Study of Gamma Ray Spectroscopy using Single Channel and Multiple Channel Analysers

Gayatri P
3rd year, Integrated M.Sc. Physics
Roll No.: 2211185
(Dated: April 30, 2025)

In this experiment, we investigate the gamma ray spectroscopy of sever radioactive materials, using a scintillation detector in both SCA and MCA modes. Using the known spectrum of Cs-137, we determine the operating voltage of the detector and find its resolution, which turns out to be 9.14%. In the multiple channel mode, using the known peak energy sources, we calibrate the spectrum to find the peak energies of a Na-22 source. We also compute the mass absorption coefficient of Aluminum by studing the penetration of gamma rays as we vary its thickness.

I. THEORY

A. Gamma spectroscopy

Gamma spectroscopy studies the energy spectrum of gamma-ray sources. Gamma rays produced by radioactive sources are of various energies and intensities and can interact with matter in several ways (Fig. 1). Three significant ways are,

1. **Photoelectric (up to several hundred keV):** The photoelectric effect occurs when a low-energy gamma photon interacts with matter. In this process, the photon transfers its entire energy to an electron, ejecting it from the material. The ejected electron's kinetic energy equals the initial photon energy minus the electron's binding energy within the material.
   This phenomenon is highly advantageous for gamma-ray spectroscopy. Since the entire photon energy is deposited in the detector, it generates an output pulse directly proportional to the gamma-ray energy. This results in a distinct full-energy peak in the measured spectrum, allowing for accurate identification of the radioactive source.
   At typical gamma-ray energies, photoelectrons are most likely ejected from the innermost electron shell (K-shell). The binding energies of K-shell electrons range from a few keV for low-atomic-number materials to tens of keV for higher atomic numbers.
   To conserve momentum, the atom recoils during photoelectron emission. However, this recoil energy is generally negligible.
   For monoenergetic gamma rays, the photoelectron's kinetic energy equals the incident gamma-ray energy. Consequently, the distribution of photoelectron kinetic energies would ideally be a single, sharp peak (delta function) corresponding to the full gamma-ray energy.
   In reality, due to factors like energy loss within the material and detector response, the peak will have a finite width. For non-monoenergetic gamma-ray sources, multiple Gaussian-shaped peaks will be observed in the energy spectrum.

2. **Pair production (predominates around 5-10 MeV):** Pair production is a significant interaction process for gamma rays with energies exceeding 1.022 MeV, with a more pronounced effect above 2.5 MeV. In this process, a high-energy gamma-ray photon interacts with the nucleus of an atom, converting its energy into the creation of an electron-positron pair. The energy conservation equation for this process is:

$$E_{e^-} + E_{e^+} = h\nu - 2m_e c^2 \tag{1}$$

   The created electron and positron lose their kinetic energy through interactions with the surrounding material, typically traveling only a few millimeters before coming to rest.
   When the positron comes to rest, it annihilates with an electron, resulting in the emission of two 511 keV gamma rays traveling in opposite directions.
   The probability of pair production is zero below the energy threshold of 1.022 MeV (twice the electron rest mass). It increases with increasing gamma-ray energy, reaching a plateau at around 100 MeV.

3. **Compton scattering:** In the Compton effect, the gamma ray scatters from an electron, transferring an amount of energy that depends upon the angle of scatter.

$$E^{'} = \frac{E}{1 + \frac{E(1-\cos\theta)}{mc^2}} \tag{2}$$

   here $E^{'}$ is the scattered energy of the gamma-ray, E is the incident gamma-ray energy, θ is the angle of scatterring, the term m_0c^2 is the electron's rest mass, equal to $511keV$. The energy given to the electron is: $E_e = E - E^{'}$. The maximum energy given to an electron in Compton scattering occurs for a scattering angle of 180°. These impacts will be especially pronounced for low-incident gamma-ray

energy. They entail smoothing off the increase in the continuum towards its top extreme and adding a limited slope to the Compton edge's abrupt drop. These effects are frequently obscured by the detector's finite energy resolution, but they can be seen in spectra from detectors with high inherent resolution.

