Nuclear Physics Laboratory Manual

June 28, 2016

1 Gamma-ray Scintillation Spectrometry

1.1 Gamma-ray interaction

A gamma ray interact with matter by three major processes: photoelectric absorption, Compton scattering, and pair production. In the photoelectric absorption process, the gamma ray loses all of its energy in one interaction. The probability for this process depends very strongly on gamma-ray energy E_γ and atomic number Z. In Compton scattering, the gamma ray loses only part of its energy in one interaction. The probability for this process is weakly dependent onE_γ and Z. The gamma ray can lose all of its energy in one pair-production interaction. However, this process is relatively unimportant for our studies since it has a threshold above 1.02 MeV.

1.1.1 Photoelectric Absorption

A gamma ray may interact with a bound atomic electron in such a way that it loses all of its energy and ceases to exist as a gamma ray. Some of the gamma-ray energy is used to overcome the electron binding energy, and most of the remainder is transferred to the freed electron as kinetic energy. A very small amount of recoil energy remains with the atom to conserve momentum. This is called photoelectric absorption. Photoelectric absorption is important for gamma-ray detection because the gamma ray gives up all its energy, and the resulting pulse falls in the full-energy peak. The probability of photoelectric absorption depends on the gamma-ray energy, the electron binding energy, and the atomic number of the atom. The probability is greater the more tightly bound the electron; therefore, K electrons are most affected (over 80% of the interactions involve K electrons), provided the gamma-ray energy exceeds the K-electron binding energy. The probability is given approximately by Equation 1.1, which shows that the interaction is more important for heavy atoms like lead and uranium and low-energy gamma rays:

$$\sigma_{ph} \propto \frac{Z^5}{E^{3.5}} \tag{1.1}$$

Photoelectric absorption is the predominant interaction for low-energy gamma rays, x rays, and bremsstrahlung.

The energy of the photoelectron E_e. released by the interaction is the difference between

the gamma-ray energy E_γ and the electron binding energy E_b:

$$E_e = E_\gamma - E_b \tag{1.2}$$

In most detectors, the photoelectron is stopped quickly in the active volume of the detector, which emits a small output pulse whose amplitude is proportional to the energy deposited by the photoelectron. The electron binding energy is not lost but appears as characteristic x-rays emitted in coincidence with the photoelectron. In most cases, these x-rays are absorbed in the detector in coincidence with the photoelectron and the resulting output pulse is proportional to the total energy of the incident gamma ray. For low-energy gamma rays in very small detectors, a sufficient number of K x-rays can escape from the..detector to cause escape peaks in the observed spectrum; the peaks appear below the full-energy peak by an amount equal to the energy of the x ray.

1.1.2 Compton Scattering

Compton scattering is the process in which a gamma ray interacts with a free or weakly bound electron ($E_\gamma >> E_b$) and transfers part of its energy to the electron. Conservation of energy and momentum allows only a partial energy transfer when the electron is not bound tightly enough for the atom to absorb recoil energy. This interaction involves the outer, least tightly bound electrons in the scattering atom. The electron becomes a free electron with kinetic energy equal to the difference of the energy lost by the gamma ray and the electron binding energy. Because the electron binding energy is very small compared to the gamma-ray energy, the kinetic energy of the electron is very nearly equal to the energy lost by the gamma ray:

$$E_e = E_\gamma - E'_\gamma \tag{1.3}$$

where E_e = energy of scattered electron
E_γ = energy of incident gamma ray
E'_γ = energy of scattered gamma ray.

The directions of the electron and the scattered gamma ray depend on the amount of energy transferred to the electron during the interaction. Equation 1.3 gives the energy of the scattered gamma ray, and Figure 1.1 shows the energy of the scattered electron as a function of scattering angle and incident gamma-ray energy.

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)} \tag{1.4}$$

where $E_{\gamma'}$ is the energy of the scattered photon γ', θ is the scattering angle for the direction of γ' relative to the direction of the incident gamma-ray, γ, E_γ is the energy of the incident photon γ and $m_0 c^2$ is the rest mass energy of the electron and is equal to 511 keV.

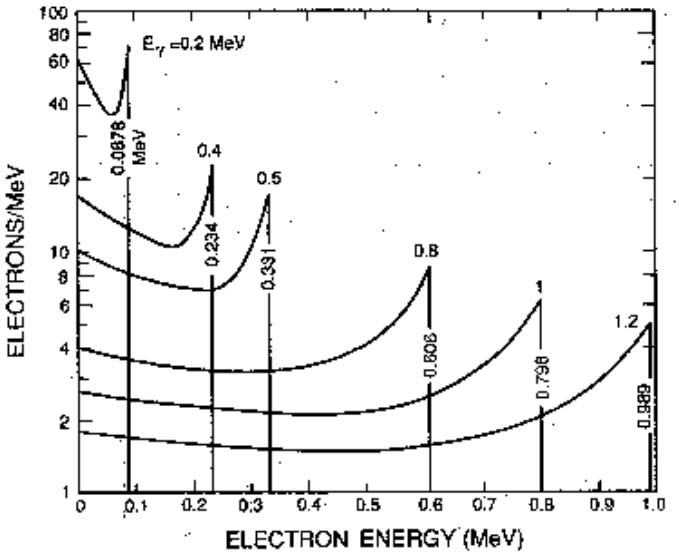

Figure 1.1: Energy of Compton-scattered electrons as a function of scattering angle and incident gamma-ray energy (E_γ). The sharp discontinuity corresponds to the maximum energy that can be transferred in a single scattering.

This energy is minimum for a head-on collision where the gamma ray is scattered 180° and the electron moves forward in the direction of the incident gamma ray. For this case the energy of the scattered gamma ray is given by Equation 1.5 and the energy of the scattered electron is given by Equation 1.6:

$$E'_\gamma(\text{min}) = \frac{E_\gamma}{1+\frac{2E_\gamma}{m_0c^2}} \simeq \frac{m_0c^2}{2} = 256 \text{ keV; if } \mathrm{E}_\gamma >> \frac{\mathrm{m_0c^2}}{2} \tag{1.5}$$

$$E_e(\text{max}) = E_\gamma\left[1-\frac{1}{1+\frac{2E_\gamma}{m_0c^2}}\right] \simeq E_\gamma - \frac{m_0c^2}{2} = E_\gamma - 256 \text{ keV; if } \mathrm{E}_\gamma >> \frac{\mathrm{m_0c^2}}{2} \tag{1.6}$$

When a Compton scattering occurs in a detector, the scattered electron is usually stopped in the detection medium and the detector produces an output pulse that is proportional to the energy lost by the incident gamma ray. Compton scattering in a detector produces a spectrum of output pulses from zero up to the maximum energy given by Equation 1.6.

The scattering cross-section for this process does not depend on atomic number Z but on the density of electrons (= NZ, N = number of atoms per cm^3) present in the scatterer. Hence, in practice, a Z-dependence is observed.

1.1.3 Pair Production

A gamma ray with an energy of at least 1.022 MeV can create an electron-positron pair when it is under the influence of the strong electromagnetic field in the vicinity of a nucleus. In this interaction the nucleus receives a very small amount of recoil energy to conserve momentum, but the nucleus is otherwise unchanged and the gamma ray disappears. This interaction has a threshold of 1.022 MeV because that is the minimum energy required to create the electron and positron. If the gamma-ray energy exceeds 1.022 MeV, the excess energy is shared between the electron and positron as kinetic energy.

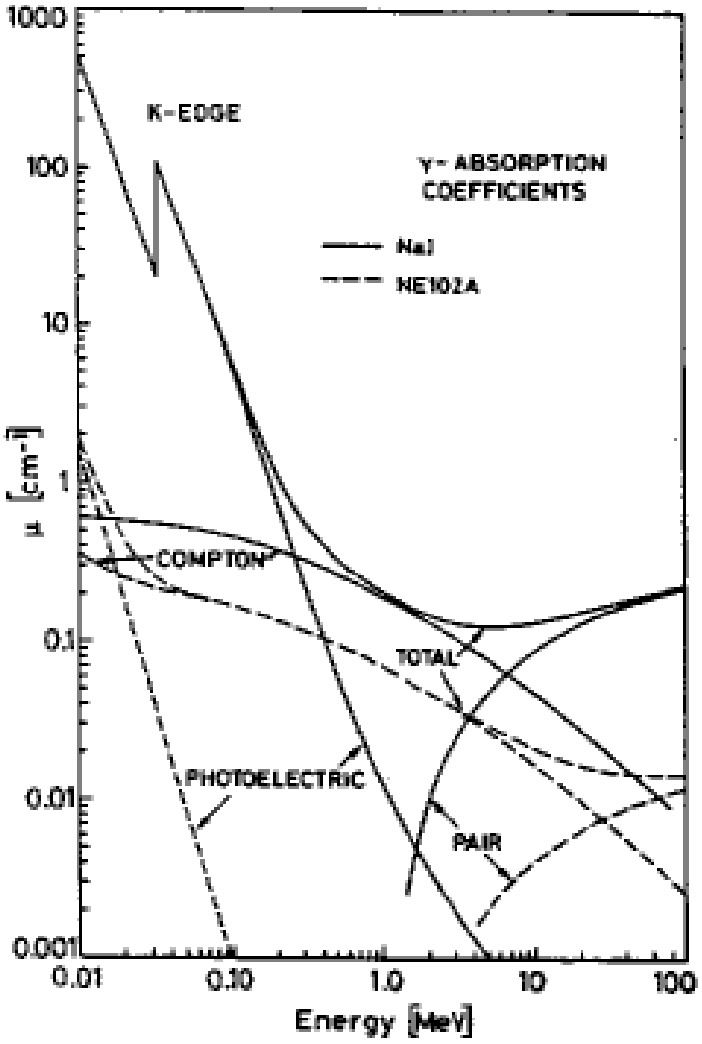

Figure 1.2: Gamma ray absorption coefficients for NaI(Tl) and NE102A plastic scintillator. Note the difference in the relative magnitudes of the photoelectric and Compton cross sections.

The electron and positron from pair production are rapidly slowed down in the absorber. After losing its kinetic energy, the positron combines with an electron in an annihilation

process, which releases two gamma rays with energies of 0.511 MeV. These lower energy gamma rays may interact further with the absorbing material or may escape. In a gamma-ray detector, this interaction often gives three peaks for a high-energy gamma ray. The kinetic energy of the electron and positron is absorbed in the detector. One or both of the annihilation gamma rays may escape from the detector or they may both be absorbed. If both annihilation gamma rays are absorbed in the detector, the interaction contributes to the full-energy peak in the measured spectrum; if one of the annihilation gamma rays escapes from the detector, the interaction contributes to the single-escape peak located 0.511 MeV below the full-energy peak; if both gamma rays escape, the interaction contributes to the double-escape peak located 1.022 MeV below the full-energy peak. The relative heights of the three peaks, depend on the energy of the incident gamma ray and the size of the detector.

Pair production is impossible for gamma rays with energy less than 1.022 MeV. Above this threshold, the probability of the interaction increases rapidly with energy. The probability of pair production varies approximately as the square of the atomic number Z and is significant in high-Z elements such as Lead or Uranium. In lead, approximately 20% of the interactions of 1.5-MeV gamma rays are through the pair-production process, and the fraction increases to 50% at 2.0 MeV. For carbon, the corresponding interaction fractions are 2% and 4%. Since the highest γ-ray energy we commonly encounter in our laboratory is 1.33 MeV emitted from a ^{60}Co nucleus and since the pair-production cross-section is rather small at this energy, we will not discuss any further about the role of this process in scintillation γ-spectrometry.

