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# DETECTION OF THE BACKGROUND SUPPRESSED COMPTON SCATTERED PEAKS FOR THE $180^{O}$ REFLECTED 511 keV γ -RAY BY THE γ- γ COINCIDENCE TECHNIQUE

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**ABSTRACT:**

In the present project work we have carried out an experimental technique where background suppressed Compton scattered ($180^o$) peaks for the 511 keV γ-ray have been detected by the γ-γ coincidence spectroscopic technique. Here we use positron annihilated two oppositely (~ $180^o$) directed 511 keV γ rays. Positrons from a radioactive nucleus ($^{22}$Na) have been used for the present work.

Positron is an antiparticle of electron. Both positron and electron has a rest mass of $m_oc^2$ = 511 keV. Positrons normally annihilate with an electron in the medium (e.g., solid, liquid, gas etc.) normally emitting two oppositely directed 511 keV γ rays. In the present project we have used two identical High Purity Germanium (HPGe) detector placed at $180^o$ angle. Detailed electrons and circuit diagram will be discussed in the *experimental setup* sections. After setting up the γ-γ coincidence spectrometer the peaks for the $180^o$ Compton scattered 511 keV γ-ray (~ $0.33m_oc^2$ and $0.66m_oc^2$) have nicely been identified.

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## Introduction

### Gamma-Ray Interactions with matter

Gamma-ray interacts with the matter in three different processes.

1. Compton scattering
2. Photoelectric process
3. Pair production

### 1. Compton Scattering

The Compton scattering process is the process by which a □-ray transfers its energy partially to an electron.

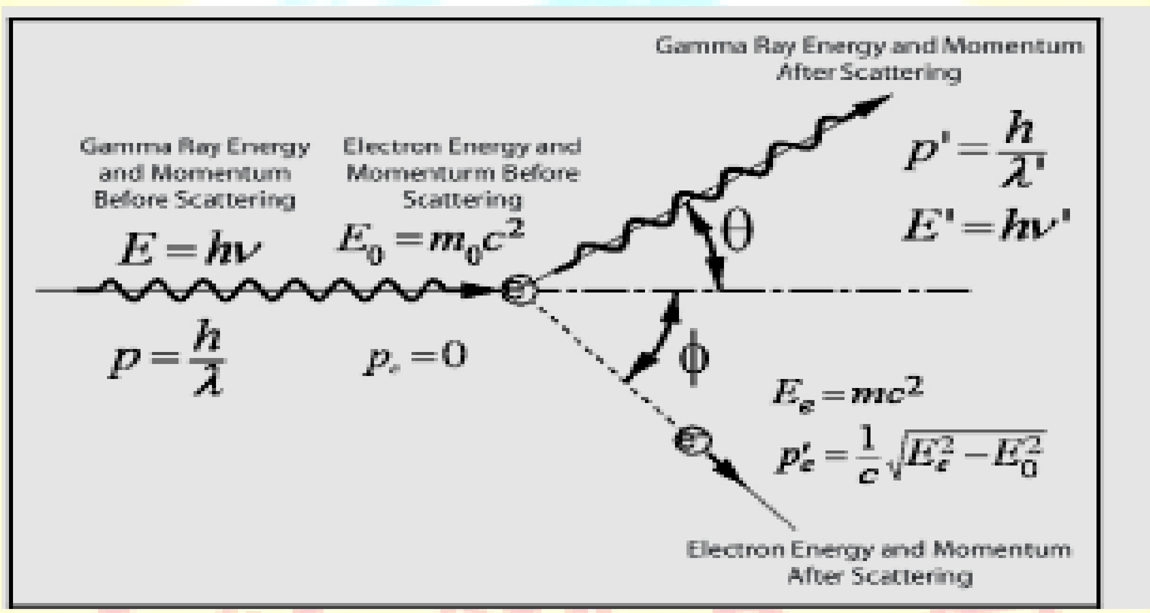


Figure 1 Compton scattering diagram for an incident photon with an electron.

The energy of the incoming photon is divided between the scattered photon and the recoil electrons by the relationship that is dependent on the scattering angle. The energy of the recoil electron is

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

$E_{e-}$ is the kinetic energy of the electron. h□ and h□ '□ □ is the incident photon energy and the scattered photon energy respectively. □ is the scattering angle.