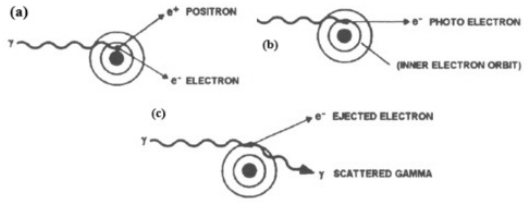


FIG. 1: An overview of the process behind (a) pair formation (b) photoelectric effect and (c) Compton scatteting

B. Scintillation Detector

The basic setup of a scintillation detector is illustrated in Fig. 2.

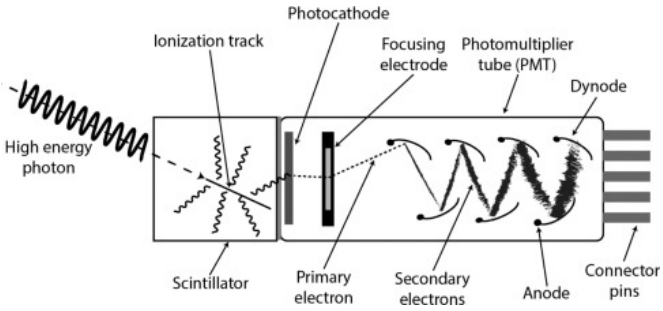


FIG. 2: Schematic diagram of a scintillation detector [1].

When gamma ray enters the scintillation chamber, it iteracts with the gas present their energy is converted to an energetic electron via either the photoelectric effect, Compton scattering or pair production. This electron is captured by the photocathode and the signal is then amplified in the photomultiplier tube and picked up by the collector.

The spectrometer's resolution is statistically derived. When the detector absorbs energy, it releases a varying number of photons. These photons, in turn, generate a variable number of photoelectrons at the cathode. The total electron count at the photomultiplier's anode is proportional to the detector's energy absorption and is influenced by the voltage between dynodes. Detector resolution, defined as the full width at half maximum of the photopeak spectrum, is independent of the linear amplifier's gain.

C. Mass absorption coefficient

We know that gamma rays interact with matter. The total mass absorption coefficient can be measured from Lambert's law. the decrease in intensity of radiation as it passes through the absorber is given by:

$$I = I_0 e^{-mx}$$

where
I = intensity after absorption
I_0 = intensity before absorption
m = mass absorption coefficient
x = density thickness in g/cm^3

Density thickness is the product of material density times thickness in cm. the half-value layer (HLV) is defined as the density thickness of the absorbing material at which intensity is reduced to half of the original value.

II. EXPERIMENTAL SETUP

Apparatus

1. SCA setup
2. MCA setup
3. Radioactive source (Cs-137, Na-22, Ba-133, Co-60)
4. Aluminium blocks
5. A computer for analysis

The scintillation detector used in this experiment is made up of a Sodium Iodide crystal that is optically connected to a photomultiplier. There are three connections available: UHF, circular I/O, or Minihex & BNC. The detector's high voltage (operating voltage) is supplied by the HV module and attached to the UHF connection. The Minihex 5 pin I/O connection is used to deliver low voltages from the Minibin power supply to the pre-amplifier. A BNC cable connects the detector output to the linear amplifier input. A `NUCLEONIX` scintillation detector or its equivalent can be linked to the `NUCLEONIX` Gamma Ray Spectrometer electrical unit. A GR611M unit is used for linear amplification as well as measuring counts in the SCA mode.

