1.0 INTRODUCTION

GAMMA- RAY INTERACTIONS

Of the various ways gamma rays can interact in matter, only three interaction mechanisms have any real significance in gamma-ray spectroscopy: photoelectric absorption, Compton scattering, and pair production. As detailed in the following sections (i, ii & iii), photoelectric absorption predominates for low-energy gamma rays (up to several hundred keV), pair production predominates for high-energy gamma rays (above 5-10 MeV), and Compton scattering is the most probable process over the range of energies between these extremes. The atomic number of the interaction medium has a strong influence on the relative probabilities of these three interactions, as can be seen from the formulae and plots given. The most striking of these variations involves the cross section for photoelectric absorption, which varies approximately as $Z^{4.5}$. As we shall see from the following discussion, because photoelectric absorption is the preferred mode of interaction, there is a premium on choosing detectors for gamma-ray spectroscopy from materials that incorporate elements with high atomic number.

(i) PHOTOELECTRIC ABSORPTION

Photoelectric absorption is an interaction in which the incident gamma-ray photon disappears. In its place, a photoelectron is produced from one of the electron shells of the absorber atom with a kinetic energy given by the incident photon energy ($h\nu$) minus the binding energy of the electron in its original shell (E_b). This process is shown in Fig.1. For typical gamma-ray energies, the photoelectron is most likely to emerge from the K shell, for which typical binding energies range from a few keV for low-Z materials to tens of keV for materials with higher atomic number. Conservation of momentum requires that the atom recoils in this process, but its recoil energy is very small and usually can be neglected.

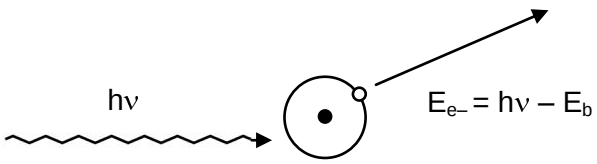

Fig. 1: Process of photoelectric absorption

The vacancy that is created in the electron shell as a result of the photoelectron emission is quickly filled by electron rearrangement. In the process, the binding energy is liberated either in the form of a characteristic X-ray or Auger electron. In iodine, a characteristic X-ray is emitted in about 88% of the cases. The auger electrons have extremely short range because of their low energy. The characteristic X-rays may travel some distance (typically a millimeter or less) before being reabsorbed through photoelectric interactions with less tightly bound electron shells of the absorber atoms. Although escape of these X-rays can at times be significant, for now, we assume that they are also fully absorbed in keeping with our simplified model.

Thus, the effect of photoelectric absorption is the liberation of a photoelectron, which carries off most of the gamma-ray energy, together with one or more low-energy electrons corresponding to absorption of the original binding energy of the photoelectron. If nothing escapes from the detector, then the sum of the kinetic energies of the electrons that are created must equal the original energy of the gamma-ray photon.

Photoelectric absorption is therefore an ideal process if one is interested in measuring the energy of the original gamma ray. The total electron kinetic energy equals the incident gamma-ray energy and will always be the same if mono-energetic gamma rays are involved. Under these conditions, the differential distribution of electron kinetic energy for a series of photoelectric absorption events would be a simple delta function as shown Fig.2. The single peak appears at a total electron energy corresponding to the energy of the incident gamma rays.

Fig. 2: Photopeak corresponding to photoelectron absorption events

(ii) COMPTON SCATTERING

The result of a Compton scattering interaction is the creation of a recoil electron and scattered gamma-ray photon, with the division of energy between the two dependent on the scattering angle. A sketch of the interaction is given in figures 3a & 3b.

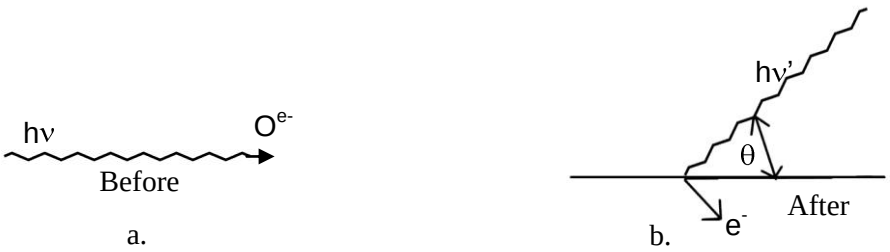

Fig. 3: Process of Compton scattering

The energy of the scattered gamma ray hν' in terms of its scattering angle θ is given by

$$h\nu' = \frac{h\nu}{1 + (h\nu/m_0c^2)(1 - \cos\theta)} \qquad (1)$$

where m_0c^2 is the rest mass energy of the electron (0.511 MeV). The kinetic energy of the recoil electron is therefore

$$E_{e^-} = h\nu - h\nu' = h\nu \left(\frac{(h\nu/m_0c^2)(1 - \cos\theta)}{1 + (h\nu/m_0c^2)(1 - \cos\theta)} \right) \qquad (2)$$

Two extreme cases can be identified:

- A grazing angle scattering or one in which $\theta \cong 0$. In this case, Eqs. (1) and (2) predict that $h\nu' \cong h\nu$ and Ee- $\cong 0$. In this extreme, the recoil Compton electron has very little energy and the scattered gamma ray has nearly the same energy as the incident gamma ray.
- A head-on collision in which $\theta=\pi$ In this extreme, the incident gamma ray is backscattered toward its direction of origin, whereas the electron recoils along the direction of incidence. This extreme represents the maximum energy that can be transferred to an electron in a single Compton interaction. Equations (1) and (2) yield for this case.

$$h\nu' \Big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/ m_0c^2} \tag{3}$$

$$E_{e-} \Big|_{\theta=\pi} = h\nu \left(\frac{2h\nu/ m_0c^2}{1 + 2h\nu/ m_0c^2} \right) \tag{4}$$

In normal circumstances, all scattering angles will occur in the detector. Therefore, a continuum of energies can be transferred to the electron, ranging from zero up to the maximum predicted by Eq. (4). Fig.4. shows the shape of the distribution of Compton recoil electrons predicted by the Klein-Nishina cross section for several different values of the incident gamma-ray energy. For any one specific gamma-ray energy, the electron energy distribution has the general shape shown in the sketch below.

