Joint Institute for Nuclear Research

FINAL REPORT ON THE INTEREST PROGRAMME

“Radiation Protection and the Safety of Radiation Sources” Project

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Wave 10

Abstract

This report discusses the definition of radiation and delves deeply into the radiation detectors and their types which resembles the main tools and instruments used in nuclear physics industry for means of measurement and application of nuclear safety from radiation dangers and harms to people and environment.

This report shows the process of calculating the efficiencies of BGO and NaI detectors, calibration, and use of detectors to determine and identify other unknown sources from their energy spectrum throughout the different tasks requested along the project.

Also, the report discusses a specific aspect of radiation and their interaction with materials which is attenuation coefficient of different materials to radiation and discusses the concept of radiation range especially the range of alpha particles in air medium.

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Introduction

Radiation is the spontaneous emission of energy or particles from unstable atomic nuclei, plays a significant role in various fields, from medical diagnostics to nuclear power generation. However, its uncontrolled presence can pose health and safety risks. Therefore, the ability to effectively detect and identify radioactive sources is crucial.

This report delves into the world of radiation detection, exploring various types of detectors and their functionalities discussing the concept of detector efficiency and methods for its calculation, along with calibration technique used to ensure accurate measurements and the application of these detectors in identifying unknown radioactive sources. By analyzing the detected radiation's energy spectrum and comparing it to known radioactive isotopes to know the source's identity.

Furthermore, the report shifts to exploring the attenuation coefficient of radiation in different materials. This coefficient quantifies the rate at which the radiation loses its intensity as it travels through the materials. In addition to understanding the range, or maximum distance of which alpha particles can travel before being completely absorbed which in itself have a major contribution to many applications of radiation in real life in the field of nuclear medicine.

Radioactive Sources and Types of Radiation

A radioactive source is a known quantity of an element or radionuclide that emits radiation. Radiation can be Alpha particles, Beta Particles (β^+ or β^-), neutrons or Gamma rays. And also, can be classified into ionizing and non-ionizing radiation.

Radiation Detectors

A radiation detector is a device, or an instrument used to detect different types of radiation emitted from radioactive sources and collecting data about them such as: Energy spectrum of a radioisotope.

Types of Radiation Detectors

1. Gaseous Ionization detector

A type of radiation detector that is used to detect the presence of ionizing particles and measure them through their ionization effects on a gas-filled sensor. When a particle has energy enough to ionize a gas atom or molecule, a current flow can be measured and thus giving indication of ions or electrons.

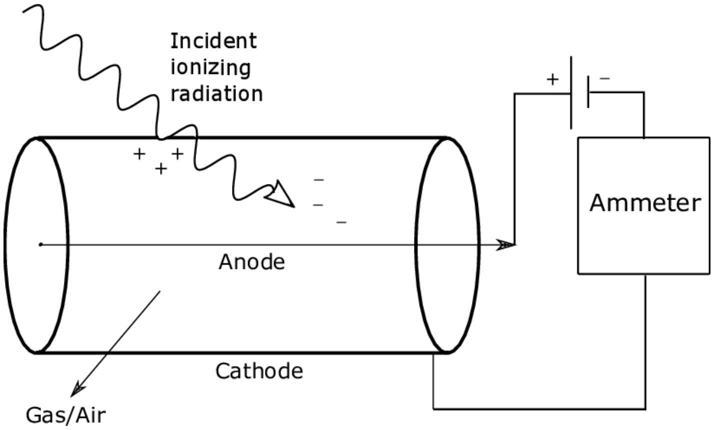

Figure 1: Gaseous Ionization Detector
Source: https://www.researchgate.net/figure/A-schematic-diagram-of-a-gas-filled-detector-illustrating-the-principle-of-operation-of_fig2_350483296

2. Scintillator detector

An instrument for detecting and measuring ionizing radiation by using the excitation effect of incident radiation on a scintillating material and detecting the resultant light pulses where the light pulses are produced due to excitation effect by the scintillator material and then photons are converted to an electrical signal by a sensitive photodetector, usually a photomultiplier tube (PMT), a charge-coupled device (CCD) camera, or a photodiode.

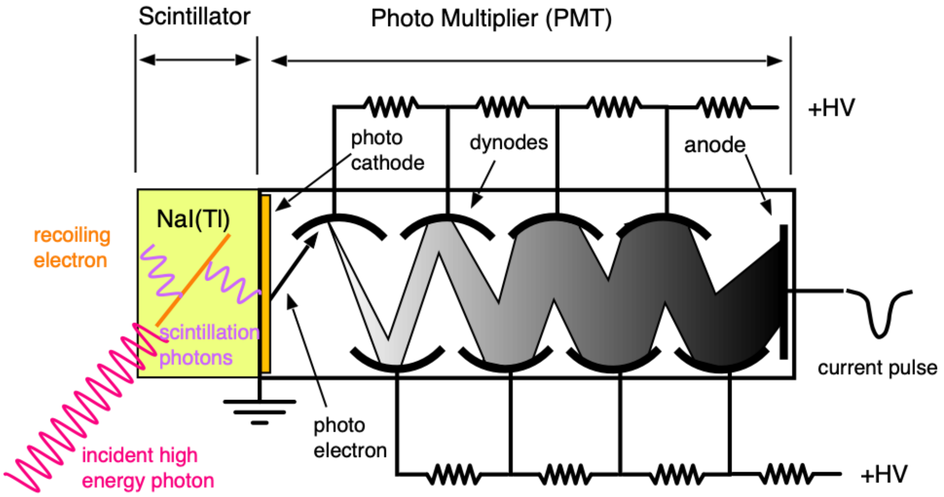

Figure 2: Scintillator Detector
Source: https://wanda.fiu.edu/boeglinw/courses/Modern_lab_manual3/scintillator.html

