A REPORT

ON

Characterisation using Rutherford Backscattering Spectrometry

And

Analysing Compton effect using Gamma ray Spectrometry

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Keywords: Backscattering, Tandetron, Gamma ray spectroscopy, Compton scattering, HPGe detector, NaI detector, Compton edge

Project area: Analysing spectrums of gamma ray spectroscopy.

Abstract: The objectives of this experiment are to study the Compton scattering with the help of gamma ray spectrum of Cs-137, Ba-133, Co-60 using HPGe and NaI detectors. We observe the changes in the gamma ray spectrum by changing the initial experimental conditions and comparing the spectrum of different elements and studying the principles and kinetics of Rutherford Backscattering Spectrometry.

Signature of student **Signature of PS Faculty**

Date: **Date:**

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Characterisation using Rutherford Backscattering Spectrometry

And

Analysing Compton effect using Gamma ray Spectrometry

Objective of experiment

Rutherford Backscattering Spectrometry

The objective of this experiment is to study the characteristics of Tungsten Oxide (WO3) thin layer sample and find the width of the thin layer.

Gamma Ray Spectrometry

The objectives of this experiment is to study the Compton scattering with the help of gamma ray spectra of Cs-137, Ba-133, Co-60 using HPGe and NaI detectors.

Abstract

Gamma rays are a form of electromagnetic radiation like infrared rays, ultraviolet rays etc; Some of the important uses of gamma rays include treating cancer, astronomical studies and spectrometry. In this study we will be looking at how gamma ray spectrometry is used in analyzing Compton effect.

Rutherford Backscattering Spectrometry named after the British physicist is an analytical technique used primarily to analyse the surfaces of samples in a non-destructive and sensitive fashion. In this study we will be looking at the kinetics and experimental procedure of this technique.

INTRODUCTION

Rutherford Backscattering Spectrometry (RBS)

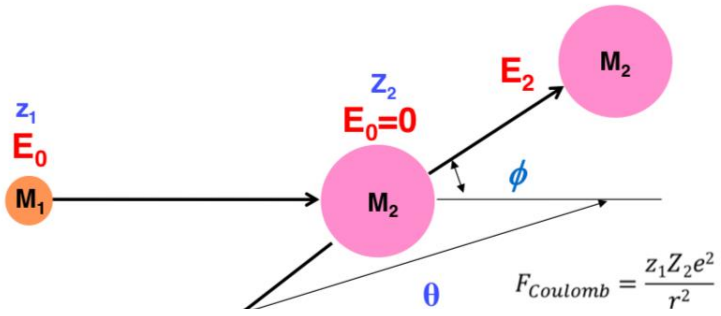
Rutherford backscattering spectrometry provides in depth information about the properties of a surface. It is a non-destructive method which is sensitive to all the elements in the periodic table. This technique is used to ensure accurate quantification and detect trace elements better than ppm levels. RBS also demonstrates accurate depth resolution compared to other surface analytical methods.

Elastic Collisions

An elastic collision is an encounter between two bodies in which the total kinetic energy of the two bodies after the encounter is equal to their total kinetic energy before the encounter. Perfectly elastic collisions occur only if there is no net conversion of kinetic energy into other forms such as heat or noise and therefore they do not normally occur in reality.

During the collision of small objects, kinetic energy is first converted to potential energy associated with a repulsive force between the particles, then this potential energy is converted back to kinetic energy (when the particles move with this force, i.e. the angle between the force and the relative velocity is acute).

The collisions of atoms are elastic collisions



$$\frac{1}{2}M_1 v^2 = \frac{1}{2}M_1 v_1^2 + \frac{1}{2}M_2 v_2^2 \qquad \text{(Eq.1)}$$

$$M_1 v = M_1 v_1 \cos\theta + M_2 v_2 \cos\phi \qquad \text{(Eq.2)}$$

$$0 = M_1 v_1 \sin\theta - M_2 v_2 \sin\phi \qquad \text{(Eq.3)}$$

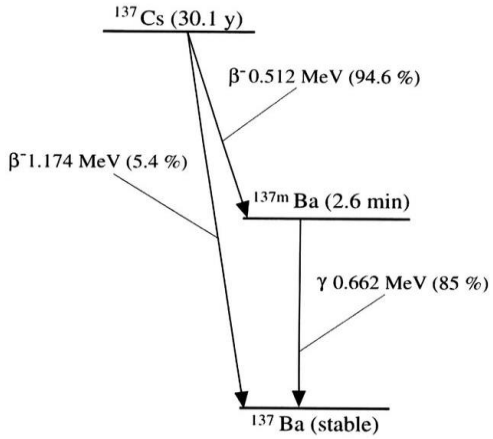
Solving Eq. 2 and 3 and eliminating first, then v2, one finds the ratio of particle velocities, and we can show that the energy of projectile (M1) after collision can be found through the following relationship

$$E_1 = E_0\left[\frac{\left(M_2^2 - M_1^2\sin^2\theta\right)^{1/2} + M_1\cos\theta}{M_2 + M_1}\right]^2$$

Ratio of E_1 and E_0 is called **kinematic factor**: $k = \frac{E_1}{E_o} = \left[\frac{\left(M_2^2 - M_1^2\sin^2\theta\right)^{1/2} + M_1\cos\theta}{M_2 + M_1}\right]^2$

Gamma ray Spectrometry

Gamma rays are produced as a result of nuclear reactions. When a high energy nucleus comes down to a lower energy state it emits gamma rays as depicted in the figure below.