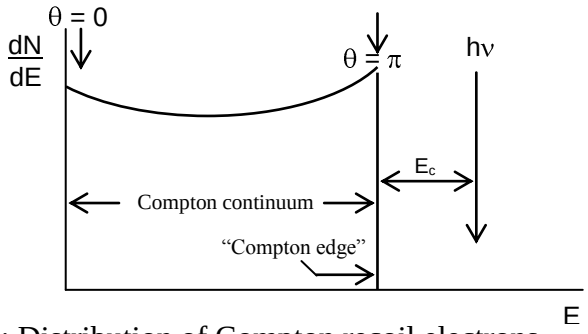

Fig. 4 : Distribution of Compton recoil electrons

The gap between the maximum Compton recoil electron energy and the incident gamma-ray energy is given by

$$E_c = h\nu - E_{e-} \Big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu / m_0c^2} \tag{5}$$

In the limit that the incident gamma-ray energy is large, or $h\nu >> m_0c^2/2$, this energy difference tends toward a constant value given by

$$Ec \cong \frac{m_0c^2}{2} = 0.256 \text{ MeV} \tag{6}$$

The preceding analysis is based on the assumption that Compton scattering involves electrons that are initially free or unbound. In actual detector materials, the binding energy of the electron prior to the scattering process can have a measurable effect on the shape of the Compton continuum. These effects will be particularly noticeable for low incident gamma-ray energy. They involve a rounding-off of the rise in the continuum near its upper extreme and the introduction of a finite slope to the abrupt drop of the Compton edge. These effects are often masked by the finite energy resolution of the detector but can be evident in the spectra from detectors with high inherent resolution. The finite momentum of orbital electrons also causes gamma-ray photons that are scattered at a fixed angle from a mono-energetic source to have a narrow distribution in their energy (the "Doppler spread"), as contrasted with a single energy predicted by Eq. (1)

(iii) PAIR PRODUCTION

The third significant gamma-ray interaction is pair production. The process occurs in the intense electric field near the protons in the nuclei of the absorbing material and corresponds to the creation of an electron-positron pair at the point of complete disappearance of the incident gamma-ray photon. Because energy of $2m_0c^2$ is required to create the electron-positron pair, minimum gamma-ray energy of 1.02 MeV is required to make the process energetically possible. If the incident gamma-ray energy exceeds this value, the excess energy appears in the form of kinetic energy shared by the electron-positron pair. Therefore, the process consists of converting the incident gamma-ray photon into electron and positron kinetic energies, which total

$$E_{e-} + E_{e+} = h\nu - 2m_0c^2 \qquad (7)$$

For typical energies, both the electron and positron travel a few millimeters at most before losing all their kinetic energy to the absorbing medium. A plot of the total (electron + positron) charged particle kinetic energy created by the incident gamma ray is again a simple delta function, but it is now located $2m_0c^2$ below the incident gamma-ray energy, as illustrated in Fig. 5. In our simple model, this amount of energy will be deposited each time a pair production interaction occurs within the detector.

This energy corresponds to the position of the double escape peak in actual gamma-ray pulse height spectra.

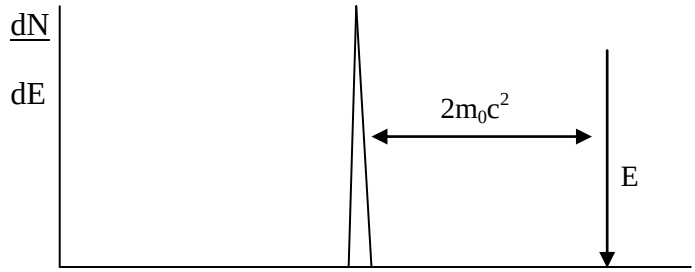

Fig. 5: Peak corresponding to the total kinetic energy of the pair (electron+ positron) created during pair production process

The pair production process is complicated by the fact that the positron is not a stable particle. Once its kinetic energy becomes very low (comparable to the thermal energy of normal electrons in the absorbing material), the positron will annihilate or combine with a normal electron in the absorbing medium. At this point both disappear, and they are replaced by two annihilation photons of energy m_0c^2 (0.511 MeV) each. The time required for the positron to slow down and annihilate is small, so that the annihilation radiation appears in virtual coincidence with the original pair production interaction.

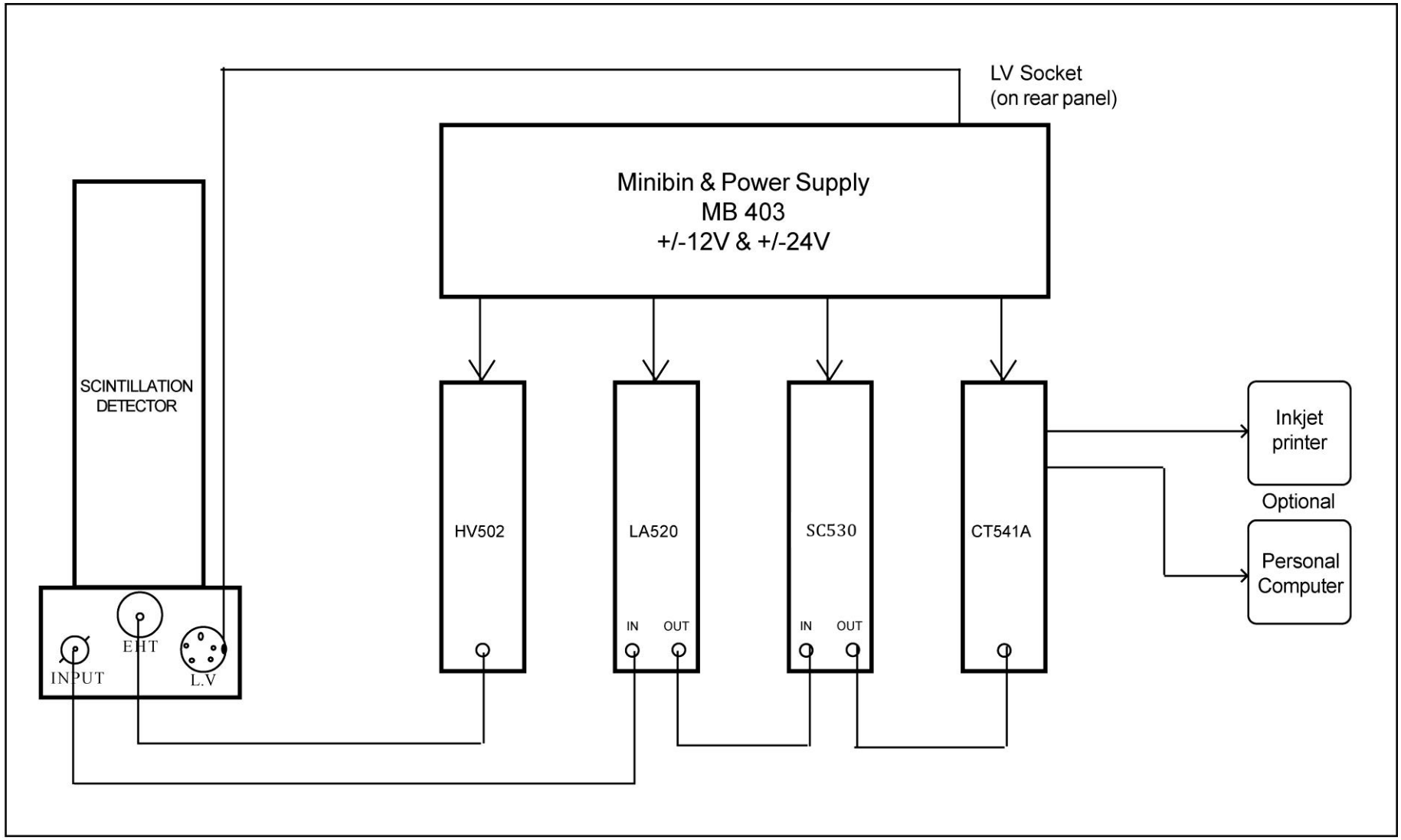

Fig. 10: Block diagram of MINIM based Gamma Ray Spectrometer

2.0B. 2 BLOCK DIAGRAM DESCRIPTION (GR611M)

Refer to the block diagram, given in Fig.10. It consists of Scintillation Detector SD 151 or its equivalent, High Voltage unit HV 502, Linear Amplifier LA 520, Single Channel Analyzer SC 530 & Counter Timer CT 541A. All these modules are housed inside Minibin and Power Supply Type: MB403. Minibin and Power Supply provides low voltage supplies +/- 12V & +/- 24V to these modules. The Scintillation Detector is coupled to the main electronics unit. The assembly of scintillation detector and main electronic unit is called as Gamma Ray Spectrometer. This unit is essentially used for studying the Gamma Ray Spectra of Gamma isotopes.