## 2. Photoelectric process

In the photoelectric absorption, the incident $\gamma$- ray transfers its total energy to an electron.

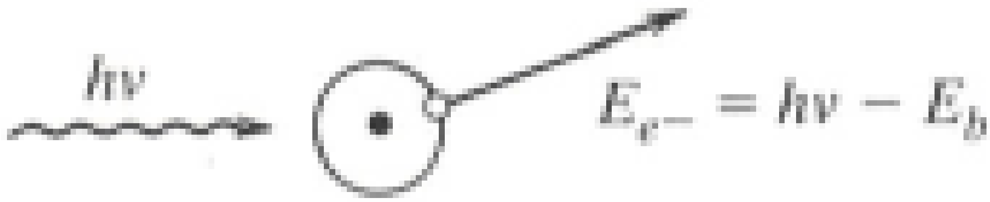


Figure 2 Diagram of the photoelectric process

The kinetic energy that this electron carries off is $E_{e-} = h\nu - E_b$, where $E_b$ is the binding energy of the electron in its original shell.

## 3. Pair Production

The Pair production is a gamma-ray that turns into an electron-positron pair. There is a minimum amount of gamma-ray energy that is required for this process to take place. This minimum energy is the mass of the electron-positron pair, $2m_0c^2$. Therefore, the conservation of kinetic energies gives

$E_{e-} + E_{e+} = h\nu - 2m_0c^2$

Here $E_{e-}$ and $E_{e+}$ are the kinetic energy of the produced electron and positron.

## COMPTON SCATTERING THEORY

When $\gamma$-ray fall on matter (of low atomic number) the scattered ray in a certain direction contained with the frequency of the incident radiation and a second component with a lower frequency or longer wavelength. The lower frequency component originates from the inelastic scattering of the incident radiation. Such scattering is called Compton Scattering.

### Compton shift

Let us consider a $\gamma$-ray photon of frequency $\upsilon_o$ , energy E= $h\upsilon_o$ and momentum M= $\frac{h\upsilon_o}{c}$ collides with an electron at rest in the target. The initial momentum $(M_1)$ of the electron is zero and its initial energy $(E_1)$ is the rest mass energy $m_oc^2$. As a result the electron is ejected with a velocity v in a direction making an angle $\phi$ with that of the incident $\gamma$-ray photon. The scattered

$\gamma$-ray photon of frequency $\upsilon$, energy $E^{/}= h\upsilon$ and momentum $M^{/}=\frac{h\upsilon}{c}$ moves in a direction at an angle $\theta$ with the incident radiation. Thus the mass of the electron m moving with velocity v is given by

$$m=m_o/ (1-v^2/c^2)$$

where $m_o$ is the mass of the electron at rest and c is the velocity of light.

Applying the law of conservation of energy to the Compton scattering process, we get

$m_oc^2 + h\upsilon_o = h\upsilon + mc^2$ (1)

Since momentum is a vector quantity, applying the law of conservation of momentum along the x-axis ,we get

$\frac{h\upsilon_o}{c} = \left(\frac{h\upsilon}{c}\right) \cos\theta + mv \cos\emptyset$ (2)

Similarly along the y-axis, we get

$0=\frac{h\upsilon}{c} \times \sin\theta - mv\times \sin\emptyset$ (3)

Where $\frac{h\upsilon_o}{c}$ is the initial momentum of the gamma ray and $\frac{h\upsilon}{c}$ is the momentum of the scattered gamma ray.

Multiplying eqs. (2) and (3) by c , we get

$h\upsilon_o - h\upsilon \times \cos\theta = mvc\times \cos\emptyset$ (4)

$h\upsilon \times \sin\theta = mvc\times \sin\emptyset$ (5)

Squaring the eqs. (4) and (5) and adding, we get

$m^2v^2c^2 = h^2(v_o^2 + v^2 - 2vv_o \times \cos\theta)$ (6)

Dividing this equation by $c^2$ and using the relation $\lambda = \frac{c}{v}$, one obtains

$m^2v^2 = \frac{h^2}{\lambda_o^2} + \frac{h^2}{\lambda^2} - \frac{2h^2\times\cos\theta}{\lambda\lambda_o}$ (7)

From equation (1)