- Bismuth Germanate Detector (BGO)
  It is a type of scintillator detector of a high-density, high-Z scintillation material of the chemical formula Bi4Ge3O12. It is widely used in radiation detection due to its high stopping power for gamma rays and other ionizing radiation due to the presence of bismuth, which makes it very effective at stopping gamma rays and other high-energy radiation.

Figure 3: BGO Detector
source: https://www.researchgate.net/figure/A-BGO-detector-consisting-a-5-diameter-by-5-thick-bismuth-germanate-crystal-viewed-by_fig5_230924411

Task 1: Calculation of detector resolution

In this task, it was required to calculate the resolution of the BGO detector. Where:

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

The Standard deviation σ and Mean were determined using ROOT software by using "Fit panel" option in "Tools" tab. These parameters are collected for each sample where each sample has a different applied voltage on a detector (starting from 1200 V to 2000 V).

Table 1: Co-60 Energy peaks fitting and calculated resolution

Applied Voltage	Mean	Sigma	Res
1200	1.482	0.5799	0.9195
1300	1.38	0.2708	0.4611
1400	1.926	0.2879	0.3513
1500	2.984	0.4591	0.3616
1600	4.412	0.6224	0.3315
1700	6.131	0.7428	0.2847
1900	10.67	1.218	0.2683
2000	13.65	1.527	0.2629

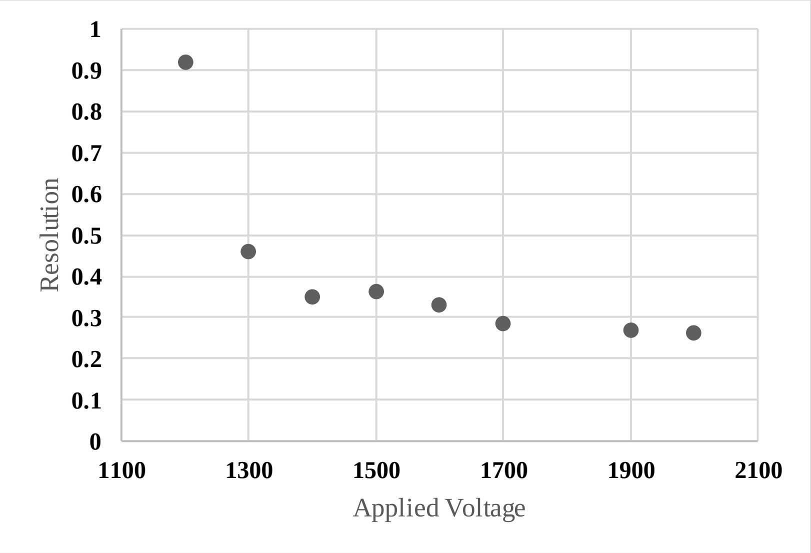

Figure 4: Applied Voltage - Resolution Graph

<u>Task 2</u>: Calibration of the detector and detection of an unknown source

The objective of this task is to calibrate the detector and determine the calibration equation to allow the detector to be used accurately when used for measuring other radioactive sources.

Co-60 and Cs-137 were used as a known source with known energy peaks. A graph is plotted between Energy peak in MeV and Mean. The calibration equation is determined and is applied to other samples to determine the element through its energy spectrum, more specifically through inserting the mean of energy peaks of the unknown source.

Table 2: Fitting of Co-60 and Cs-137 energy peaks by ROOT software

Element	Peak (Kev)	Mean	Energy/Channel
Cs-137	662	6.47458	102.2460144
Co-60	1252.85	12.251	102.2651212
Co-60	2500	24.3615	102.6209388

Calibration equation is $y = 9.7284x + 0.0458$

Where x represents Energy of the peak and y represents the mean of the peak.