SCINTILLATION DETECTOR

It consists of a Sodium Iodide crystal optically coupled to a photomultiplier. It has got three connectors, UHF, circular I/O or Minihex & BNC connector. The high voltage (operating voltage) required for the detector is fed from the HV module and is connected to the UHF connector. Minihex / 5 pin I/O connector is used to feed in the low voltages to pre-amplifier from Minibin power supply. The output of the detector is given to the linear amplifier input through a BNC cable. Scintillation detector of NUCLEONIX make or its equivalent can be connected to NUCLEONIX Gamma Ray Spectrometer electronic unit.

HIGH VOLTAGE UNIT (HV 502)

It is basically a two-bit module which generates 0 to 2000 V. It has got HV out (UHF connector) and the ten turn dial / helipot for changing the EHT continuously from 0 to 2000 V. It can deliver up to a maximum current of 1mA. Line & Load regulation is better than 0.001%. HV indication is provided on a three and half DPM.

Output from the HV 502 is fed to Scintillation Detector through a UHF cable for biasing of the detector.

Typically detector bias can be from 600V to 800V.

LINEAR AMPLIFIER (LA520)

Linear Amplifier LA 520 uses solid-state/Integrated circuits extensively in its design. Featuring excellent non-overload characteristics, a high gain, low equivalent input noise and flexibility of pulse shaping, LA 520 is ideally suited for use with Nuclear Counting Systems such as Gamma Ray Spectrometers and other similar units.

SINGLE CHANNEL ANALYSER (SC530)

Single Channel Analyzer receives the input from Linear Amplifier LA 520 output. SC 530 essentially scans the input pulses for differential pulse height analysis and gives out TTL output pulses for the windowed pulses. Output from SC 530 is fed to Counter Timer CT 541A for counting purpose. SC530 can be operated in three modes.

COUNTER TIMER (CT541A)

Counter timer CT 541A is a two-bit module. It can count the events for a preset time. Elapsed time and counts are indicated on the 8x2 LCD displays. Input can accept input pulses of POS or NEG polarity of unipolar / bipolar or TTL pulse.

Counter timer CT 541A has keypad buttons for operation and is designed around a microcontroller. It can acquire data in three modes of operation namely

a. Preset Scaler b. CPS c. CPM.

Readings up to 1000 can be stored and recalled back onto the display. Further unit has built-in printer port for direct data printing and serial port for downloading of readings to PC.

5.0 LIST OF EXPERIMENTS USING GAMMA RAY SPECTROMETER

5.1 STUDY OF ENERGY RESOLUTION CHARACTERISTICS OF A SCINTILLATION SPECTROMETER AS A FUNCTION OF APPLIED HIGH VOLTAGE

PURPOSE : To Study the dependence of Energy Resolution on the Applied High Voltage and to determine the best Operating Voltage for the Scintillation Detector.

THEORY: Resolution of a scintillation spectrometer is specified in percentage and defined as the 'full-width at half maximum of the photopeak spectrum. Usually, a Cs-137 source is selected as the reference and the resolution is specified with respect to its monoenergetic gammas of energy 662 keV. Finite resolution for the spectrometer is a result of the various statistical processes involved in the detection. Thus the energy expenditure in the scintillator results in the number of photons liberated which fluctuates. Likewise, the number of photons reaching the cathode, the number of photoelectrons liberated and the multiplication at the dynodes are all fluctuating quantities. Assuming Gaussian statistics to hold for all fluctuating quantities, the resultant characteristics distribution can be worked out and the full width of the distribution is the uncertainty in the determination of the total number under the distribution. The total number of electrons collected at the anode of the photomultiplier is proportional to the energy expended in the scintillator. Thus the fractional spread (or resolution) decreases with increasing energy. The over-all multiplications (gain) in the photomultiplier being dependent on the inter-dynode potential, the resolution is expected to vary with the inter-dynode potential (or the applied high voltage). The resolution should, however, be independent of gain of the linear amplifier.