Figure 1.2 illustrates the difference in the three cross sections for γ-rays in NaI(Tl) and NE102A plastic scintillator (effectively carbon atoms). While the Compton cross sections in both materials are comparable, the photoelectric and pair production cross sections are several orders of magnitudes higher in the NaI.

1.2 Gamma-ray spectrometer

A scintillation γ-ray spectrometer is schematically shown in the block diagram of Fig. 1.3. In this figure both SCA and MCA modes are shown. We will use both the modes independently for measuring γ-ray energies.

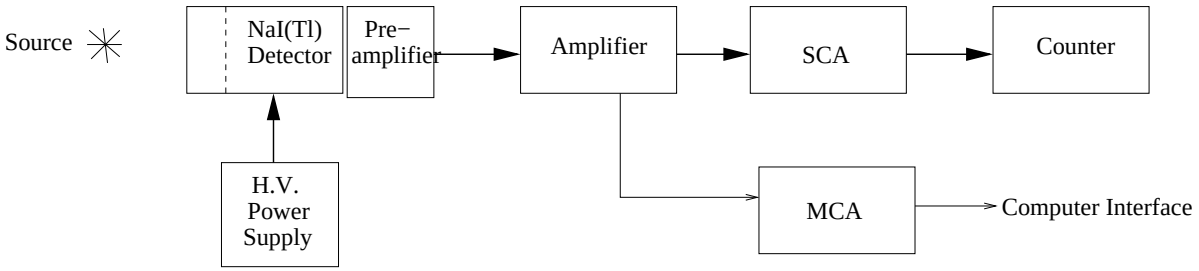

Figure 1.3: Block diagram of a Scintillation γ-ray spectrometer assembly

A brief description of the components of this assembly (Fig. 1.3) and their working principle is given below.

1.2.1 NaI(Tl) Detector :

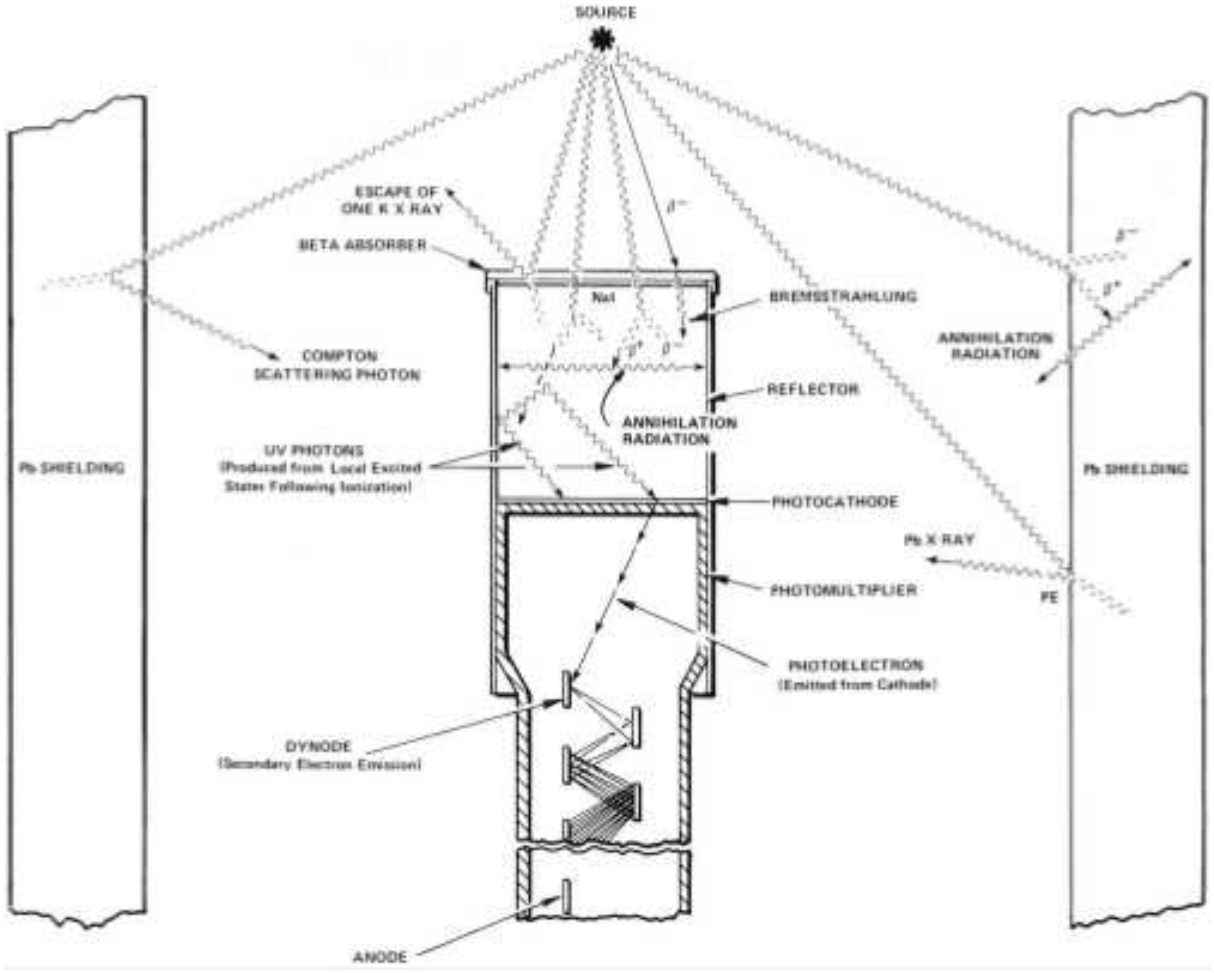

Figure 1.4: The structure of the NaI(Tl) detector and various types of gamma-ray interactions that occur in the typical source-detector-shield configuration.

The structure of the NaI(Tl) detector is illustrated in Figure 1.4. A crystal of sodium iodide (NaI) activated with a very small quantity of thallium (Tl) serves as the scintillator. When a charged particle or a photon enters its volume, it interacts with the electrons causing ionization of the sodium iodide. This creates excited states in the crystal that decay by emitting visible light photons. This emission is called a scintillation and, hence, this type of sensor is known as a scintillation detector. The thallium doping of the crystal is critical for shifting the wavelength of the light photons into the sensitive range of the photocathode. Fortunately, the number of visible-light photons is proportional to the energy deposited in the crystal by the gamma ray. After the onset of the flash of light, the intensity of the scintillation decays approximately exponentially in time, with a decay time constant of 250 ns. Surrounding the scintillation crystal is a thin aluminum enclosure, with a glass window at the interface with the photocathode, to provide a hermetic seal that protects the hygroscopic NaI against moisture absorption. The inside of the aluminum is lined with a coating that reflects light to improve the fraction of the light that reaches the photocathode.

At the photocathode, the scintillation photons release electrons via the photoelectric effect. The number of photoelectrons produced is proportional to the number of scintillation photons, which, in turn, is proportional to the energy deposited in the crystal by the gamma ray.

The remainder of the photomultiplier tube consists of a series of dynodes enclosed in the evacuated glass tube. Each dynode is biased to a higher voltage than the preceding dynode by a high voltage supply and resistive biasing ladder in the photomultiplier tube base. Because the first dynode is biased at a considerably more positive voltage than the photocathode, the photoelectrons are accelerated to the first dynode. As each electron strikes the first dynode the electron has acquired sufficient kinetic energy to knock out 8 to 10 secondary electrons. Thus, the dynode multiplies the number of electrons in the pulse of charge. The secondary electrons from each dynode are attracted to the next dynode by the more positive voltage on the next dynode. This multiplication process is repeated at each dynode, until the output of the last dynode is collected at the anode. By the time the avalanche of charge arrives at the anode, the number of electrons has been multiplied by a factor ranging from 10^6 to 10^8, with higher applied voltages yielding larger multiplication factors. For the selected bias voltage, the charge arriving at the anode is proportional to the energy deposited by the gamma ray in the scintillator.

The preamplifier collects the charge from the anode on a capacitor, turning the charge into a voltage pulse. Subsequently, it transmits the voltage pulse over the long distance to the supporting amplifier. At the output of the preamplifier and at the output of the linear amplifier, the pulse height is proportional to the energy deposited in the scintillator by the detected gamma ray. The Multichannel Analyzer (MCA) measures the pulse heights delivered by the amplifier, and sorts them into a histogram to record the energy spectrum produced by the NaI(Tl) detector.

For an ideal detector and supporting pulse processing electronics, the spectrum of 662-keV gamma rays from a ^{137}Cs radioactive source would exhibit a peak in the spectrum whose width is determined only by the natural variation in the gamma-ray energy. The NaI(Tl) detector is far from ideal, and the width of the peak it generates is typically 7% to 10% of the 662-keV gamma-ray energy. The major source of this peak broadening is the number of photoelectrons emitted from the photocathode for a 662-keV gamma-ray. Statistical fluctuations in the secondary electron yield at the first dynode and fluctuations in the light collected from the scintillator also make a small contribution to broadening the width of the peak in the energy spectrum. Because the broadening is dominated by the number of photoelectrons, and that number is proportional to the gamma-ray energy, the FWHM of a peak at energy E is approximately proportional to $\frac{1}{\sqrt{E}}$

Because the scintillation has a 250-ns decay time constant, it is important to collect the resulting charge pulse from the photomultiplier tube for at least four time constants (i.e., 1 μs). This collection time ensures that 98% of the light will contribute to the analyzed pulse height, thus assuring that the best possible energy resolution can be achieved. If a 0.5-μs shaping time constant is chosen on the linear amplifier, the amplifier output pulse will reach its maximum amplitude in approximately 1.1 μs. Hence this is the minimum shaping time constant that can be employed. If high counting rates are not expected, and the dead time caused by the pulse width is not a problem, a 1- μs shaping time constant can be selected. The latter choice delivers a pulse that reaches peak amplitude in approximately 2.2 μs.

For an MCA having a conversion time $< 2\ \mu s$, the dominant source of dead time is the duration of the amplifier output pulse. The dead time comprises the sum of the time to reach peak amplitude and the width of the pulse at the baseline. For the 0.5 μs shaping time constant, the dead time amounts to about 5 μs, and for the 1 μs time constant, the dead time is approximately 10 μs. Consequently, the NaI(Tl) system will experience a 10% dead time loss in the range of 10,000 to 20,000 counts/second, depending on the choice of amplifier shaping time constant. Above 20,000 counts/second, the gain of the photomultiplier tube can be affected by the counting rate. Consequently, 20,000 counts/second is a reasonable upper limit for normal operation. For more information on pulse shaping and the relevant dead time, see the book by G.F. Knoll.

1.2.2 Electronic Modules

The components of a $\gamma-$ray spectrometer schematically shown in Fig. 1.3 are:

High voltage supply (H.V.) :

The H.V. supply is a stabilized voltage supply required to supply the necessary operating voltage to the PMT. Commonly about 800 to 1000 V is used. The anode is held at the highest potential and the cathode the lowest.

