Gamma-Ray Spectroscopy

AIM
1. To study the energy spectrum of gamma rays emitted from a radioactive source.
2. Determine energy calibration with ^{137}Cs and ^{22}Na, and calculate the photopeak energy of an unknown source.
3. To determine the energy resolution and its variation with detector operating voltage.

EQUIPMENTS REQUIRED

1. NaI(Tl) detector assembly
2. Gamma-ray spectrometer
3. Essentially following cables are used:
   - Signal cable (BNC to BNC) – 03 No.
   - HV cable (UHF to MHV) – 01 No.
   - LV cable (5 pin I/O connector) – 01 No.
4. Oscilloscope
5. Radioactive sources

INTRODUCTION
Gamma ray interaction with matter
There are three dominant gamma-ray interactions with matter:
1. Photoelectric effect
2. Compton scattering
3. Pair production

Photoelectric effect
The photoelectric effect is a common interaction between a low-energy photon and a material. In this process the photon interacts with an electron in the material losing all of its energy. The electron is ejected with an energy equal to the initial photon energy minus the binding energy of the electron. This is a useful process for spectroscopy since an output pulse in a detector is produced that is proportional to the gamma-ray energy, as all the energy of the gamma ray is transferred to the detector. This produces a characteristic full-energy peak in the spectrum that can be used for the purpose of identifying the radioactive material.

The probability of the photoelectric effect is strongly dependent on the Z of the atoms in the matter and the photon energy; it is the dominant process at low photon energy. The probability has discontinuities at the binding energies of the electrons in the constituent atoms in the matter because the probability of transferring the energy to an electron with higher binding energy than the incoming photon energy is zero. The probability of the photoelectric effect therefore rapidly decreases when transitioning from a photon energy just above the binding energy of the electrons to an energy just below it.

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.

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

where E' is the scattered energy of the gamma ray. E is the incident gamma-ray energy. θ is the angle of scatter. The term m_0c^2 is the rest mass of the electron, equal to 511 keV. The energy given to the electron is:

$$E_e = E - E'$$ (2)

The maximum energy given to an electron in Compton scattering occurs for a scattering angle of 180°, and the energy distribution is continuous up to that point (since all scattering angles up to 180° are possible). This point is known as Compton edge and can be easily calculated using Eq.1 for gamma-rays of known energies. If the photon is on a trajectory towards the detector, it can Compton scatter at a small angle and still result in hitting the detector. However, since all Compton scattering transfers some energy to the electron, the scattered photon will not deposit its full initial energy in the detector, and it will not contribute to the full-energy peak.

Pair production
Pair production can occur when the gamma-ray energy is greater than 1.022 MeV and is a significant process at energies above 2.5 MeV. The process produces a positron and electron pair that slows down through scattering interactions in the matter. When the positron comes to rest it annihilates with an electron producing a pair of 511 keV gamma rays that are emitted back-to-back. The probability of pair production is 0 up to the energy threshold of twice the electron mass (1.022 MeV/c2) and it increases with energy up to 100 MeV where it becomes constant.

Figure 1 shows the probability of the three dominant interaction processes in matter as a function of photon energy. The figure displays the discontinuity at the binding energy of the electrons in the atom, the decrease of the probability of photoelectric effect when the energy increases, the dominance of Compton scattering at medium energies and the dominance of pair production at higher photon energies.
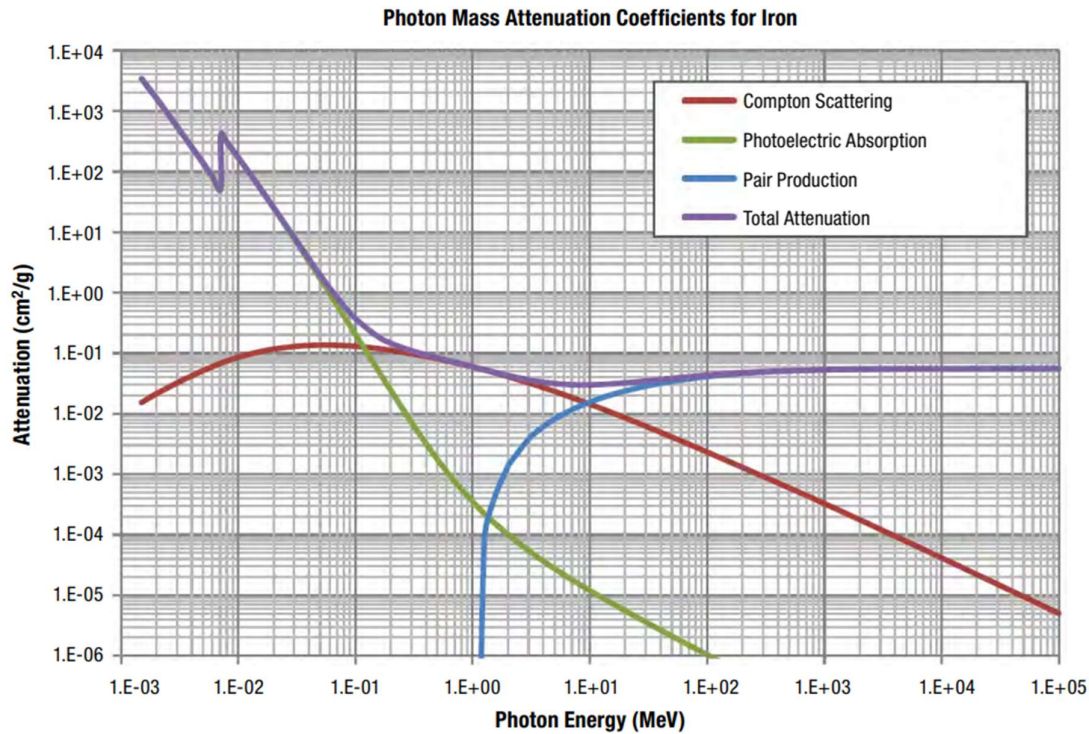
Figure 1: Probability of photon interactions as a function of energy.

