Experiment 3
Study of gamma energy spectrum using a scintillation detector with Multi-Channel Analyser

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Aim

- **Part A**:
  - To calibrate the MCA by a known radio-active source i.e Co^{60} with a NaI(Tl) 2x2 detector.
  - To find the γ-ray energies of unknown sources like Cs^{137}, Ba^{133} and Na^{22} using the same NaI(Tl)2x2 detector.
- **Part B**:
  - To find the detector resolution and photo-peak efficiency of different types of detectors [NaI(Tl) 2x2, NaI(Tl) 3x3, NaI(Tl) 5x5, NaI(Tl) 7x7, NaI(Tl) 2x2 Well-Type, CdZnTe and HpGe] at 1.173 Mev and 1.332 Mev using Co-60 radioactive source.

Theory

In this experiment we study about detection of γ-radiation by scintillator detectors. A gamma ray entering a scintillator crystal produces a rapidly moving free electron that, in turn, loses its energy by excitation of the ions in its path as it travels through the crystal. This excitation energy is given off in various ways (to be discussed later in this section). Thus a single high energy gamma ray entering the scintillator produces a flash of low energy photons.

These photons are directed to the photosensitive surface of a **photomultiplier tube** (PMT), where they eject electrons via the photoelectric effect. The electrons are collected in the photomultiplier and amplified to yield a current pulse, which is converted to a voltage pulse whose height is proportional to the number of photoelectrons and is thus proportional to the number of photons reaching the tube, which in turn is proportional to the initial energy of the fast electron. The output pulses of the PMT are amplified and then recorded. Therefore the output pulse is proportional to the energy deposited in the scintillator.

The amplified pulses are analysed by a **multi-channel analyser** (MCA) which sorts the pulses according to their height and counts the number of pulses whose height is between E to $E + \Delta E$ for an entire range of E simultaneously. The energy of the detected signal is proportional to the channel number. The proportionality constant can be calculated by using a source with known peak energies E_A and E_B and finding the corresponding channel numbers A and B for the respective peaks. The proportionality constant

is then given by

$$\alpha = \frac{E_A - E_B}{A - B}$$

Using this proportionality constant we can calibrate the MCA for a given HV supply and amplifier gain. After calibration, we can find the energy spectra of unknown sources. In our experiment we use Co^{60} for calibration, and find the unknown peak energies of sources Cs^{137}, Ba^{133} and Na^{22}. The peak energies of these sources are given below.

Table 1: Energy and intensity of different sources

Sl no	**Nuclide**	**Half-life (Yrs)**	**Intensity (%)**	**Energy (MeV)**
1	Co^{60}	5.27	100	1.173
			100	1.332
2	Cs^{137}	30	100	0.662
3	Ba^{133}	10.66	8	0.382
			34	0.08
			69	0.356
			14	0.302
			7	0.276
4	Na^{22}	2.6	100	1.275
			e^- e^+ annihilation	0.511

To analyse the spectrum, we must understand how γ-rays interact with matter. Although a large number of possible interactions are known, the three key interaction mechanisms are as following:

- Photoelectric effect
- Compton effect
- Pair production

Which of these processes contributes the most is mainly dependent on the atomic number of the material and the energy of the photon. We study them one by one.

When the γ-photon collides with an atom, it may impinge upon an orbital electron and transfer all of its energy to this ejecting it from the atom. This is called the **photoelectric effect**. This process only takes place with K or L-electrons and occurs more often with substances with a high atomic number. Very shortly after the emission of the photoelectron, another bound atomic electron falls into the vacancy (or cascades down sequentially) with the subsequent emission of X-rays, which have a large probability of producing light pulses in the scintillator by exciting other loosely bound electrons. These processes (initial photoelectron ejection and subsequent X-ray production and interaction with the crystal) usually happen within the resolution time of the counter, so in the end the photomultiplier output pulse corresponds to the full gamma ray energy, if the photoelectron stops in the crystal and if no light escapes the crystal. Thus the photoelectric effect results in a peak, called the **photopeak**, at an energy equal to that of the incoming gamma ray.

The gamma ray photon may also get scattered through an angle by an electron without being fully absorbed, in a process known as **Compton effect**. The scattered electron then recoils and carries away some of the gamma rays energy, which is then detected by the photomultiplier. scatterings. The energy of the Compton-scattered gamma ray E'_γ as a function of the scattering angle θ and the initial energy E_γ is given by

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

where c is the speed of the light and m is the mass of the electron. The energy of the scattered electron, which is the energy loss of the gamma ray, then varies from zero (when $\theta = 0$) to a maximum of $\frac{2E_\gamma^2}{2E_\gamma + mc^2}$(when $\theta = 180°$). This maximum energy is called the **Compton edge**. The energy distribution of Compton scattered electrons is essentially a constant. So the Compton spectrum produced by a photomultiplier tube is an almost a plateau from zero up to the Compton edge where it drops off sharply.