Preamplifier :

In this case preamplifiers most commonly used are emitter followers or cathode followers. These followers have high input impedance and low output impedance. Such a unit is placed close to the PMT. The PMT delivers output at a high impedance which needs to be fed to an emitter follower having an input impedance of a few mega ohms. The output is taken via a pulse transmission cable (characteristic impedance : 50 or 100 Ω) to the input of a linear amplifier.

Linear amplifier :

The linear amplifier is used to amplify the pulses fed at its input from the preamplifier. A linear amplifier is one which has a constant output to input amplitude ratio over a large dynamic range, say from $>$ zero input pulse amplitude to a few volts depending on the voltage gain at which the amplifier is being operated. The output saturates at about 12V being safely linear up to 10V. If, for example, the gain is set at 100, the largest input pulse amplitude up to which the output will remain linear is $10/100 = 0.1$V.

Single channel analyzer (SCA) :

This instrument is now used to sort out and record the amplifier output pulses into slots according to their amplitudes. The amplitude distribution thus recorded is the γ-ray spectrum. It should be appreciated that a monoenergetic γ-ray produces a Compton continuum and a single peak corresponding to photoelectric absorption (total energy absorption). This results in pulses of different pulse height from the detector.

The Pulse height selection is done through two discreminators; Lower level Discriminator (LLD) and Upper level Discriminator (ULD). Pulses are allowed through the device only when the pulse height of the signal lies between the thresholds of the two discreminators, i.e. if the LLD is set at 1 V and ULD at 1.2 V, the SCA will alow pulses of height between 1-1.2 V.

SCA works in three modes, Integrated, Normal and Window modes. In integrated mode the ULD is redundent, i.e., pulse heights above the threshold of LLD are allowed through the device. In the Normal mode, the two discriminators work independently and thresholds can be adjusted in a independent way. In the Window mode the ULD is working as a fixed window over the LLD such that the threshold value for ULD is always LLD + WIN.

Our aim is to record the spectrum of the γ-rays. A spectrum is obtained by recording the frequency distribution of the pulse amplitude. As has been mentioned in the preceding paragraph, an SCA does the job of sorting and thus recording the distribution.

Scaler :

This instrument simply counts the number of pulses fed into its input and present this information on a visual display. In general, it accepts properly shaped signal either from a discriminator or a pulse shaper.

The Multichannel Pulse-Height Analyzer (MCA) :

The other major concept introduced in this experiment is the Multichannel Analyzer (MCA). It is responsible for measuring the height of each pulse delivered by the linear amplifier. Over the period of time the gamma rays are counted, the MCA sorts the pulses, according to pulse height, into a histogram that represents the spectrum of gamma-ray energies intercepted by the NaI(Tl) detector. The MCA is the central analyzer for many of the experiments in this series. Rather than including a complete description of its function in each experiment, the student is referred to the document entitled, For details see ortec manual for the Multichannel Pulse-Height Analyzer.

The MCA listed in the Equipment required for this experiment uses software in a supporting personal computer to operate the instrument and display the spectrum. The MCA connects to the computer via a USB cable. It is important to become familiar with the controls that are accessible through the software. You will need to know how to start/stop data acquisition, clear the contents of the memory, select the digital resolution, adjust the upper and lower

discriminator thresholds, set the preset live time, monitor the percent dead time, read the peak positions with the mouse pointer, set regions of interest, and calibrate the horizontal scale to read in keV (energy). One of the benefits of the MCA is the incorporation of a live time clock. This feature automatically corrects for dead time losses by measuring elapsed time only when the spectrometer is not busy processing a pulse.

1.3 Gamma-ray Spectrum

A typical γ-ray spectrum is shown in Fig. 1.5.

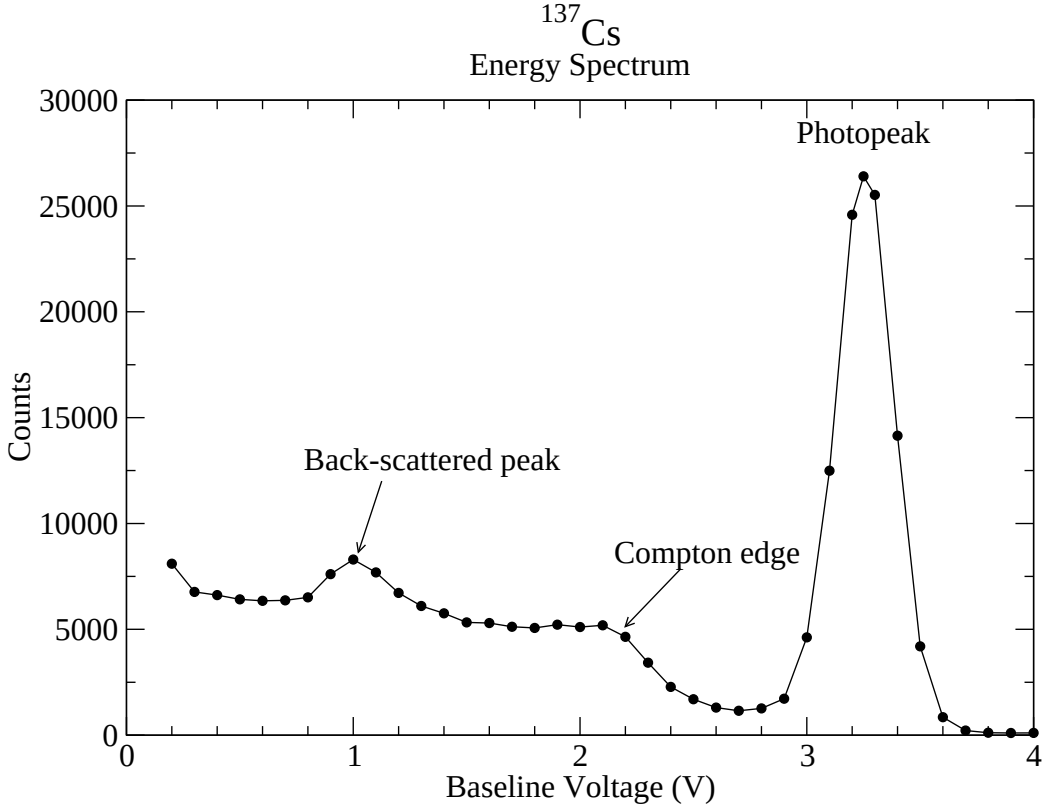

Figure 1.5: The spectrum of 662 keV γ-rays from ^{137}Cs measured with a scintillation Spectrometer.

The characteristic features of the above γ-ray spectrum are described below :

(i) The photopeak or the full-energy peak is related to those events which culminate in complete absorption of the incident γ-ray energy within the scintillator. This, as has been explained earlier, happens when (a) the incident γ-ray undergoes photoelectric absorption and (b) when concurrent with the absorption of the secondary electron after a Compton

interaction, the scattered secondary γ-ray is completely absorbed thus depositing its entire energy within the scintillator.

The pulse amplitudes corresponding to complete absorption of the incident γ-rays have a narrow distribution and therefore show up as a peak known as the photopeak or full-energy peak having a finite width. The peak point represents the γ-ray energy and the corresponding pulse amplitude is proportional to the incident γ-ray energy.

The pulses do not have a unique amplitude for a given absorbed energy for statistical reasons and appear as a gaussian distribution. Thus the photopeak is a gaussian rather than a very sharp peak.

To calibrate the γ-ray spectrometer we now record the spectra of a few γ-rays of known energies and determine from them the full-energy peak positions. A graph is then drawn with these γ-ray energies and the corresponding peak positions. A straight line through the points will give the calibration line for the spectrometer.

Note that this calibration will change if the PMT supply voltage or the amplifier gain is changed or both are changed.

To find any unknown γ-ray ennergy, its spectrum is first drawn and the full-energy peak position determined. The γ-ray energy corresponding to this position is read from the calibration curve.

(ii) To the left of this photopeak we have a more or less flat pulse amplitude distribution which is generated due to the continuous distribution in the energies of the secondary electrons originating in the scintillator from Compton scattering of the incident γ-rays. The Compton edge occurs at a point corresponding to $(E_e)_{max}$ (see equation 1.6).

(iii) The backscatter peak originates from secondary γ-rays scattered from surrounding materials (viz., the PMT housing, shield, walls, table, etc.) received by the scintillator. It is a broad peak, mostly corresponding to Compton secondaries scattered around θ=180^o from the surrounding materials, hence the name backscatter peak.

The common radioactive γ-ray sources which we use in laboratory work are given in the following table. Their decay schemes are given in Appendix.

From the table we find that except ^{54}Mn and ^{137}Cs, all other sources emit more than one $\gamma-$rays. As such we will get only one photopeak when we use a ^{54}Mn or a ^{137}Cs source, but more than one from the other sources. The scintillation γ-ray spectrum recorded with a ^{60}Co source is given below in Fig. 1.6 as an example.

In this spectrum two photopeaks, one corresponding to the 1173 keV and the other to 1332 keV γ-rays have appeared. Two Compton edges should have been seen but because of finite energy resolution, as well as for the fact that the Compton edge corresponding to the 1332 keV γ-ray falls near the left hand edge of the photopeak of the 1173 keV γ-ray, it remains hidden.

A γ-ray spectrum is characterized by the following :

Table 1.1: Details of the radioactive sources and their products. For details, see decay schemes of the sources at the end.

Source	Half-life	Gamma-ray Energy	Decay products
^{133}Ba	10.7 yrs.	81, 302, 356, 383	^{133}Cs
^{22}Na	2.6 Yrs	511 and 1274	^{22}Ne
^{137}Cs	30.7 Yrs	662	^{137}Ba
^{54}Mn	312 days	835	^{54}Cr
^{57}Co	271 days	14.4 and 122	^{57}Fe
^{60}Co	5.3 Yrs	1173 and 1332	^{60}Ni
^{152}Eu	13.5 Yrs	122, 245, 344, 779 964, 1085, 1112 and 1408	

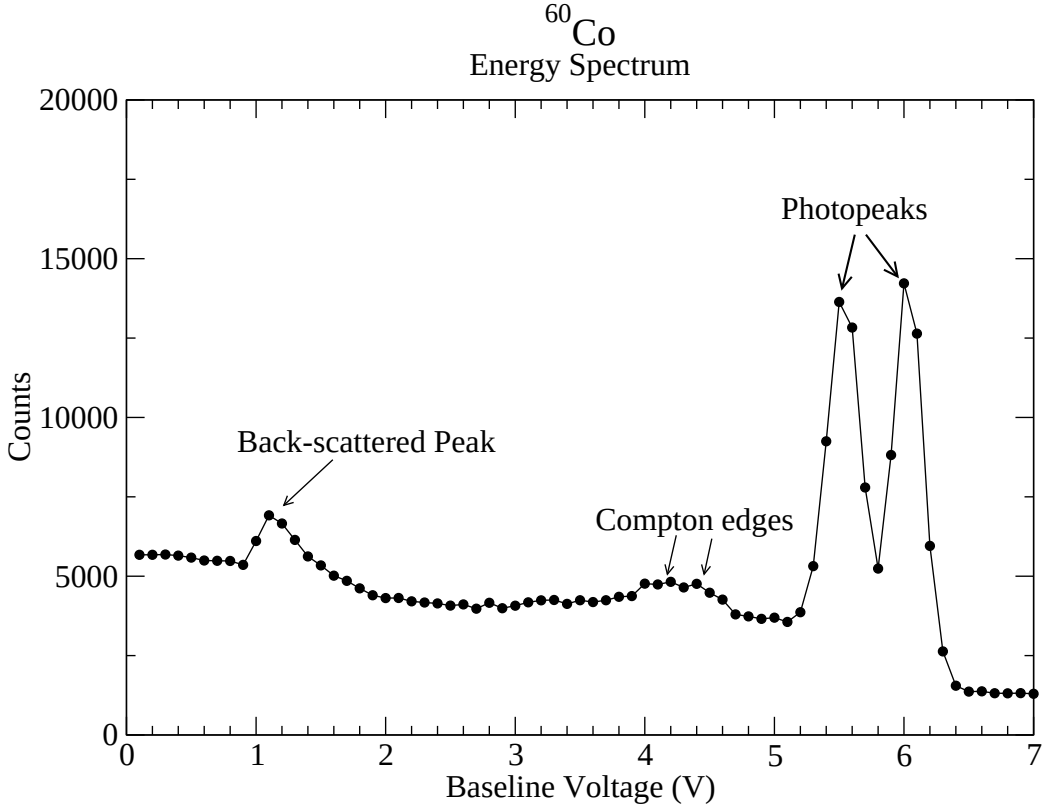

Figure 1.6: A typical γ-ray spectrum of a ^{60}Co source recorded with a NaI(Tl) based scintillation spectrometer.

