Gamma Ray Spectroscopy using SCA and MCA

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Gamma-ray spectroscopy was performed using a NaI(Tl) scintillation detector with Single Channel Analyzer (SCA) and Multi Channel Analyzer (MCA) systems. The ^{137}Cs photopeak was analyzed at different operating voltages to determine the full width at half maximum (FWHM) and energy resolution, and the optimal operating voltage was found to be 650 V with a resolution of about 11.8%. Energy spectra of ^{137}Cs and ^{60}Co were recorded using the MCA, and the detector resolution was evaluated to be 8.8% for ^{137}Cs and 9.5% in energy using the ^{60}Co peaks. The spectrometer was calibrated using ^{133}Ba, ^{137}Cs, and ^{60}Co. This calibration was used to identify an unknown source as ^{22}Na from its characteristic gamma-ray energies. The mass absorption coefficient of aluminium was determined to be $(0.063 \pm 0.002)\,\mathrm{cm^2 g^{-1}}$, which was consistent with the literature values. These results demonstrate the performance of the NaI(Tl) scintillation detector for gamma-ray spectroscopy.

I. OBJECTIVE

1. To study the dependence of resolution on operating voltage using SCA
2. To study the spectrum of ^{137}Cs using SCA
3. To study the spectrum of ^{137}Cs and ^{60}Co using MCA
4. To calibrate the Gamma-Ray Spectrometer using known sources
5. To find the energy of an unknown isotope using MCA
6. To determine the Mass Absorption coefficient using MCA.

II. THEORY

A. Interaction of Gamma Rays with Matter

When gamma rays pass through matter, they interact primarily through three mechanisms:

1. Photoelectric absorption
2. Compton scattering
3. Pair production

The probability of each process depends on the gamma-ray energy and the atomic number Z of the absorber. Photoelectric absorption dominates at low energies ($\sim$ 100 keV), Compton scattering dominates at intermediate energies, and pair production becomes significant at high energies (above $\sim$ 1.02 MeV) [1].

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1. *Photoelectric Absorption*

In photoelectric absorption, the incident gamma-ray photon is completely absorbed by an atom and an electron is ejected from one of the atomic shells. The kinetic energy of the emitted photoelectron is given by

$$E_{e^-} = h\nu - E_b, \tag{1}$$

where $h\nu$ is the energy of the incident photon and E_b is the binding energy of the electron (See Fig. 1).

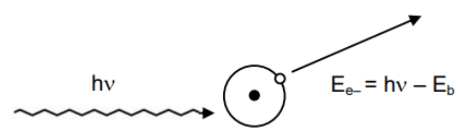

FIG. 1. Illustration of Photoelectric effect

The vacancy created in the inner shell is filled by outer electrons, leading to the emission of characteristic X-rays or Auger electrons. If all secondary radiations are absorbed within the detector, the total energy deposited equals the original gamma-ray energy. Hence, photoelectric absorption events produce a delta function in the differential distribution of the kinetic energy. This peak corresponds to the energy of the incident gamma rays and is called the photopeak.

2. *Compton Scattering*

In Compton scattering, the gamma-ray photon scatters from an electron, transferring part of its energy to the electron and emerging with reduced energy. The energy of the scattered photon $h\nu'$ is given by:

$$h\nu' = \frac{h\nu}{1 + (\frac{h\nu}{m_0 c^2})(1 - \cos\theta)}, \tag{2}$$

where $m_0c^2 = 0.511$ MeV is the rest energy of the electron and θ is the scattering angle (See Fig. 2).

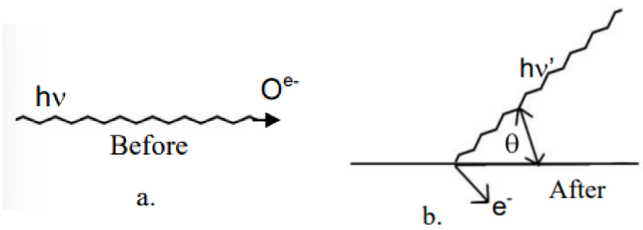

FIG. 2. Schematic diagram of Compton scattering showing the incident photon, scattered photon, and recoil electron.