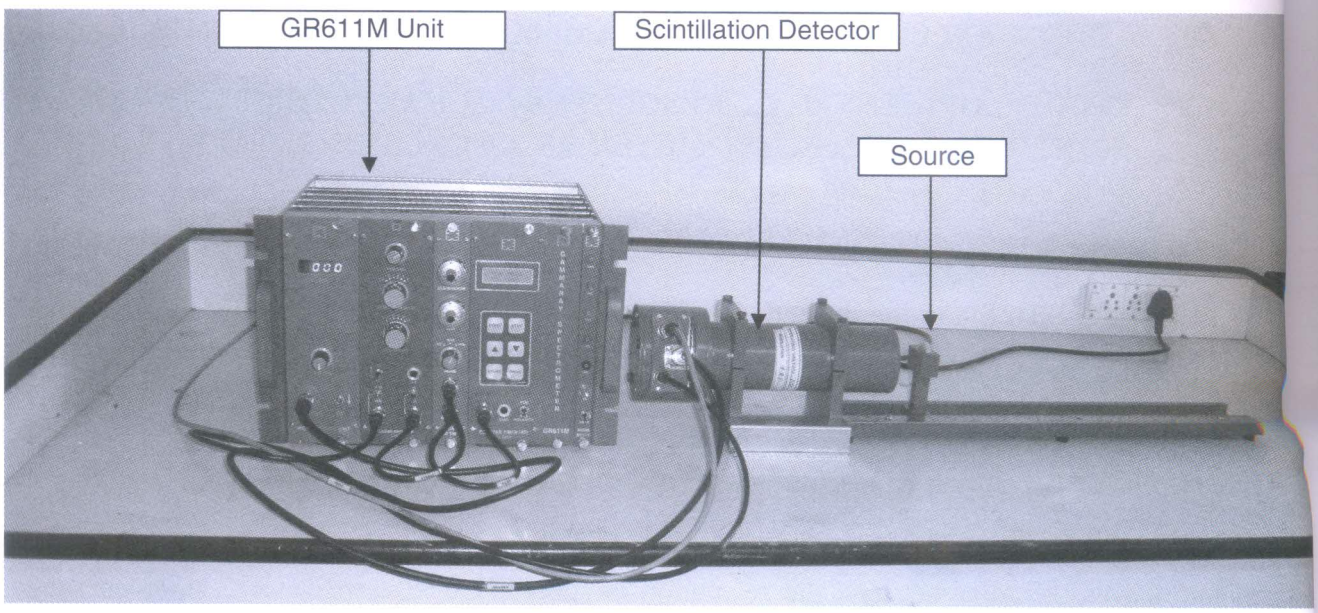

Fig. 15 : Experimental setup with GR611M unit

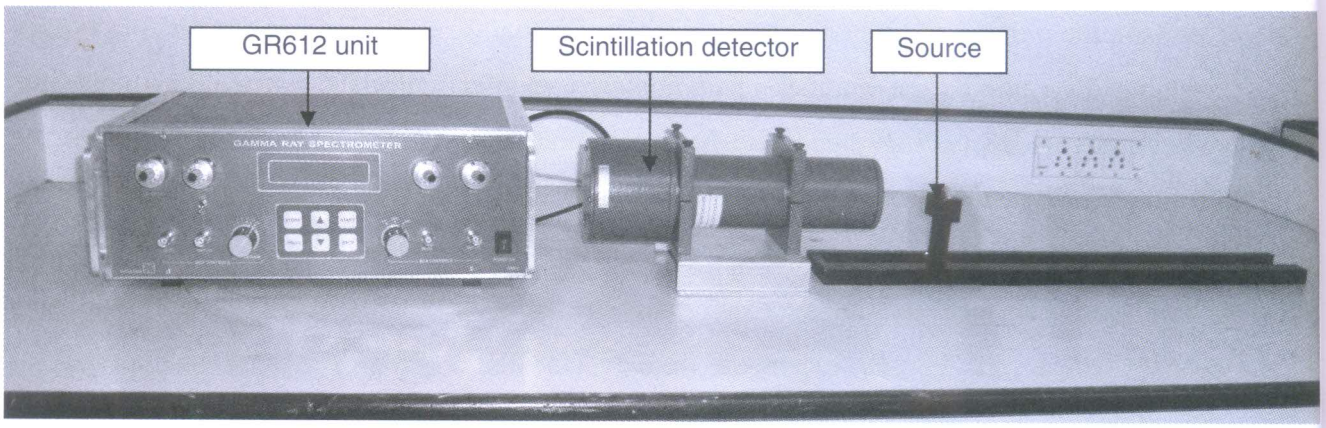

Fig. 16 : Experimental setup with GR612 unit

PROCEDURE:

- Make system interconnections & default settings for either GR611M or 612 model.
- Place a Cs-137 radioactive standard source at a distance of 4 to 5 cm from the face of the scintillation detector.
- Set controls on the instrument to default settings as described in the earlier section.
- Set HV on the instrument to **650 Volts.** .
- Now adjust amplifier gain such that the photopeak pertaining to 662 keV energy of Cs-137 is approx. 3.0V (amplitude). [Described in previous section also refer to Fig. 13. in the previous pages]

- This we do usually with the idea of using the GRS and to study the gamma energies in the range of 100 keV to 2.0 MeV over which NaI scintillation detectors are used and to cover within 8V /10V linear range of the amplifier .
- Now set the single channel analyzer MODE switch controls in GRS to WINDOW (WIN) position, LLD/Base line dial to 0.0V and ULD/window dial to 1.0 turns (equal to 100mV window)
- Operate the GRS in preset time mode and select the preset time so as to get at least 5000 counts in the peak channel. Normally a preset time of 30/60 sec. is selected.
- Take reading with LLD (Base line) starting from 2.4V in steps of 0.1(100mV) till you cross Cs-137 photo-peak i.e., may be up to 3.5/4.0V.
- Tabulate the readings and plot a graph of **count rate** Vs **LLD / Base line** on a graph sheet or in EXCEL in PC as shown in the Fig. 17.
- Now extrapolate Cs-137 photo-peak to mark peak channel No (LLD point) which is at 2.9 (LLD setting) (it can also be noticed from the data of Table-1). To simplify the experiment for the student we are taking LLD in steps of 0.1 only. To get more precise peak position, one can take additionally data counts at 2.85V and also at 2.95V to ascertain correct peak location if needed.

Repeat the experiment with different voltages viz.,650,700,750,800 and 850 Volts. Adjust the gain of the linear amplifier so as to get the CS-137 photo peak around 3.0 volts for each applied voltage. Tabulate the data. Calculate the resolution in each case. Plot the resolution as a function of applied voltage.

It can be observed that the resolution varies with the applied voltage, and best resolution is obtained for a particular applied voltage. That particular voltage is to be fixed as the operating voltage for the scintillation detector being used.

DATA, ANALYSIS & COMPUTATIONS

OPERATING VOLTAGE: 650V

Table -1	
Base Line (V)	Counts
3.4	65
3.3	73
3.2	108
3.1	785
3	4702
2.9	7208
2.8	4369
2.7	1669
2.6	723
2.5	460
2.4	415

Table - 2
Operating Voltage : 650V
FWHM = 0.24V
Max. Height at 2.9V
Resolution : 0.24/2.9 = 8.3%