1.3.1 Energy resolution :

Referring to the spectrum of a mono energetic γ-ray source, viz., ^{137}Cs we define :

$$\%\text{Resolution (FWHM)} = \frac{\Delta E}{E} \times 100\% = \frac{k \times 100\%}{\sqrt{E}} \tag{1.7}$$

Where E is the energy of the peak, ΔE is the FWHM of the peak in energy units, and k is a proportionality constant characteristic of the particular detector. Equation 1.7 indicates that the percent energy resolution of the NaI(Tl) detector improves as the gamma-ray energy increases.

1.3.2 Photofraction :

Photofraction which is determined from the measured spectrum is defined as :

$$\text{Photofraction} = \frac{\text{(area under the full energy peak)}}{\text{(area under the total spectrum)}} \tag{1.8}$$

Here, "area" represents total number of counts which can be obtained by summing the counts on Y-axis for a desired region of interest in the spectrum. It represents the fraction of the recorded γ-ray intensity that is completely absorbed in the scintillator. This is an important quantity which is needed for evaluation of relative intensities of γ-rays from a measured complex spectrum. When a spectrum is measured with a source that emits γ-rays of more than one energy the spectrum is found to consist more than one photopeak and a composite Compton continuum. The spectrum therefore assumes a complex appearance. Photofraction is energy dependent and decreases as incident γ-ray energy increases.

1.3.3 Detection efficiency :

Efficiency of a detector is limited due to its size and shape. Charged particles can be stopped easily in a detector of small active volume, whereas large volume of matter is required to stop uncharged particles like gamma rays and neutrons. Therefore, a detector with limited size does not have 100% efficiency.

Efficiency is classified into two parts; absolute and intrinsic. Absolute efficiency is defined as

$$\epsilon_{\text{abs}} = \frac{\text{Number of pulses recorded}}{\text{Number of radiation quanta emitted by the source}} \tag{1.9}$$

and depends upon source to detector geometry and shape and size of the detector. Intrinsic photopeak efficiency is defined as

$$\epsilon_{\text{int}} = \frac{\text{Number of pulses recorded}}{\text{Number of radiation quanta incident on detector}} \tag{1.10}$$

and no longer includes the solid angle subtended by the detector as an implicit factor. The two efficiencies are related by the expression

$$\epsilon_{\text{int}} = \epsilon_{\text{abs}} \times \frac{4\pi}{\Omega,} \tag{1.11}$$

where Ω is the solid angle subtended by the detector from the actual source position and is given by

$$\Omega = \frac{(\text{area of the detector } (\text{cm}^2))}{s^2}, \tag{1.12}$$

Here, s is the source-to-detector distance in cm. The radius of the NaI(Tl) detector is 2.54 cm.

1.4 EXPERIMENT 1 : Gamma-ray spectroscopy

1.4.1 Part-I : Energy calibration and measurement of energy of an Unknown Gamma Source

Purpose

Part-I :
(a) Energy calibration using the radioactive sources of known γ-ray energies and determination of the energy of the γ-ray from an unknown source.

(b) Determination of energy resolution and photofraction.

(c) Energy dependence of resolution and Photofraction.

Apparatus

1. NaI(Tl) Detector
2. High Voltage (H.V.) Power supply
3. NIM crate
4. Preamplifier
5. Amplifier
6. Single Channel Analyzer (SCA)
7. Timer/Counter

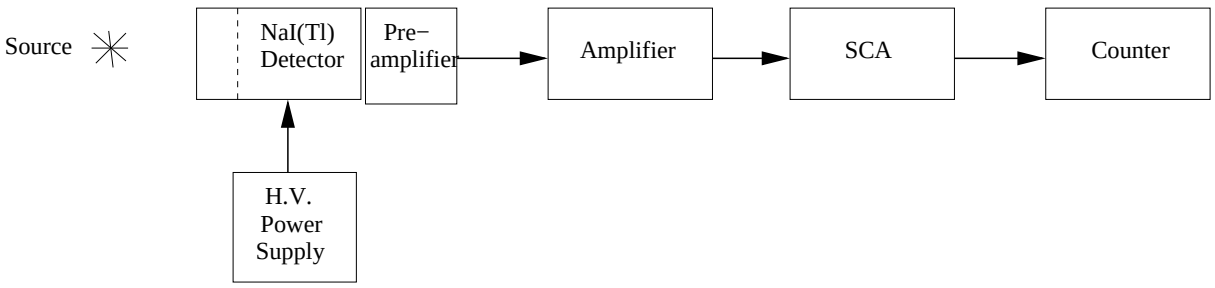

Figure 1.7: Schematic diagram of a SCA-based gamma-ray spectrometer

Methodology

Photograph of a typical gamma-ray spectrometer is shown in Fig. 1.8. The electronics box includes power supply for PMT and preamplifier, Amplifier, SCA and Timer/Counter. The preamplifier is at the base of detector and PMT combination. The dimensions of the NaI(Tl) crystal is 2" $\times$ 2".

Figure 1.8: A typical gamma-ray spectrometer based on NaI(Tl) detector. Preamplifier is included at the base of the detector. The box contains H.V. power supply for PMT and preamplifier, Amplifier, SCA and Counter.

1. Setup the γ-ray spectrometer and try to identify its components. Connect the cables as per the diagram given in Fig. 1.7.

2. Check if the switch of H.V. Unit is in OFF position. Switch on the power of NIM Bin.

3. Apply proper H.V. (as specified on the setup) slowly to the photomultiplier tube. Wait for 5 minutes for the apparatus to stabilize.

4. Place a radioactive source (say ^{137}Cs) at a suitable distance from the NaI(Tl) detector. Check the output of the preamplifier using a Digital Storage Oscilloscope (DSO). You should see signal pulses with varying pulse height. Connect the output of the preamplifier to the input of the amplifier.

5. Set the shaping time of the amplifier to 0.5 or 1 μs. In the setup from Para-electronics it is internally set to 0.5 μs. Check the output signal of the amplifier using DSO (see Fig. 1.9). Compare the polarity of the signal with that of preamplifier. Adjust the gain of the amplifier such that the signal pulse obtained for ^{137}Cs source (662 keV) is around 3 V. This will allow the spectrometer to measure γ-ray energy up to 2.2 MeV as the electronic modules can take a maximum of 10 V signal. If the required energy is more than the above limit, we need to reduce the gain of the amplifier accordingly.

6. Set the SCA in the "window" mode (WIN) and change the width of window to 0.1 V. It is adjusted through 10-turn pot. The maximum width of the window is 1 V for Nucleonix setup and 2 V for the setup from Para-electronics . Therefore, one complete turn of the pot corresponds to a Window of 0.1 V in Nucleonix setup and 0.2 V in the setup from Para-electronics.

7. Set the measurement time at 10 sec. Measure the pulse amplitude spectrum by taking

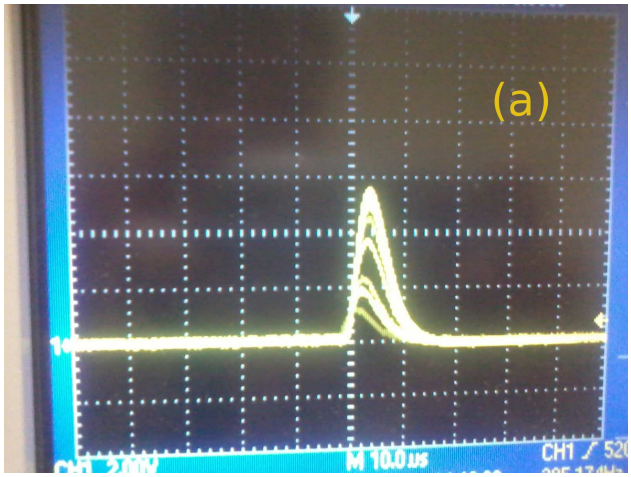

Figure 1.9: Amplifier output of a NaI(Tl) gamma ray spectrometer as seen on DSO screen

counts as a function of LLD bias settings in steps of 0.1 V. Do not change the gain of the amplifier till you have completed measurements for all the radioactive sources.

8. Keeping the SCA window fixed at the same value, record counts for ^{137}Cs, ^{133}Ba, ^{60}Co and ^{22}Na and ^{54}Mn sources one after another as a function of the LLD bias settings. Try to complete the measurements for all the sources on the same day in order to avoid a change in gain setting of the amplifier by other group of students. Record the following data and fill the Table 1.2.

   Source :
   Activity :
   Date of Manufacture :
   SCA Window :
   Preset time :

Table 1.2: Data for energy spectrum of ??? source

LLD	Counts	Background counts	Net counts	LLD	Counts	Background counts	Net counts
0.1				..			
0.2				..			
0.3				..			
0.4				..			
..				..			
..				..			
..				..			

9. Remove the radioactive source to a distance far from the detector. Take background count for the same time period as taken for the source. Take at least 10 background readings with different LLD values encompassing the whole range of spectrum. The

background counts should not depend upon LLD values. Calculate average of the background counts and subtract this from the counts measured for the sources.

10. Plot the data with net counts along y-axis and LLD bias along x-axis for each of the sources used. Mark out the peak positions and record the data in Table 1.3.

Table 1.3: Photopeak positions for the different radioactive sources used in the investigation

Source	Gamma-ray Energy	Peak Position
^{133}Ba		
^{22}Na		
^{137}Cs		
^{54}Mn		
^{60}Co		

11. Take one of the source as unknown and plot the energies corresponding to respective peak positions of the other sources as shown in Fig. 1.10 against LLD bias at which peaks have occurred.

