Experiment 4
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 -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 -radiation by scintillator detectors.There are two types of scintillator detectors used commonly, inorganic crystals and organic scintillators. Here we shall use the inorganic type. 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. 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.

Photomultiplier tubes are vacuum tubes in which the first major component is the photocathode. A photon may interact in the photocathode to eject a low energy electron into the vacuum. 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. Since the height is proportional to the γ-ray energy the histogram reproduces the γ energy distribution i.e. 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 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.

Nuclide	**Half life(years)**	Intensity(%)	Energy(MeV)
Co^{60}	5.27	100	1.173
		100	1.332
Cs^{137}	30	100	0.662
		8	0.382
		34	0.08
Ba^{133}	10.66	69	0.356
		14	0.302
		7	0.276
Na^{22}	2.6	100	1.275
		e^-e^+ annihlation	0.511

There are multiple ways in which γ-rays interact with matter. The key ones are discussed in brief below,

- **Photo electric effect**: This is a phenomenon in which incoming electromagnetic radiation liberates an electron from the surface of a metal. This requires the photons to have a greater energy than the work function of the electrons.
  The equation for Photo-electric effect is $h\nu = \frac{1}{2}mv^2 + \Psi$
  where Ψ is the work function of the electron and ν is the incoming photon frequency.
- **Compton scattering**: This is a phenomenon in which an incoming photon knocks an electron off it's trajectory. Generally, when a photon strikes an electron, the outgoing photon has energy less than that of the incoming photon, the rest of it's energy and it's momentum is transferred to the electron.
  $\lambda_f - \lambda_i = \frac{h}{mc}(1 - \cos(\theta))$.
  In our case, the interaction is between a γ photon and a free electron in the $NaI(TI)$ crystal. The energy of the outgoing photon in terms of the incoming photon turns out to be

$$E_{\gamma'} = \frac{E_\gamma}{1 + 1.96E_\gamma(1 - \cos(\theta))}$$

- **Pair production**: This is a process in which a γ ray photon spontaneously produces an electron-positron pair near a large nucleus. This process can only happen in the vicinity of a large nucleus because the nucleus gives some sort of a inertial frame.
  This process cannot happen in vacuum because of kinematic reasons, as one could easily move into a frame where the momentum along the line of photon's motion disappears for the electron-positron pair, but one cannot move to a frame where the photon is at rest. The interaction threshold is 1.033 MeV.

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 (E). 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

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

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.

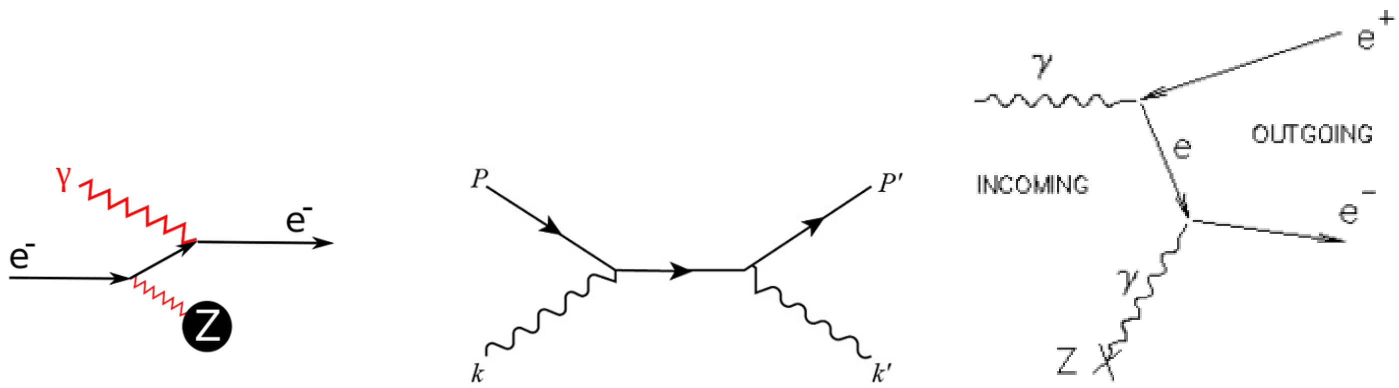

Figure 1: Feynman diagrams for Photoelectric, Compton effects and Pair production

Procedure

- **Part A**
  - Calibrate the MCA by known radioactive source i.e. Co^{60} with NaI(Tl) 2x2 and determine the peak energies of the other sources 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.