The kinetic energy of the recoil electron is

$$E_{e^-} = h\nu - h\nu' = \frac{h\nu\,(\frac{h\nu}{m_0c^2})(1-\cos\theta)}{1+(\frac{h\nu}{m_0c^2})(1-\cos\theta)}. \tag{3}$$

The maximum energy transfer occurs for $\theta = 180°$ (backscattering),

$$E_{e^-}^{\max} = \frac{2h\nu^2}{m_0c^2 + 2h\nu}. \tag{4}$$

This results in a continuous distribution of electron energies in the detector known as the *Compton continuum*, which ends at the *Compton edge*.

3. Pair Production

Pair production occurs when a gamma-ray photon with energy $h\nu \geq 1.02$ MeV interacts with a nucleus and is converted into an electron-positron pair. The excess energy appears as the kinetic energy of the pair.

After losing its kinetic energy, the positron is annihilated by an electron, producing two photons of energy 0.511 MeV each. Depending on whether these photons escape or are absorbed, single escape and double escape peaks may appear in the spectrum.

B. Scintillation Detector (NaI(Tl) & Photomultiplier tubes (PMT)

A scintillation detector is an instrument that converts gamma-ray energy into visible light and then into an electrical signal for measurement. Here, we use a thallium-doped sodium iodide crystal, NaI(Tl), as the scintillator.

When a gamma-ray photon interacts in the crystal through photoelectric absorption or Compton scattering, energetic electrons are produced. These electrons excite electrons in the crystal lattice from the valence band to the conduction band. The Thallium doping, replacing 1 in 1000 atoms of NaI, introduces more energy levels in the crystal's band structure that act as **activation sites**. These faciliate electron-hole recombination, producing low-energy visible-light photons (See Fig. 3). The number of photons produced is proportional to the energy of the incident gamma-ray.

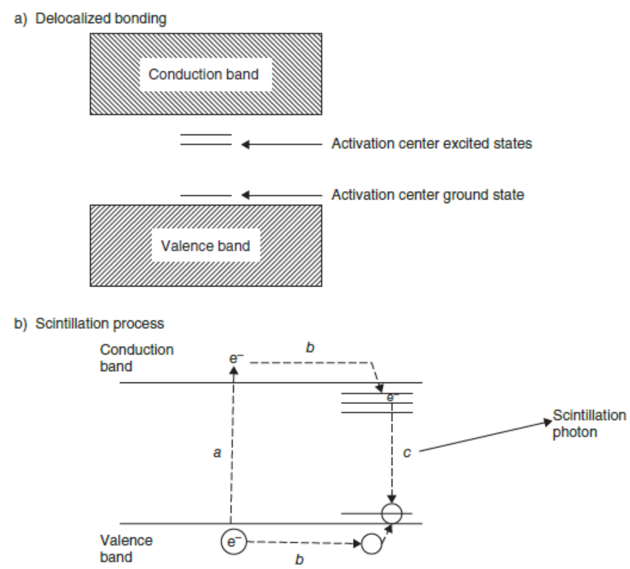

FIG. 3. Scintillation Mechanism in NaI(Tl) crystal

The scintillation light is collected by a photomultiplier tube (PMT) optically coupled to the crystal. The PMT converts light photons into photoelectrons at the photocathode and multiplies them through a series of dynodes, producing an electrical pulse at the anode. The amplitude of this pulse is proportional to the energy of the incident gamma ray. The electronics (a pre-amplifier and a Linear Amplifier) then process these pulses to obtain the pulse height (energy) spectrum.

C. Gamma Ray Energy Spectrum

The observed pulse height spectrum consists of:

- A **photopeak** due to photoelectric absorption,
- A **Compton continuum** due to Compton scattering,
- A **Compton edge** corresponding to maximum Compton energy transfer,

For ^{137}Cs, the main gamma energy is 662 keV, which produces a prominent photopeak in the spectrum.