III. OBSERVATION AND CALCULATIONS

A. Estimation of operating voltage of the Scintillation Detector

We have obtained the count vs. LLD voltage plots for different values of operating high voltage. The resolution for a particular operating voltage is defined as the ratio of the FWHM of the distribution and the peak count value. It can be observed that the resolution varies with the applied voltage and the voltage at which we get the best

LLD (V)	Counts at different Operating Voltages				
	450V	500V	550V	600V	650V
2.4	1688	1084	-	-	1282
2.5	1794	1181	-	-	1575
2.6	1801	1096	-	-	2163
2.7	1959	1055	2897	2083	4028
2.8	2112	1096	4153	2912	7715
2.9	2194	2008	7871	4914	9342
3	2275	8220	10203	9417	9167
3.1	2146	11619	8135	11449	7286
3.2	2094	9304	6475	8943	6473
3.3	1913	4464	5378	7096	5450
3.4	1799	1642	4437	5931	4457
3.5	-	-	-	4782	3154
3.7	-	-	-	4093	2120
3.8	-	-	-	3569	1147

TABLE I: LLD vs. Count data for Cs-137 at different operating voltages

resolution is fixed as the operating voltage for the rest of the experiment.

Table I details the V versus count data at different operating voltages. Figs. 3 to 7 plot the V versus count data to a Gaussian fit and Table II summarises the estimation of ideal operating voltage from the resolutions.