The aim of this experiment is to determine the spectrum of gamma-rays emitted from the radioactive source using a gamma ray spectroscopy technique.

Gamma-ray spectroscopy

Gamma ray spectroscopy is a technique to find distribution of the intensity (or spectrum) of gamma rays with various photon energies. Scintillation detector with the Single-Channel Analyzer (SCA) is one of the detector systems used for the spectroscopy (Schematic shown in Fig. 2). The interaction of ionizing radiation with the detector produces charge particles which are collected by applying electric field. The collected charge from the detector is converted to a voltage pulse which is fed to the preamplifier.

The preamplifier amplify the signal and acts as an interface between the detector and the amplifier. It acts as a high impedance load for the detector and a low impedance source for the amplifier. Preamplifier is kept as close as possible to the detector unit to minimize the signal loss and to maximise the Signal to Noise Ratio (SNR).

The linear amplifier changes the pulse shape and increases its size. The **single channel analyser** (SCA) sorts the pulses by pulse height and counts the number of pulses within individual pulse height intervals which then plotted as a spectrum.
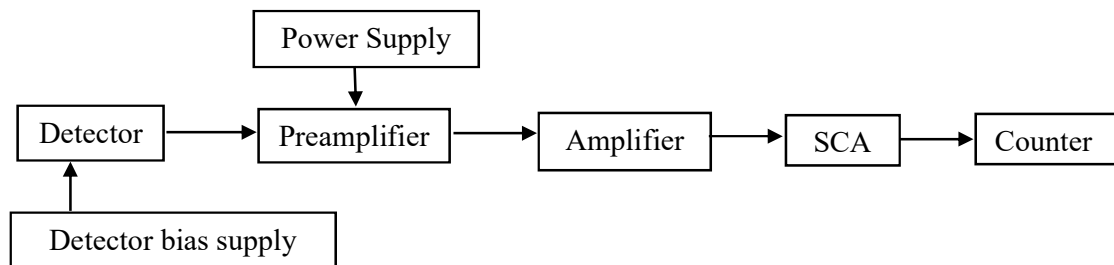

Figure 2: Schematic of Gamma-ray spectroscopy system.

Scintillation Detector Material: The scintillation detectors are used for the determination of the high-energy part of X-ray spectrum. The primary electrons produced by the gamma-ray interaction with the scintillation detector raises secondary electrons to the conduction band, leaving holes in the valence band. In some cases, the energy given to the electron may not be quite sufficient to raise it to the conduction band. Then, the electron and hole could remain electrostatically attracted to each other as an entity called an *exciton*. In terms of the band structure model, this represents elevation to an extra band just below, but continuous with, the conduction band, as illustrated in Figure 3. If the electrons are allowed to de excite by falling back to the valence band, they will emit electromagnetic radiation. If this radiation is in, or near, optical wavelengths, it can be detected by a photomultiplier or other light-measuring device to provide the detector signal. This is the basis of the scintillation detector.

The properties of a good scintillation detector are:
1) there must be a reasonable number of electron–hole pairs produced per unit of gamma-ray energy;
2) it would be very desirable for the material to have a high stopping power for gamma radiation (which means, in practice, high density and atomic number);
3) for spectrometry, the response must be proportional to energy;
4) the scintillator must be transparent to the emitted light so that the light does not get absorbed in the material itself
5) the decay time of the excited state must be short to allow high count rates;
6) the material should be available in optical quality in reasonable amounts at reasonable cost;
7) the refractive index of the material should be near to that of glass (ca. 1.5) to permit efficient coupling to photomultipliers.