1. Energy Resolution analysis using Photopeak

Ideally, for gamma rays of 662 KeV, the photopeak in the pulse height spectrum should be a delta function. In practice, however, it exhibits a finite width due to statistical fluctuations in scintillation light production, limitations of the associated electronics, etc. Therefore, the width of the photopeak is measured quantitatively using FWHM. The Full Width at Half Maximum (FWHM) is defined as the width of the photopeak at half of its maximum height. In this experiment, the FWHM is determined for different operating voltages of the detector to identify the operating condition that provides the best energy resolution.

The energy resolution R of a detector is defined as

$$R(\%) = \frac{\text{FWHM}}{V_p} \times 100. \tag{5}$$

where V_p is the peak channel LLD value and FWHM is calculated by performing a Gaussian fitting over the photopeak, by the formula

$$FWHM = 2\sqrt{2ln(2)}\ \sigma \approx 2.355\ \sigma \tag{6}$$

where σ is the standard deviation of the Gaussian fit. A smaller value of R indicates better resolving power of the detector.

D. Mass Absorption Coefficient

When a narrow beam of gamma rays passes through an absorbing material of thickness x, its intensity decreases due to interactions in the medium [2]. This attenuation is described by the exponential law

$$I = I_0 e^{-mx}, \tag{7}$$

where I_0 is the incident intensity, I is the transmitted intensity, and m is the total-mass absorption coefficient of Al. Using Half intensity thickness to calculate m, we get the equation,

$$m = \frac{ln(2)}{HVL} = \frac{0.693}{HVL} \tag{8}$$

where HVL is the Half Value Layer in terms of density thickness.

III. APPARATUS

Scintillation detector, High voltage unit, Linear amplifier, Single channel analyzer, Multi channel analyzer, Counter timer, Aluminium blocks, Gamma sources (^{137}Cs, ^{60}Co, ^{133}Ba and ^{22}Na), Anuspect software

IV. OBSERVATIONS

A. SCA Observations

TABLE I. Observation of SCA count rates for varying LLD voltage for different operating voltages (450 V, 500 V, and 550 V).

Operating Voltage = 450V		Operating Voltage = 500V		Operating Voltage = 550V	
LLD Voltage(V)	Counts	LLD Voltage(V)	Counts	LLD Voltage(V)	Counts
2.4	624	2.4	618	2.4	634
2.5	601	2.5	572	2.5	590
2.6	928	2.6	680	2.6	691
2.7	1659	2.7	1308	2.7	1307
2.8	3700	2.8	2975	2.8	2994
2.9	6406	2.9	5699	2.9	5521
3.0	7536	3.0	7518	3.0	7561
3.1	5102	3.1	5970	3.1	6458
3.2	2222	3.2	2908	3.2	3170
3.3	717	3.3	959	3.3	1028
3.4	218	3.4	294	3.4	241
3.5	118	3.5	121	3.5	148

TABLE II. Observation of SCA count rates for varying LLD voltage for different operating voltages (600V and 650V).

Operating Voltage = 600V		Operating Voltage = 650V	
LLD Voltage(V)	Counts	LLD Voltage(V)	Counts
2.4	576	2.4	582
2.5	5768	2.5	538
2.6	728	2.6	784
2.7	1546	2.7	1415
2.8	3651	2.8	3228
2.9	6399	2.9	6063
3.0	7561	3.0	7565
3.1	5436	3.1	5771
3.2	2249	3.2	2425
3.3	629	3.3	800
3.4	194	3.4	228
3.5	107	3.5	110

TABLE III. Observations of ^{137}Cs spectrum using SCA

Operating Voltage = 650V					
LLD Voltage(V)	Counts	LLD Voltage(V)	Counts	LLD Voltage(V)	Counts
0.4	613	1.5	1446	2.6	1333
0.5	647	1.6	1557	2.7	1757
0.6	817	1.7	1641	2.8	2693
0.7	1008	1.8	1624	2.9	6624
0.8	1127	1.9	1660	3.0	3492
0.9	1194	2.0	1460	3.1	1836
1.0	1237	2.1	1301	3.2	629
1.1	1262	2.2	1298	3.3	256
1.2	1298	2.3	1104	3.4	112
1.3	1381	2.4	1154	3.5	99
1.4	1335	2.5	1216		