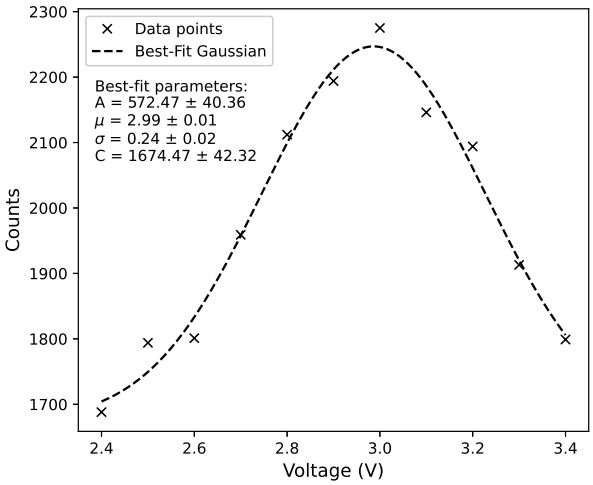


FIG. 3: Cs-137 photopeak spectrum at 450V

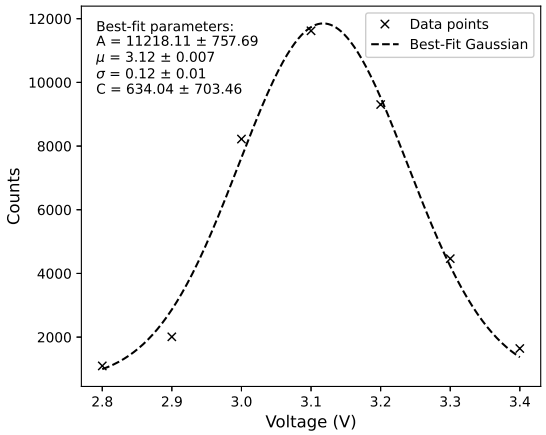


FIG. 4: Cs-137 photopeak spectrum at 500V

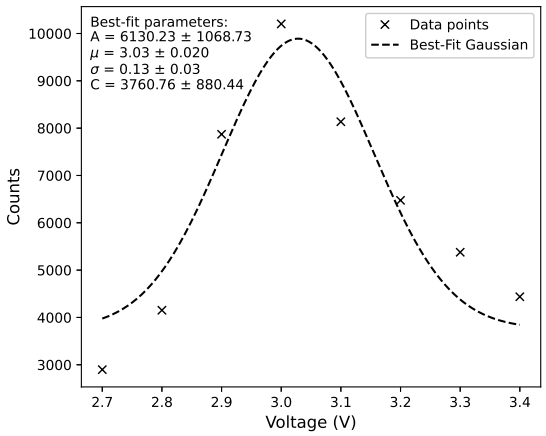


FIG. 5: Cs-137 photopeak spectrum at 550V

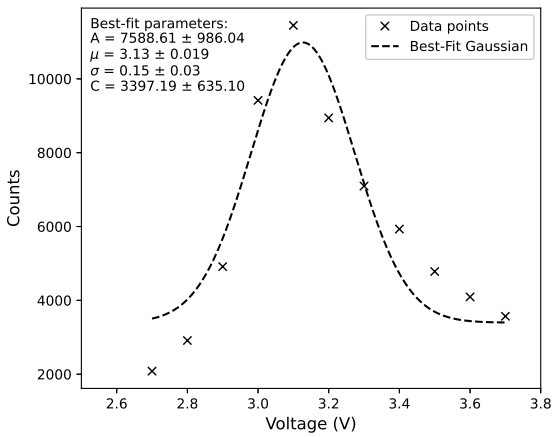


FIG. 6: Cs-137 photopeak spectrum at 600V

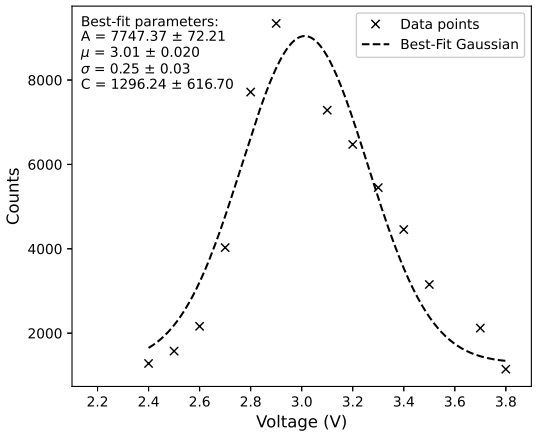


FIG. 7: Cs-137 photopeak spectrum at 650V

LLD (V)	Count	LLD (V)	Count
1	3560	2.3	1127
1.1	2881	2.4	954
1.2	2564	2.5	915
1.3	2414	2.6	1134
1.4	2332	2.7	2471
1.5	2338	2.8	7688
1.6	2187	2.9	11254
1.7	2209	3	6572
1.8	2207	3.1	2265
1.9	2189	3.2	690
2	2077	3.3	223
2.1	1761	3.4	135
2.2	1452	3.5	92

TABLE III: LLD vs. Count data for Cs-137 at an operating voltage of 500V

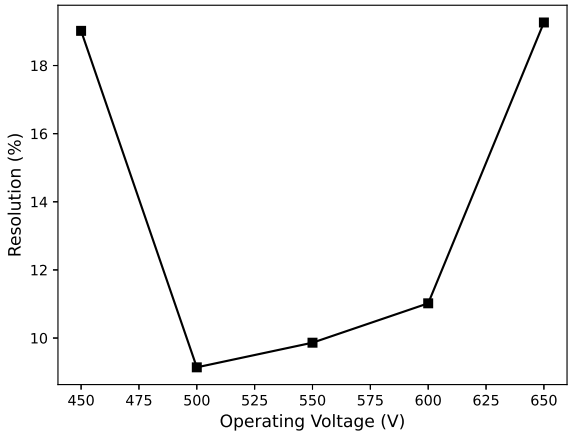


FIG. 8: Applied voltage vs. resolution characterstics

Operating Volt.	Max. Height at (V)	FMWH	Resolution (%)
450	2.99	0.57	19.02
500	3.11	0.28	9.14
550	3.02	0.30	9.86
600	3.13	0.34	11.02
650	3.12	0.34	19.26

TABLE II: Operating voltage vs FMWH and resolution

Hence from Fig. 8, we have the best operating voltage for the setup as 500V with a resolution of 9.14%.

B. Study of Cs-137 spectrum using SCA

Now, fixing the SCA setup at the operating voltage, we took V vs count data for Cs-137. The values are given in Table III and plotted in Fig. 9.