Data

The data for both Part A and Part B is too large to be provided here. Though I shall attach a folder with all the data in the same zip file as this pdf. The plots representing the data are given below.
(https://drive.google.com/drive/folders/1g0UMSse9f4dRFQv6aB734GXpblalWfdf?usp=sharing)

Results & Analysis

Part A

We fit the two peaks of the Co-60 spectrum to obtain the mean channel numbers, A = 1435.0452 and B = 1627.6278 from plots. We also know these peaks correspond to the energies E_A= 1.173 MeV and E_B = 1.332 MeV. Hence we calculate the proportionality constant

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

We shall use this constant to find energies of Cs^{137}, Ba^{133}, Na^{22} γ-ray sources. The spectra are plotted below. We have used standard values from the table above.

Part B

For Co^{60} spectrum, we get two peaks. For the γ spectrum we obtain from each detector, we fit the two peaks with a Gaussian individually, then get the mean and the FWHM. For this I wrote a small code to get the results directly from the data. We also calculate the photopeak efficiency from the above results for both peaks.

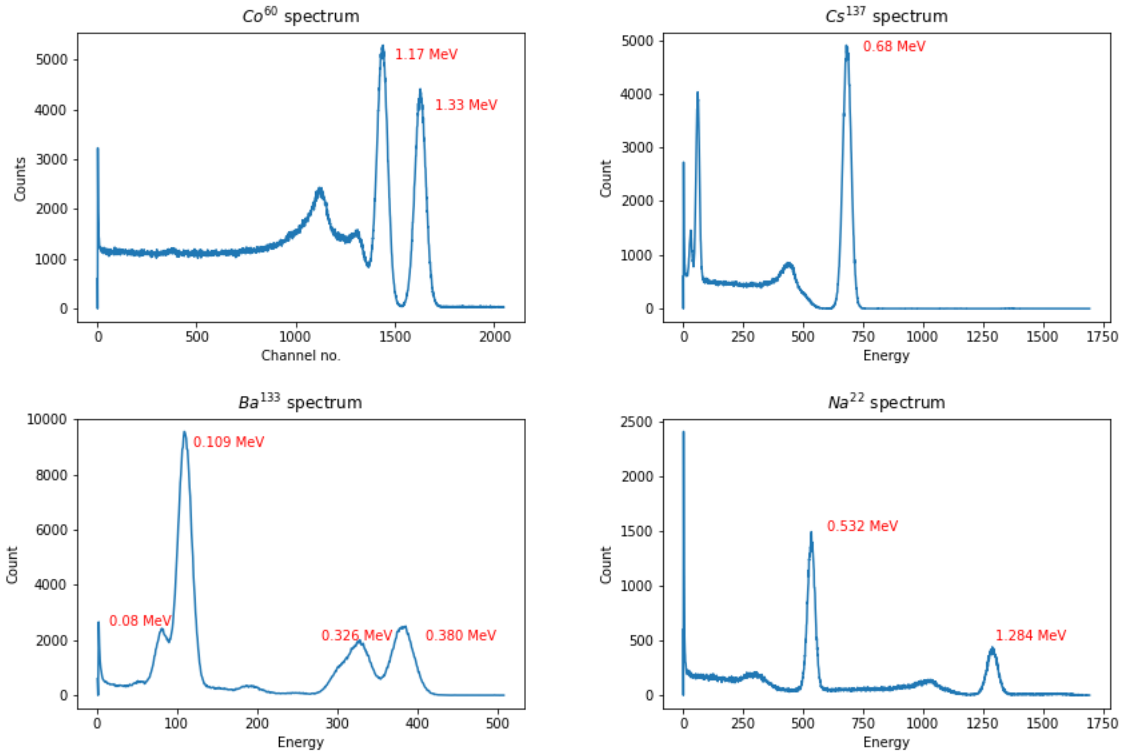

Figure 2: γ spectra for Co^{60}, Cs^{137}, Ba^{133}, Na^{22}

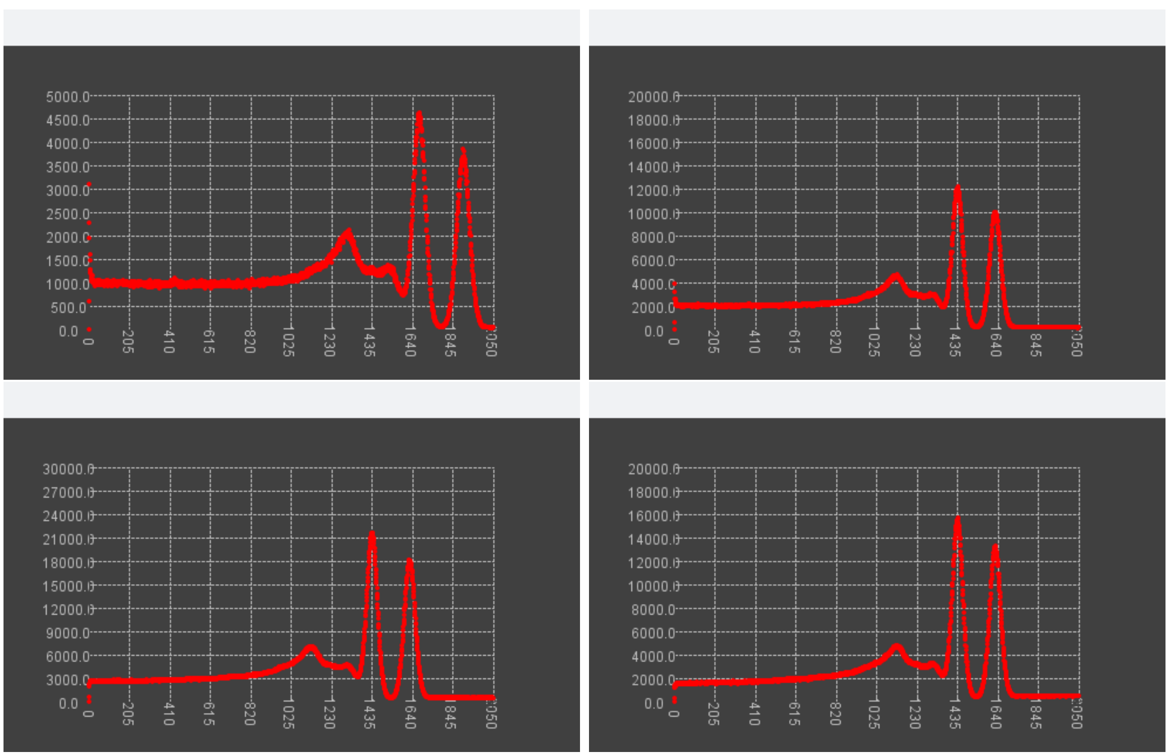

Figure 3: Co^{60} spectra using NaI 2x2, NaI 3x3, NaI 5x5, NaI 7x7 respectively.

The photpeak efficiency and energy resolutions are given in table below.