$mc^2 = m_o c^2 - h(\nu - v_o)$

squaring this equation, we get

$m^2c^4 = m_o^2c^4 + h^2(v - v_o)^2 - 2m_oc^2h(v - v_o)$ (8)

Subtracting eqs. (6) from (8), we get

$m^2c^2(c^2 - v^2) = -2h^2(1 - \cos\theta)\, vv_o + m_o^2c^4 - 2h(v - v_o)m_oc^2$

Using the relation $m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}$, eq. (8) becomes

$$\frac{m_o^2c^2(c^2-v^2)}{1-\frac{v^2}{c^2}} = -2h^2 v v_o(1-\cos\theta) + m_o^2c^4 - 2h(v-v_o)\, m_o c^2$$

Simplifying this eq., we get

$$2h(v-v_o)\, m_o c^2 = 2h^2 v v_o(1-\cos\theta)$$

Cancelling 2h and dividing by $v v_o$ , we get

$$\frac{v_o - v}{v v_o} = \frac{h}{m_o c^2}(1-\cos\theta)$$

or $\frac{1}{v} - \frac{1}{v_o} = \frac{h}{m_o c^2}(1-\cos\theta)$ (9)

Using the relation $\lambda = \frac{c}{v}$, we get

$$\frac{\lambda}{c} - \frac{\lambda_o}{c} = \frac{h}{m_o c^2}(1-\cos\theta)$$

$\lambda - \lambda_o = \Delta\lambda = \frac{h}{m_o c}(1-\cos\theta)$ (10)

This change in wavelength is known as compton shift. This shift depends only upon $\theta$ only.

Energy of scattered photon

From eq. (9) ,we get

$$\frac{1}{hv} = \frac{1}{hv_o} + \frac{1}{m_o c^2}(1-\cos\theta)$$

or $\frac{1}{hv} = \frac{m_o c^2 + (1-\cos\theta) h v_o}{h v_o m_o c^2}$

or $hv = \frac{h v_o m_o c^2}{m_o c^2 + (1-\cos\theta) h v_o}$

or $hv = \frac{h v_o}{1 + \frac{h v_o}{m_o c^2}(1-\cos\theta)}$

At $\theta = 180^o$

$$hv = \frac{h v_o}{1 + \frac{h v_o}{m_o c^2} \times 2}$$

Since $hv_o = m_o\, c^2$

$$\mathbf{hv = \frac{1}{3} m_o\, c^2}$$

Kinetic energy of the recoil electron

$$E_k = hv_o - hv$$

$$E_k = m_o\, c^2 - \frac{1}{3} m_o\, c^2$$

$E_k = \frac{2}{3} m_o c^2$

**Gamma ray detectors**

**1. PMT + $BaF_2$ scintillator**

When a □-photon incident on a scintillator crystal a short lived flash of light is emitted from it. This is called scintillation--- the result of a fluorescence process. This scintillation light travels to a light detecting device known as a photomultiplier tube (PMT). The PMT has a photosensitive surface in it which, upon incidence of light on it, emits photoelectrons. The bunch of electrons so emitted undergo multiplication in number within the tube and are finally collected by an anode producing a voltage pulse. The scintillation-PMT combination constitutes the basic unit of the detector assembly.

**2. HPGe detector**

Detectors made from this germanium are usually called Hyper Pure Germanium (HPGe) detectors. The cylindrical planar HPGe detectors having two plane faces on two sides on which electrodes are deposited are called planar detectors. These detectors may be fabricated to have depletion layer thickness' of 1cm or a little more.

These detectors may be fabricated from high purity n-type germanium. One face of such a disc is heavily doped with a donor impurity to make a rectifying contact and this face serves as the positive electrode. The negative electrode is formed on the opposite face by heavily doping with an acceptor impurity, the contact being non rectifying.

Larger HPGe detectors have coaxial geometry where one electrode is formed along the axis of a cylindrical hyper-pure Ge crystal. On the cylindrical outer surface is formed the other electrode. The major characteristics of the HPGe detector are high atomic number, low impurity concentration (large depletion depth), low ionizing energy required to produce an electron-hole pair, high conductivity, compact size, first time response, high resolution and relative simplicity of operation.