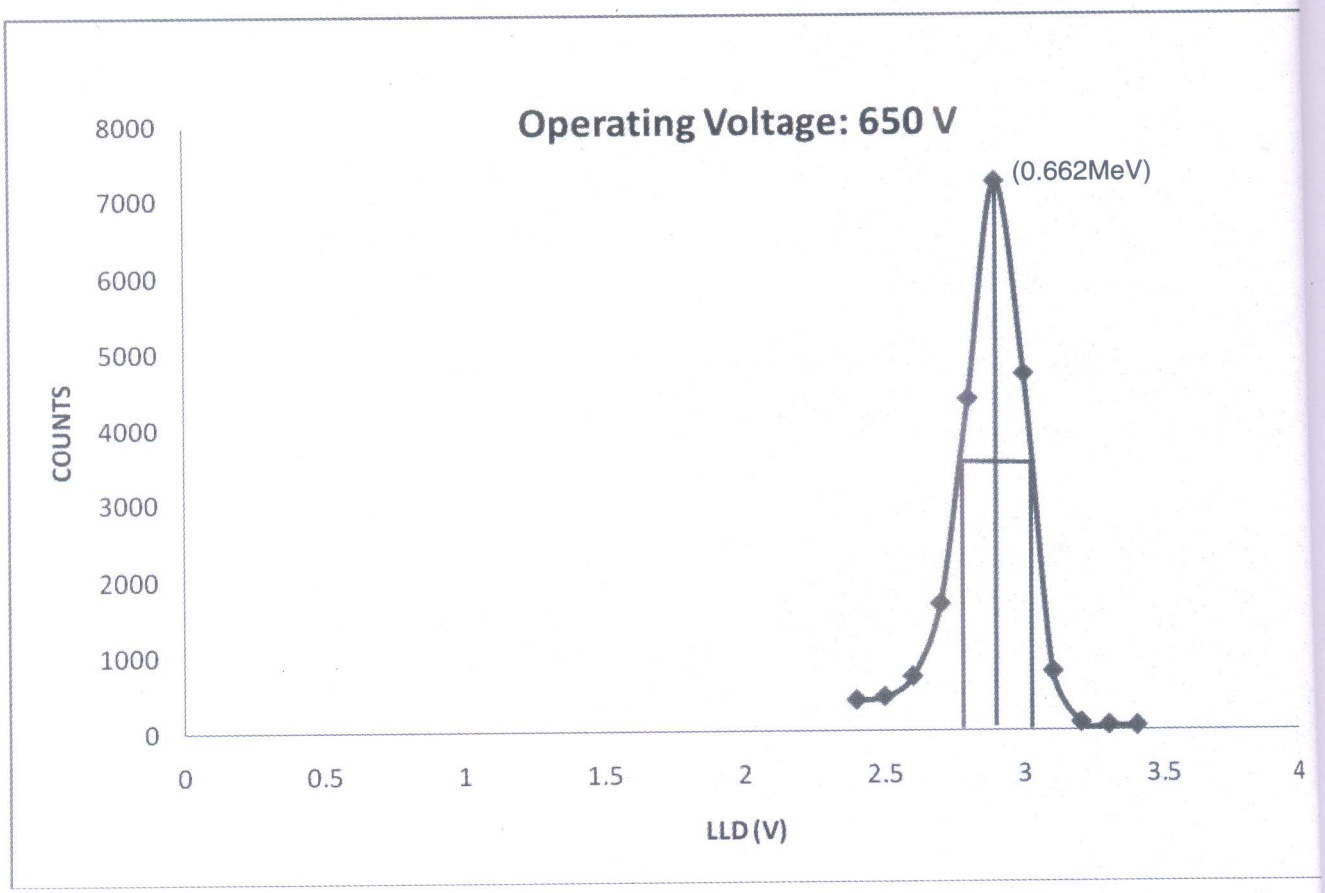

Fig. 17 : Cs-137 photopeak spectrum at 650V

OPERATING VOLTAGE: 700 V:

Table -3	
Base Line (V)	Counts
3.4	75
3.3	93
3.2	169
3.1	785
3	6389
2.9	6722
2.8	2896
2.7	1154
2.6	611
2.5	392
2.4	387

Table - 4
Operating Voltage : 700V
FWHM = 0.24V
Max. Height at 2.95V
Resolution : 0.24/2.95 = 8.1%

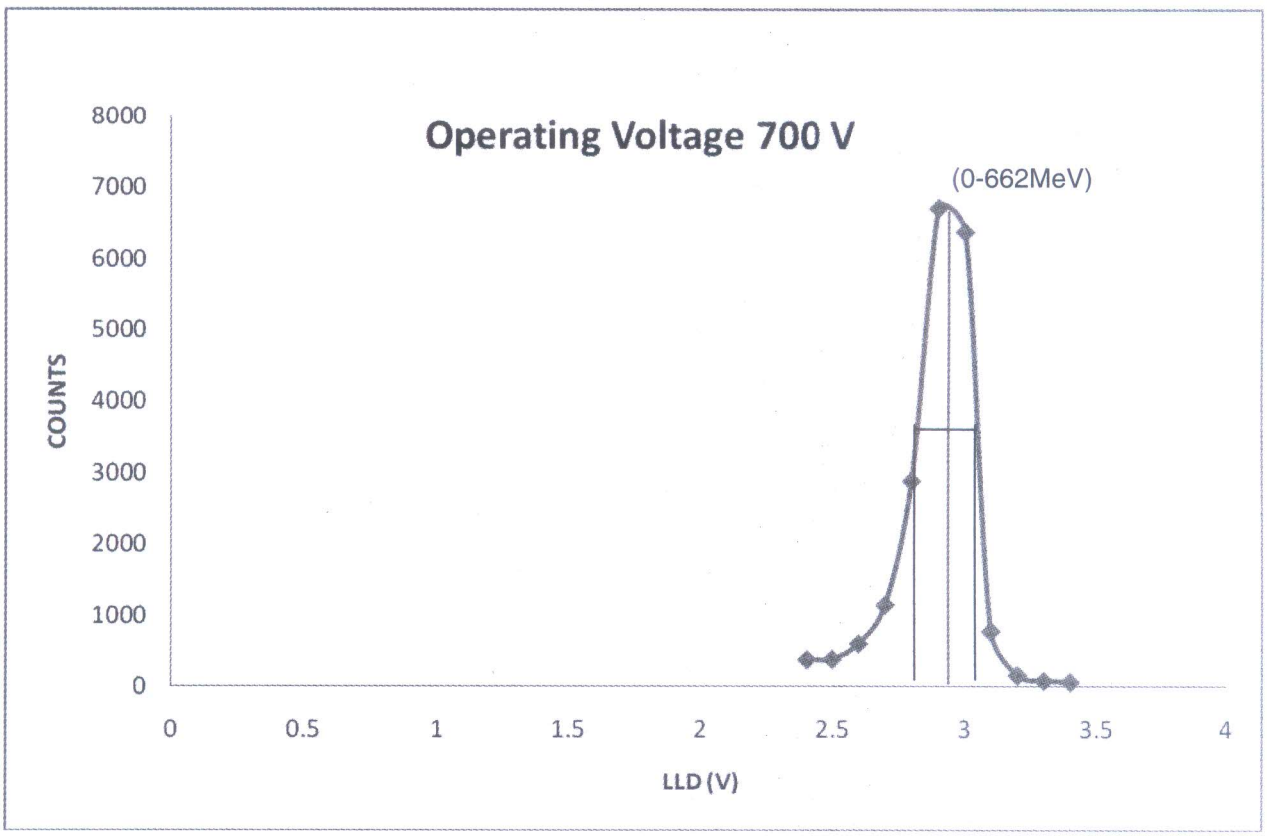

Fig. 18 : Cs-137 photopeak spectrum at 700V

OPERATING VOLTAGE: 750 V:

Table -5	
Base Line (V)	Counts
3.4	51
3.3	71
3.2	85
3.1	189
3	1729
2.9	6708
2.8	7356
2.7	2581
2.6	1237
2.5	638
2.4	467
2.3	424

Table - 6
Operating Voltage : 750V
FWHM = 0.22V
Max. Height at 2.85V
Resolution : 0.22/2.85 = 7.7%