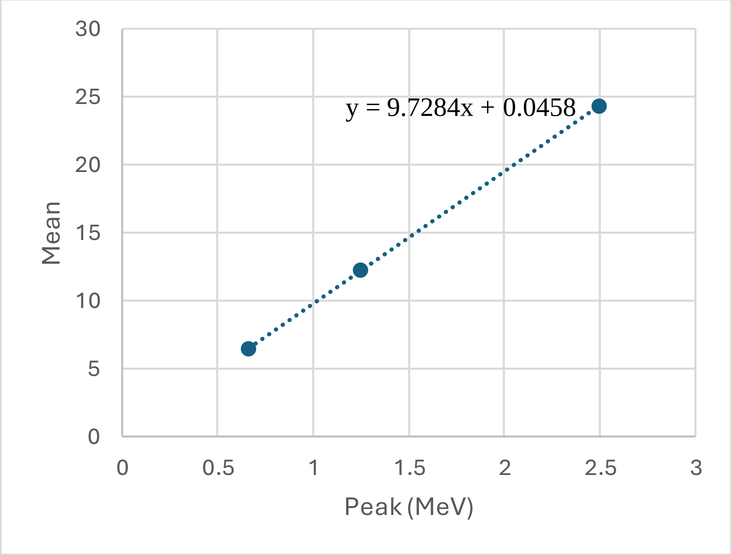

Figure 5: Peak - Mean Graph

The mean of the unknown source’s energy peaks can be inserted into the calibration equation to determine the energy peak (by solving for x) and therefore, characterize the element.

Table 3: Inserting mean into calibration equation and element identification

Peak #	Peak (Mev)	Mean	Element
1	0.02509868	0.28997	Sn-199m
2	0.0346576	0.382963	I-125 or Te-125m
3	0.044566732	0.479363	-
4	0.055220694	0.583009	-
5	0.101682702	1.03501	Pa-234

Elements are determined through looking up the energies table[1].

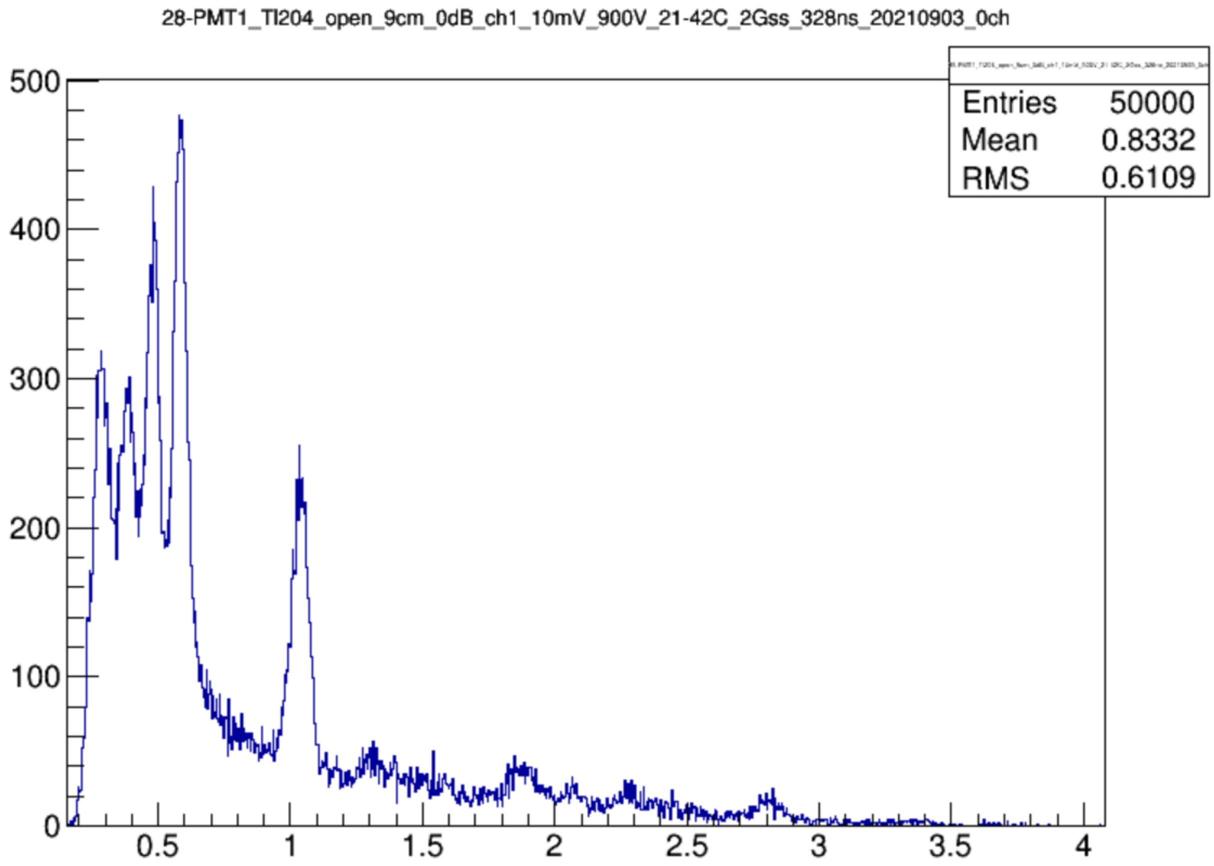

Figure 6: Energy spectrum of the unknown source

- Sodium Iodide Detector (NaI)

A type of scintillation detector that uses a scintillator material of sodium iodide (NaI) crystal doped with thallium (Tl). The NaI crystal produces photons in response to the incidence of gamma radiation, and the amount of light produced is proportional to the energy of the gamma photon which is later detected by a photomultiplier tube (PMT), which translates the light into an electrical signal that can be analyzed to determine the energy and intensity of the gamma radiation.