The materials obeying these properties are sodium iodide (NaI), caesium iodide (CsI), calcium fluoride (CaF2), bismuth germanate (BGO) and, recently, lanthanum halides. In this experiment NaI is employed as the scintillator material. The scintillation mechanism depends on the structure of the crystal lattice. In a pure inorganic crystal lattice such as NaI, electrons are only allowed to occupy selected energy bands. The forbidden band or band gap is the range of energies in which electrons can never be found in the pure crystal. The absorption of energy can elevate electrons from the valence band to the conduction band leaving a gap in the valence band. However, the return of an electron to the valence band with the emission of a photon is an inefficient process. Few photons are released per decay, the energy is emitted by other mechanisms. In addition, band gap widths in pure crystals are such that the resulting emitted photon is too high to lie within the visible range.

This difficulty was eliminated by the introduction of an activator (about 10^{-3} mol fraction) that produces defect lattice sites which give rise to extra levels within the forbidden band i.e., between the valence and conduction bands. The activators are the impurities added to the crystal. Tl is added to NaI in trace amounts. They create special sites in the lattice at which the band gap structure, the energy structure, is modified. The energy structure of the overall crystal is not changed, just the energy structure at the activator sites. At the few activator sites within the sample, the energy structure is modified. When an electron–hole pair is formed, the hole may migrate to a nearby activator site. Electrons in the conduction band and within the exciton band will tend to be captured by the excited activator states. When these levels de-excite (mean lifetime is about 0.1 μs) the energy released will be lower and the electromagnetic radiation will be of a longer wavelength, perhaps in the visible range that can be easily detected by the photomultiplier tube.
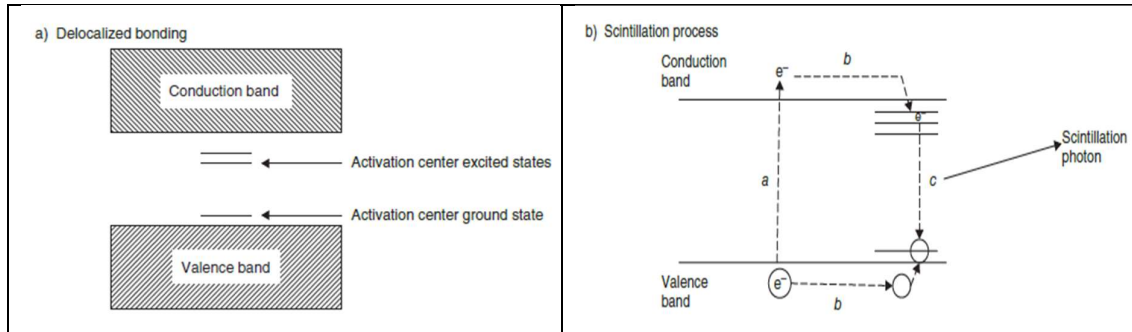
Figure 3.

Photomultiplier Tubes: The light output from a scintillator material is very low and that needed to be enhanced prior to the measurement. This is done by the photomultiplier tubes (PMT) (shown in Fig. 4) whose function is given below.

1. The light photon strikes a light sensitive layer, the **photocathode**, causing it to emit a photoelectron.
2. The photoelectrons are focused electrostatically onto the first of a series of electron multiplier stages, called **dynodes**. These emits more electrons than they receive, thus amplifying the signal.
3. The dynodes are kept at gradually increasing negative potential by using the resistor as the voltage divider (shown in the figure 3). The electrons from the first dynode are multiplied at the second dynode, and again at the third, all the way down the chain. This is the electron multiplication stage.
4. The amplified signal is then collected at the anode and passed out to the measurement circuits. The electrons are then collected at the anode to produce a signal.
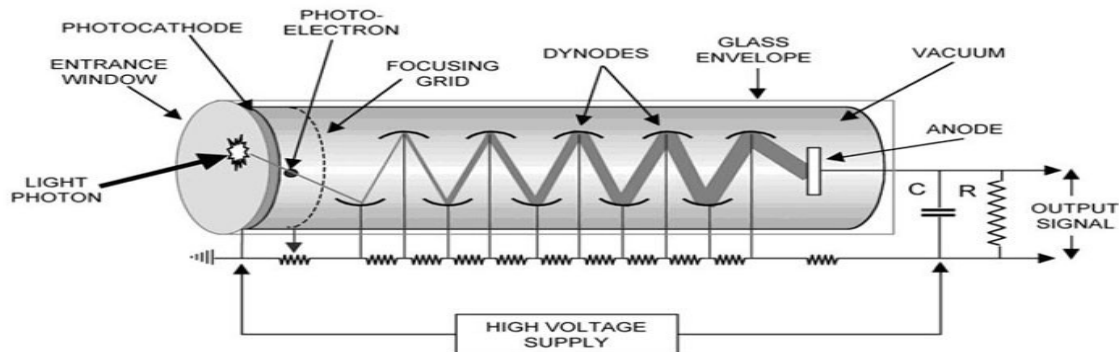

Figure 4: Working of a Photomultiplier Tube.