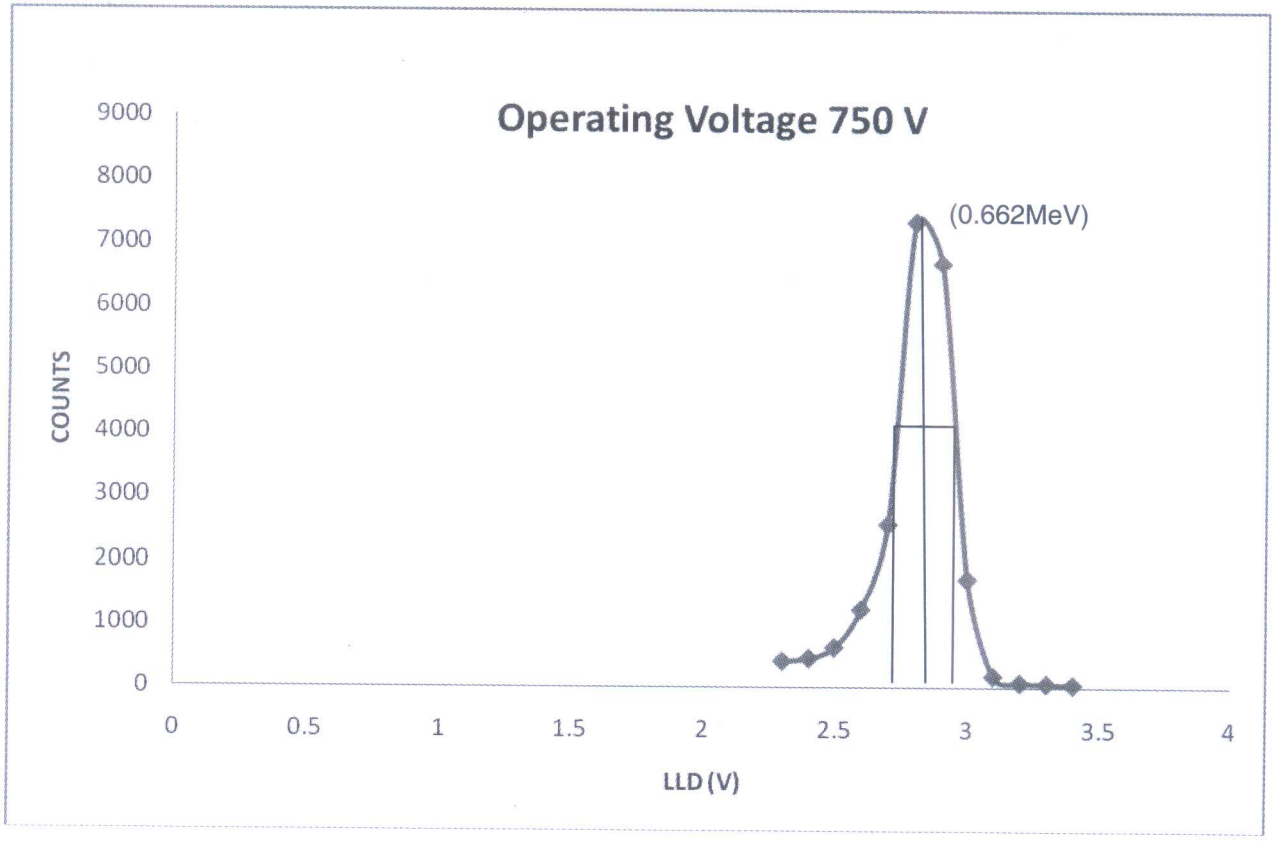

Fig. 19 : Cs-137 photopeak spectrum at 750V

OPERATING VOLTAGE: 800 V:

Table -7	
Base Line (V)	Counts
3.4	55
3.3	63
3.2	79
3.1	115
3	394
2.9	1305
2.8	5036
2.7	5118
2.6	1868
2.5	803
2.4	481
2.3	450

Table - 8
Operating Voltage : 800V
FWHM = 0.22V
Max. Height at 2.75V
Resolution : 0.22/2.75 = 8%

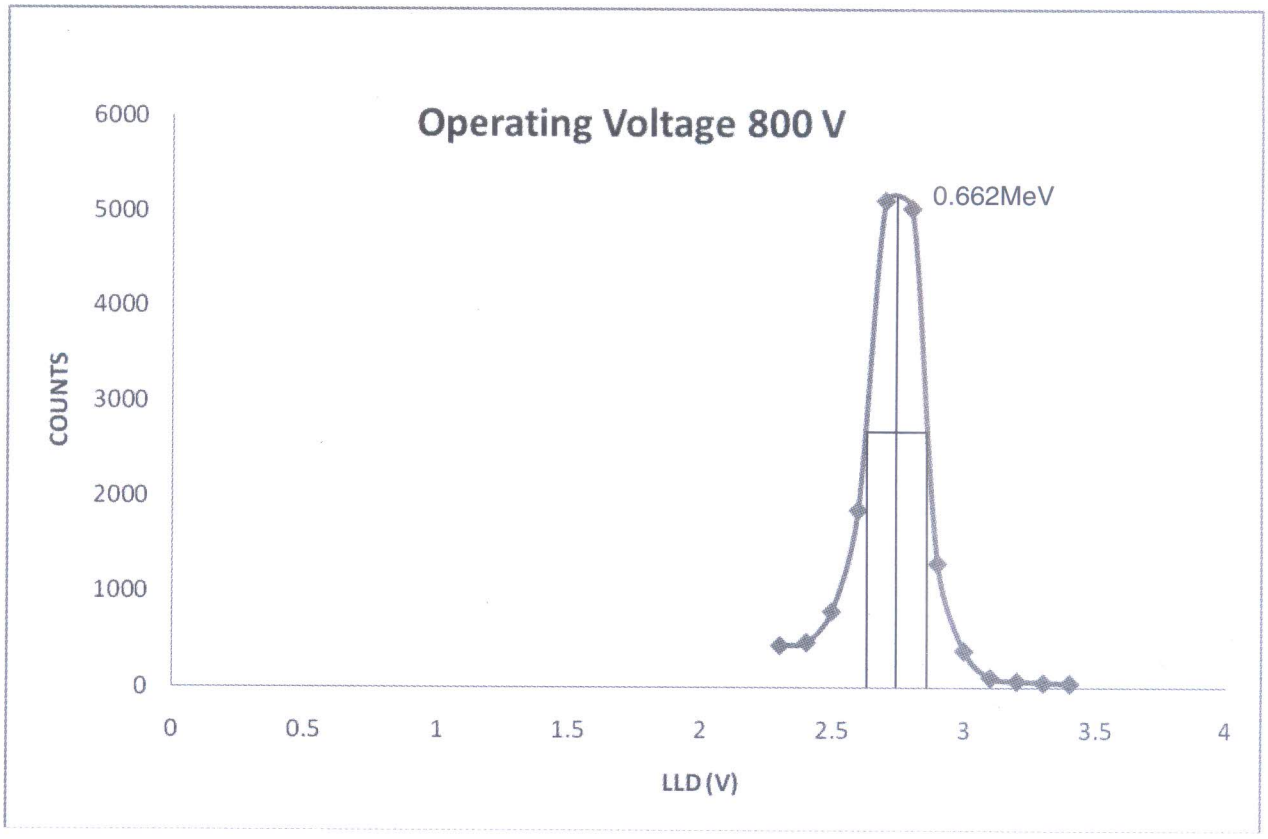

Fig.20 : Cs-137 photopeak spectrum at 800V

OPERATING VOLTAGE: 850 V:

Table -9	
Base Line (V)	Counts
3.4	61
3.3	59
3.2	144
3.1	1998
3	5442
2.9	5833
2.8	2479
2.7	930
2.6	422
2.5	348
2.4	376

