for Al

Attenuation Coefficient of Cu

Table 10 Variation of intensity with Cu thickness

Thickness (cm)	I/I_0
0	1
0.02	0.771
0.05	0.554
0.07	0.46
0.1	0.2724
0.15	0.147
0.2	0.0725
0.25	0.04
0.3	0.0182
0.35	0.00864
0.4	0.00225

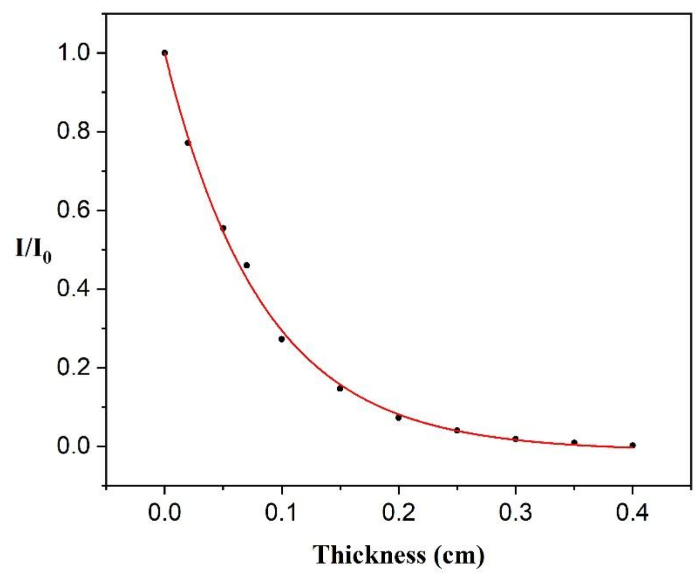


Figure 21 Attenuation curve for Cu

- The results are summarized in the following table:

Table 11 Attenuation coefficients for Al and Cu

Element	$\mu\ (cm^{-1})$	$\mu/\rho\ (cm^2/g)$
Al	0.8	0.29
Cu	11.93	1.33

Task 5. The Range of α-Particles in Air Using SRIM

Overview

Alpha particles, when emitted from a radioactive source, travel a specific distance based on their initial **kinetic energy and the stopping power** of the material they penetrate.

To assess their range in air at 5 MeV, a **Monte Carlo simulation** was performed using SRIM software, and the following graphs were obtained:

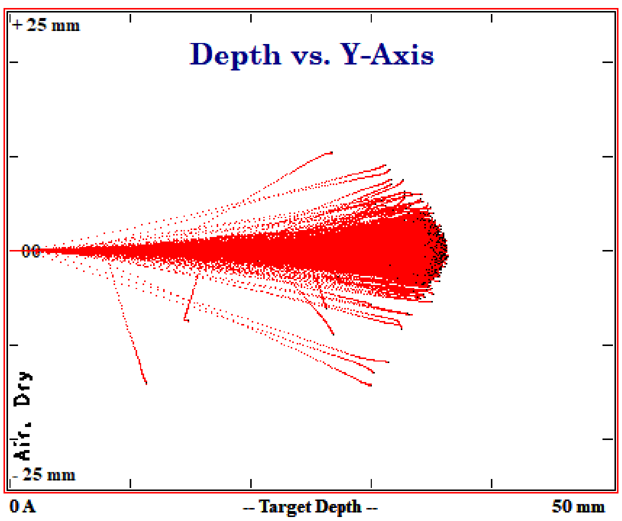


Figure 22 Simulation of alpha particles travelling in air

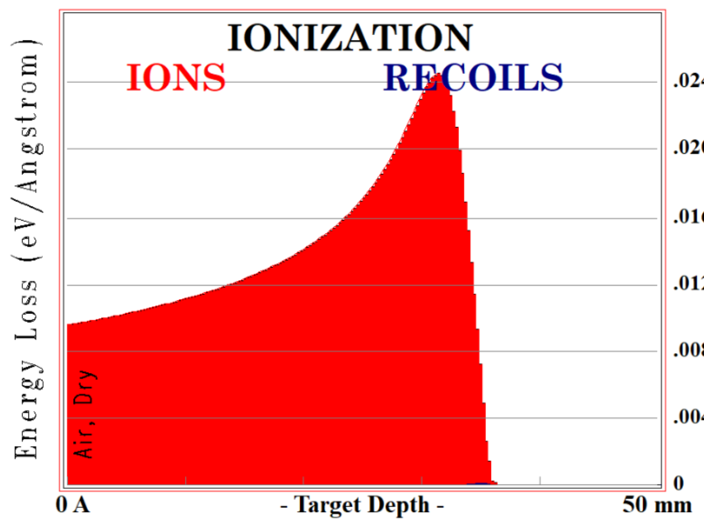


Figure 23 Bragg curve of alphas

Observation

- Each line represents the trajectory of a single alpha particle as it **slows down and eventually stops** due to interactions with air molecules.
- The majority of particles stop at around 40 - 50 mm. This matches with the known behavior of alpha particles, which travel only **few centimeters** in air due to their low penetration.
- As alphas slow down, they lose energy more rapidly, **forming a peak** near the end of their path.

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