$Cs \quad ^{137}\rightarrow Ba \quad ^{137} + \beta \quad ^{-}\rightarrow *Ba \quad ^{137} \rightarrow Ba \quad ^{137} + \gamma$

Although 100% conversion of Cs to the excited state of Ba does not occur, these gamma rays are continuously emitted from a radioactive element we used in the experiment.

When an incoming gamma ray interacts with an electron, it either transfers all of its energy to the electron or undergoes Compton scattering , the probability of occurrence of these events sums out to be 1.

$\Sigma(\varrho e + \varrho\gamma) = 1$.

Photoelectric effect is seen at a particular energy which gives us the highest peak in the gamma ray spectrum and in addition we also get the spectrum of Compton scattering and noise from the

background. We also get a signal from the natural background radiation such as ^{40}K which has a radiation value of 1460.8 keV, due to this we get peaks in some parts of the spectrum.

Compton scattering

When gamma ray interaction with an electron occurs it undergoes scattering which means the electron gets some energy from the incoming gamma ray and the gamma ray gets scattered, this process is called Compton scattering.

In Compton scattering wavelength change by a factor of $\Delta\lambda = \frac{h(1-cos(\theta)}{mc}$

Change in $\lambda$is equal to $\Delta\lambda = \lambda^{|} - \lambda$,

Where $\theta$is the angle between the incident gamma ray and the scattered gamma ray. And we observe that the energy of scattered gamma radiation (γ) is given by the equation,

$E\gamma^{|} = \frac{h\nu}{1+\frac{h\nu(1-cos(\theta))}{mc^2}}$

and energy of the electron is,

$Ee = h\nu - \frac{h\nu}{1+\frac{h\nu(1-cos(\theta))}{mc^2}}$ (As the sum of both energies should be $h\nu$).

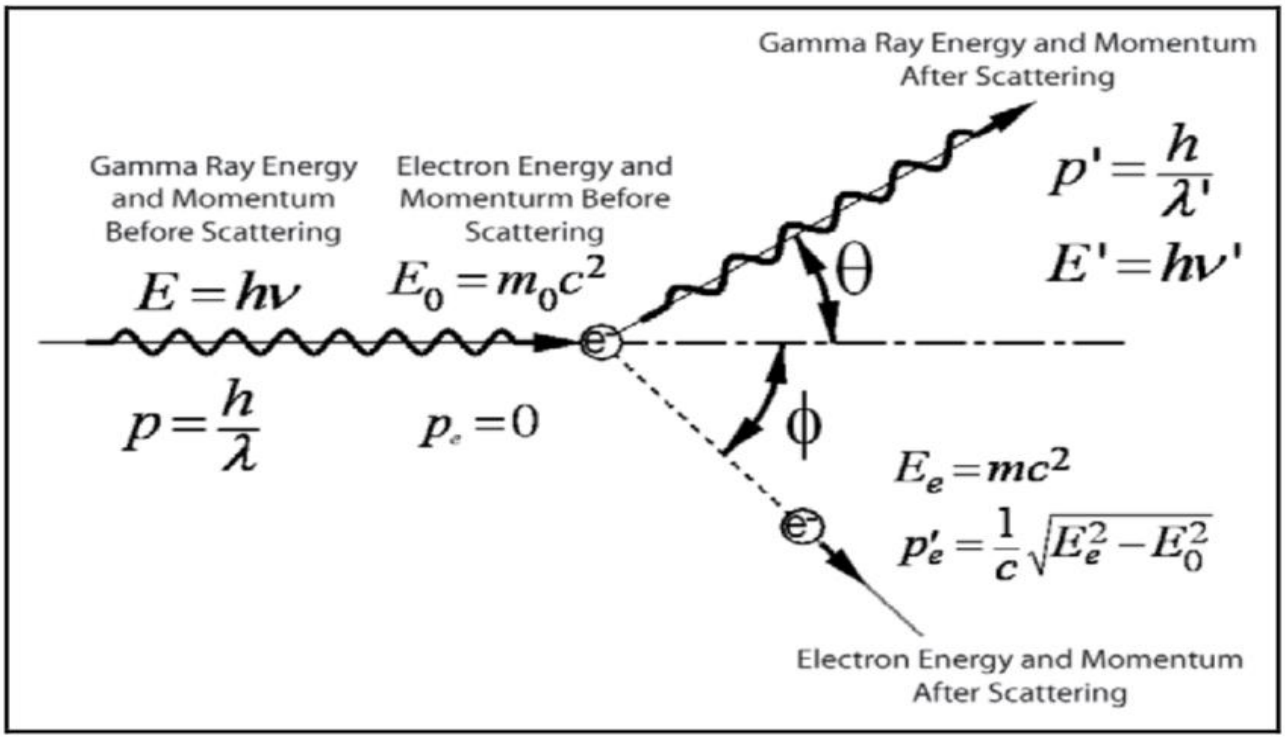
Here,

Both energy and momentum are conserved as no external force is applied

total energy before the interaction of electron and gamma ray is equal to the sum of energy of electron and the energy of scattered gamma ray,

$E\gamma = Ee + E\gamma^{|} = h\nu$.