Task 3: Calculating the detector's resolution and calibration of the detector.

As shown before in the previous tasks, the same methods are applied to complete the objective but with NaI detector which is of a higher accuracy than BGO detector.

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[1] Source: https://web.physics.indiana.edu/courses/p451/examples/Gamma_Energies_table.pdf

Table 4: Resolution Calculations using 2 energy peaks of Co-60

Applied Voltage (Volts)	**Peak (keV)**	**Mean**	**Sigma**	**Resolution %**
900	1173	23.68	0.608	6.03%
	1333	26.58	0.584	5.17%
1000	1173	40.65	0.966	5.58%
	1333	45.47	0.955	4.93%
1100	1173	65.83	1.528	5.45%
	1333	73.28	1.472	4.72%
1200	1173	98.76	2.01	4.78%
	1333	108.5	1.839	3.98%
1300	1173	137.4	2.52	4.31%
	1333	148.9	2.357	3.72%

Table 5: Applied Voltage - Resolution values of 1173 KeV peak

At peak 1173 keV	
Applied V	Res
900	6.03%
1000	5.58%
1100	5.45%
1200	4.78%
1300	4.31%

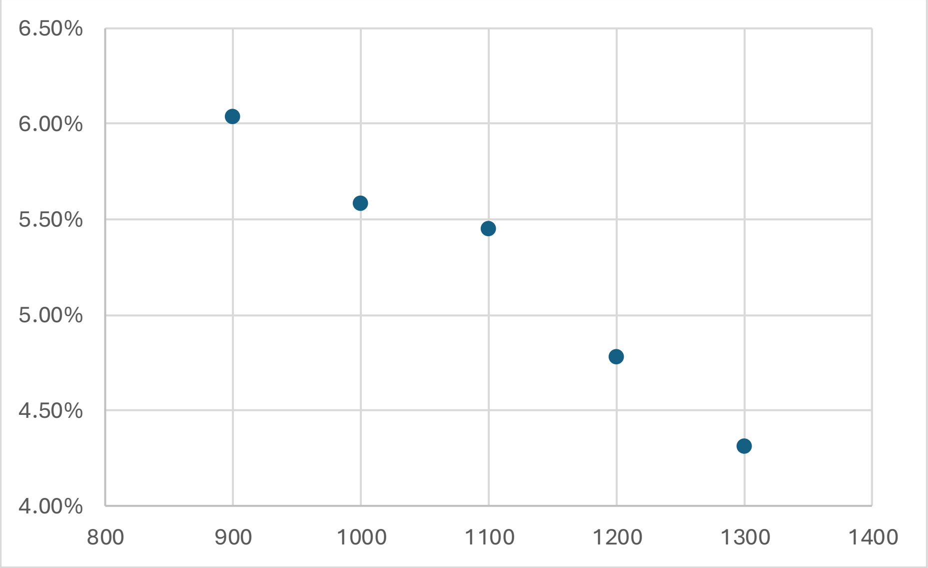

Figure 7: Applied Voltage - Resolution Graph of 1173 KeV Energy peak of Co-60

Table 6: Applied Voltage - Resolution values of 1333 KeV peak

At peak 1333 keV	
Applied V	Res
900	5.17%
1000	4.93%
1100	4.72%
1200	3.98%
1300	3.72%

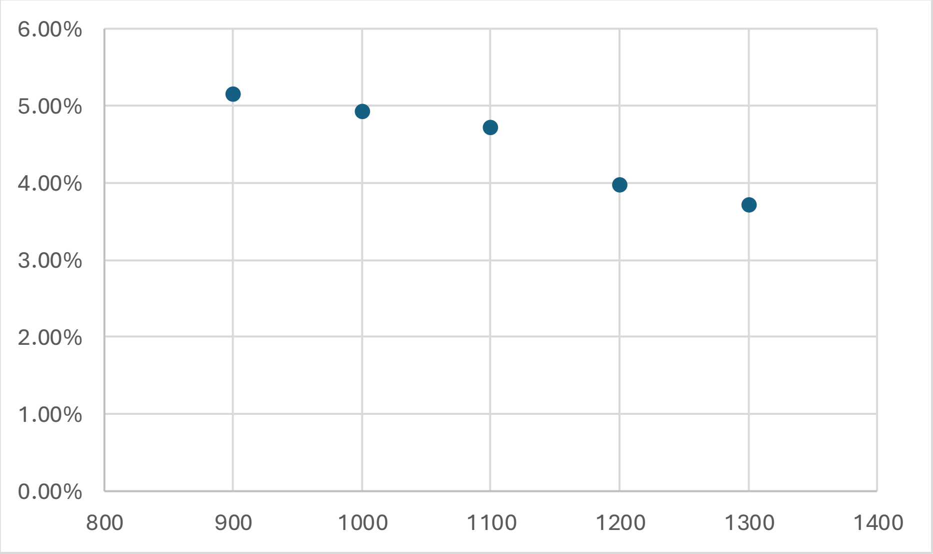

Figure 8: Applied Voltage - Resolution Graph of 1333 KeV Energy peak of Co-60

After calculating the resolution, it is required to determine the calibration equation of the detector.