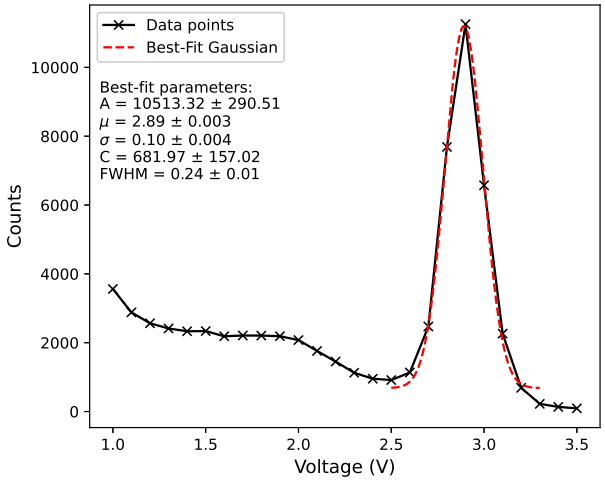
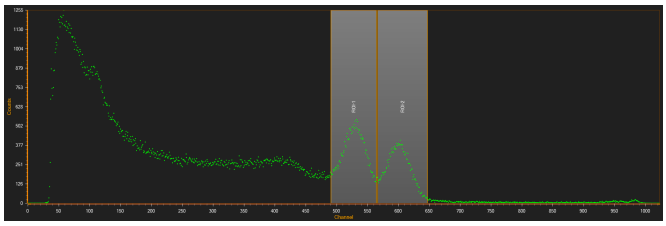


FIG. 9: Energy Spectrum of Cs-137

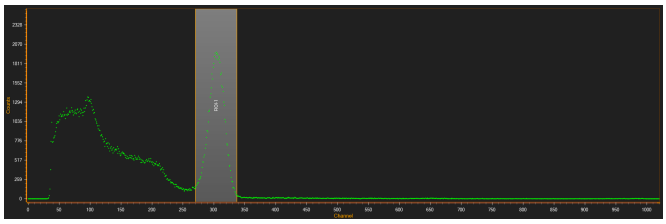
In Fig. 9, using the photopeak at 662 keV, the resolution of the detector can be calculated from the FWHM and the μ value as, $\boxed{8.37\%}$.

C. Study of Co-60 and Cs-137 spectra using MCA

Fig. 10 shows the energy spectra of Cs-137 and Co-60 analysed my the MCA.



(a) Co-60



(b) Cs-137

FIG. 10: Plots showing the Energy Spectrum analysed using MCA

The details of the analysis are presented in Tables IV and V.

Start	269
End	337
Peak	304.9182
TM/HM	1.7814
FMHM	28.0935
Gross	61475
Net	54885.5

TABLE IV: Cs-137 Peak Report

	Peak 1	Peak 2
Start	566	490
End	646	564
Peak	602.3283	530.2158
TM/HM	1.7433	1.5238
FMHM	34.2273	37.2411
Gross	18378	25152
Net	10116	12274

TABLE V: Co-60 Peak Report

From tables IV and V, we can estimate the resolution of the detector as,

- Cs-137: 9.21%
- Co-60 (Peak 1): 5.68%
- Co-60 (Peak 2): 7.02%

D. Energy Calibration of the spectrometer & Estimation of Energy of an Sample Isotope

Now, using the multiple channel analyser, three different sources were placed in front of detector at once and spectrum was analysed to obtain the calibration curve. The energy spectrum used were of Cs-137, Co-60 and Ba-133, whose photopeaks are known to us.

Fig. 11 shows the combined energy spectrum and table VI summarises the peaks shown in the figure.