Table - 10
Operating Voltage : 850V
FWHM = 0.25V
Max. Height at 2.95V
Resolution : 0.22/2.95 = 8.5%

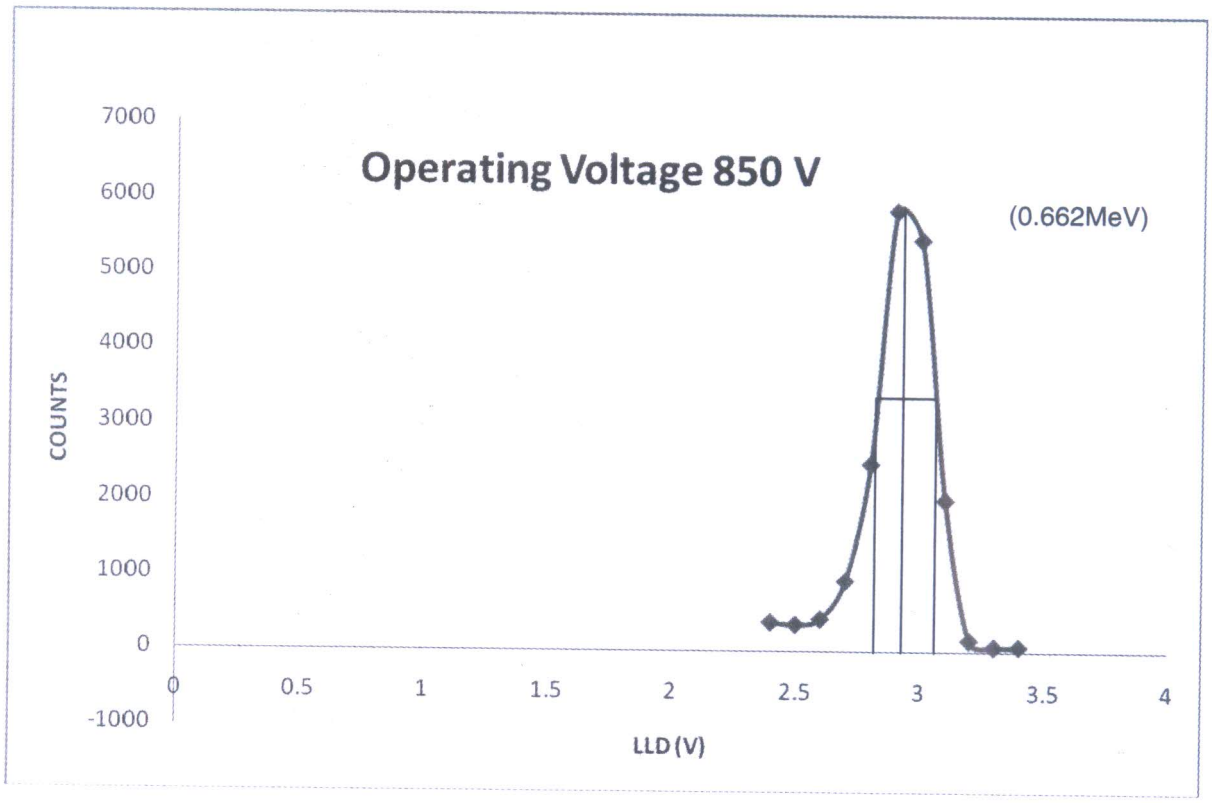

Fig. 21 : Cs-137 photopeak spectrum at 850V

- **FWHM:** Full width at half maximum is the channel width of the Cs-137 photopeak spectrum at half the peak height. In the graph of photopeak spectrum, one can draw a horizontal line at half peak height and see the width. Also from the data of Table-1, one can see that half the peak height will be (7208/2) = 3604. The LLD values corresponding to the counts 3604 are 2.78 and 3.02.

  Hence, FWHM = (3.02-2.78) V
  = 0.24

- **Resolution (%):** Resolution of a NaI scintillation detector is defined as the ratio of FWHM divided by peak channel LLD value.

  $$\text{Resolution} = \left(\frac{0.24}{2.9}\right)$$

  In percentage = 0.24 /2.9 X 100 = 8.28%

- Both resolution & FWHM are important for NaI scintillation detectors and are universally specified with a Cs-137 standard source by the manufacturer of the detector when they supply. Typically resolution for these detectors range from 7.5 % to 9.5%.

SUMMARY:

Table - 11

Applied Voltage (volts)	Resolution
650	8.3 %
700	8.1 %
750	7.7 %
800	8 %
850	8.5 %

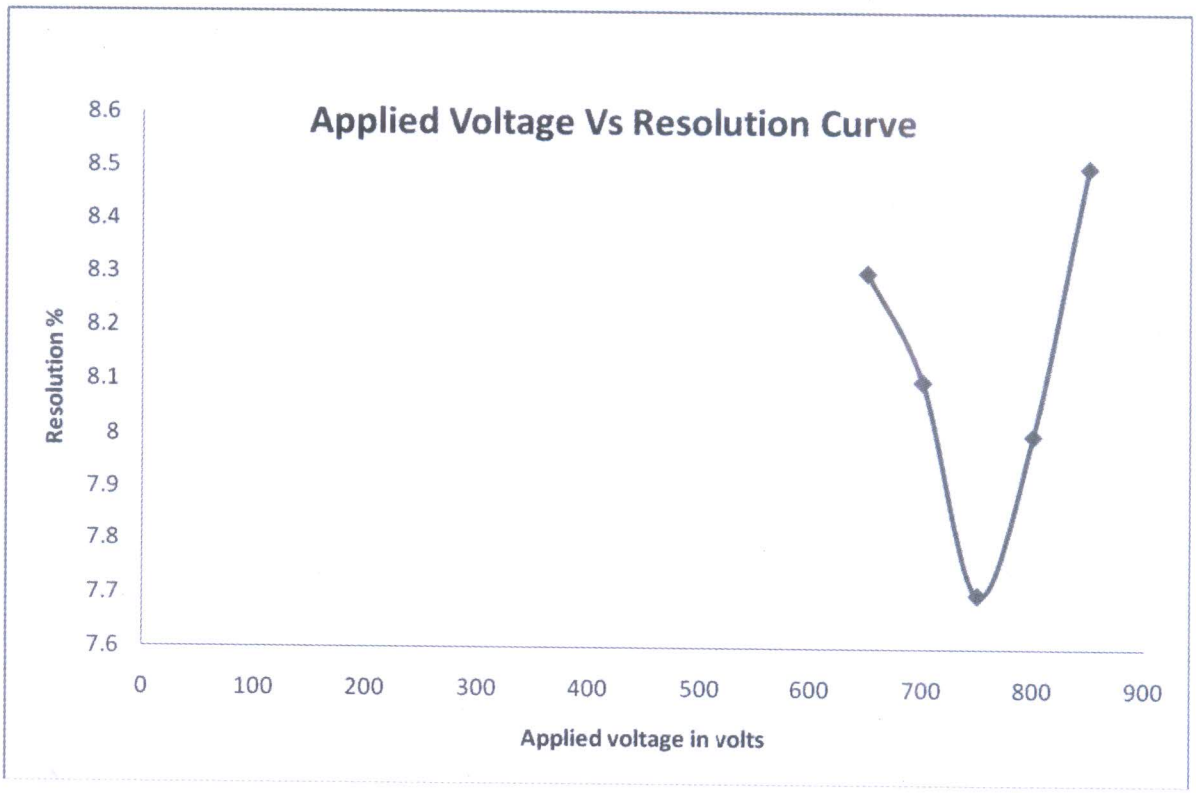

Fig.22 : Applied voltage Vs. resolution characteristics.