The high number of information carriers leads to a small percentage fluctuation and this is the reason for the high energy-resolution of Ge detectors. However, the detector cannot simply consist of the semiconductor material and two electrodes because there are inherent impurities in these materials. Both Si and Ge have a valence 4 and when an impurity of valence 3 (acceptor) or 5 (donor) exists in the crystal, it lowers the energy necessary to create electron-hole pairs and this tends to create too much noise. The Ge crystal with acceptor impurities is called p-type (Ge) material and the same with donor impurities is called n-type (Ge) material. The solution is to create a p–n junction at one electrode and to polarize it so that no current passes through when there is no ionizing radiation (this is called reverse biasing or using non injecting or blocking electrodes). This creates a region called the depletion layer (Figure 3) where few charge carriers remain, resembling a pure semiconductor. With a sufficient voltage, the electric field can create a large enough depleted volume to make a viable detector. The intrinsic region (depleted volume) is sensitive to ionizing radiation particularly –X rays and  -rays. The performance of a detector depends on its depletion depth, which is inversely proportional to the net impurity concentration in the detector material.

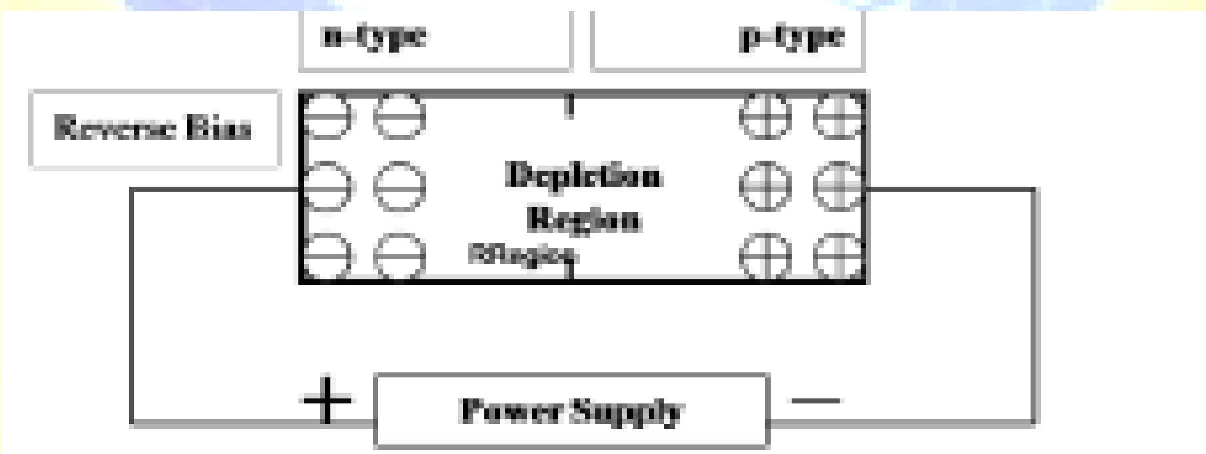


Figure 3: Creation of depletion region in the Ge semiconductor crystal.

With negative bias is applied ,the charge carriers are drawn away from the junction, creating a region depleted of charge carriers that acts as a solid-state ion chamber.

The reason that high level of purity in the material is desired has to do with the depletion region. The depletion region is desired to be as large as possible. The depletion equation is

$$d = \left(\frac{\epsilon V}{e N}\right)^{1/2}$$

where e is the electronic charge ,epsilon is the dielectric constant, V is the reverse bias voltage, and N is the net impurity concentration in the bulk semiconductor material. As it follows from the Equation the lower the impurity concentration, the higher the depletion depth is. Germanium is chosen for the reason that current manufacturing techniques allow for germanium to be refined such that the purity concentration is as low.

**Energy Resolution**

The great advantage to using a germanium detector is the fact that they have excellent energy resolution for gamma-ray spectroscopy. A high energy resolution means that the detector can discriminate between gamma-rays with similar energies. The more resolution a detector has , the more defined a gamma spectrum becomes. Recall that the resolution of a detector is defined as

$$R = \frac{H_0}{\mathrm{FWHM}}$$

where $H_0$ is the centroid peak number and FWHM is the full-width half-maximum of the peak. There are three factors that give germanium the excellent resolution that it has: the inherent statistical spread in the number of charge carriers, variations in the charge collection efficiency, and contributions of electronic noise. Some of these factors will dominate over the other factors, but this is dependent on the energy of the radiation and the size and quality of the detector in use