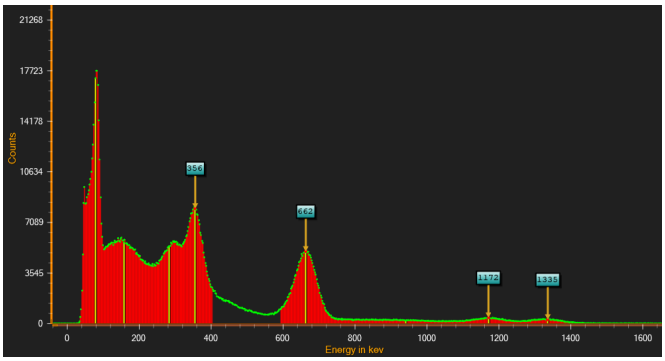


FIG. 11: The combined energy spectrum of Cs-137, Co-60 and Ba-133, with four known peaks highlighted

Source	Energy (keV)	Peak Channel
Ba-133	356	169.9308
Cs-137	662	302.922
Co-60	1172	525.6078
Co-60	1335	598.9153

TABLE VI: Known energy sources calibrated across a range of 1024 channels

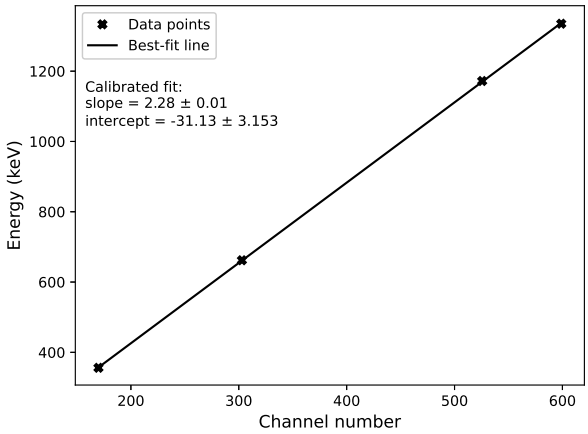


FIG. 12: Calibration curve for the MCA

Fig. 12 shows the calibrated curve for the detector. Now we can analyse the energy spectrum of an unknown sample using this curve.

Thickness (cm)	Gross count	Net count
0.0	28241	27187
0.5	25646	24592
1.0	23825	22771
1.5	21531	20477
2.0	19060	18006
2.5	17824	16770
3.0	15909	14855
3.5	14218	13164
4.0	13417	12363
4.5	11981	10927
5.0	10965	9911
5.5	9903	8849
6.0	9078	8024

TABLE VII: Net and gross counts around a fixed 662 keV peak with varying thicknesses of Al kept in front of the detector. Background count = 1054.

Analysis of an the energy spectrum of Na-22

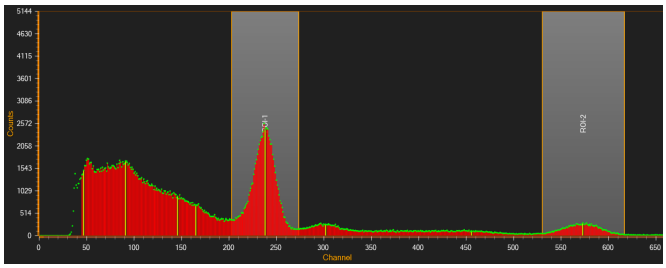


FIG. 13: The energy spectrum of Na-22

Fig. 13 shows the energy spectrum of Na-22. Two peaks were detected at channels 238.1277 and 573.4547 respectively. Therefore, using the fit calibration curve obtained previously, the corresponding energy values are 511.80 keV and 1276.35 keV respectively.

E. Estimation of the Mass Absorbance Coefficient of Aluminium

For 662 keV gamma rays, the mass absorption coefficient of Al is measured by placing aluminum blocks of different thicknesses between the detector and the source. The net count (= total count − background noise) as a function of thickness is presented in Table VII.