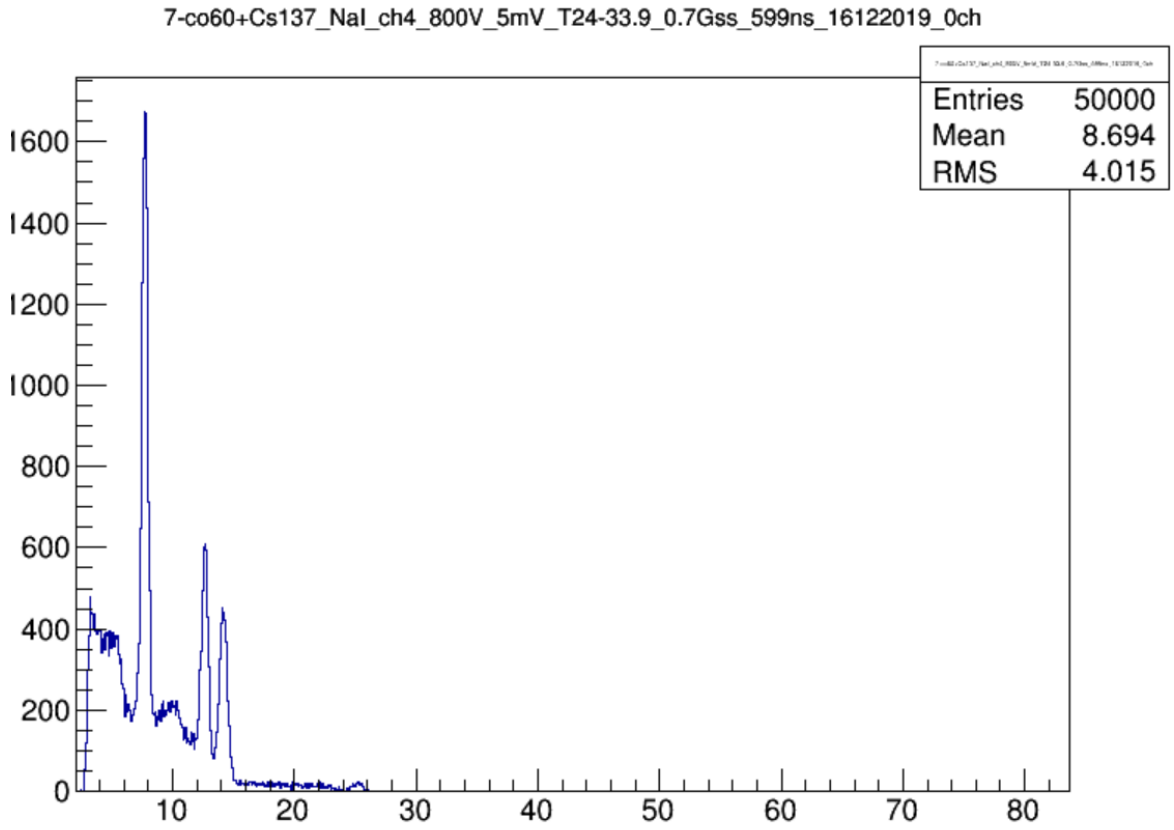

Figure 9: Co-60 and Cs-137 sample for calibration of the detector

Table 7: Fitting of Co-60 and Cs-137 energy peaks by ROOT software

Element	**Peak (MeV)**	**Mean**	**Energy/Channel**
Cs-137	0.662	7.711	0.085850156
Co-60	1.173	12.64	0.092833683
Co-60	1.333	14.15	0.094172336

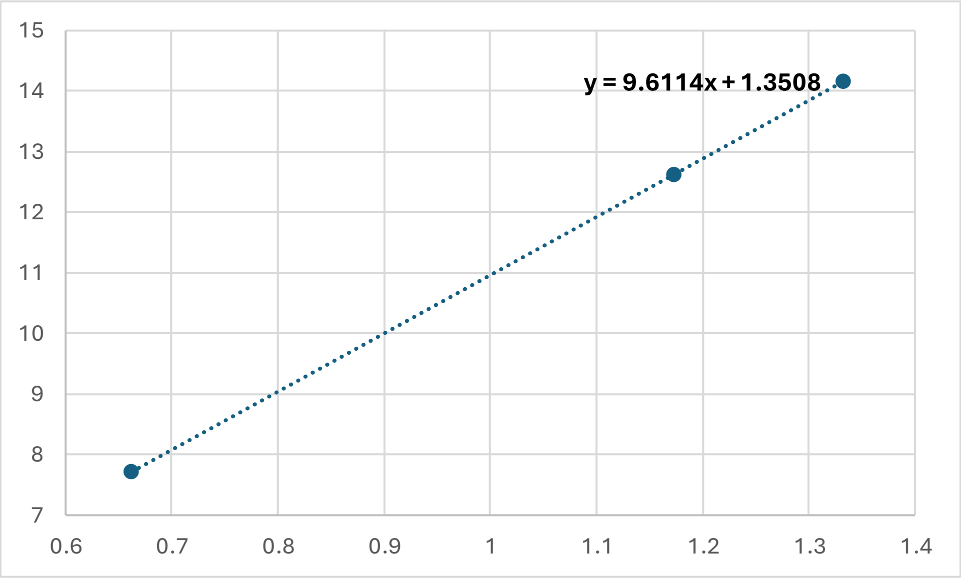

Figure 10: Calibration curve of NaI detector

Calibration equation is $y = 9.6114x + 1.3508$

After determining the calibration equation, it can be used to identify other radioactive elements as done previously.