The discussion above refers to gamma rays that are Compton scattered by electrons within the scintillator. It is also possible for a gamma ray to be Compton scattered into the scintillator from an interaction outside the scintillator. In this case the observed signal is from the scattered gamma and not from the recoiling electron. The scattered gamma ray could then be detected through the photoelectric effect. However, because of the geometry of the detector, most of the gamma rays scattered into the scintillator will have been scattered through a large value of θ (almost 180°). But $cos\theta$ varies only slowly with θ for θ near 180°, which means that these gamma rays will have energies close to $\frac{mc^2 E_\gamma}{2E_\gamma + mc^2}$, the resulting energy peak is called the **backscatter peak**. However it is not generally observable in the absence of a backscatterrer, such as a sheet of lead placed around the outside of the scintillator.

If the incoming gamma ray energy is above 1.02 MeV $= 2mc^2$, the rest mass of an electron-positron pair, the gamma ray can spontaneously create an electron-positron pair and be totally absorbed. If both the electron and positron lose all of their kinetic energy while still in the scintillator, they would produce a photomultiplier pulse corresponding to an energy $2mc^2$ below the gamma ray energy ($E - 2mc^2$).

On plotting the energy spectrum data obtained from the MCA, we can observe the photoelectric peak, Compton edge and backscatter peak. By fitting the photopeak using a Gaussian function, we can obtain the peak voltage (E) and the full width at half maxima (δE). The resolution of the MCA is then given by

$$R = \frac{\delta E}{E} \times 100\,\%$$

We can also find the photopeak efficiency, which is defined as the ratio of the area under the peak to the area under the entire spectrum. Since the width of each channel is fixed, the formula reduces to

$$\text{Photopeak Efficiency} = \frac{\text{Sum of counts in the peak}}{\text{Total counts in the spectrum}}$$

In our experiment we compare the energy resolution and photopeak efficiency of different detectors viz. NaI(Tl) 2x2, NaI(Tl) 3x3, NaI(Tl) 5x5, NaI(Tl) 7x7, NaI(Tl) 2x2 Well-Type, CdZnTe and HpGe.

Procedure

We prepare our experimental setup in RADlab software using

- γ-ray sources (Co^{60}, Cs^{137}, Ba^{133} and Na^{22}),
- γ-ray detector [NaI(Tl) 2x2, NaI(Tl) 3x3, NaI(Tl) 5x5, NaI(Tl) 7x7, NaI(Tl) 2x2 Well-Type, CdZnTe and HpGe],
- high voltage power source,
- pre-amplifier,
- amplifier,
- multi-channel analyser (MCA)

The setup is shown in the following figure.