$P\gamma = Pe + P\gamma^{|}$.


Gamma Ray Energy and Momentum After Scattering
Gamma Ray Energy and Momentum Before Scattering
Electron Energy and Momenturm Before Scattering
$E = h\nu$
$E_0 = m_0 c^2$
$p = \frac{h}{\lambda}$
$p_e = 0$
$p' = \frac{h}{\lambda'}$
$E' = h\nu'$
θ
ϕ
$E_e = mc^2$
$p'_e = \frac{1}{c}\sqrt{E_e^2 - E_0^2}$
Electron Energy and Momentum After Scattering

Plots:

Energy of the scattered electron:

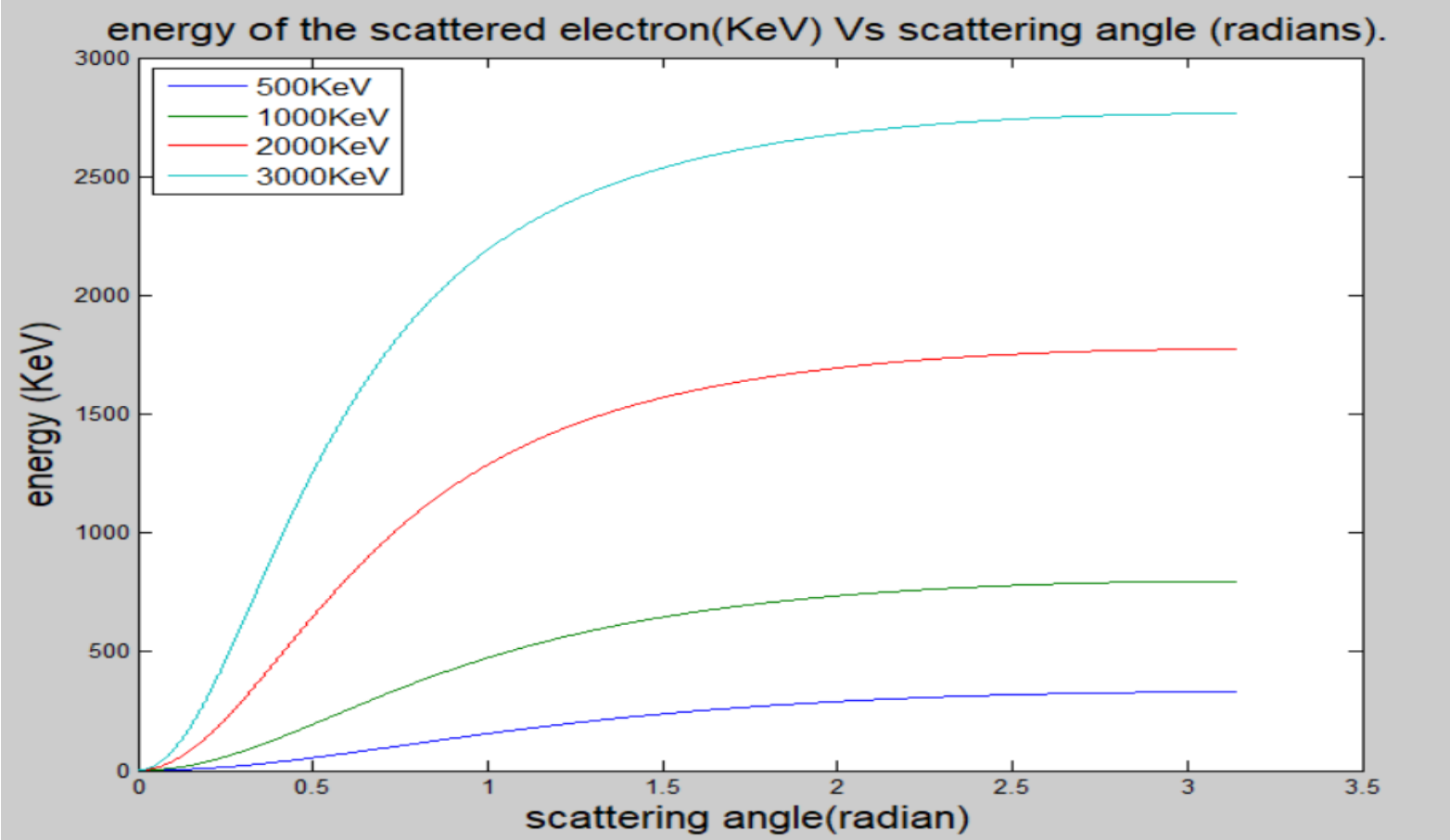


Fig 1

y=$\frac{hv(1-cos(x))}{\frac{mc^2+hv(1-cos(x))}{hv}}$ for different hv,y=Eγ',$x=\theta$.

We take different values of hv (different energies of gamma rays) and energy of the scattered electron (KeV) with scattering angle θ(radians) is plotted.

Hence from the graph we infer that 100% of energy of the incoming gamma ray cannot be transferred to the scattered electron.