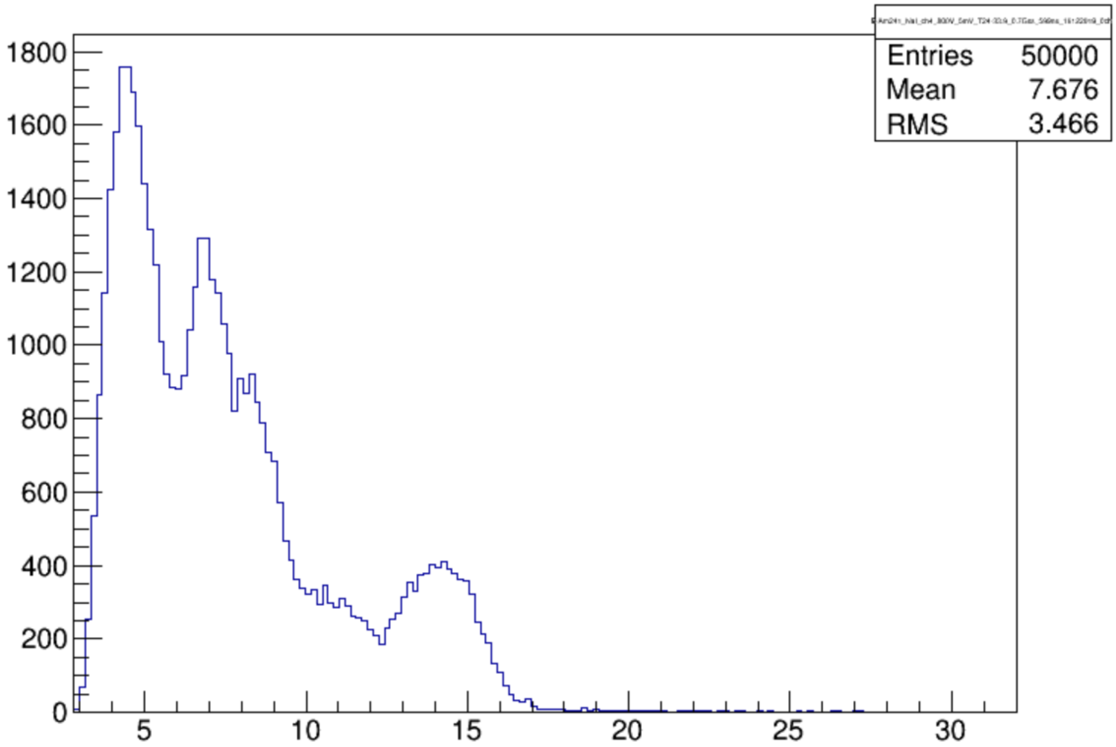

Figure 11: Energy spectrum of unknown source.

Table 8: Identification of unknown source using the calibration equation of the detector

Peak #	Peak (MeV)	Mean	Element
1	0.333499802	4.5562	Hf-180m
2	0.577851302	6.90476	-
3	0.709449196	8.1696	-
4	1.318756893	14.0259	-

3. Semiconductor detector

A type of radiation detector that utilizes a semiconductor material, such as silicon, to measure the effect of incident charged particles or photons. They operate on the principle of induced charges. When ionizing radiation enters the semiconductor, it interacts with the material, creating electron-hole pairs. The number of these pairs is proportional to the energy of the incident radiation that can be used as a parameter to detect the energy of radiation. By collecting these electron-hole pairs, a detection signal is generated to be recorded, providing information about the intensity and energy of the incident radiation.

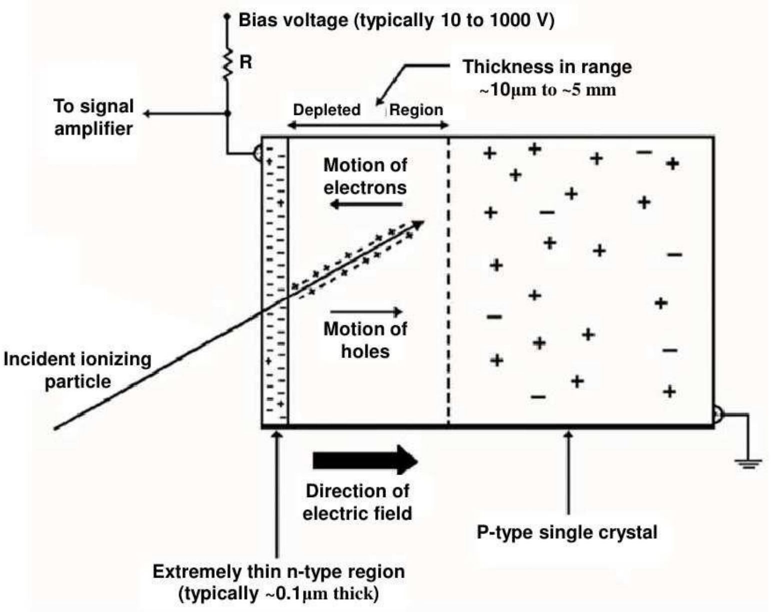

Figure 12: Semiconductor Detector
source: https://www.researchgate.net/figure/Schematic-diagram-of-semiconductor-detector-silicon-based-detector-Radiation_fig9_269704941