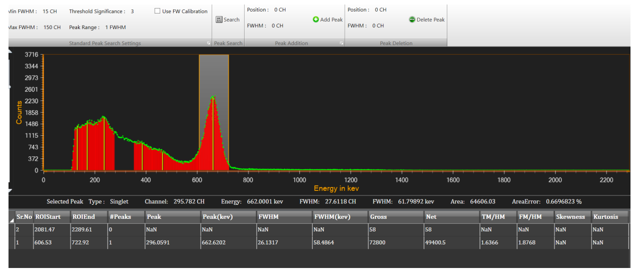

FIG. 4. Pulse height spectrum of ^{137}Cs recorded using the MCA, showing the photopeak and Compton continuum

B. MCA Observations

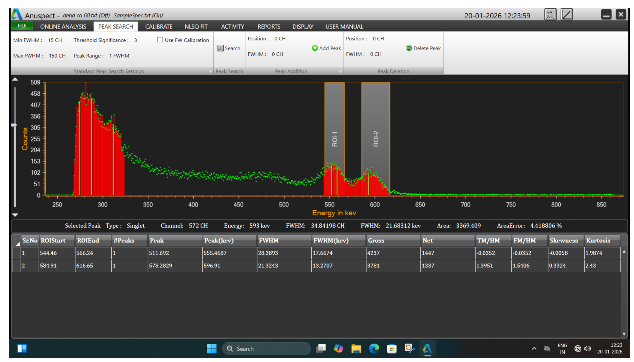

FIG. 5. Pulse height spectrum of ^{60}Co recorded using the MCA, showing the two characteristic photopeaks.

TABLE IV. Observations for Mass Absorption Coefficient of Al. (Background Counts = 1009)

Thickness (mm)	Gross Counts	Net Counts
72	8885	7876
66	9570	8561
60	10366	9357
54	11772	10763
48	12601	11652
42	14163	13154
36	15590	14581
30	17102	16093
24	18804	17795
18	20800	19791
12	22949	21940
6	25035	24026
0	27686	26677

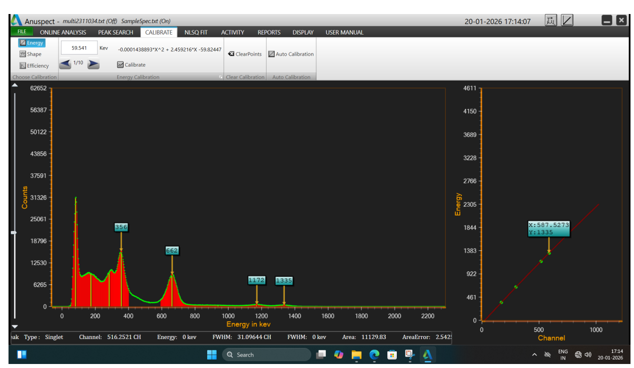

FIG. 6. Direct energy calibration curve obtained using the MCA Anuspect software with known radioactive sources.

TABLE V. Peak channel positions and corresponding gamma-ray energies for different known sources.

Source	Peak channel	Energy (in keV)
^{133}Ba	170.7242	355.8292
^{137}Cs	298.9051	662.3919
^{60}Co (Peak 1)	587.5273	1335.363
^{60}Co (Peak 2)	516.2521	1171.402