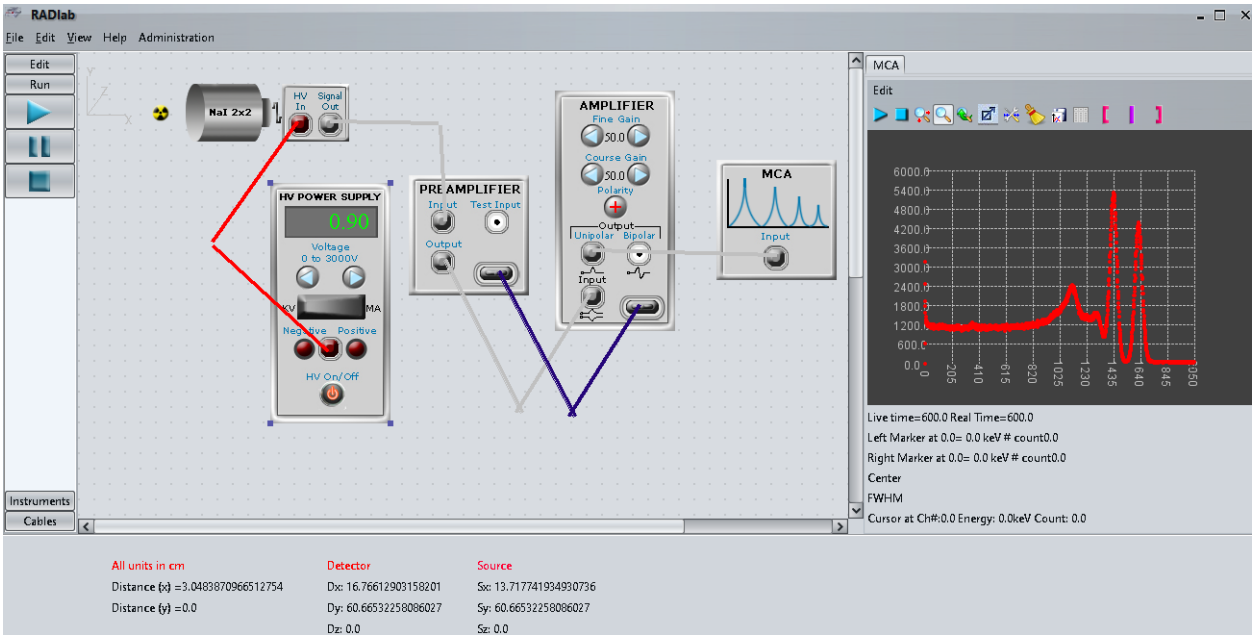


Figure 1: Experimental Setup

Part A

The NaI(Tl) 2x2 detector was chosen. The HV supply was set to 0.9 KV, and course gain and fine gain of the amplifier were both set to 50. The spectra of all 4 sources were determined one by one. The source and detector were aligned vertically and horizontal distance was kept at 3.048 cm. The $Co-60$ spectrum was used to calibrate the MCA and the peak energies of the other sources were determined subsequently.

Part B

The Co^{60} source was fixed and its spectrum was obtained using different detectors. The HV supply and amplifier gains were modified for each detector for optimum signal to noise ratio. For each detector the photopeak efficiency and energy resolution were calculated at 1.173 MeV and 1.332 MeV, and the values were compared.

Observational Data

The entire MCA data for both Part A and Part B of the experiment are provided in the Excel spreadsheet `Expt4_18ms019_data.xlsx` submitted alongside this report in order to keep this document short and precise. The MCA output graphs for Part A are given in the next section and those for Part B are given below.