Preamplifier: The detector set up is followed by a pre-amplifier. The purposes of a preamplifier are to amplify the relatively small signals produced by the radiation detector, to match impedance levels between the detector and subsequent components in the system, and to shape the signal pulse for optimal signal processing by the subsequent components.

Amplifier: Many of the Nuclear Detectors give small amplitude pulse outputs. These output pulses cannot be directly counted or analysed by scalers, count rate meters and single channel analyser, without being first amplified. The amplifier in a nuclear detection system is designed to amplify the still relatively small pulses from the preamp to sufficient amplitude (volts) to drive auxiliary equipment (pulse-height analyzers, scalers, etc.), and to reshape the slow decaying pulse from the preamp into a narrow one to avoid the problem of pulse pile-up at high counting rates and to improve the electronic SNR.

Single Channel Analyzer (SCA):
A Single Channel Analyzer is essentially used for pulse height analysis. It has THREE modes of operations namely INTEGRAL, NORMAL & WINDOW. In Gamma Ray Spectrometer the scintillation detector pulse output is proportional to the Gamma Energy and hence accurate measurement of pulse height by *Single Channel Analyzer* will give the energy information.

Counter Timer: Microcontrolled based state-of-art counter/timer designed around a eight bit microcontroller chip. It can count both positive and negative pulses in the range of 100 mV to 10V and upto a maximum frequency of 1MHz.

Resolution: In ideal scenario every gamma-ray of the same energy detected should give rise to a count in the same channel of the gamma-ray spectrometer. But in real situation peaks are spread over several channels, with preponderance at a central point, which can be identified as gamma-ray energy (E). This deviation may be due to the uncertainties in the emission spectrum of the gamma rays or within the detection and measurement processes. The parameter used to express the energy resolution is FWHM – the **F**ull **W**idth of the peak at **H**alf **M**aximum height, usually expressed in keV. The resolution (R) is defined as:

$$R = \frac{FWHM}{H_0} \text{ x } 100 \qquad (H_0 \text{ is the location of peak centroid)}$$

The resolution is a dimensionless quantity usually expressed in percentage. It is evident that smaller the value for the energy resolution R the better the detector will be able to distinguish two energies lie closer. In general, the scintillation detectors used for gamma ray spectroscopy have a resolution in the range 3 – 10 %.

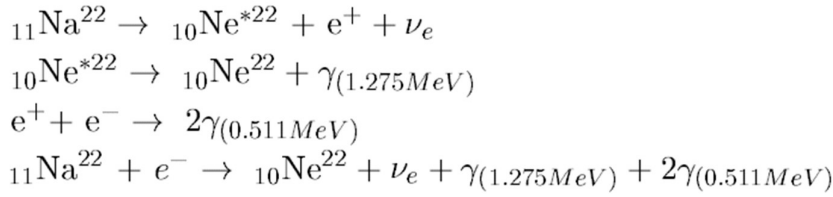**Expt. 1: To study the gamma ray spectrum from a radioactive source.**
Introduction: This experiment focuses on the qualitative analysis of the energy spectrum of gamma-rays emitted from a radioactive source Cs-137 or other. Here we would like to plot counts vs. energy and identify photopeak or full energy peak, Compton distribution and Compton edge. It may be noted that a spectrum from a source with only one gamma-ray energy consists of a peak (the photo peak or the full-energy peak) and a distribution on the low-energy side (to the left) of the photo peak. If there are several photo peaks in a spectrum, the studied radiation must contain several different energies.
In the experiment we do not measure the energy. Here we measure the counts vs. voltage or channel number. For a given set of parameters like operating voltage of detector, amplifier gain and discriminator voltage etc., one can perform the energy calibration using the radioactive sources with known gamma-ray energy.
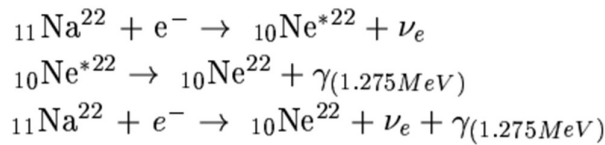
There are different gamma-ray emitting radioactive sources like ^{22}Na, ^{54}Mn, ^{60}Co, ^{137}Cs etc. The high energy photons are produced in nuclear transitions. The nuclei in excited states can move to lower energy states by means of beta decay, inverse beta decay or electron capture. A resulting by-product of these decay mechanisms is a gamma ray photon. A few decay processes are shown below.