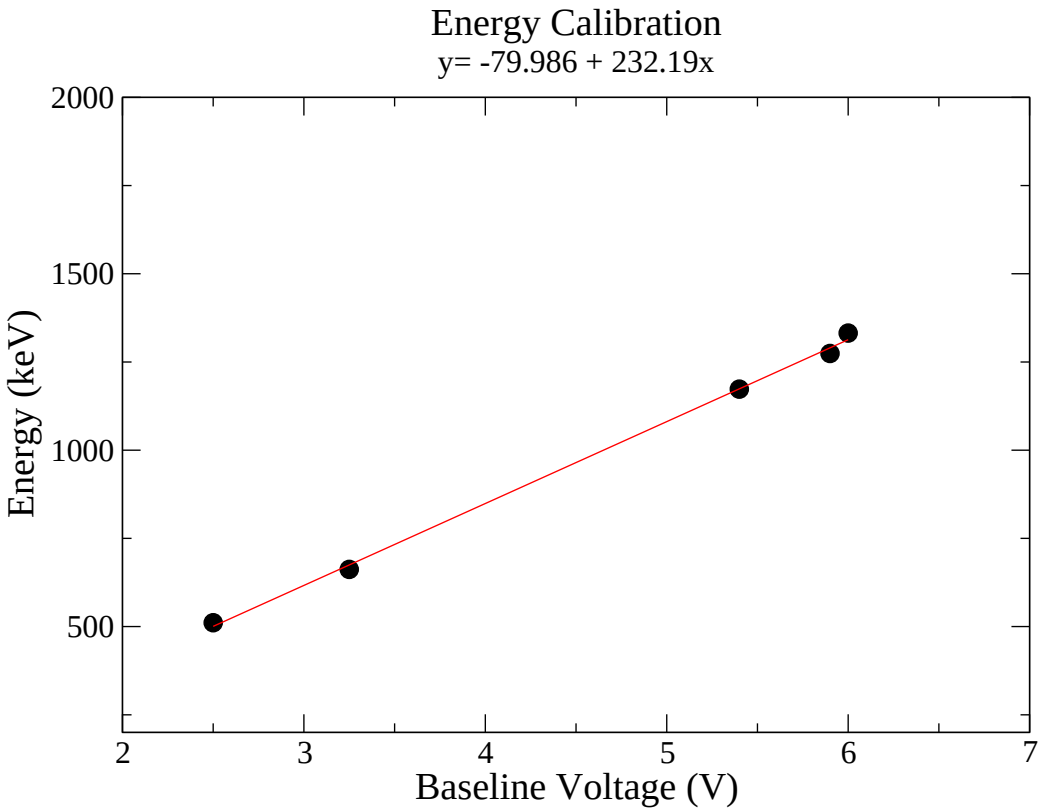

Figure 1.10: Calibration curve for the γ-ray spectrometer

The curve drawn through this points should be a straight line which may or may not pass through the origin. This is the calibration curve for your spectrometer for the given H.V. and the amplifier gain setting. Note down the calibration coefficients.

12. Find out unknown energy of the γ ray using the calibration coefficients.

13. From all the spectra you have drawn by now, find FWHM and energy resolution. Tabulate as follows :

Table 1.4: Data for energy resolution of the detector

Source	Gamma-ray energy	ΔE	R= ΔE/E

By assuming the energy dependence of resolution as a power of energy, i.e. R $\propto$ E^n, plot a graph of lnR vs lnE. Make a linear fit to the data and find the exponent from the slope. Try to justify the result.

Table 1.5: Data for photofraction of the detector

Source	Gamma-ray energy	Photopeak Ch. No.	Area under Photopeak (X) (X)	Area under total spectrum (Y) (Y)	Photofraction = X/Y

14. Determine photofraction for only those sources which emit only one γ-ray. These sources are ^{137}Cs, ^{54}Mn and ^{22}Na. Record your data in Table 1.5.

15. Assuming energy dependence of photofraction as P $\propto$ E^n, plot lnP vs lnE data. Make a linear fit to find the exponent from the slope. Try to justify the result.

1.4.2 Part-II Spectrum Analysis of ^{137}Cs and ^{60}Co.

Purpose

(a) To understand some of the features, i.e. Compton edge, Compton continuum and the backscatter peak, usually present in a pulse-height spectrum.

(b) To measure energy values for the Compton edge and the backscatter peak and its comparison with the values from Compton formula.

Relevant information

The photopeak is created when the gamma-ray photon interacts in the scintillator via the photoelectric effect. The photon encounters an orbital electron that is tightly bound to a nucleus. The entire energy of the photon is transferred to the electron, causing the electron to escape from the atom. The gamma-ray photon disappears in the process. As the photoelectron travels through the scintillator, it loses its energy by causing additional ionization. At the end of the process, the number of ionized atoms is proportional to the original energy of the photon. As the electrons re-fill the vacancies in the ionized atoms, visible light photons are generated. This is the source of the scintillation, wherein the number of visible photons is proportional to the original energy of the gamma-ray. Consequently, the event populates the photopeak in the spectrum. This peak is often called the full-energy peak, because a two-step interaction, a Compton scattering followed by a photoelectric interaction, also contributes a small number of events to the full-energy peak.

The Compton interaction is a pure, kinematic collision between a gamma-ray photon and what might be termed a free electron in the NaI(Tl) crystal. By this process, the incident gamma-ray photon gives up only part of its energy to the electron as it bounces off the free electron. The recoiling electron loses energy by causing ionization as it travels through the crystal. Thus the number of visible photons in the resulting scintillation is proportional to the recoil energy of the Compton electron. The amount of energy transferred from the gamma-ray photon to the recoiling electron depends on whether the collision is head-on or glancing. For a head-on collision, the gamma ray transfers the maximum allowable energy for the Compton interaction. Although it involves a photon and an electron, the interaction is similar to a billiard-ball collision. The reduced energy of the scattered gamma ray can be determined by solving the energy and momentum conservation equations for the collision. The solution for these equations in terms of the scattered gamma-ray energy can be written as

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)} \tag{1.13}$$

where $E_{\gamma'}$ is the energy of the scattered photon γ', θ is the scattering angle for the direction of γ' relative to the direction of the incident gamma-ray, γ, E_γ is the energy of the incident photon γ and $m_0 c^2$ is the rest mass energy of the electron and is equal to 511 keV.

For a head-on collision, the gamma-ray is scattered backwards along its initial trajectory, and $\theta = 180°$. For this condition, the backscattered gamma-ray energy becomes

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{2E_\gamma}{m_0 c^2}} \tag{1.14}$$

If this backscatter event happens in the detector, the maximum energy transferred to the recoiling electron will be

$$E_e = E_\gamma - E_{\gamma'} \tag{1.15}$$

Thus, the maximum energy that can be recorded in the spectrum for a gamma ray that interacts in the detector by Compton scattering is given by the equation 1.15. This defines the energy of the Compton edge in Figures 1.5 and 1.6. For an initial gamma-ray energy of 1 MeV, the above equations predict that the Compton edge will occur at ~ 0.80 MeV, and the energy of the backscattered gamma ray will be ~ 0.20 MeV.

Because the gamma-ray photon can be scattered through any angle from 0 to 180°, and the scattered photon can escape the detector, the energy deposited in the detector can vary from the maximum at the Compton edge through all values down to zero. This is the genesis of the Compton continuum in Figures 1.5 and 1.6. Note that there is a small, but finite, probability that the Compton scattered photon will be subsequently absorbed in the crystal by the photoelectric process. This two-step interaction will generate a pulse that falls in the full-energy peak.

The backscatter peak in Figures 1.5 and 1.6 is caused by Compton scattering from an entirely different location. Consider a gamma ray emitted by the radioactive source in a direction heading away from the detector. This gamma ray can encounter material in the neighborhood of the radioactive source and undergo Compton scattering. If the scattering angle is 180° the scattered gamma ray travels back towards the detector with an energy defined by equation 1.14. If this lower-energy gamma ray interacts in the scintillator by the photoelectric effect, it will contribute to a photopeak at the lower energy. Typically this backscatter peak will be of low intensity, if there is minimal material behind the radioactive source. Usually, the backscatter peak is rather broad, because of the range of directions that can contribute to the peak. For an initial gamma-ray energy of 1 MeV, equation 1.14 predicts that the backscatter peak will occur at 0.20 MeV.

Table 1.6: Determination of Compton edge and Backscattered peak

Source	Back-scattered peak (keV)	Using Compton formula (keV)	Compton edge edge (keV)	Using Compton formula (keV)

Methodology

1. From the energy spectrum plot for the ^{137}Cs source, find out the Compton edge and backscatter peak and determine the baseline voltages corresponding to these peaks.

2. Using calibration coefficients calculate their energies and fill the data in Table 1.6.

3. Calculate their energies using Compton formula and enter the values in Table 1.6.

4. Do the same for the ^{60}Co source. In this case you may not find two distinct Compton edges and backscatter peaks corresponding to two photon energies, 1332 and 1173. Instead, you will see a broad peak as both the peaks are not resolved.

If the backscatter peak is not very pronounced in your spectrum, it can be enhanced by accumulating a spectrum with a sheet of lead placed behind the source. Use a sheet from the absorber kit.

Does this calculation agree with your measured value?

1.5 EXPERIMENT 3 : Activity of a Gamma Emitter Using SCA (Relative Method)

1.5.1 Purpose

We already have discussed the procedures for determining γ-ray energy. Another unknown associated with the gamma-ray source is the activity of the source, which is usually measured in Curie (Ci); 1 Ci $=3.7 \times 10^{10}$ disintegrations/second. Most of the sources used in nuclear experiments have activities of the order of micro-Curie (μCi). The purpose of this experiment is to outline one procedure, called the relative method, by which the activity of a source can be determined.

In using the relative method, it is assumed that the unknown source has already been identified from its gamma-ray energies. For this example, assume that the source is ^{137}Cs. Then all that is necessary is to compare the activity of the unknown source to the activity of a standard ^{137}Cs source that will be supplied to you. For convenience, call the standard source S1 and the unknown source U1.

1.5.2 Procedure

1. Switch on the power of NIM Bin (Nucleonix)/Electronic Box (Paraelectronics). Apply specified High Voltage to the photomultiplier tube.

2. Using DSO set the gain of Amplifier so that signal pulse for the 662-keV γ ray from ^{137}Cs source is around 3 V.

Table 1.7: Data for the known source

Source	Present Activity	Range of LLDs for Photopeak	Counts	Average Counts ($\Sigma U1$)	Background Counts (Σb)

3. Place source S1 close to the face of the NaI(Tl) detector. Scan the range of LLD for the photopeak of ^{137}Cs source. Since you have set it around 3 V, the range should be between say 2.5-3.5 V. Make a table similar to Table 1.2 of experiment 1 to record your data.

4. Set the LLD of your setup at the value corresponding to the left part of the photopeak and set the Window size to include the photopeak.

5. Measure the counts for 2 mins. Take 5 sets of such readings and fill the Table 1.7. Take the average of all the counts and define this as $\Sigma S1$.

6. Remove source S1 and replace it with a source of unknown activity (U1), positioned exactly the same distance from the crystal as S1 was. Repeat steps 3-5 for the source U1 and fill the Table 1.8. Let us call the average count sum as $\Sigma U1$.

Table 1.8: Data for the unknown source

Source	Present Activity	Range of LLDs for Photopeak	Counts	Average Counts ($\Sigma U1$)	Background Counts (Σb)

7. Remove source U1 and accumulate background counts for the same period of live time that was used for the two sources.

1.5.3 Exercises

a. Solve the Activity of the unknown source U1 using the formula

$$A_{U1} = \frac{\Sigma_{U1} - \Sigma_b}{\Sigma_{S1} - \Sigma_b} A_{S1}, \tag{1.16}$$

where A_{S1} is the activity of the standard source, S1, and A_{U1} is the calculated activity of the unknown source, U1.