Figure 2: Co^{60} spectrum using NaI 2x2

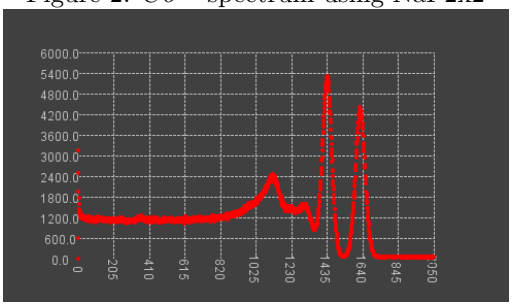


Figure 3: Co^{60} spectrum using NaI 3x3

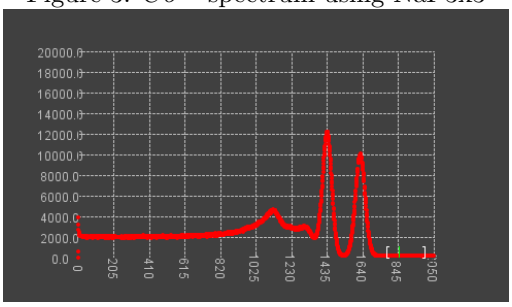


Figure 4: Co^{60} spectrum using NaI 5x5

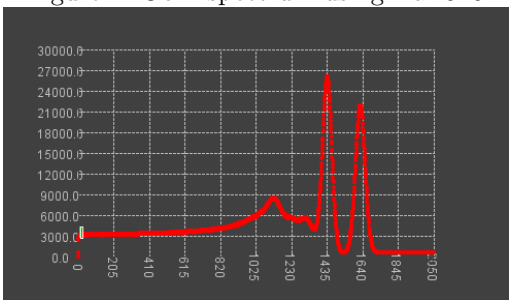


Figure 5: Co^{60} spectrum using NaI 7x7

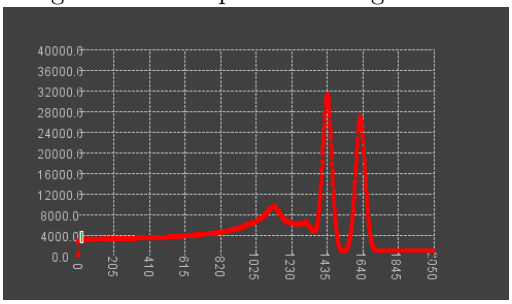


Figure 6: Co^{60} spectrum using NaI 2x2 well type

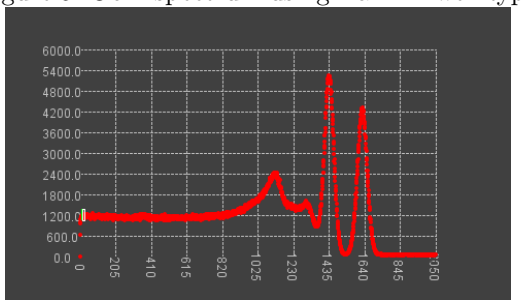


Figure 7: Co^{60} spectrum using CdZnTe

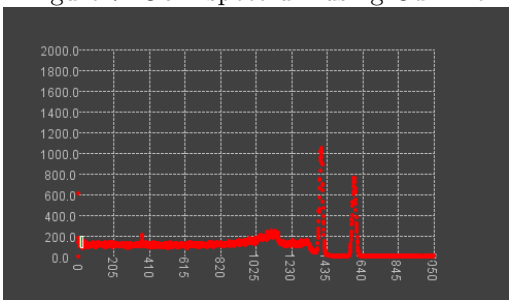
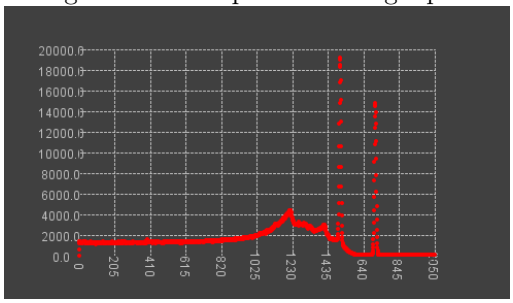


Figure 8: Co^{60} spectrum using HpGe



Results and Analysis

Part A

We fit the two peaks of the Co-60 spectrum (fig. 9) to obtain the mean channel numbers, $A = 1435.39$ and $B = 1627.59$. We know these peaks correspond to the energies $E_A = 1.173$ MeV and $E_B = 1.332$ MeV. Hence we calculate the proportionality constant

$$\alpha = \frac{E_A - E_B}{A - B} = 0.827\,\text{KeV}$$

Using this proportionality constant we find the energies of Cs-137, Ba-133 and Na-22 γ-ray sources. The spectra of these sources along with the energies of observable peaks is given in figs. 10, 11 and 12. We see that the obtained energies agree reasonably with the standard values provided in table 1.