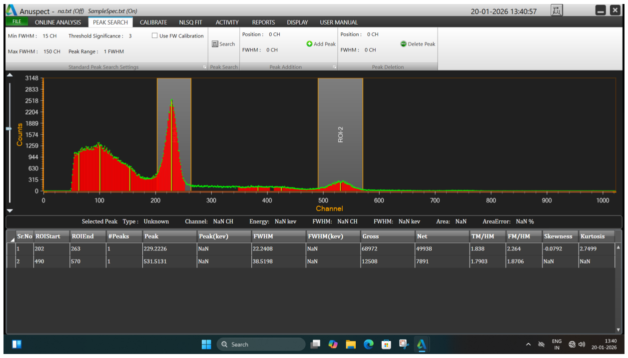

FIG. 7. Gamma-ray spectrum of the unknown radioactive source using MCA

V. DATA ANALYSIS

A. Determining operating voltage for SCA

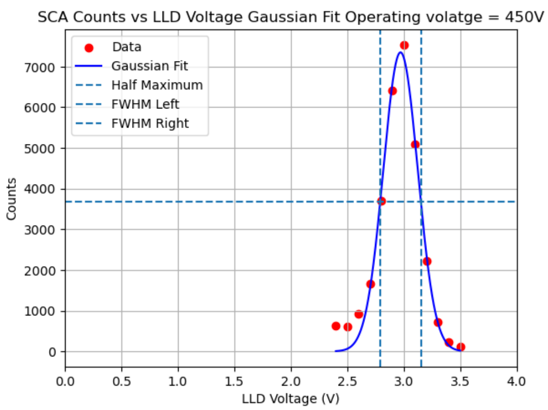

FIG. 8. SCA spectrum of ^{137}Cs at an operating voltage of 450 V with Gaussian fit to the photopeak (From Table I).

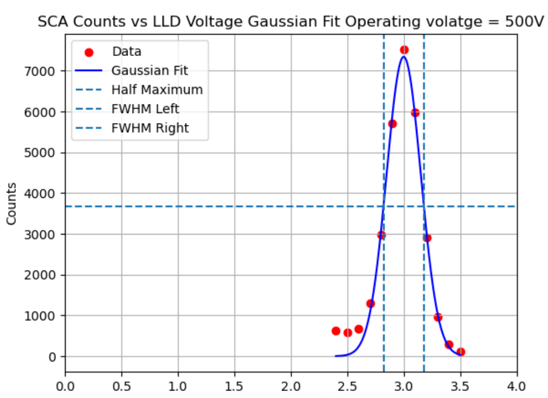

FIG. 9. SCA spectrum of ^{137}Cs at an operating voltage of 500 V with Gaussian fit to the photopeak (From Table I).

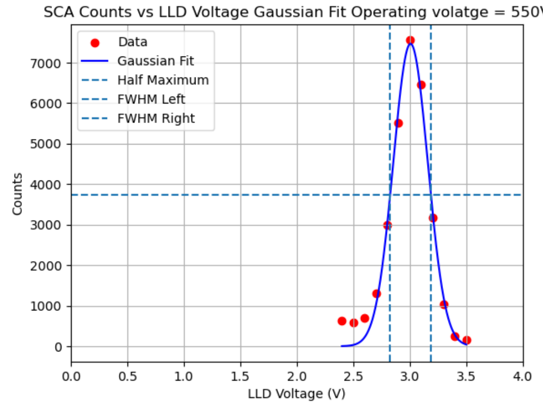

FIG. 10. SCA spectrum of ^{137}Cs at an operating voltage of 550 V with Gaussian fit to the photopeak (From Table I).

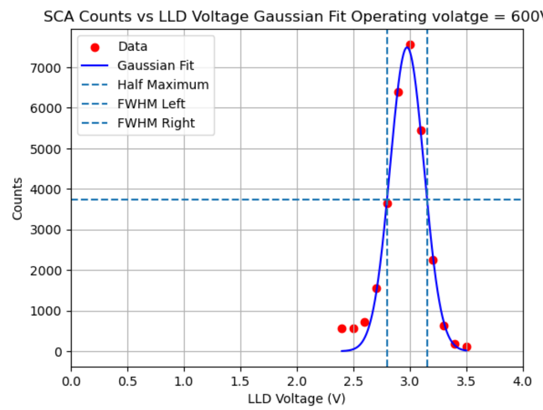

FIG. 11. SCA spectrum of ^{137}Cs at an operating voltage of 600 V with Gaussian fit to the photopeak (From Table II).

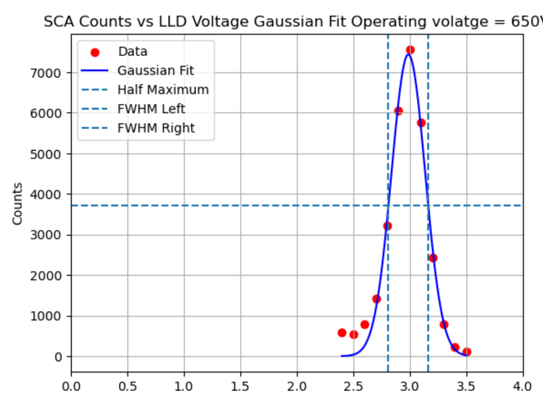

FIG. 12. SCA spectrum of ^{137}Cs at an operating voltage of 650 V with Gaussian fit to the photopeak (From Table II).