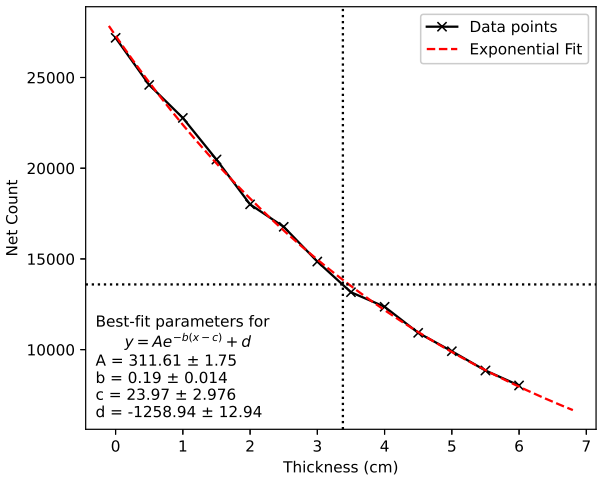


FIG. 14: Net count vs. thickness for aluminium. The dotted line highlights the half-value thickness at around 3.38cm

From the graph Observed value of Half value thickness (thickness at which counts are reduced to half) is 3.38cm. This means density thickness $= 3.38 \times 2.7 = 9.13$ gm/cm^2 (using the density of aluminium). Hence, the mass absorption coefficient comes out to be,

$$m = \frac{\ln(2)}{9.13} = 0.076 \text{ gm/cm}^2$$

IV. ERROR ANALYSIS

The error in a quantity $Q(a_1, a_2, ..., a_n)$ is calculated using,

$$\Delta Q = \sqrt{\left(\sum_i^n \frac{\partial Q}{\partial a_i} \Delta a_i\right)^2} \tag{3}$$

Resolution of the detector

The uncertainity in resolution of the detector at the operating voltage can be calculated as from FWHM and the voltage at peak height, which comes out to be 0.92%.

Peak energy values of Na-22

The uncertainity in energy is directly a function of the uncertainities in the calibration curve. These values come out to be (511.80 ± 3.95) keV and (1276.35 ± 6.54) keV.

Mass Absorbance Coefficient of Al-22

The uncertainity in m is directly a related to the uncertainity in the estimation of HVT which is 0.5 cm. Hence Δm comes out to be 0.01 gm/cm^2.

V. DISCUSSION & CONCLUSION

The operating voltage of the scintillation detector was found to be 500V, where the detector exhibits a resolution of $(9.14 \pm 0.92)\%$. Using this we successfully analysed the energy spectrum of Cs-137 using SCA. The error in the Gaussian curve fitting to find resolution could be reduced further by increasing the number of data points. Now, by calibrating the MCA channels with known gamma sources, we were able to accurately determine the gamma energy peaks of Na-22, which came out to be (511.80 ± 3.95) keV and (1276.35 ± 6.54) keV. These are very close to the literature values of 511 keV and 1274.5 keV respectively. We then calculated the mass absorption coefficient of aluminium to be (0.076 ± 0.011) g/cm^2. Hence, it is an efficient material for shielding against gamma radiation.

VI. PRECAUTIONS AND SOURCES OF ERROR

1. Inaccurate energy or efficiency calibration could impacts results. So, accurately calibrate the detector and MCA before measurements.
2. Voltage or temperature fluctuations lead to calibration drift, hence monitor the temperature carefully.
3. Contamination in the sample could lead to incorrect data.
4. Make sure to properly shield the radioactive source when not in use. Use proper handling tools to avoid any accidents.
5. Background radiation could cause incorrect data, so properly shield the setup.

[1] T. W. Kerlin and B. R. Upadhyaya, Chapter 16 - nuclear plant instrumentation, in *Dynamics and Control of Nuclear Reactors*, edited by T. W. Kerlin and B. R. Upadhyaya (Academic Press, 2019) pp. 213–235.

[2] SPS, *Experimental Manual: MCA with Anuspect*, Nucleonix Systems (2023).

[3] SPS, *Gamma ray spectroscopy with Single Channel Analyser*, NISER (2023).