**Table 1. Conventional gamma ray sources:**

| Source Name | Half life | Gamma ray energy |
|---|---|---|
| $^{60}Co$ | 5.26 year | 1172 keV<br>1332 keV |
| $^{137}Cs$ | 30 year | 662 keV |
| $^{133}Ba$ | 10.5 year | 270 keV<br>300 keV<br>355 keV<br>380 keV |

| | | |
|---|---|---|
| $^{22}$Na | 2.6 year | 511 keV<br>1276 keV |

**Experimental Setup**

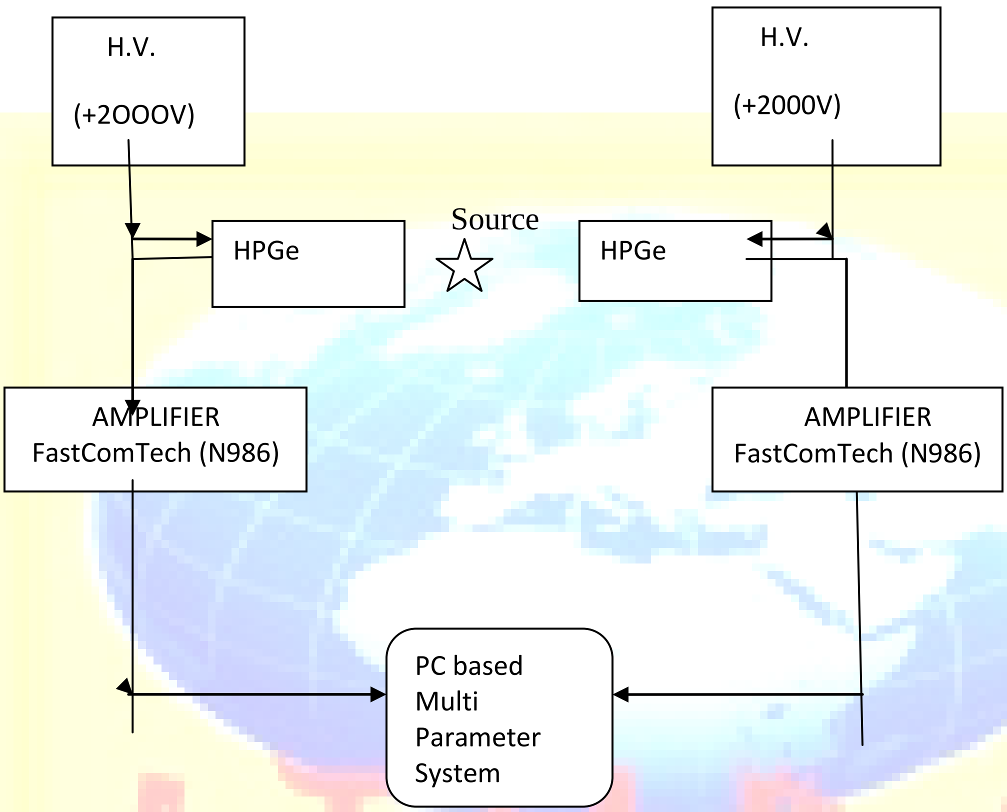


Figure 4. The typical □ □-□ □ coincidence assembly using two identical HPGe detectors

**The required instruments are as follows:**

High Voltage (HV) Power supply; High purity Germanium γ-ray detector; Amplifier (FastComTech N986 / Ortec 572); Multiparameter (MPA) System (PC based)

**Preamplifier (preamp)**

The purpose of the preamp is to avoid changes that can occur to the time constant of a pulse if the PMT is directly connected to the main/linear amplifier. The preamp has several ways of maximising its signal to noise ratio. The first is simply to attach it as closely as possible to the detector itself. The second is to terminate its capacitance rapidly. However, the preamp does not shape the received pulse and has a short output time with a linear tail.

**Amplifier**

The main/linear amplifier is used for two reasons. The first is to produce a gain in amplitude; the second is to shape the tail pulse from the preamp into a linear pulse. The amplification factor can be modified using both fine and coarse gain controls. In addition, the shaping time can also be adjusted and the affect of this will vary with differing rates.