Energy of the scattered gamma ray:

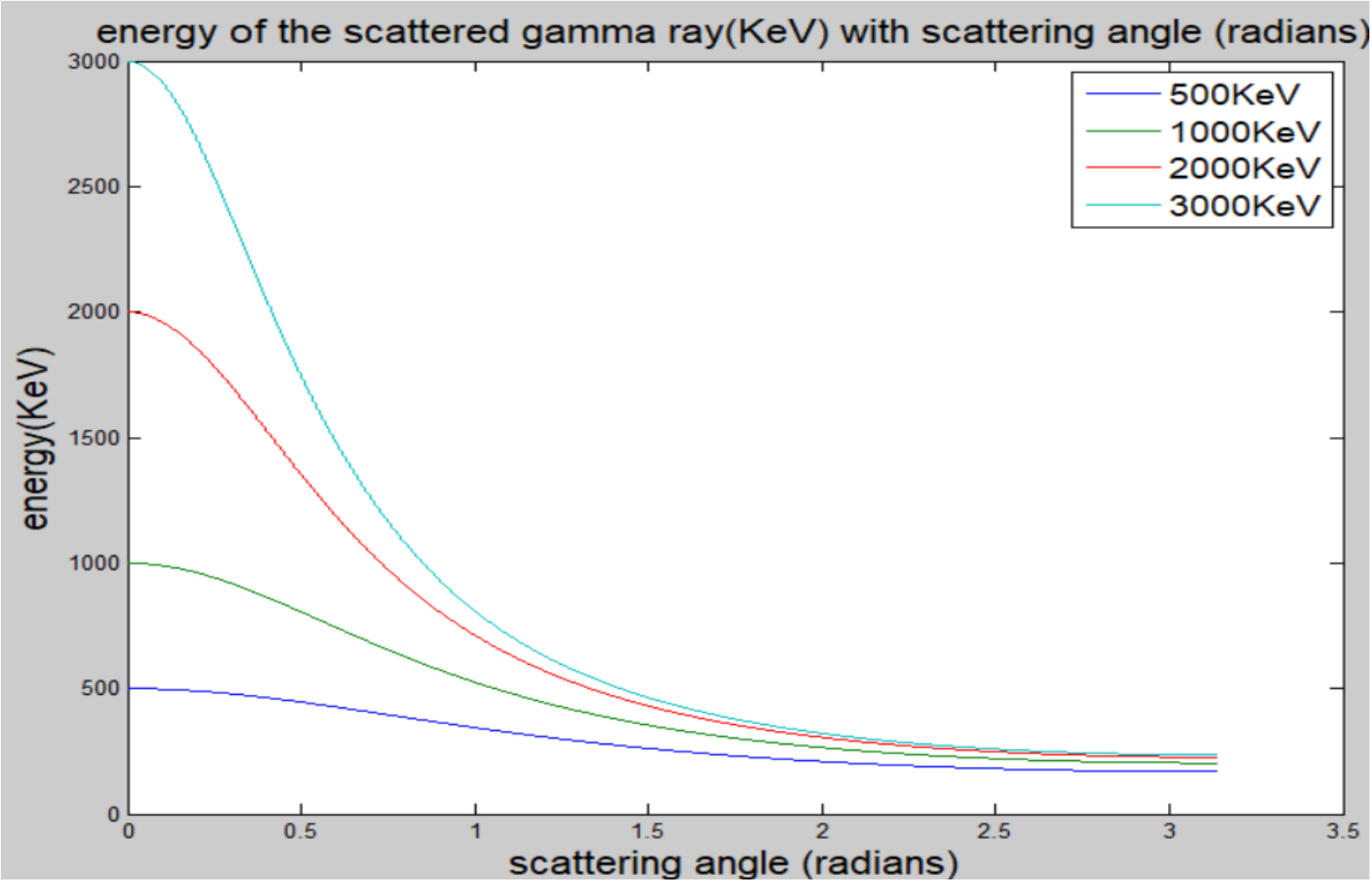


Fig 2

y= $\frac{h\nu}{1+\frac{h\nu(1-cos(x))}{mc^2}}$ for different $h\nu$,y=Eγ',$x=\theta$.

Repeating the above stated process and plotting we obtain this graph.

As we can see in fig 1 and fig 2 sum of the energies at any angle is equal to a constant value $h\nu$(energy of the radiation).