NOTE : Since the efficiency of the detector is only energy dependent, the standard and unknown sources do not have to be the same isotope. It is necessary only that their gamma energies be approximately the same ($\pm 10\%$) in order to get a fairly good estimate of the absolute gamma activity of the unknown. However, this relaxation of the comparison requirements may be invalid if one of the sources has a more complicated decay scheme, or if the gamma-ray decay fraction is different for the two isotopes.

b. Check the nominal activity listed on the label attached to the unknown source. How closely does your calculated value match that number?

c. Estimate the error involved in your result.

1.6 EXPERIMENT 4 : Activity measurement of a Gamma Emitter using absolute method

1.6.1 Apparatus

1. NaI(Tl) Detector
2. H.V. Power supply
3. NIM crate
4. Preamplifier
5. Amplifier
6. MCA

1.6.2 Part-I : Measurement of activity of a radioactive source

Purpose

The activity of the radioactive source used in Experiment 1.5 can be determined by the absolute method. The purpose of this experiment is to outline the procedure for this method. Here, the source to be measured will be called U1.

Relevant Information

To calculate absolute activity of the source we need to know how many decay per sec is obtained from the source. The radioactive source emits radiations in 4π direction which means that our detector of diameter d placed at a distance s will detect a fraction of the total number of disintegrations. Also, detectors are not 100% efficient, i.e. all the radiations incident on the detector are not detected by the detector due to their limited size and the type of material used as detector medium. Therefore, we need to determine efficiency of the detector which will be used for the measurement of activity.

Absolute photopeak efficiency of a detector can be measured by taking a ratio of the number of photons contributing to photopeak and the number of photons emitted by the source. In this experiment ^{152}Eu source of known activity will be used to determine efficiency of the detector.

1.6 EXPERIMENT 4 : Activity measurement of a Gamma Emitter using absolute method

Following expression can be used for the calculation of absolute photopeak efficiency

$$\epsilon_p = \frac{N_t}{A.t.f} \tag{1.17}$$

where N_t is the number of counts in photopeak measured in time t, A is the present activity of the source and f is the emission probability of the gamma ray as listed in Table 1.9.

One can also calculate intrinsic photopeak efficiency of a detector by considering geometrical factor related to detector size and source to detector distance, i.e. solid angle subtended by the detector at the source point (see section 1.3.3).

Table 1.9: Gamma Decay Fraction, (f), for some Common Isotopes

Source	Gamma energy (keV)	Decay fraction (f) (in %)
^{241}Am	59.5	35.9
^{133}Ba	80.99	34.1
	302.9	18.34
	356.0	62.0
	383.8	8.9
^{137}Cs	661.7	85.2
^{60}Co	1173.2	99.9
^{60}Co	1332.5	99.98
^{22}Na	511	178
^{22}Na	1274	99.94
^{54}Mn	835	99.98
^{152}Eu	121.8	28.7
	244.7	7.6
	344.3	26.6
	778.9	12.96
	964.1	14.7
	1085.9	10.2
	1112.0	13.7
	1408.0	20.87

Efficiency depends upon energy of the photon as higher energy photons can escape easily from the detector compared to low-energy photon. The energy dependence of efficiency can be expressed as :

$$\epsilon_p = a.E_\gamma^- b, \tag{1.18}$$

where a and b are constant parameters which can be determined from the fit of the efficiency values as a function of γ-ray energies. Usually, a plot for ϵ_p vs. E_γ is drawn in log-log scales

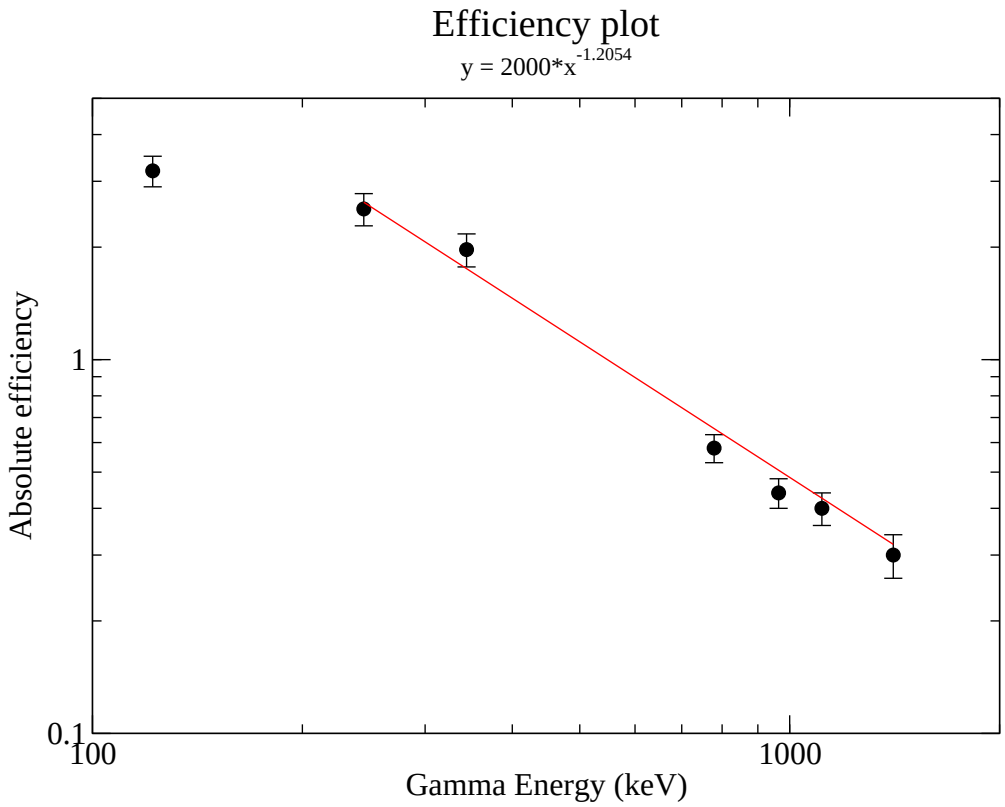

Figure 1.11: Absolute efficiency of a 2" × 2" NaI(Tl) detector using ^{152}Eu source

and the parameters a and b are obtained from a fit. A typical plot for absolute photopeak efficiency obtained for a NaI(Tl) detector of dimensions 2" × 2" is shown in Fig. 1.11.

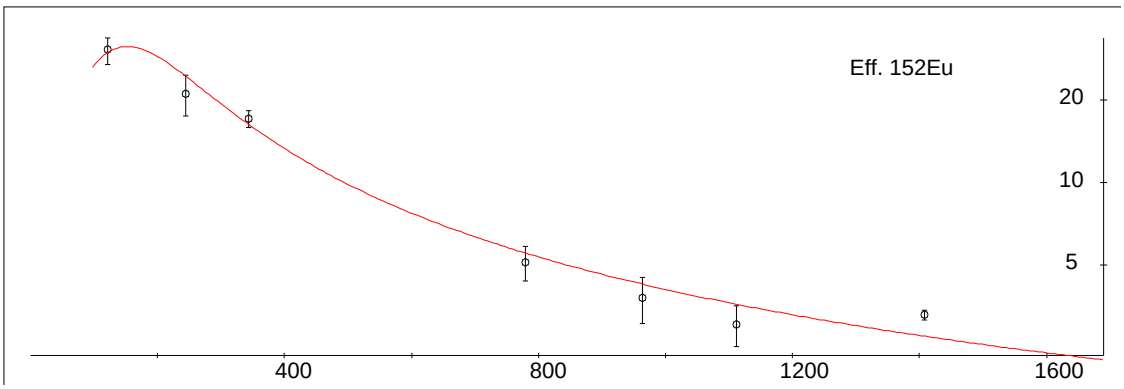

Figure 1.12: Relative efficiency of a 2" × 2" NaI(Tl) detector using ^{152}Eu source

Efficiency relative to 1408 keV γ ray of ^{152}Eu is shown in Fig. 1.12. A polynomial fit to the efficiency data is also displayed. A decrease in efficiency for $E_\gamma < 200$ keV is quite evident

from the figure.

The activity of the source can be calculated by

$$A_{U1} = \left(\frac{\Sigma U1 - \Sigma b}{t}\right) \frac{1}{\epsilon_p f} \tag{1.19}$$

Procedure

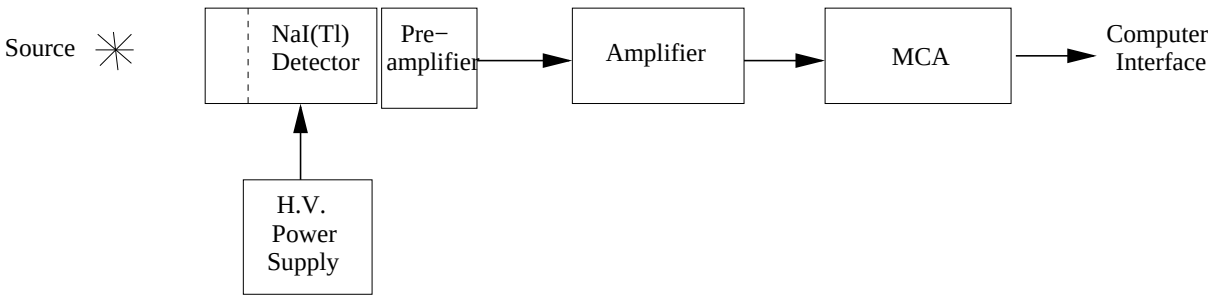

Figure 1.13: Schematic diagram of gamma-ray spectrometer using MCA

Make the connections as given in Fig. 1.13.

Determination of efficiency

A ^{152}Eu source will be used to determine efficiency of the detector. The advantage with the ^{152}Eu source is that it emits several transitions with γ-ray energies between 122 keV and 1408 keV (see Table 1.9).

1. Note down the distance between the detector and the source. This is required for the calculation of intrinsic photopeak efficiency.

2. Switch on the power of NIM Bin, Apply specified High Voltage to the photomultiplier tube. Wait for 5 minutes to get the system stabilize.

3. Using DSO set the gain of Amplifier so that signal pulse for the 662-keV γ ray from ^{137}Cs source is around 3 V. This will ensure that the spectrometer can measure energy up to 2 MeV (approximately three times of 662 keV). You can further increase the gain of amplifier so that the 1408 keV gamma ray from ^{152}Eu appears at the end of the MCA screen. This will spread the spectrum over the entire screen of MCA.

4. Place a ^{152}Eu source in front of the detector and accumulate spectrum for 20 mins so that sufficient count is available for weaker transitions. Note down the activity of the source and date of manufacture. The energy spectrum for the decay of ^{152}Eu source is shown in Fig 1.14.