4. Pixel detector

It is one of the most recent types of detectors. It consists of an array of pixels[2], each of which functions as an independent small detector that can detect and measure the energy and position of ionizing radiation.

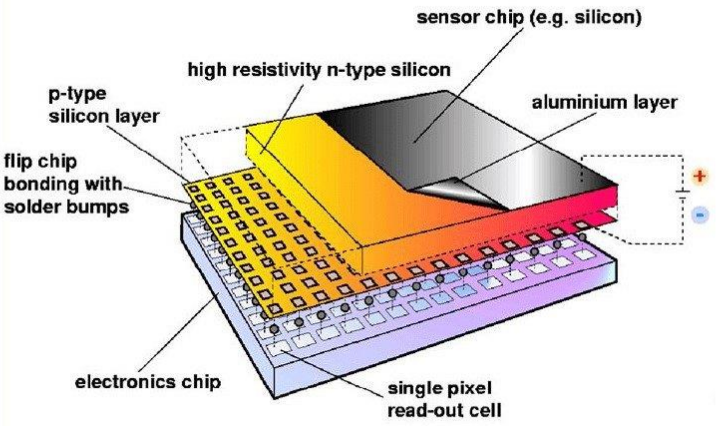

Figure 13: Pixel Detector
source: https://www.researchgate.net/figure/Overview-of-the-hybrid-pixel-detector-layers-Obtained-from-34_fig3_325298919

Attenuation Coefficient

Attenuation coefficient describes the fraction of a beam that is absorbed or scattered per unit thickness of the absorber governed by the following equation:

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

Where μ is the attenuation coefficient, I is the intensity of radiation at thickness x and I_o is the intensity at 0 thickness.

Task 4: Determine the attenuation coefficient of radiation in Copper (Cu) and Aluminum (Al) shields

Table 9: Ratio of incident radiation at different thicknesses of Cu

Thickness (cm)	I/Io
0	1
0.2	0.73931
0.25	0.7357
0.4	0.68065
0.8	0.58611
1	0.53827
1.2	0.48042

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[2] The term "pixel" is short for "picture element" and refers to the smallest unit of a digital image.

Table 10: Ratio of incident radiation at different thicknesses of Al

Thickness (cm)	I/Io
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

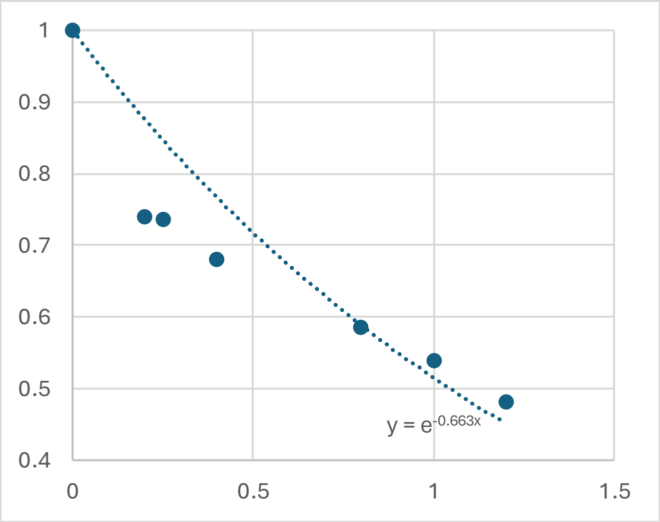

Figure 14: Thickness - I/Io Plot in Cu

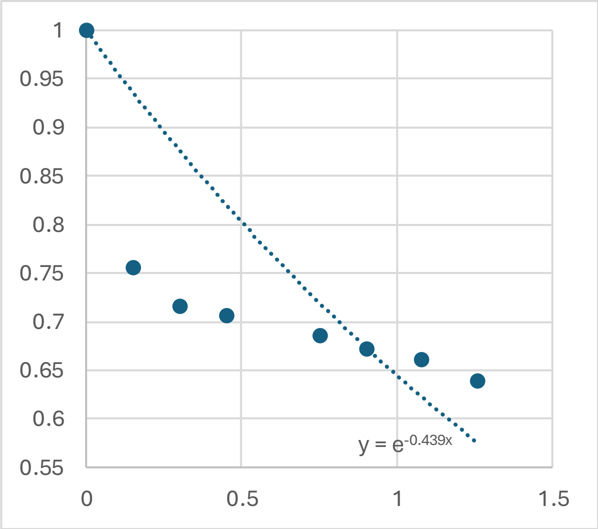

Figure 15: Thickness - I/Io Plot in Al

Using Microsoft Excel to show the equation of the trendline, it is determined that:

- Cu

The equation of the trendline is: $y = e^{(-0.663x)}$

$$\therefore \mu = 0.663$$

- Al

The equation of the trendline is: $y = e^{(-0.439x)}$

$$\therefore \mu = 0.439$$

Alpha Particles (α) Radiation

An alpha particle is a positively charged particle that is radiated spontaneously from the nuclei of some radioactive elements. It is a helium ion with an electrostatic charge of +2. Alpha particles consist of two protons and two neutrons bound together.