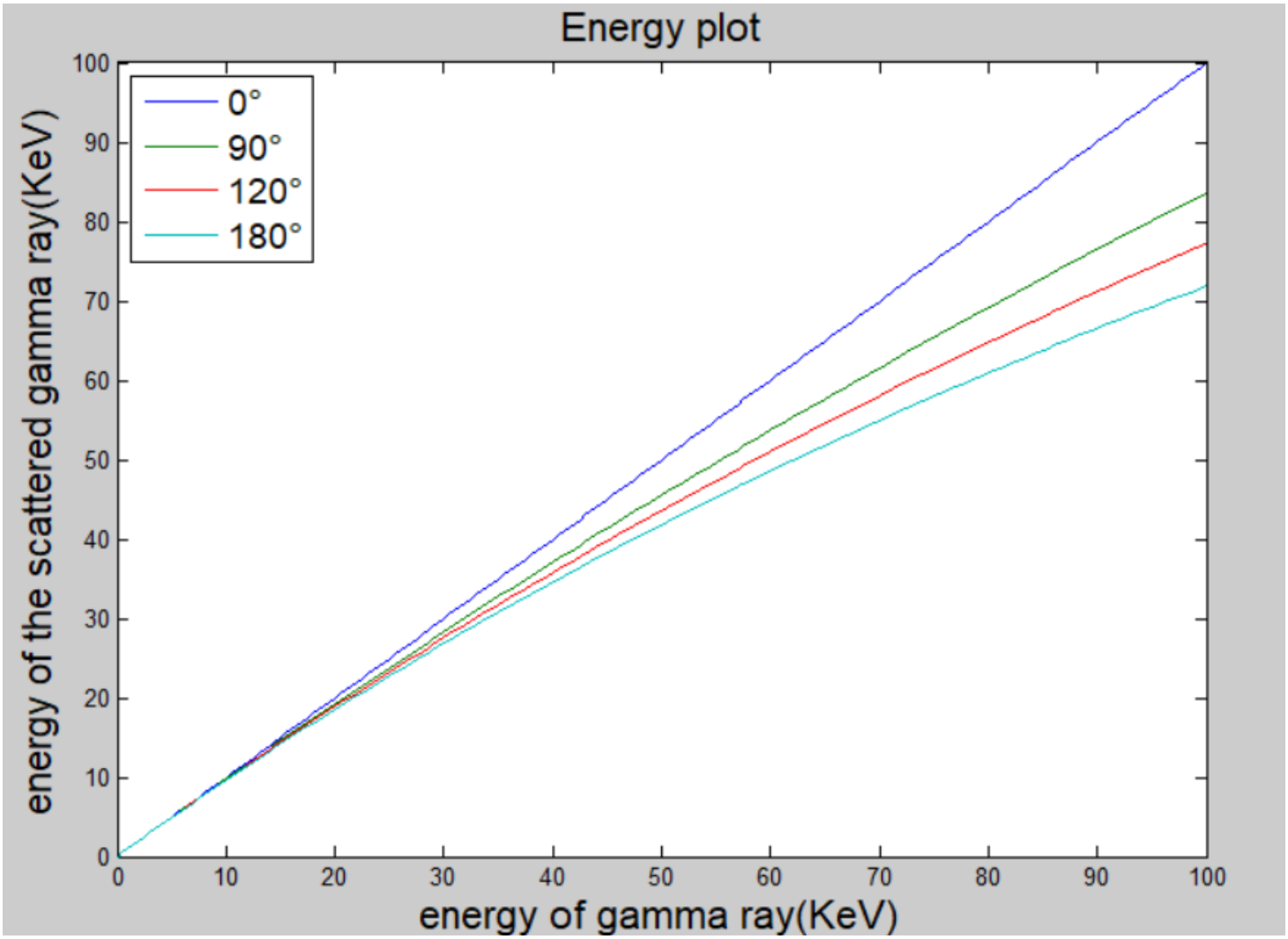


Fig 3

y= $\frac{\square}{1+\frac{x(1-cos(\theta))}{mc^{2}}}$ for different θ,y=Eγ $^{|}$,$x=h\nu$.

We take different $\theta(radian)$ (different scattering angle). It is plotted for the energy of the scattered gamma ray (KeV) with energy of the incident gamma ray(KeV). In this plot it can be seen that the curve with angle 180 degree represents the energy of gamma ray at the compton edge. You can see here that the energy of Compton edge increases with increasing initial energy but at a decreasing rate.

Energy plot of electron:

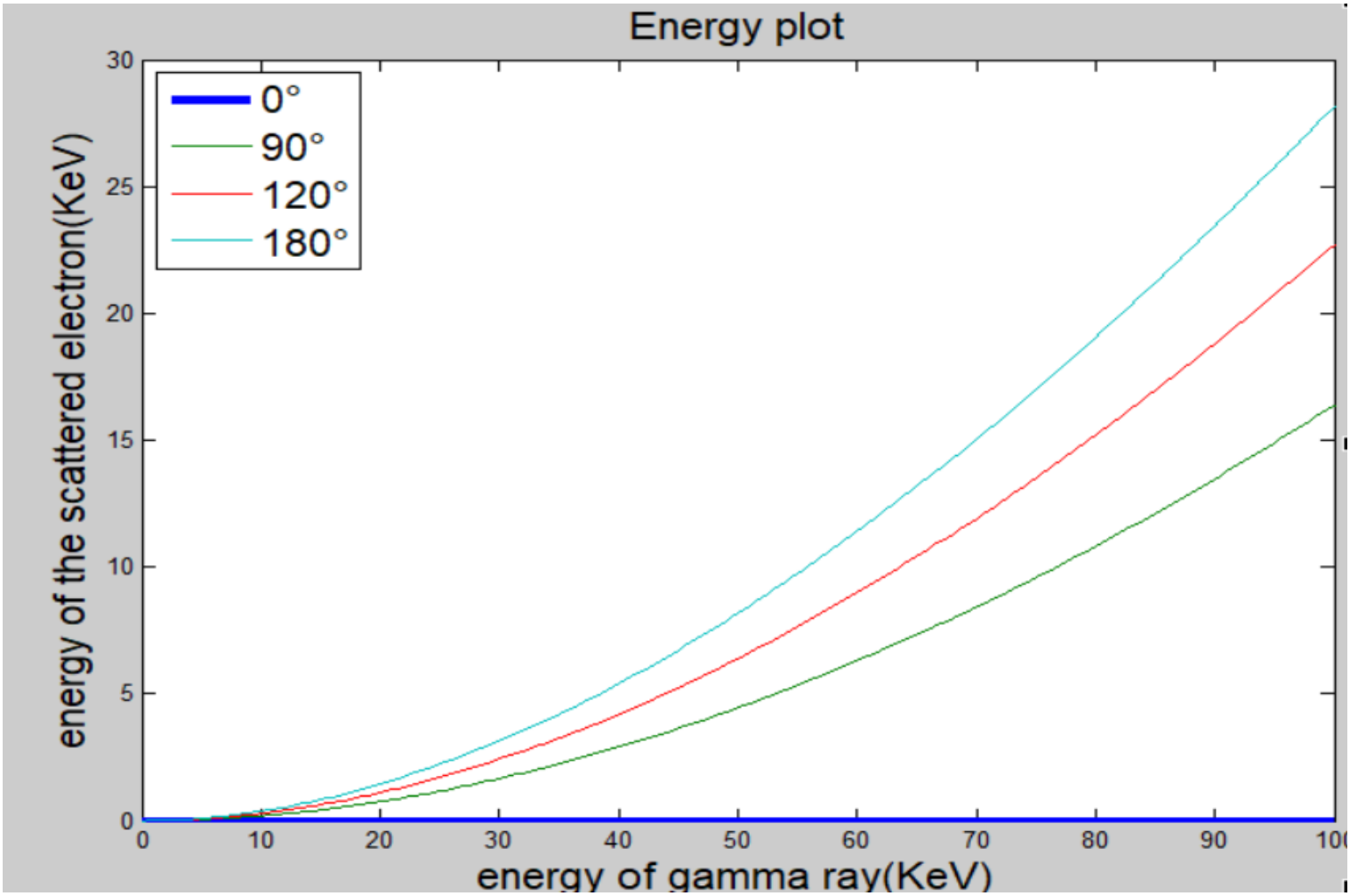


Fig 4

y= $\frac{x^2(1-cos(\theta)}{mc^2+x(1-cos(\theta))}$ for different $h\nu$,y=Ee,x=$h\nu$.

We take different $\theta(radian)$ (different scattering angle). It is plotted for the energy of the scattered electron(KeV) with energy of the incident gamma ray(KeV).

At angle $\theta = 0, \Rightarrow$ y=*0*, which gives that energy gained by scattered electron is 0, and 100% energy of incident gamma ray is gone to scattered gamma ray.

Procedure

Rutherford Backscattering Spectrometry

For this experiment we have used a Duoplasmatron ion source, 3MV Tandetron accelerator and a tungsten oxide(WO3) thin layer sample.

The Duoplasmatron ion source produces a plasma of either hydrogen or helium at 15 keV. We then extract the H- ions and apply a positive potential in between and grounded at the ends, this is called a Tandetron. The H- ions that we're extracted gets to the center of the Tandetron accelerator through the potential of 1MV with the help of steerers to guide the beam which work using magnetic fields, here they are bombarded with nitrogen gas and gets converted into H+ and again they are accelerated with the help of potential of 1 MV towards the sample. So, in total they are accelerated through 2 MV potential. So the total energy gained by the H+ projectile in the end by this method is 2600 KeV.

High level vacuum is maintained in the Tandetron accelerator using a turbomolecular pump, this is done to minimize the interaction of ions with the atoms present in air.

The above picture shows a complete setup of 3 MV Tandetron accelerator

Gamma Ray Spectroscopy

For this experiment we have used a high purity Germanium detector which has a single crystal in it . We have also used a sodium iodide detector to detect the gamma-ray signal. These detectors use electrical pulses and amplify them to get the results. After this we have extracted the results and plotted a graph between the energy and its intensity.

The high purity Germanium detector has a covering of aluminum which is 10 mm away from the front of Germanium crystal, Germanium crystal size is 64 mm and the aluminum width is 0.67 mm , the diameter of the aluminum is 59mm.

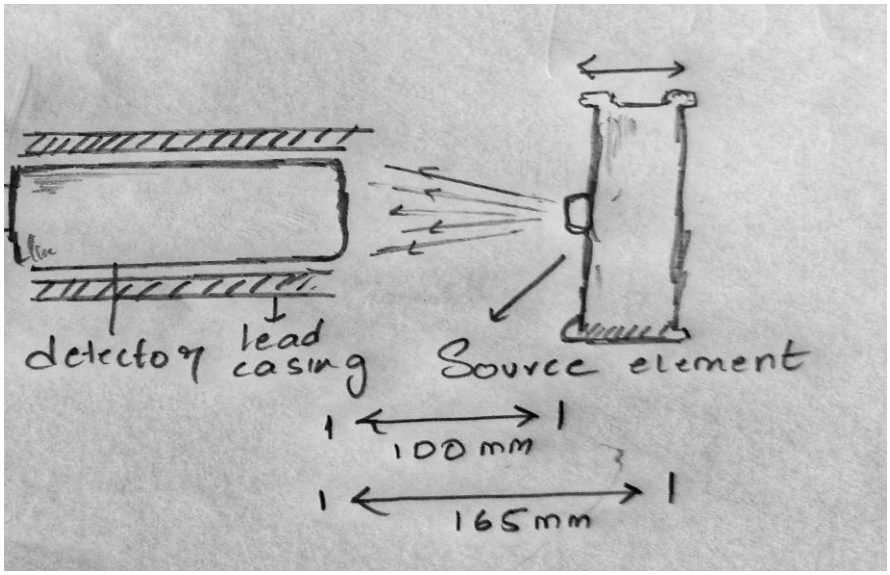
High Purity Germanium detector (HPGe)

NaI detector

High purity germanium gives sharp peaks whereas NaI gives a broad peak. This shows that the HPGe is more precise in differentiating the wavelengths. NaI on other hand gives us the result of various wavelengths which gives us a broad peak. We can say that the resolution of HPGe detector is more and the sensitivity of the NaI detector is more.