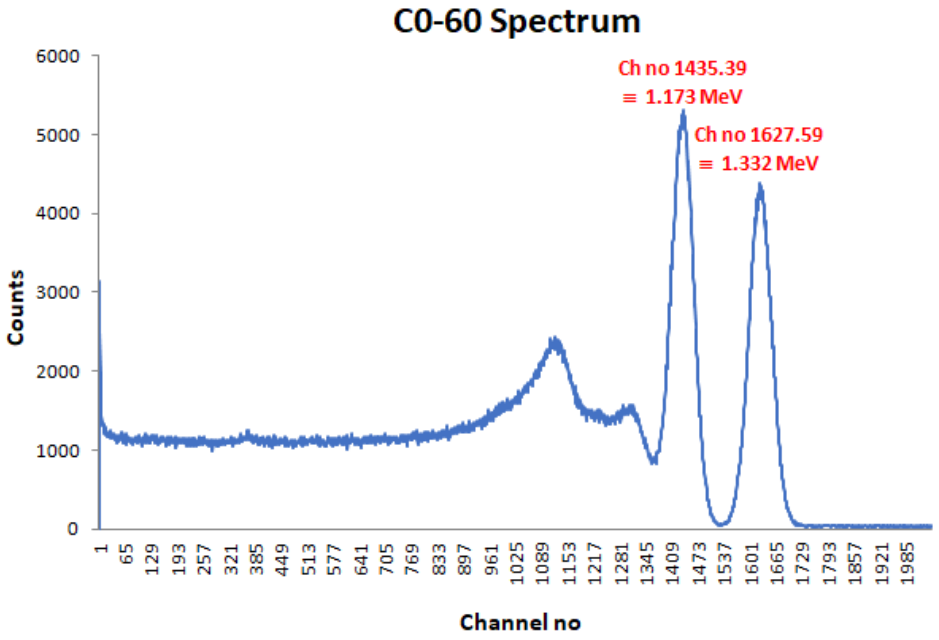


Figure 9: γ-ray spectrum of C0-60

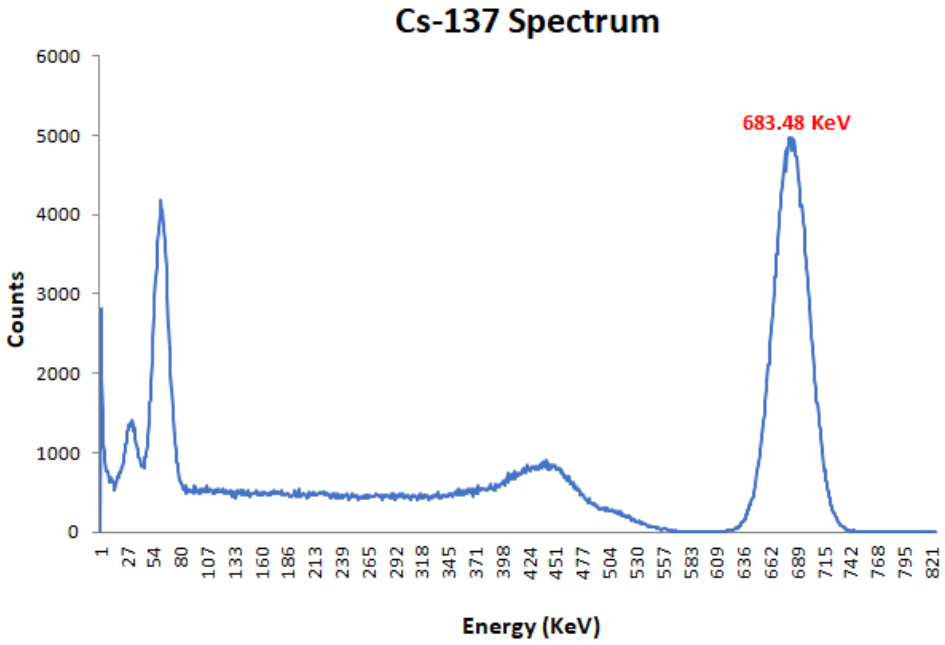


Figure 10: γ-ray spectrum of Cs-137

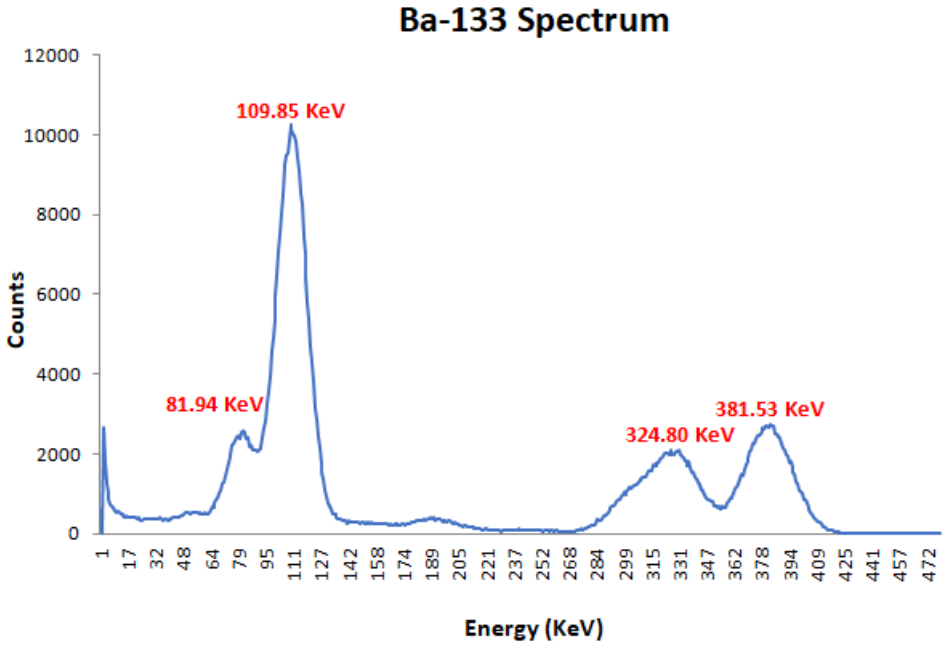


Figure 11: γ-ray spectrum of Ba-133

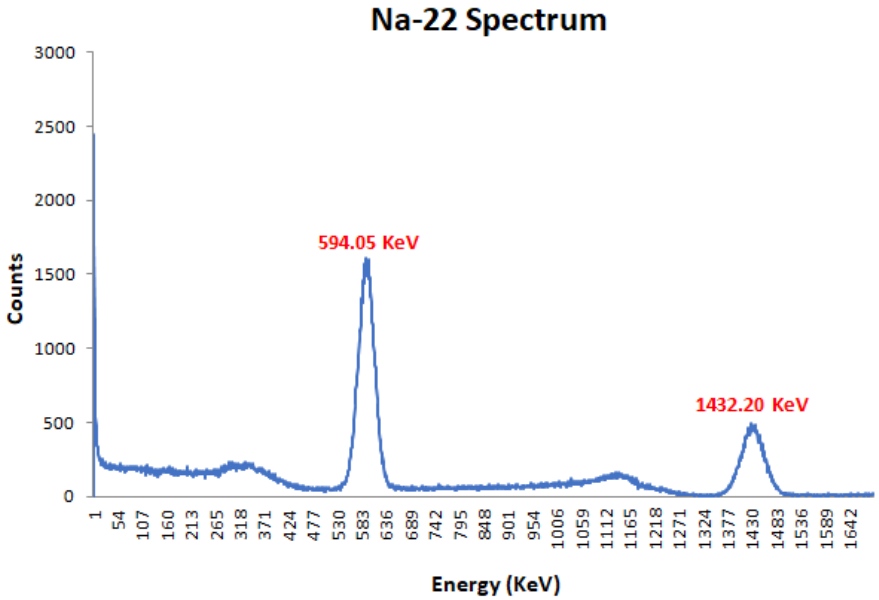


Figure 12: γ-ray spectrum of Na-22

Part B

For the Co-60 γ-ray spectrum obtained through each detector we fit the two peaks individually and obtain the mean and FWHM. For each detector we also find the total counts and sum of counts for each peak. Then we calculate the photopeak efficiency and energy resolution of different detectors at 1.173 MeV and 1.332 MeV using the formulae provided in the theory section. The results are given below.

Table 2: Photopeak Efficiency and Energy Resolution of different detectors at 1.173 MeV and 1.332 MeV

Detector type		**NaI(Tl) 2x2**	**NaI(Tl) 3x3**	**NaI(Tl) 5x5**	**NaI(Tl) 7x7**	**NaI(Tl) 2x2 well type**	**CdZnTe**	**HpGe**
HV supply (kV)		0.9	1.2	1.5	2	0.9	0.7	1.1
Amplifier	Course	50	50	50	50	50	150	230
gain	Fine	50	50	50	50	50	0	0
Total counts		2451961	4881528	9367308	10703567	2444451	207905	3119151
1.173 MeV	Counts	366288	855762	1861587	2228447	366656	23819	26110
	Efficiency	**0.149386**	**0.175306**	**0.1987323**	**0.208197**	**0.149995234**	**0.114567**	**0.0083709**
	Mean	1435.39	1435.66	1435.9	1436.11	1435.37	1401.73	1505.51
	FWHM	65.26	61.5	63.09	63.69	65.2	20.79	11.4