CONCLUSION :

From the above observations, it can be concluded that optimum (best) resolution is obtained at 750 V, and hence the same voltage of 750 V is to be used as the best operating voltage for this detector under study.

5.2 STUDY OF Cs-137 SPECTRUM AND CALCULATION OF FWHM & RESOLUTION FOR A GIVEN SCINTILLATION DETECTOR

PURPOSE:

Resolution is an important parameter which determines the quality of any scintillation detector. The purpose of this experiment is to calculate FWHM (Full Width at Half Maximum of the Photopeak) and resolution for a given scintillation detector.

PROCEDURE:

The experimental setup is same as that was shown in Fig. 15/16.

- Make system interconnections & default settings for either GR611M or 612 model.
- Place a Cs-137 radioactive standard source at a distance of 4 to 5 cm from the face of the scintillation detector.
- Set HV on the instrument to **operating voltage (750 V)**, specified by the manufacturer of scintillation detector.
- Now adjust amplifier gain such that the photo-peak pertaining to 662 keV energy of Cs-137 is approx. 3.0 V (amplitude). [Described in previous section also refer to Fig.13. in the previous pages]
- This we do usually with the idea of using the GRS to study the gamma energies in the range of 100 keV to 2.0 MeV over which NaI scintillation detectors are used and to cover within 8 V /10 V linear range of the amplifier.
- Now set the single channel analyzer MODE switch controls in GRS to WINDOW (WIN) position, LLD/Base line dial to 0.0 V and ULD/window dial to 1.0 turns (equal to 100mV window)
- Operate the GRS in preset time mode with preset time set to 60 sec.
- Take readings with LLD (Base line) starting from 0.4V in steps of 0.1(100 mV) till you cross Cs-137 photopeak i.e., may be up to 3.5/4.0 V.
- Tabulate the readings & plot the graph of **count rate** Vs **LLD / Base line** on a graph sheet or in EXCEL in PC as shown in the Fig. 23.

Data Analysis & Computations:

For Cs 137 (0.662 MeV)

Table – 12

LLD	Counts	LLD	Counts
0.4	25741	2.0	5930
0.5	20183	2.1	4806
0.6	17148	2.2	4428
0.7	16452	2.3	4628
0.8	17991	2.4	4112
0.9	17632	2.5	4325
1.0	16145	2.6	7269
1.1	14856	2.7	28527
1.2	13651	2.8	70999
1.3	28421	2.9	55856
1.4	12724	3.0	17579
1.5	12186	3.1	4786
1.6	11980	3.2	1911
1.7	12354	3.3	1226
1.8	11277	3.4	1006
1.9	8163	3.5	906

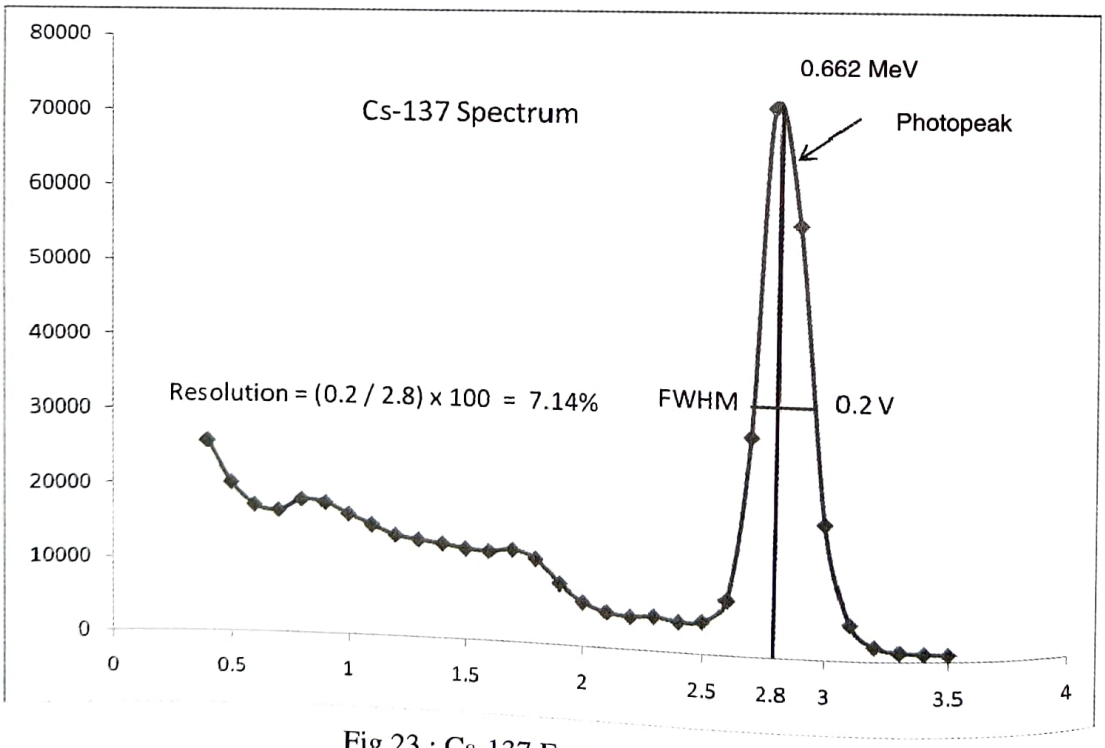

Fig.23 : Cs-137 Energy spectrum

- **FWHM:** Full width at half maximum is the channel width of the Cs-137 spectrum at half the peak height. From the graph one can draw a horizontal line at half peak height & see the width. Also from the tabulated data one can see that half the peak height will be (70, 999 / 2) = 35,499. To obtain exact baseline for these data counts one can repeat the data recording at LLD setting of 2.75V & 2.95 V which may yield data counts very close to half the peak height. Assuming these to be FWHM baseline (LLD) / channels we have

  FWHM = (2.95 – 2.75) V
  = 0.20

- **Resolution (%):** Resolution of a NaI scintillation detector is defined as the ratio of FWHM divided by peak channel LLD value.

  Resolution = 0.20 / 2.8
  In percentage = 0.20 /2.8 X 100 = 7.14 %

- Both resolution & FWHM are important for NaI scintillation detectors and are universally specified with a Cs-137 standard source by the manufacturer of the detector when they supply. Typically resolution for these detectors range from 7.5 % to 9.5%. Resolution is also specified sometimes in keV. This is calculated and illustrated in Experiment-3.