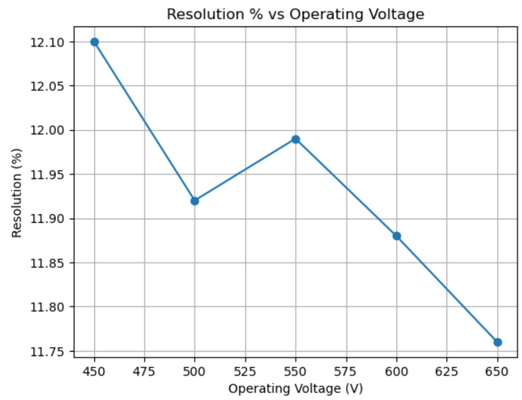

FIG. 13. Variation of energy resolution of the NaI(Tl) detector with operating voltage (From Table VI)

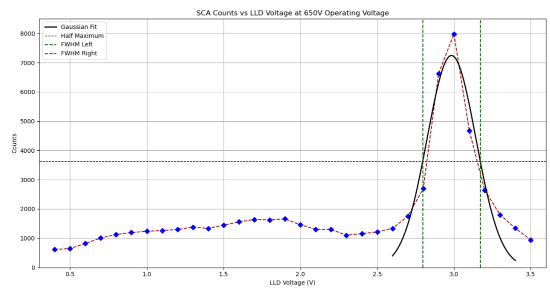

FIG. 14. Pulse height spectrum of ^{137}Cs recorded using the SCA, showing the photopeak used for Gaussian fitting and resolution determination (From Table III).

OP (V)	x_0 (V)	σ (V)	FWHM (V)	R(%)	$\chi^2_{\rm red}$
450	2.97	0.1527	0.3596	12.10	176.095
500	3.00	0.1518	0.3575	11.92	176.071
550	3.01	0.1531	0.3606	11.99	189.643
600	2.98	0.1501	0.3536	11.88	159.254
650	2.99	0.1493	0.3515	11.76	177.074
650*	2.98	0.1594	0.3754	12.58	435.916

TABLE VI. Gaussian fit parameters of the photopeak for different operating voltages (OP). Here x_0 is the mean peak position, σ is the standard deviation, FWHM is the full width at half maximum, R is the energy resolution, and $\chi^2_{\rm red}$ is the reduced chi-squared value of the fit. The * reading is for full spectrum of ^{137}Cs (For Figures 8, 9, 10, 11, 12, 14).

B. ^{137}Cs spectrum using MCA and Resolution Calculation

From the ^{137}Cs spectrum obtained through MCA (See Figure 4), we calculate Resolution using FWHM and Peak Channel,

$$\begin{aligned} R(\%) &= \frac{FWHM}{Peak\ Channel} \times 100\% \\ &= \frac{26.1317}{296.0591} \times 100\% \\ R(\%) &= 8.8\% \end{aligned}$$

C. ^{60}Co spectrum and Resolution in terms of Energy

In the ^{60}Co spectrum using MCA, we obtain 2 photopeaks for energies 1.17 MeV and 1.33 MeV at peak channels 511.69 and 578.28 respectively (See Figure 5).

Energy difference = 1.33 - 1.17 = 0.16MeV = 160KeV Channel Difference = 578.28 - 511.69 = 66.59 channel Therefore, 66.59 channels correspond to 160KeV.

1 channel corresponds to 160/66.59 = 2.40KeV.

From the ROI report for ^{60}Co spectrum, it is observed that FWHM is 26.13 channels.

So, in terms of energy,

$$FWHM = 26.13 \times 2.40 = 62.71 KeV$$

Hence Resolution,

$$R(\%) = \frac{FWHM}{E_p} = \frac{62.71}{662} \times 100\% = 9.5\%$$

D. Calibration using known sources

We calibrated the Gamma-Ray spectrometer using 3 known sources, ^{137}Cs, ^{60}Co and ^{133}Ba. We obtain the calibration equation between Energy (KeV) vs Peak Channel using two methods (See Figure 6 and 15).