We have taken a high purity germanium detector and placed the Cs*137*at a distance of 100mm by

using a scale. We aligned it in such a way that it is placed at the center of the Ge crystal. We have also used Nitrogen gas for the Ge crystal to work efficiently. We did the following because the gamma rays interact with the electrons of the germanium crystals and get scattered. They produce a low ampere signals which gets amplified through an amplifier. We used the resulting signal to plot the graph.



Then we have placed the Co*60*at the same distance of 100 mm from the front of detector and repeated the experiment.

After that we have placed Ba 133 at a distance of 100 mm and repeated the experiment.

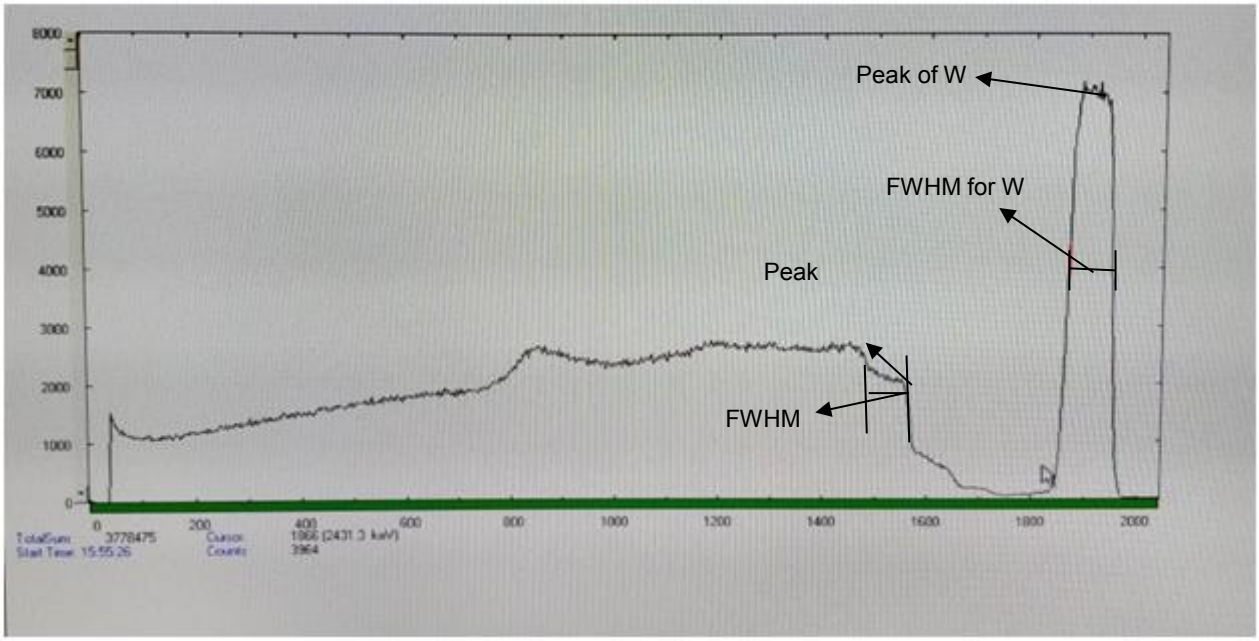
For analysing the result after changing the initial condition of the gamma ray spectrum using HPGe, we have used a 11mm lead casing (config 3) and a 40mm lead casing (config 4) such that the uncovered portion of the casing is 11 mm and 40 mm respectively. Also the source is placed at a distance of 100 mm from front of the High purity germanium detector and it is aligned such that it is at the center of the detectors front.

Then we have taken the Sodium Iodide detector in order to compare the results of the Cs 137 without the Aluminum plate and with the Al plate (config 2) when placed behind the Cs 137,