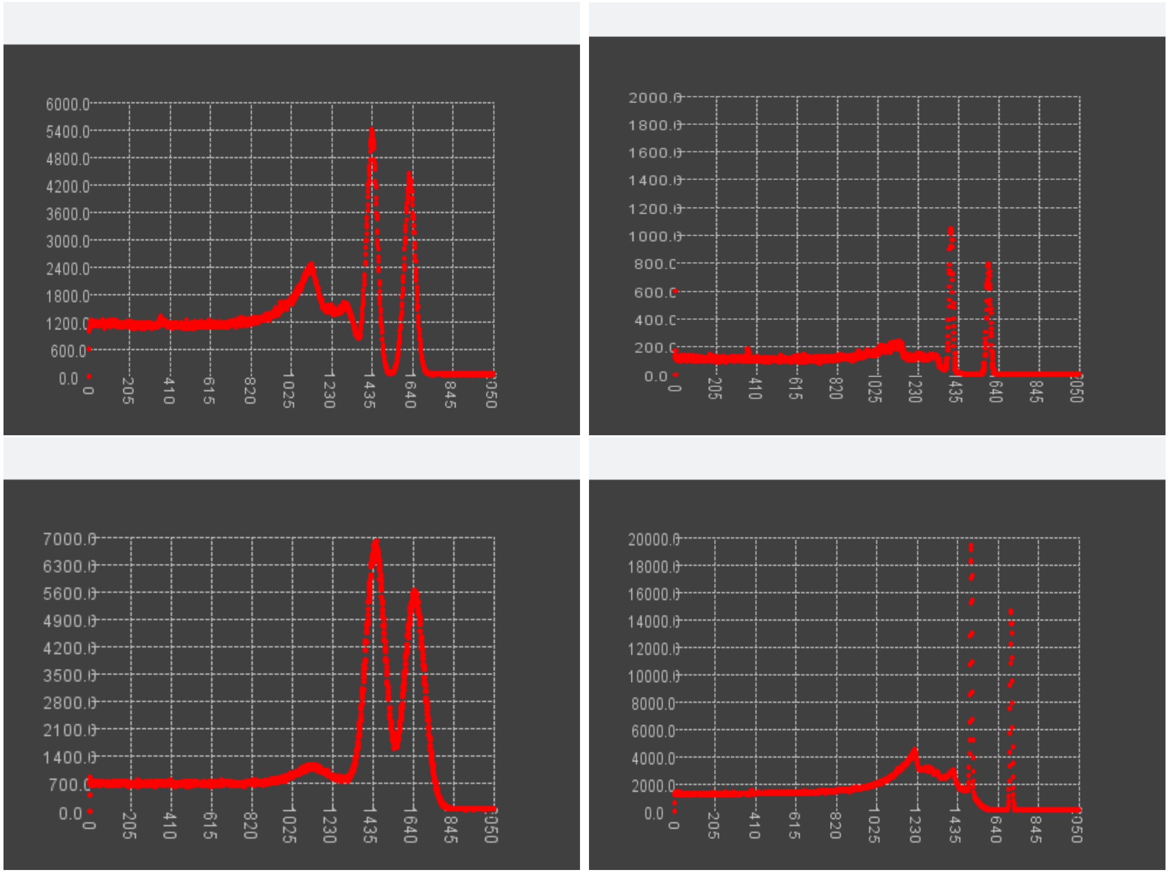

Figure 4: Co^{60} spectra using NaI 2x2 well type , CdZnTe, BgO, HpGe respectively.

Detector type		NaI 2x2	NaI 3x3	NaI 5x5	NaI 7x7	NaI 2x2 well type	CdZnTe	BgO	HpGe
HV supply (kV)		0.9	1.2	1.5	2	0.9	0.7	1.2	1.1
Amplifier	Course	70	50	50	50	50	150	130	230
Gain	Fine	0	50	50	50	50	0	50	0
Total count		2439835	4875318	7731585	5301651	2443635	207837	2586156	3118067
	Counts	359917	846795	1516734	1089821	369696	23864	874016	269342
	Efficiency	0.1475	0.1737	0.1962	0.2056	0.1513	0.1148	0.338	0.0864
1.73 MeV	FWHM	78.6671	67.2377	67.5478	67.3593	67.3155	21.1608	127.5786	12.6201
	Centroid	1674.69	1435.54	1435.84	1436.03	1435.32	1401.77	1451.81	1505.5
	Resolution	0.047	0.0468	0.047	0.0469	0.0469	0.0151	0.0879	0.0084
	Counts	299591	699698	1284946	944263	300213	19042	711070	193635
	Efficiency	0.1228	0.1435	0.1662	0.1781	0.1229	0.0916	0.275	0.0621
1.33 MeV	FWHM	77.0351	66.4041	67.0735	67.7759	67.9511	23.549	126.9693	12.2777
	Centroid	1898.89	1627.778	1627.8483	1627.913	1627.6657	1592.097	1649.2149	1708.1354
	Resolution	0.0406	0.0408	0.0412	0.0416	0.0405	0.0148	0.077	0.0072

Conclusion

We calibrated the MCA using the known energies of Co^{60} and found the unknown energies of the others.
The photpeak efficiency increases with the size of the detectors for NaI, therefore NaI 7x7 is the most energy efficient while having similar resolution to the other NaI detectors. BgO detector has the highest energy efficiency but isn't that good in terms of resolution. HpGe and CdZnTe detectors have the highest resolution but low energy efficiency.