**Multichannel pulse height analyzer (MCA)**

An MCA is an instrument which sorts all the incoming pulses according to their amplitudes and accumulates the counts in different memory channels (cf. scalers) as they arrive, each channel having been designated to a given pulse amplitude. Moreover, with an MCA the entire 10 volt spectrum can be divided into a large number of channels (4096 channels are quite common) making the window width (also called channel width) quite narrow. Each channel then corresponds to a particular value of V. For example, a 4096 channel MCA makes possible a 10 volts spectrum to be recorded with a window width of □ V = 10/4096 = 2.44mV. It is clear that the instrumental resolution in this case is very high. Moreover, when a spectrum from a radioactive source having a short lifetime is required to be recorded, an SCA will be found to be unsuitable because point by point recording of counts with it will take a time during which the source may decay considerably. In this case an MCA becomes indispensable since only it can perform the task of recording the entire spectrum in a short time.

**Experiments**

At first we had taken two HPGe detectors. The detectors are placed in $180^o$ angle (exactly in opposite direction). Using these two detectors with the associate electrons and multi-parameter data acquisition system a □-□ □ coincidence assembly have been set-up. Using different standard radioactive sources (as listed in the Table 1) the detectors are calibrated. The calibrations of both the detectors are exactly similar. Figure 5 shows a typical gamma ray spectrum (for the radioactive $^{22}Na$ source). Apart from the 511 keV photopeak there is a broad Compton continuum. In this figure there are two small peaks (at energies ~ 170 and 341 keV) which are due to the $180^o$ Compton (from the other detectors) scattered peaks.

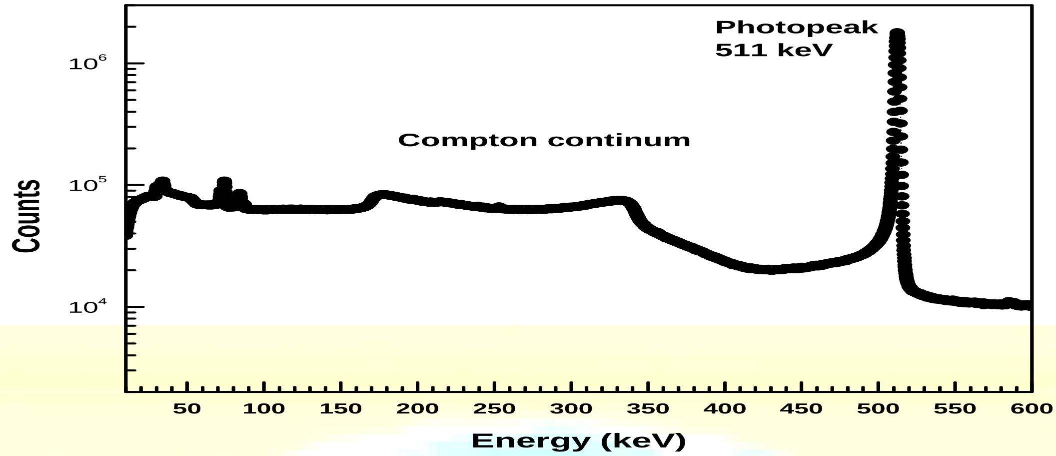


Figure 5. A typical gamma ray spectrum in a HPGe detector

Next using different $\gamma$-ray sources like $60_{Co}$ ,$22_{Na}$, $137_{Cs}$ both the detectors have been calibrated. Figure 6 shows the linearity of the detectors. Here we have also evaluated the energy of an un-known □-ray source ($133_{Ba}$) from graph the energy of $133_{Ba}$ is 355.32 KeV and the actual value is 356 KeV. Thus the experimental result is very close to the actual value.