1) ^{22}Na

The excited state of ^{22}Na decays to a stable Ne with a half-life of 2.6 years. ^{22}Na undergo inverse beta decay (90%) as well as electron capture (10%). The reaction for inverse beta decay is as follows:
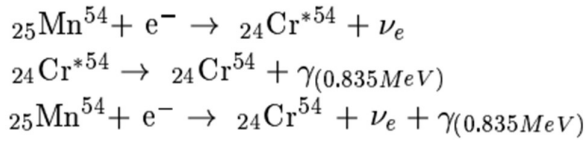
$$_{11}Na^{22} \rightarrow \ _{10}Ne^{*22} + e^+ + \nu_e$$
$$_{10}Ne^{*22} \rightarrow \ _{10}Ne^{22} + \gamma_{(1.275MeV)}$$
$$e^+ + e^- \rightarrow \ 2\gamma_{(0.511MeV)}$$
$$_{11}Na^{22} + e^- \rightarrow \ _{10}Ne^{22} + \nu_e + \gamma_{(1.275MeV)} + 2\gamma_{(0.511MeV)}$$

The reaction for electron capture is as follows:

$$_{11}Na^{22} + e^- \rightarrow \ _{10}Ne^{*22} + \nu_e$$
$$_{10}Ne^{*22} \rightarrow \ _{10}Ne^{22} + \gamma_{(1.275MeV)}$$
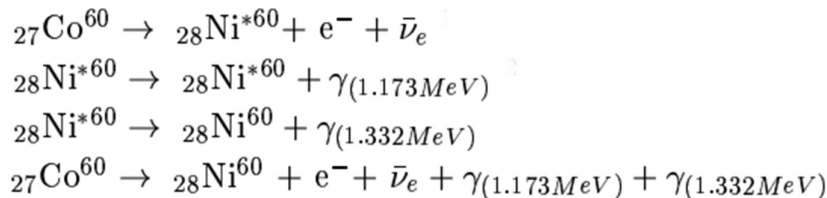$$_{11}Na^{22} + e^- \rightarrow \ _{10}Ne^{22} + \nu_e + \gamma_{(1.275MeV)}$$

2) ^{54}Mn

The excited state of ^{54}Mn decays to a stable state of ^{54}Cr by electron capture with a half-life of 312 days. The reaction is as follows:
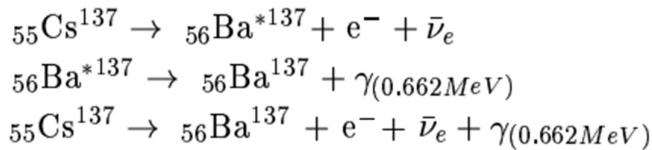
$$_{25}Mn^{54} + e^- \rightarrow \ _{24}Cr^{*54} + \nu_e$$
$$_{24}Cr^{*54} \rightarrow \ _{24}Cr^{54} + \gamma_{(0.835MeV)}$$
$$_{25}Mn^{54} + e^- \rightarrow \ _{24}Cr^{54} + \nu_e + \gamma_{(0.835MeV)}$$

3) ^{60}Co

The excited state of ^{60}Co decays to stable ^{60}Ni by beta decay through various excited states of Ni with a half-life of 5.2 years. The reaction is as follows:

$$_{27}Co^{60} \rightarrow \ _{28}Ni^{*60} + e^- + \bar{\nu}_e$$
$$_{28}Ni^{*60} \rightarrow \ _{28}Ni^{*60} + \gamma_{(1.173MeV)}$$
$$_{28}Ni^{*60} \rightarrow \ _{28}Ni^{60} + \gamma_{(1.332MeV)}$$
$$_{27}Co^{60} \rightarrow \ _{28}Ni^{60} + e^- + \bar{\nu}_e + \gamma_{(1.173MeV)} + \gamma_{(1.332MeV)}$$

4) ^{137}Cs

The excited state of ^{137}Cs decays to stable ^{137}Ba by beta decay with a half-life of 30 years. The reaction is as follows:

$$_{55}Cs^{137} \rightarrow {}_{56}Ba^{*137} + e^- + \bar{\nu}_e$$
$$_{56}Ba^{*137} \rightarrow {}_{56}Ba^{137} + \gamma_{(0.662MeV)}$$
$$_{55}Cs^{137} \rightarrow {}_{56}Ba^{137} + e^- + \bar{\nu}_e + \gamma_{(0.662MeV)}$$

A typical ^{137}Cs spectrum is shown in the Fig. 5. In this figure counts are plotted as channel no. where a channel no. corresponds to some voltage value that is related to the energy. The low-energy distribution to the left of the photo peak originates from gamma quanta, which have collided with electrons in the detector crystal or in the lead shielding. The collision takes place in such a way that only part of the original energy of the gamma quantum is absorbed in the detector. This kind of collision is called Compton scattering and the low-energy distribution is the so-called Compton distribution. The Compton distribution always forms a background to the left of the photo peak with which it is associated.