Range

It is the distance travelled by alpha particles until it has no kinetic energy and recombine with electrons forming Helium atoms (stable atoms).

Task 5: Determine the Range of Alpha particles in air

Alpha radiation of 5.5 MeV energy is radiated in air and a detector is put in front of the radiation source at different distances to determine the count of the particles.

Table 11: Measurements of Alpha radiation at different distances

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

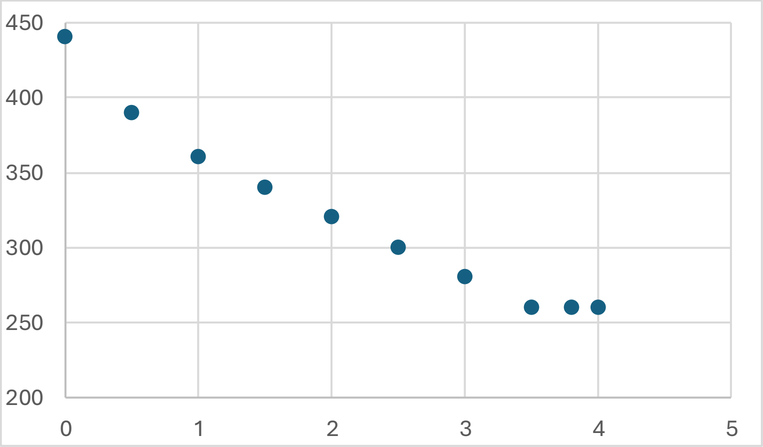

Figure 16: Distance - Counts/sec Graph

As shown in Figure (14), the range of alpha particles in air is at 3.5 cm.

For determining such range in different materials, it can be difficult to be done practically so, a Monte-Carlo simulation can be achieved by SRIM software to simulate the incidence of alpha particle on different materials (including Air) as shown in the following figures.

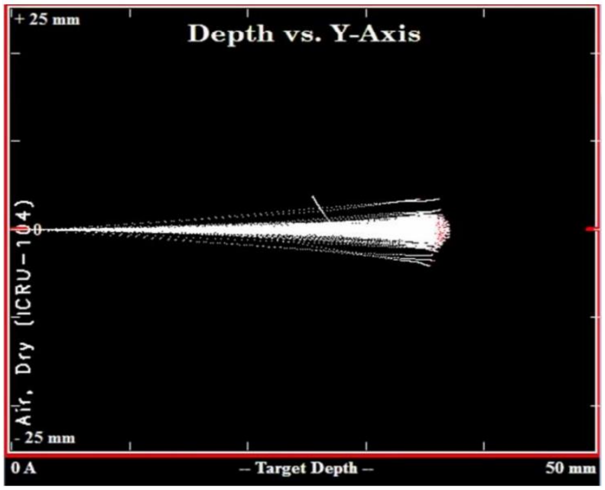

Figure 17: Depth for alpha radiation in air

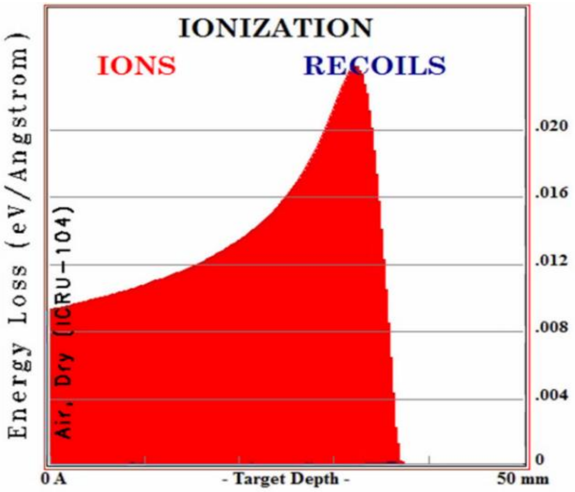

Figure 178: Ionization - Depth graph for alpha radiation

Conclusion

In conclusion, this report has explored various aspects of radiation, radiation detection, different types of detectors, their efficiencies calculation, and their calibration techniques to ensure accurate measurements alongside using different software like: ROOT and Microsoft Excel to achieve the required objectives. It is informed that knowledge empowers us to utilize radiation detectors effectively, shaping a safer environment for applications involving radioactive materials. Further research and development in detector technology can continuously improve efficiency, sensitivity, and portability, leading to even more effective radiation detection strategies. Also, the report discussed the attenuation coefficient in different shield types and range of alpha particles in air using both practical physical method and digital Monte-Carlo simulation using SRIM software.

References

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Acknowledgments

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