	Resolution	**0.045465**	**0.0428374**	**0.0439376**	**0.044349**	**0.045423828**	**0.014832**	**0.0075722**
1.332 MeV	Counts	301872	707132	1573033	1918552	301154	18869	193856
	Efficiency	**0.123115**	**0.144859**	**0.167928**	**0.179244**	**0.123199033**	**0.090758**	**0.0621502**
	Mean	1627.59	1627.73	1627.84	1627.85	1627.65	1591.99	1708.13
	FWHM	65	65.16	65.03	64.82	65.18	24	12.17
	Resolution	**0.0399363**	**0.0400312**	**0.0399486**	**0.039819**	**0.040045464**	**0.015075**	**0.0071248**

Conclusion

We see that the photopeak efficiency at 1.173 MeV as well as 1.332 MeV is maximum for NaI(Tl) 7x7 detector, so this detector is best for counts. For NaI(Tl) detectors it increases with the size of the detector. However the efficiency for CdZnTe and HpGe detectors are very low. On the other hand the energy resolution at 1.173 MeV as well as 1.332 is minimum for HpGe detector followed by CdZnTe, so these detectors are best for resolution. However NaI(Tl) detectors have higher resolution values, so these are not as good for resolution.

Note

- For Part B of the experiment data could not be taken for BgO detector as the software crashed repeatedly (around 8 times).
- The peaks were fitted individually in Origin software, amounting to a total of 22 graphs. These were not provided in the report for the sake of brevity. However, it is assured that the fitting was done with utmost diligence and rigour.