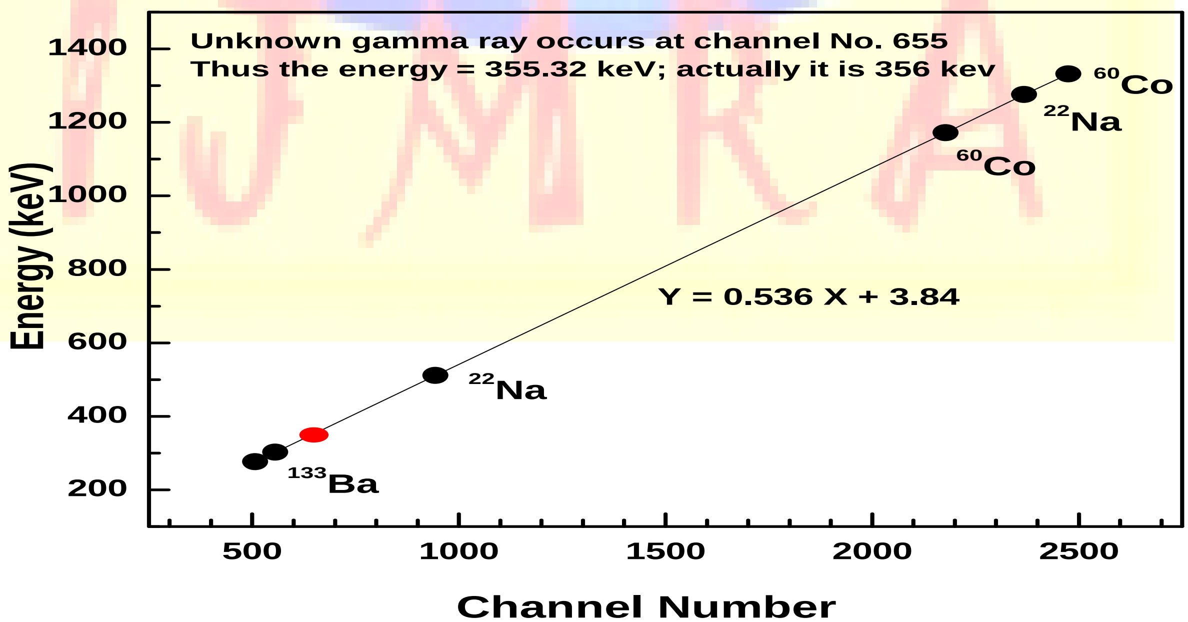

Figure 6. Energy calibration curve of the Multichannel Analyzer using known and unknown gamma ray source

After that using two detectors coincidence assembly we have recorded the □ □ □ □ coincidence spectrum with two ADC (analog to digital converter) multi parameter system. We have used two HPGe detectors which were placed $180^0$