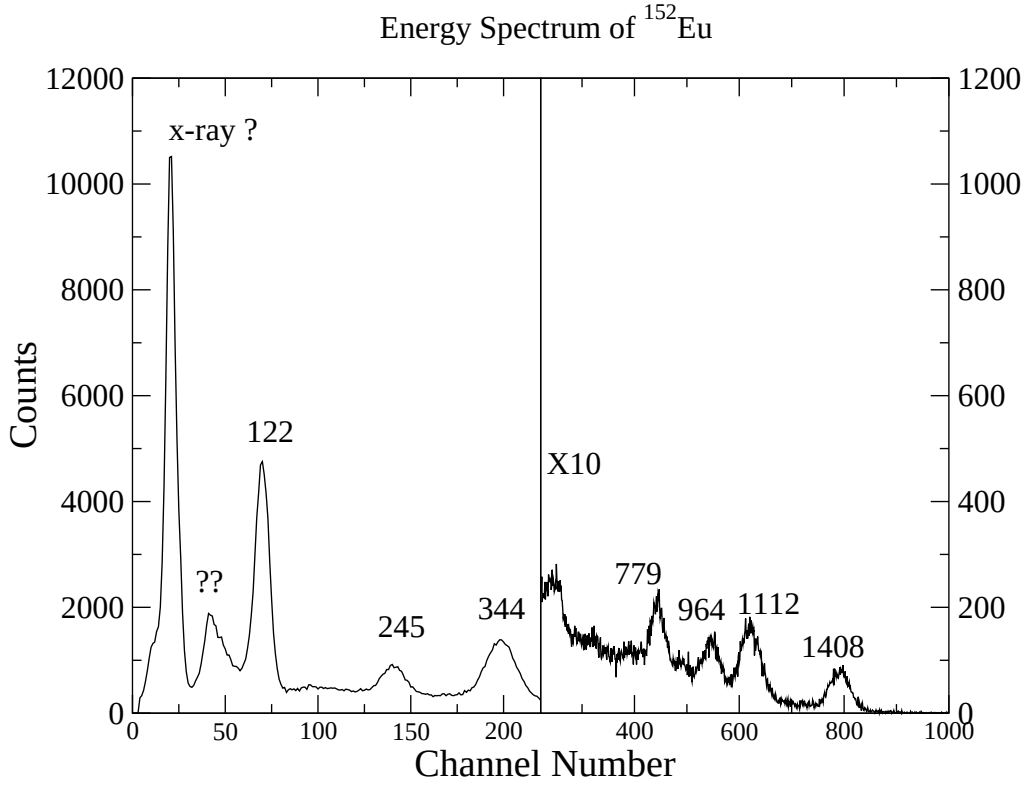

Figure 1.14: Energy spectrum for the decay of ^{152}Eu source. Higher energy spectrum is magnified by a factor 10.

You need to identify the photopeaks in Eu spectrum. The easiest way to achieve this is to look for the last peak (1408 keV) and then move towards lower energy side. You will find four close lying peaks as 1408, (1112,1085), 964 and 779 keV (see Fig. 1.14). The energy peaks (1112,1085) are not resolved by the detector. After a gap you will find 344, a small peak of 244 and a intense peak of 122 keV. X-ray peaks are visible at further lower energy.

5. Calculate centroids and area of the peaks using ROI tools of the spectrum analysis program and tabulate them in Table 1.10.

6. Calculate present activity of the source. Half-life of the ^{152}Eu source is 13.5 Years.

7. Calculate photopeak efficiency of the detector for each gamma ray energy.

8. Draw a calibration plot using the centroids (channel number) and energy of the peaks (given in Table 1.9). A calibration plot using ^{152}Eu source is shown in Fig. 1.15.

Exercise

Place a unknown source (say ^{137}Cs) and accumulate spectrum for 2 mins. Note down the centroid (channel number) of the photopeak and calculate its energy. Compare the calculated value with the standard 662 keV.

Table 1.10: Data for calibrating MCA and efficiency determination

Source	Gamma Energy	MCA channel No.	Integrated Area	Background Area	Net Area	Efficiency

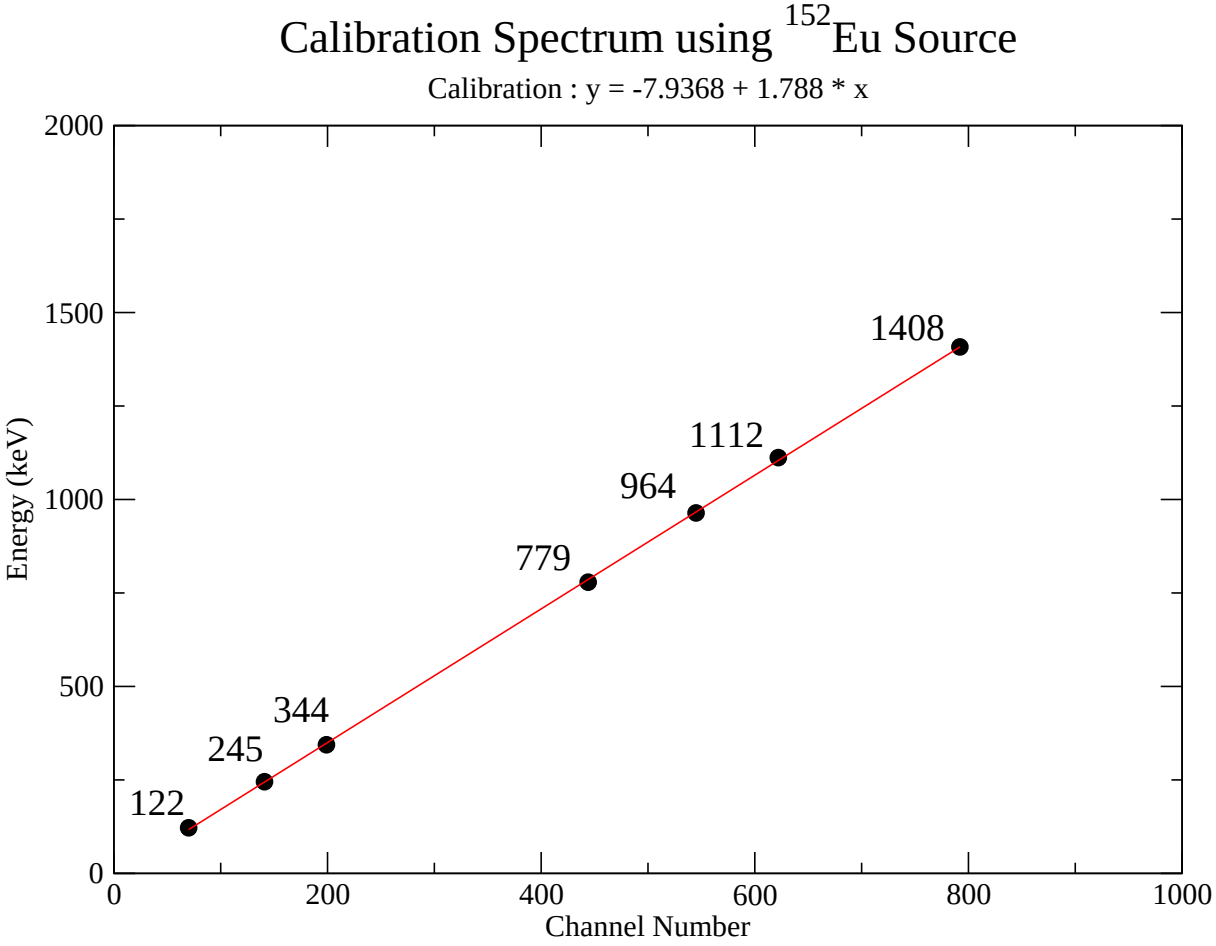

Figure 1.15: Typical calibration curve using Eu source

Activity Measurements

1. Place the unknown source on the source tray and accumulate spectrum for 10 mins.

2. Set a region of interest over the photopeak such that all the counts in the peak are included. Calculate its centroid and area of the peak.

Table 1.11: Data for determination of absolute activity of a source

Source	Centroid of the peak	Gamma energy (from calib. plot)	Integrated Area	Background Area	Net Area $\Sigma U1$	Efficiency (from eff. plot)

3. Use equation 1.19 to calculate the activity of U1. The unit of activity in equation 1.19 is disintegrations per second.

Exercises

a. Convert the activity in disintegrations per second from equation 1.19 to micro-Curie.

b. Check the nominal activity listed on the label affixed to the source. How closely does your measured activity match the nominal value listed?

c. What is the expected standard deviation in the measured activity due to the number of counts you recorded in the photopeak?

d. Calculate intrinsic efficiency of the detector using Eu source data. Your need to know the source to detector distance and the size of the detector (It is 2" diameter and 2" height).

e. Placing the source closer to the detector increases the counting rate. How does a smaller source-to-detector distance affect the accuracy of the measurement?

1.6.3 Part -II Sum Peak Analysis of ^{60}Co

Purpose

This experiment, will confirm that the sum peak for ^{60}Co has an energy of 2.507 MeV, and that the number of counts in the sum peak is given by Eq. 1.24.

Relevant Equations

There are two photons coming out of the decay of ^{60}Co. Their origin is documented by the decay scheme illustrated in Fig. 1.16.

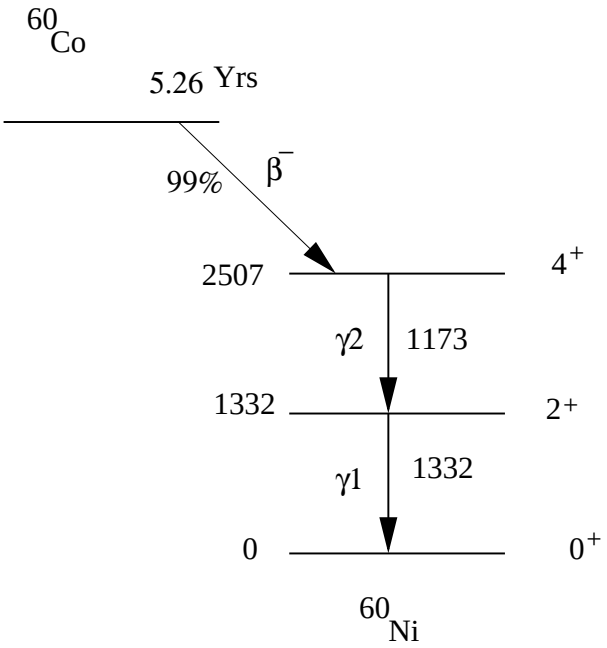

Figure 1.16: Decay scheme of ^{60}Co

Most of the time (>99%), the decay occurs by β^- emission to the 2.507 MeV excited state of ^{60}Ni. Subsequent decay to the ground state always occurs by a 1.173 MeV gamma-ray emission to the 1.332 MeV level, followed almost simultaneously by the 1.332 MeV gamma emission to the ground state. These two events are in coincidence, and have an angular correlation that deviates from an isotopic distribution by only 16%. For the purposes of this experiment we can assume that each of these gamma rays are isotropically distributed. In other words, if $\gamma 1$ departs in a particular direction, $\gamma 2$ can go in any direction that it wishes. The range of available angles (directions) for each of the two gamma-rays covers the 4π steradian of a sphere centered on the point source. There is a certain probability that $\gamma 2$

will go in the same direction as $\gamma 1$. If this occurs within the resolving time of the detector, the energies of $\gamma 1$ and $\gamma 2$ will be summed in the scintillator. Hence a sum peak will show up in the spectrum as seen in Fig 1.17.