From the Direct Method (Anuspect Software),

$$E(x) = -0.000144x^2 + 2.459216x - 59.82447 \tag{9}$$

From the Manual Method (Least squares fitting),

$$E(x) = (2.35 \pm 0.01)x + (-42.93 \pm 4.17) \tag{10}$$

The energy in manual method is calculated by using a linear least sqaures fitting for N observations. We fit the observed data-points into a form,

$$y = mx + c$$

The statistical error calculated in linear fit is done using the following formulae,

$$\sigma_y = \sqrt{\left(\sum \frac{(y_n - y_i)^2}{N-2}\right)} \tag{11}$$

Errors in slope and intercept,

$$\Delta m = \sigma_y \sqrt{\frac{\sum x^2}{((N\sum x^2) - (\sum x)^2)}} \tag{12}$$

$$\Delta c = \sigma_y \sqrt{\frac{N}{((N\sum x^2) - (\sum x)^2)}} \tag{13}$$

The uncertainty in Energy calculated for the unknown radioactive source using the Manual Method is given by,

$$\Delta E = \sqrt{(x\Delta m)^2 + (\Delta c)^2} \tag{14}$$

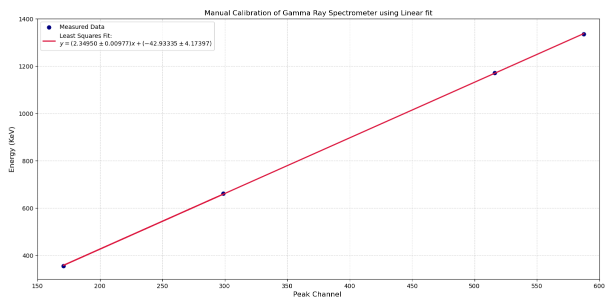

FIG. 15. Manual energy calibration curve (energy vs. channel number) obtained using least-squares fitting (From Table V).

E. Calculating energy for unknown source

For the unknown Radioactive source, we observed two peaks in the spectrum. The energy corresponding to those peaks were calculated using the calibration equations obtained from both methods. The uncertainty in Energy was calculated for Manual Method.

Peak Channel	Using Direct Method	Using Manual Method
229.2226	496.3	495.7 ± 4.7
531.5131	1206.6	1206.1 ± 6.8

TABLE VII. Calculated Energy for the Unknown source.

The energies of the two photopeaks observed in the unknown spectrum were calculated to be approximately 496 keV and 1206 keV using the energy calibration. These values are close to the known characteristic gamma-ray energies of ^{22}Na, namely 511 keV and 1275 keV. The small deviations can be attributed to the finite energy resolution of the NaI(Tl) detector and calibration uncertainties. On this basis, the unknown source is identified as ^{22}Na..

F. Mass Absorption Coefficient

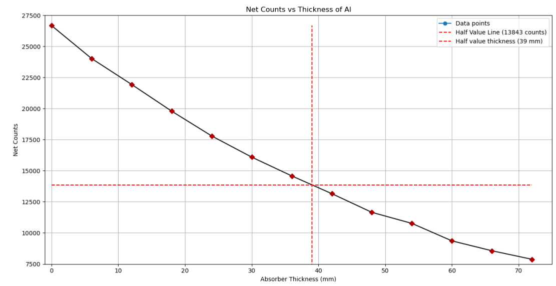

FIG. 16. Exponential decay of counts used to determine the mass absorption coefficient of Aluminium (From Table IV).

Calculating the Mass Absorption Coefficient from HVL (Half Value layer/Thickness). From the plot we obtain HVL $= 3.9 \times 2.8\ g/cm^2$ (See Figure 16). Using the formula,

$$m = \frac{0.693}{HVL} = \frac{0.693}{10.92}$$
$$m = 0.063 cm^2.g^{-1}$$

The uncertainty in m is given by,

$$\Delta m = m \times \frac{(\Delta HVL)}{HVL}$$
$$= 0.002 cm^2.g^{-1}$$

All code related to the plots, table and calculations is available on this Github Repository [3].