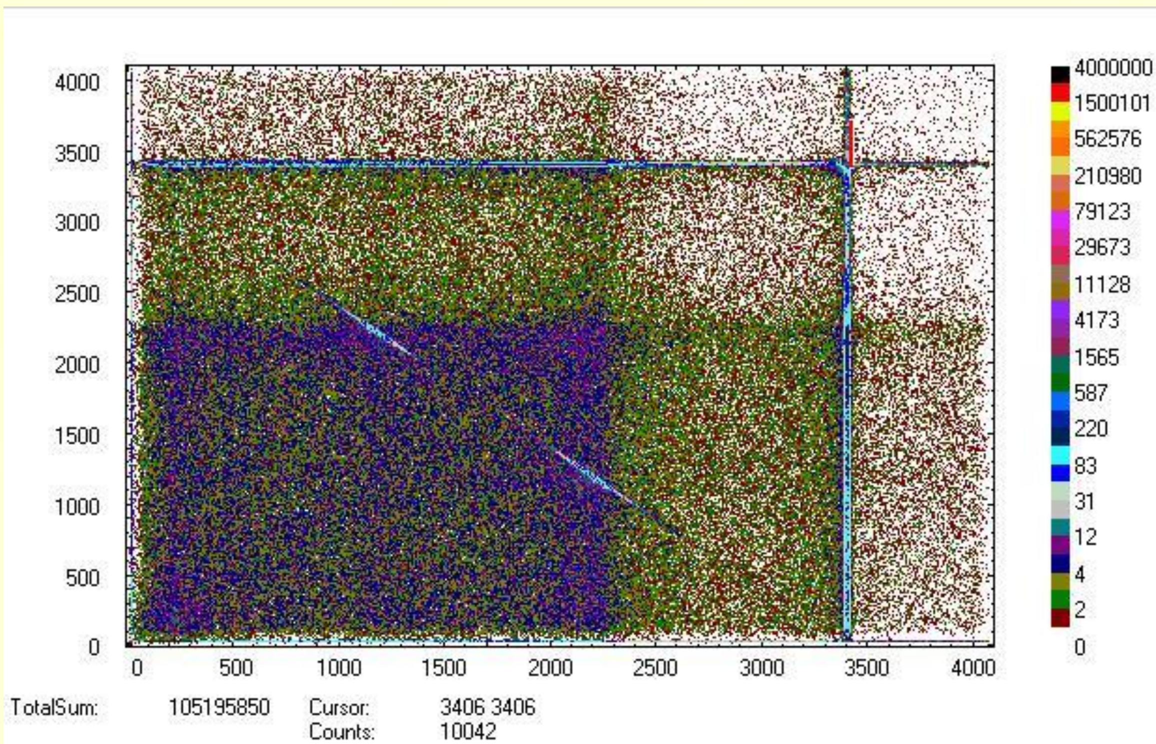


Figure 7. A typical gamma – gamma coincidence spectrum in a two dimensional multi-parameter system

oppositely directed. Between these two detectors we used $22_{Na}$ as a $\gamma$-ray source. The two detectors were connected with high voltage power supply ($\sim 2000\,V$). We got positron annihilated two oppositely ($\sim 180^0$) directed 511KeV $\gamma$-rays. Two special type of amplifiers were connected from the two detectors. The amplifier was special because it can maximize the signal to noise ratio. From these two amplifiers the signal came through " multi –parameter system " via two " analog to digital converter " in our computer and we got $\gamma$-$\gamma$ coincidence spectrum (Figure 7). Here coincidence counts are in the third direction. The selected portion data of the coincidence 180$^o$ Compton scattered 511 keV peaks are extracted from the figure 7 and is plotted in Figure 8. Figure 8 clearly shows two distinct peaks (one at ~170 keV and the other at ~341 keV).

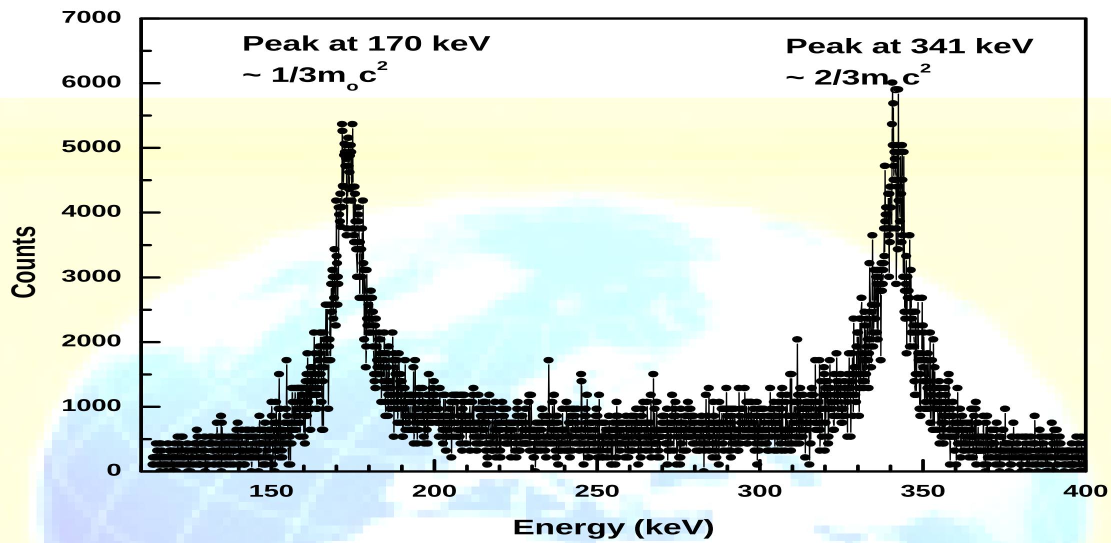


Figure 8. Coincidence spectrum of 180$^o$ Compton Scattered 511 keV γ-rays.

**Conclusion**

From this project work we identify the features of the different γ-ray spectra.We can identify the features of the γ-ray spectrum such as photopeak, Compton continuum etc. Here we have evaluated the energy of an unknown γ-ray source. In this experiment we have measured the Compton peaks for 180$^o$ scattered 511 keV γ-ray by two oppositely directed (180$^0$) HPGe detectors (using 511 keV of $^{22}$Na source) with the help of γ-γ coincidence technique. The experimentally measured peaks positions are in agreement with the theoretical values.

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