It may be noted that there is always a discriminator setting, which rejects the most low-energetic gamma quanta and the electronic noise. The discriminator setting can be adjusted but should not be changed during a measurement.
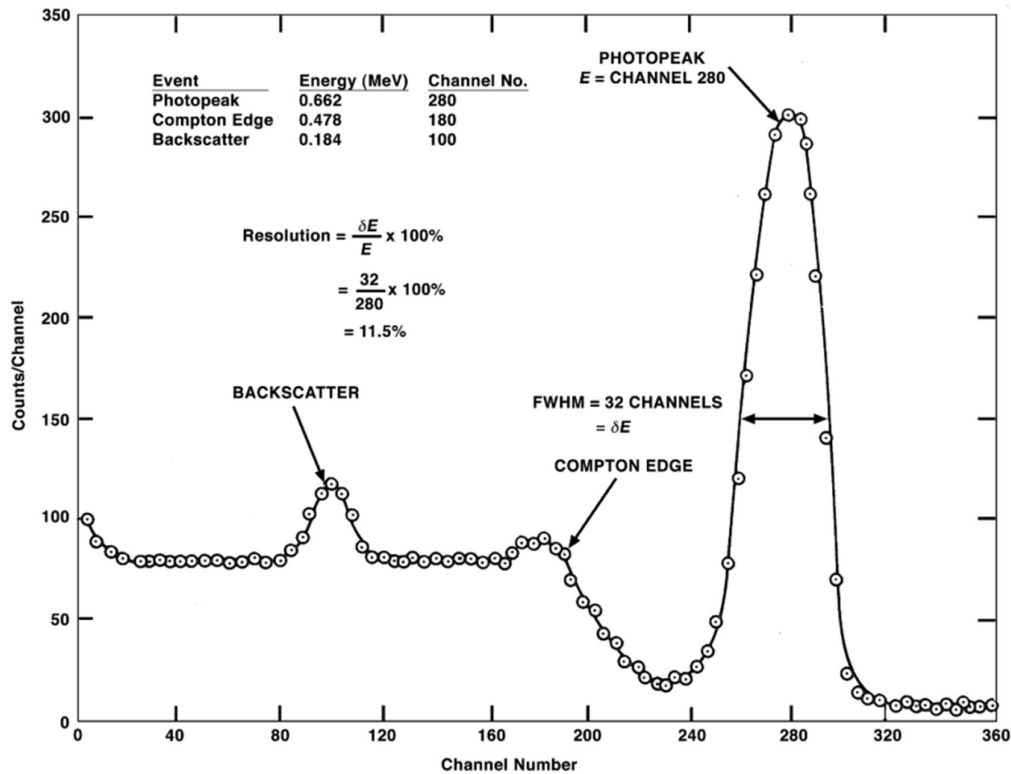

Figure 5: A typical Gamma-ray spectrum of ^{137}Cs from NaI(Tl) detector.

Figure 6: (Left) Gamma-ray spectrometer system GR611M and (Right) Detector assembly (NaI + PMT + preamplifier) set up in the laboratory.

Equipments required
1. NaI(Tl) detector assembly
2. Gamma-ray spectrometer (GR 611M)
3. Essentially following cables are used:
   - Signal cable (BNC to BNC) – 03 No.
   - HV cable (UHF to MHV) – 01 No.
   - LV cable (5 pin I/O connector) – 01 No.
4. Oscilloscope
5. Radioactive sources (Cs-137)

Procedure: The experimental setup in the laboratory is shown in Fig. 6.
1. Turn off the power to the MINI BIN, Power supply and HV 502 power supply of Gamma-ray spectrometer GR611M.
2. The detector assembly (tower like structure shown in the right side of Fig.6) consists of NaI scintillator, PMT and Preamplifier. Three terminals shown are for power supply to preamplifier, HV supply to detector system and signal output of preamplifier.
3. Connect the power supply of the preamplifier to the MiniBin. Connect HV supply of the detector system to the high voltage supply module HV 502.
4. Connect the output of the Preamplifier to the Input of Linear amplifier LA 520. Set the Input Polarity to Positive.
5. Set the gain of the Linear amplifier such that the signal peak is of the order of 3-4 volts. This will ensure the occurrence of photo peak in this range in the output of Single Channel Analyzer (SCA).

6. Set the Output of the LA 520 to UniPolar and connect to the Input of SCA.
7. SCA operation mode should be Window.
8. Set the Upper Level Discriminator (ULD) window to 0.1 or 0.2 V. The ULD window defines the channel width.
9. To measure the Gamma-ray spectrum increase Lower Level Discriminator (LLD) voltage in steps of 0.1 or 0.2 V and record the counts in the Counter till one get a photopeak (which should appear in the range 3-4 volts, refer to step 5). Here, each window width corresponds to the channel number.
10. Connect output of SCA to the Counter Timer CT 541A. One can record counts for a preset time.
11. Switch on the power supply of spectrometer GR611M. Switch On the high voltage supply module HV 502. Increase the voltage slowly to the detector operating voltage (~500 V).
12. Put the radioactive source (Cs-137) near to the detector. See output signal of Preamplifier (typically of the order of few mV) in an oscilloscope.
13. Also analyse the output of Linear Amplifier in an oscilloscope and make sure the signal peak is ranging between 3-4 V.
14. Set the preset time of counter to 60 s minimum (ensuring the collection of a reasonable statistics).
15. Record the signal count for LLD voltage starting from 0.1 or 0.2 V till the photopeak appears (around 4-5 volts)
16. Remove the radioactive source. Now record the counts without any source which is the background count N_{bkg}.
17. Prepare the following table:

LLD voltage (V)	Counts (N_{raw})	Background count (N_{bkg})	Corrected counts $N_{corr} = N_{raw} - N_{bkg}$
0.1			
0.2			
0.3			
-			
-			

18. Plot counts N_{corr} vs. LLD voltage. Analyze the distribution, identify the Compton edge, backscattering peak and photopeak.
19. Mark the LLD voltage value where the maximum of photopeak appears. This voltage value also called as channel no. corresponds to the energy of the gamma ray emitted from Cs-137.

Expt. 2: Determine energy calibration with ^{137}Cs and ^{22}Na, and calculate the photopeak energy of an unknown source.

Objective: The gamma-ray spectrometer gives the measurement of counts vs. channel number or voltage. The energy calibration allows the gamma-ray spectrum to be interpreted in terms

of energy, rather than channel number or voltage. The objective of this experiment is to find out a relationship between channels or voltage and energy.

Equipments required
1. NaI(Tl) detector assembly
2. Gamma-ray spectrometer (GR 611M)
3. Essentially following cables are used:
   - Signal cable (BNC to BNC) – 03 No.
   - HV cable (UHF to MHV) – 01 No.
   - LV cable (5 pin I/O connector) – 01 No.
4. Oscilloscope
5. Radioactive sources (Cs-137 and Na-22)

Procedure:
The energy calibration can be performed using radioactive sources of well-known gamma-ray energy. For the calibration one need at least three data point. Cs-137 having single photopeak at 0.662 MeV and Na-22 having two photopeaks at 0.511 MeV and 1.275 MeV will be used to get the energy calibration relation between voltage and energy. One can also make use of Compton edge (energy calculated from eq. 2) in the gamma-ray spectrum to add more data points. The experiments is performed as follows.
1. Turn all the electric units ON, set the detector assembly voltage to 500 V (don't exceed the HV beyond 600 V), adjust the gain of the amplifier and discriminator voltage as done in expt. 1. Keep all the settings undisturbed throughout the experiment.
2. Take the source ^{137}Cs and collect the spectrum as done in expt. 1.
3. Determine the voltage or channel position of the photo peak in the spectrum of ^{137}Cs. One may also identify the voltage or channel position of Compton edge.
4. Take the source ^{22}Na and collect the spectrum as done in expt. 1.
5. Determine the voltage or channel positions of the two photopeak in the spectrum of ^{22}Na. One may also identify the voltage or channel position of Compton edge.
6. Prepare the data table as follows:

Event	Energy (MeV)	Voltage or channel position
^{137}Cs photopeak	0.662	
^{137}Cs Compton edge	-	
^{22}Na photopeak	0.511	
^{22}Na photopeak	1.275	
^{22}Na Compton edge	-	

7. Plot the photopeak energy vs. voltage or channel number. Fit it with a straight line as shown in Fig. 6. This straight line equation gives the relation between voltage or channel position and energy.
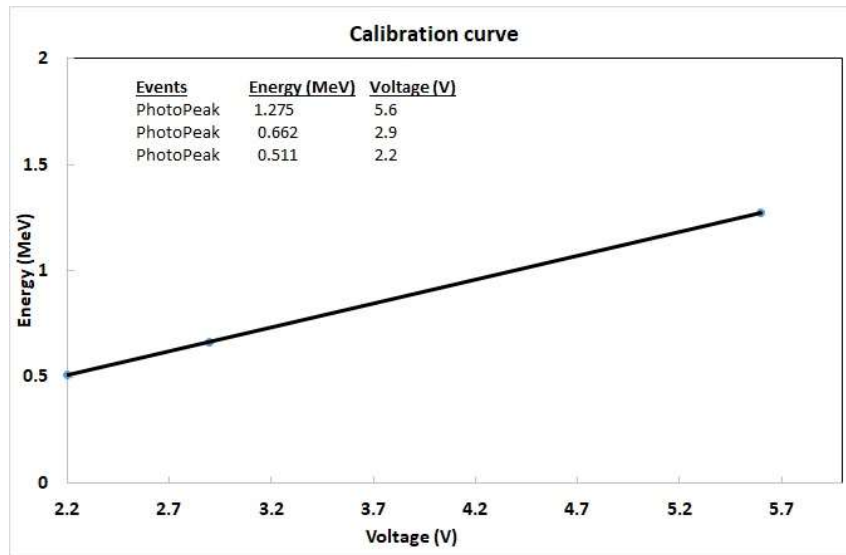8. Take an unknown source and calculate the energy of PhtotoPeak using the calibration relation.