VI. RESULTS AND DISCUSSION

A. Single Channel Analyser (SCA)

1. *Operating voltage*

The photopeaks of ^{137}Cs were analysed for various operating voltages. A gaussian fit was performed to see which one is closer to the delta-function using FWHM. The optimal operating voltage for SCA was found to be 650V with a resolution of 11.76%.

2. *^{137}Cs Spectrum*

The full spectrum for ^{137}Cs was recorded using SCA at the operating voltage 650V. It included the photopeak, the Compton continuum, and the Compton edge. The resolution was calculated by Gaussian fitting on a Region of Interest (photopeak) to be 12.58%.

B. Multi Channel Analyser (MCA)

1. Spectrum of ^{137}Cs and ^{60}Co

The ^{137}Cs pulse height spectrum recorded using MCA exhibited a photopeak, Compton continuum and a Compton edge. Using this, the resolution was calculated to be 8.8%.

Using the ^{60}Co spectrum which exhibited two characteristic photopeaks, the resolution was determined in terms of energy with the help of the known energy difference between the peaks. It was calculated to be 9.5%.

2. Energy calibration using known sources

The Gamma-Ray spectrometer was calibrated using known radioactive sources ^{133}Ba, ^{137}Cs and ^{60}Co. Calibration curves were obtained using two methods. From the Direct Method (Anuspect Software),

$$E(x) = -0.000144x^2 + 2.459216x - 59.82447 \tag{15}$$

From the Manual Method (Linear Fit),

$$E(x) = (2.35 \pm 0.01)x + (-42.93 \pm 4.17) \tag{16}$$

3. Determination of the unknown source

The pulse height spectrum for unknown source had 2 photopeaks. The channel of the photopeak and the calibration curves obtained from known sources were used to calculate the energy corresponding to the peaks. They were calculated using manual method to be,

$$E_1 = 495.7 \pm 4.7KeV$$
$$E_2 = 1206.1 \pm 6.8KeV$$

These energies are characteristic to the radioactive isotope ^{22}Na.

4. Mass Absorption Coefficient of Al

When Aluminum plates were introduced between the source and the detector, the counts decreased exponentially as a function of the Al thickness. Half value thickness was used to determine the mass absorption coefficient of Al. It was calculated to be,

$$m = (0.063 \pm 0.002)g^{-1}cm^2$$

The experimental value is close to the literacture value of Mass Absorption coefficient for Al for gamma-rays of energy 662KeV.

VII. CONCLUSION

Gamma-ray spectroscopy was successfully performed using a NaI(Tl) scintillation detector with both SCA and MCA systems. The characteristic features of the ^{137}Cs and ^{60}Co spectra, including the photopeak and Compton continuum, were clearly observed, confirming the expected interaction mechanisms of gamma rays with matter.

The energy resolution of the detector was studied as a function of operating voltage using Gaussian fits to the ^{137}Cs photopeak.

Energy calibration using ^{133}Ba, ^{137}Cs, and ^{60}Co showed an approximately linear relation between channel number and energy, and the manual calibration agreed well with the software-based method. This calibration was used to determine the energies of two peaks from an unknown source, yielding values near 496 keV and 1206 keV within experimental uncertainty. These energies correspond to ^{22}Na. The mass absorption coefficient of Al was determined using half value layer method and was consistent with the literature values.

Overall, the results demonstrate the performance of the scintillation detector for gamma-ray spectroscopy and illustrate the importance of resolution, calibration, and attenuation measurements in nuclear radiation experiments.

[1] Nucleonix Systems Pvt. Ltd. *Gamma Ray Interactions: Single Channel Analyzer (SCA) Experiment Manual*, n.d. Laboratory manual for gamma-ray spectroscopy using SCA.

[2] Nucleonix Systems Pvt. Ltd. *Gamma Ray Interactions: Multi Channel Analyzer (MCA) Experiment Manual*, n.d. Laboratory manual for gamma-ray spectroscopy using MCA.

[3] Aryan Shrivastava. P341 - nuclear physics and instrumentation lab. `https://github.com/crimsonpane23/P341-Nuclear-Physics-and-Instrumentation-Lab.git`, 2026.