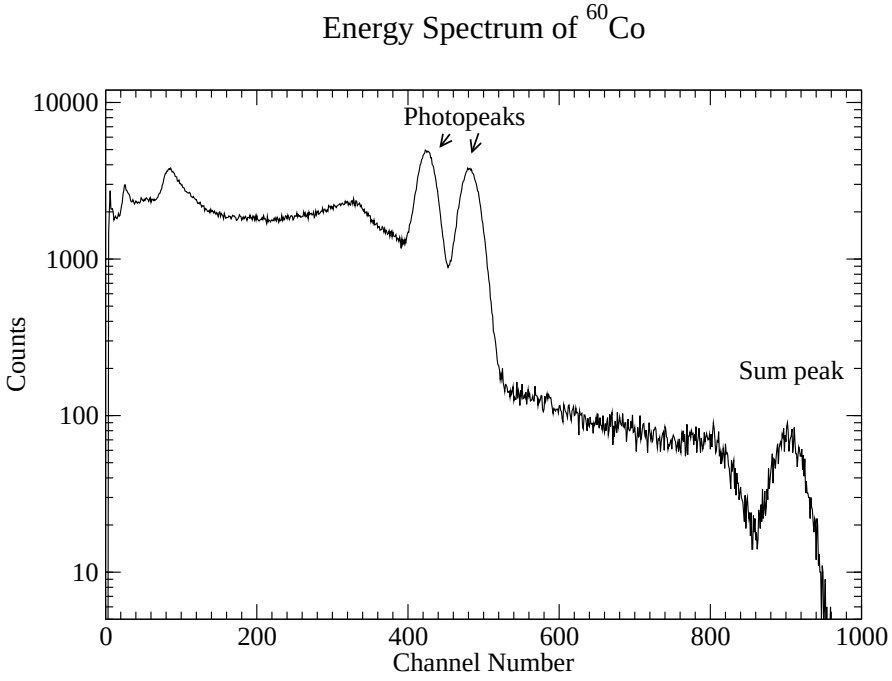

Figure 1.17: Energy spectrum for ^{60}Co decay. A sumpeak of the two photopeaks is also visible.

Using the definition used in previous experiment, we can write the number of counts, $\Sigma 1$, under the $\gamma 1$ peak as:

$$\Sigma_1 = \epsilon_1 G f_1 t A, \tag{1.20}$$

where A is the activity of the source, t is the measurement time, ϵ_1 is the intrinsic photopeak efficiency at the γ_1 energy, f_1 is the fraction of the total decays in which γ_1 is emitted and G is defined as :

$$G = \frac{(\text{area of the detector } (\text{cm}^2))}{4\pi s^2.} \tag{1.21}$$

Here, s is the source-to-detector distance in cm. The radius of the detector is 2.54 cm. The decay fractions for some of the commonly used sources are given in Table 1.9.

Similarly, the sum Σ_2 for γ_2 is given by:

$$\Sigma_2 = \epsilon_2 G f_2 t A, \tag{1.22}$$

Therefore, the number of counts in the sum peak, Σ_S, can be expressed as:

$$\Sigma_S = \epsilon_1 \epsilon_2 f_1 f_2 G^2 A t W(0^\circ), \tag{1.23}$$

where $W(0^\circ)$ is a term that accounts for the angular correlation function. For the case of ^{60}Co, $W(0^\circ) \simeq 1.0$, $f_1 \simeq f_2 \simeq 1.0$, and Eq. 1.23 can be approximately expressed as:

$$\Sigma_S \left(^{60}Co\right) = \epsilon_1 \epsilon_2 G^2 A t, \tag{1.24}$$

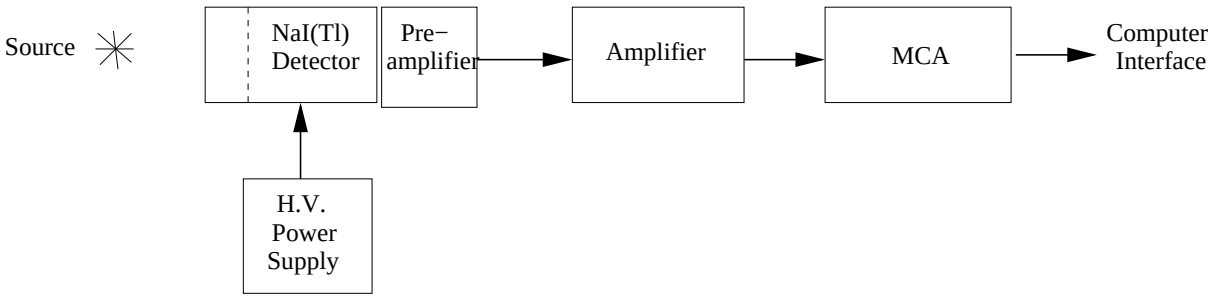

Figure 1.18: Schematic diagram of gamma-ray spectrometer

Procedure

1. Set up the electronics as shown in Fig. 1.18.

2. Adjust the gain of the amplifier so that the spectrometer can measure gamma energies up to 3 MeV. For a MCA with 1K channels, the 662 keV peak from ^{137}Cs source will be approximately at 225 channel.

Calibration

3. Place a ^{152}Eu source in front of the detector. Accumulate data for 10 mins and note down channel number of the prominent peaks in Table 1.12. You can also use sum peak of ^{22}Na (1785 keV) for calibration purpose.

4. Make a plot of energy vs channel number and determine calibration coefficients from a linear fit to the data.

5. You can use the intrinsic efficiency data from the part-I of this experiment,

Table 1.12: Data for calibrating gamma-ray spectrometer using ^{152}Eu source

Gamma Energy	Channel Number
122	
245	
344	
779	
964	
1408	

6. Find out photopeak efficiency of the detector at energies of the two gamma rays of ^{60}Co, i.e., at 1173 and 1332 keV.

7. Place a ^{60}Co source and count for a live time that is long enough to accumulate an area under the sum peak of approximately 1000 counts. Total count under the sum peak can be obtained by marking ROI throughout the peak.

1.6.4 Exercises

a. Verify that the energy of the sum peak is 2.507 MeV. Subtract the background from the sum peak and verify that its sum agrees with the prediction from Eq. 1.24. Note that either equation 1.20 or 1.22 will have to be used to measure the activity of the source according to the procedure in Experiment 1.19.

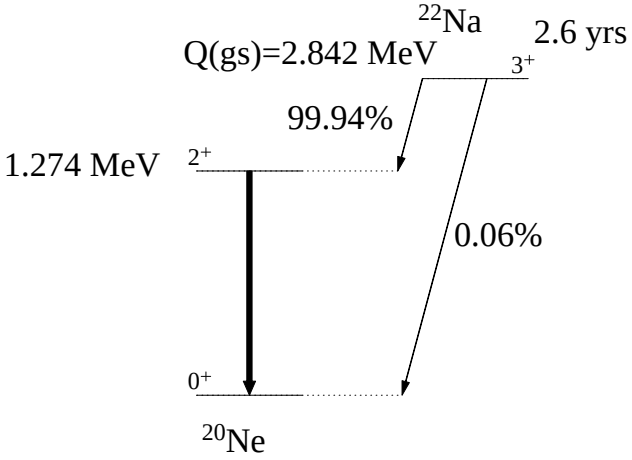

Figure 1.19: Decay scheme of ^{22}Na

b. Repeat this sum peak analysis for the ^{22}Na source. Fig. 1.19 shows the decay

scheme for ^{22}Na and a typical spectrum with the sum peak is shown in Fig. 1.20. How does the competition among β^+ and electron-capture decay to the 1.274-MeV excited state and β^+ decay to the ground state affect the calculation?

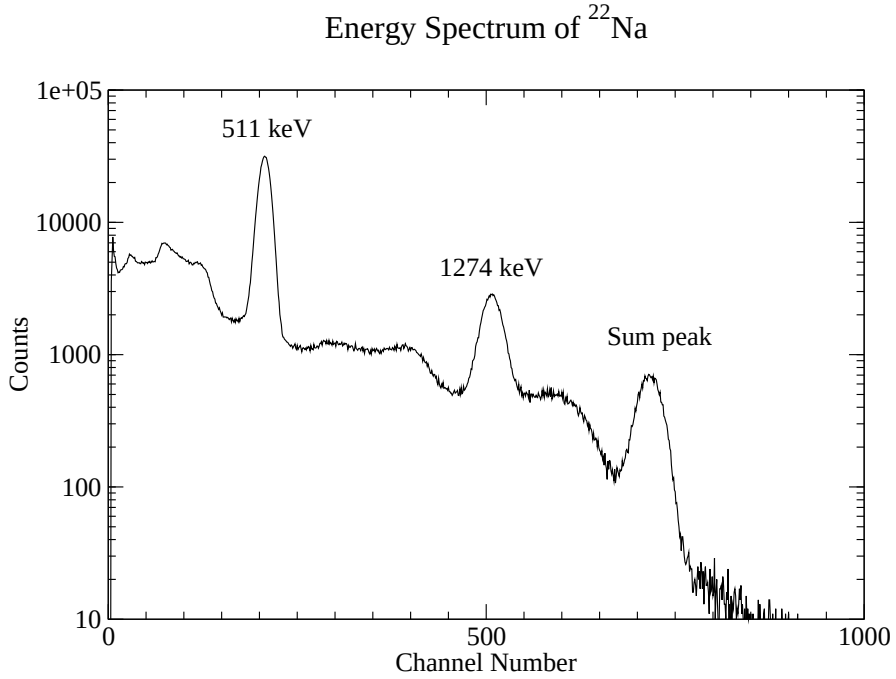

Figure 1.20: Energy spectrum for the decay of ^{22}Na. A sumpeak of the two photopeaks is also visible

Equations 1.20, 1.22, 1.23 and 1.24 provide an alternate way to determine the absolute activity of the ^{60}Co source. Divide equation 1.23 by equations 1.20 and 1.22 to yield:

$$\frac{\Sigma_S}{\Sigma_1 \Sigma_2} = \frac{W(0^\circ)}{A.t} \tag{1.25}$$

c. Measure the net counts in the 1173-keV, 1332-keV and 2505-keV peaks from ^{60}Co, and use equation 1.25 to calculate the source activity. Use the approximation, W$(0^\circ) \simeq 1.0$. How does the measured activity compare to the nominal activity on the source label? Note that you may need to account for the decay time constant and the elapsed time since the original activity certification.

d. Measure the activity of the ^{22}Na source by that same method. How does the competition among electron-capture and β^+ decay to the 1.274-MeV excited state and β^+ decay to the ground state affect the calculation? How does the measured activity compare to the nominal activity on the source label? Details of the decay radiation and branching ratio between EC/β^+ decay is shown in the data sheet.

Results:

Dataset #1:

Author: R.B. FIRESTONE Citation:Nuclear Data Sheets 106, 1 (2005)

Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus		
							Decay Scheme	ENSDF file
$^{22}_{11}$Na	0.0	3+	2.6027 y *10*	β^+	2842.3 *4*	$^{22}_{10}$Ne		

Beta+:

Energy (keV)	End-point energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
215.54 *21*	545.7 *4*	90.326 % *15*	0.19469 *19*
835.00 *23*	1820.3 *4*	0.056 % *14*	4.7E-4 *12*

Mean beta+ energy: 215.9 keV *3*, total beta+ intensity: 90.382 % *21*, mean beta+ dose: 0.19516 MeV/Bq-s *23*

Electrons:

Energy (keV)		Intensity (%)	Dose (MeV/Bq-s)
Auger K	0.82	8.74 % *3*	7.168E-5 *25*

Gamma and X-ray radiation:

Energy (keV)		Intensity (%)	Dose (MeV/Bq-s)
XR kα2	0.848	0.053 % *5*	4.5E-7 *5*
XR kα1	0.849	0.107 % *11*	9.0E-7 *9*
Annihil.	511.0	180.76 % *4*	
	1274.537 *7*	99.941 % *14*	1.27379 *18*

Figure 1.21: Data sheet for the decay of ^{22}Na.