Figure 7: Energy calibration curve fore NaI(Tl) detector.

Expt. 3: To determine the energy resolution and its variation with gamma-ray energy and PMT high voltage supply.

Objective: The aim of the experiment is to measure the resolution of NaI (Tl) detector and its variation with the gamma-ray energy and PM high voltage.

The width of the photopeak is a measure of the energy resolution of the detection system. The smaller the width, the closer two gammas can become in energy and still be observed as separate peaks in the pulse height spectrum. Consider a photopeak appearing in a pulse height spectrum at voltage V and having a full width at half maximum (FWHM) of ΔV. The energy resolution R is commonly expressed by the ratio of the photopeak's FWHM (in energy units) ΔE = mΔV to its energy E = mV + C, where m and C are the parameters obtained from the calibration relation in expt. 2. The energy resolution is easily obtained from the pulse height spectrum as

$$R = \frac{\Delta E}{E}$$

The value of R is 5-10% for NaI(Tl) detectors for 0.662 MeV gamma of ^{137}Cs. Because of the Poisson statistics of light production in the scintillator and light detection in the PMT, the FWHM is expected to increase as the square root of the gamma ray energy. Consequently, the resolution R should improve (go down) as the square root of the energy. The energy resolution will also depend on the PMT supply voltage. A typical photopeak from a ^{22}Na spectrum is shown in Fig. 8.
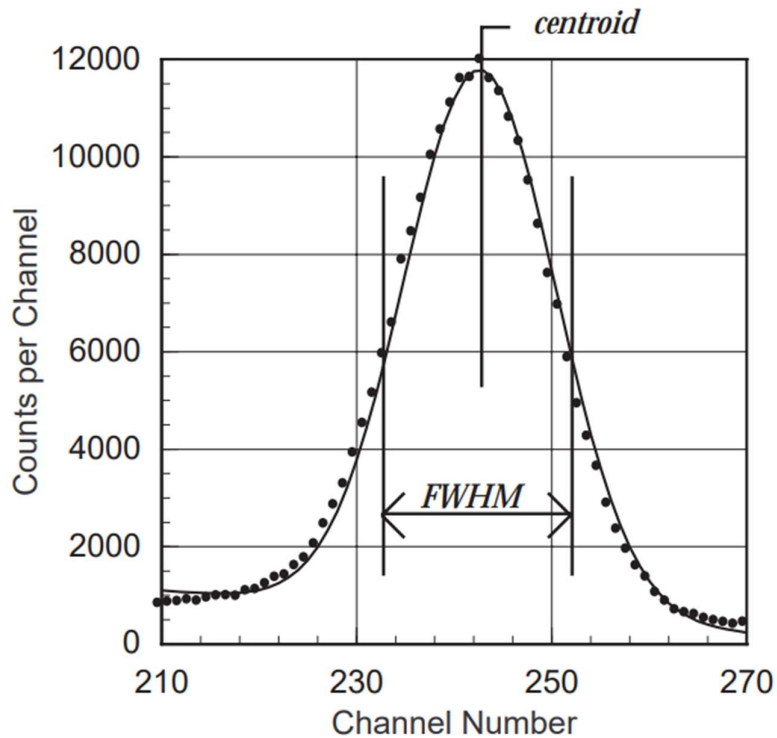
Figure 8: Gaussian fit to the 0.511 MeV photopeak from a ^{22}Na spectrum.

Equipments required

1. NaI(Tl) detector assembly
2. Gamma-ray spectrometer (GR 611M)
3. Essentially following cables are used:
   - Signal cable (BNC to BNC) – 03 No.
   - HV cable (UHF to MHV) – 01 No.
   - LV cable (5 pin I/O connector) – 01 No.
4. Oscilloscope
5. Radioactive sources (Cs-137 and Na-22)

Procedure:

1. Turn all the electric units ON, set the detector assembly voltage to 500 V (don't exceed the HV beyond 600 V), adjust the gain of the amplifier and discriminator voltage as done in expt. 2.
2. Take the sources ^{137}Cs and ^{22}Na and collect the spectrum as done in expt. 1.
3. Calculate the resolution of the single photopeak in ^{137}Cs and two PhotoPeaks in ^{22}Na in energy units using the calibration relation obtained in expt. 2.
4. Prepare a data table as follows:

Event	Energy (MeV)	Energy resolution
^{137}Cs PhotoPeak	0.662	
^{22}Na PhotoPeak	0.511	
^{22}Na PhotoPeak	1.275	

5. Plot energy resolution as a function of gamma-ray energy and interpret the observations.
6. Take the sources ^{137}Cs and collect the spectrum as done in expt. 1 for various HV values ranging between 400 V to 600 V.
7. Prepare a data table as follows:

Event	HV (volts)	Energy resolution
^{137}Cs photopeak		

8. Plot resolution vs. voltage and interpret the observations.