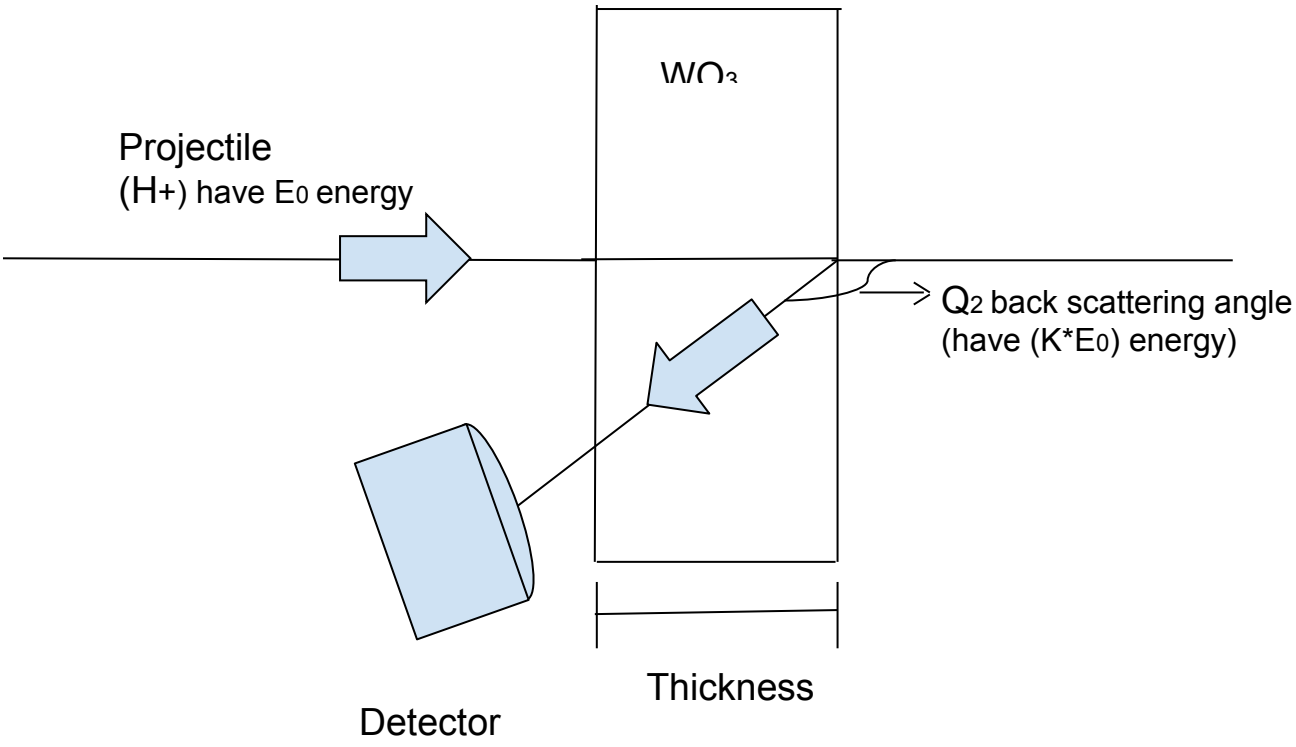
We have repeated the process by placing the Cs 137 source at a distance of 100mm from the NaI detector and it should be at the center of the front of the detector.

Results

Rutherford Backscattering Spectrometry



After calibration of the channel numbers with energy with the help of the gold sample, We obtained the above plot of intensity versus energy by using the Tungsten Oxide (WO3) thin layer sample and operating the Tandetron accelerator. With the help of Tandetron accelerator a beam of projectiles of proton (H+) of energy 2600 KeV each is generated which is incident on the tungsten oxide (WO3) thin layer and is backscattered towards the detector which is at 170 degrees from the direction of the projectile and thus the above plot is obtained. From this plot, the characterization of the thin layer can be done. The characteristic peaks of Tungsten(W) and oxygen(O) can be observed in the plot. Now for calculating the thickness of the tungsten we need to calculate the ΔE from the plot. It can be calculated by calculating the FWHM (Full width at half maximum) of the Tungsten(W) or Oxygen(O) peak. We used FWHM of Tungsten(W) peak in this case. So, ΔE = FWHM of W= 114 KeV.



[Showing back scattering of the proton]

When (H+) proton passes through the WO_3 , it losses some energy (ΔE)

$\Delta E=[S]*t$;

$$[S]=\frac{1}{cos(Q1)}\frac{dE}{dx}\text{(evaluated at } E_0\text{)} + \frac{1}{cos(180°-Q2)}\frac{dE}{dx}\text{(evaluated at } K*E_0\text{)} \text{ ; \{1\}}$$

[S] is **energy loss factor** which correspond to the energy loss.

We evaluate the ΔE from the plot of energy vs intensity,

where Q1 is the angle at which proton is incident on the target surface. In our case it is 0°.

K is kinematic factor which is $E1/E_0$;

where E1 is final energy and E_0 is initial incident energy which is incident on the target surface. In our case E_0=2600 KeV and K has a value between 0 and 1.

$$K = \frac{E_{scattered}}{E_{incident}} = \left[\frac{\left(1 - \left(\frac{M_1 \sin\theta}{M_2}\right)^2\right)^{1/2} + \frac{M_1 \cos\theta}{M_2}}{1 + \frac{M_1}{M_2}} \right]^2$$

E	Ion energy
M_1	Mass of incident ion
M_2	Mass of t arget atom
θ	Scattering angle

Q2 is the angle at which proton is reflected back from the target surface. In our case it is 170°.

Form the graph we get the value of ΔE= 114 KeV,

And $\frac{dE}{dx}$(evaluated at E_0) =33.2 KeV,

$\frac{??}{dx}$(evaluated at K*E_0) =33.6KeV.

We have used a program called SRIM (Stopping and range of ions in matter) to calculate the above differentials.

By using equation 1, we get

[S]=33.2+34.1=77.3 KeV/micron,

t=ΔE/[S]=114/77.3 = 1.47micron.

Gamma ray Spectrometry.

High purity Germanium detector(HPGe)

Config 3.

11 mm from the front of detector.

Config 4 .

40 mm from the front of the detector.

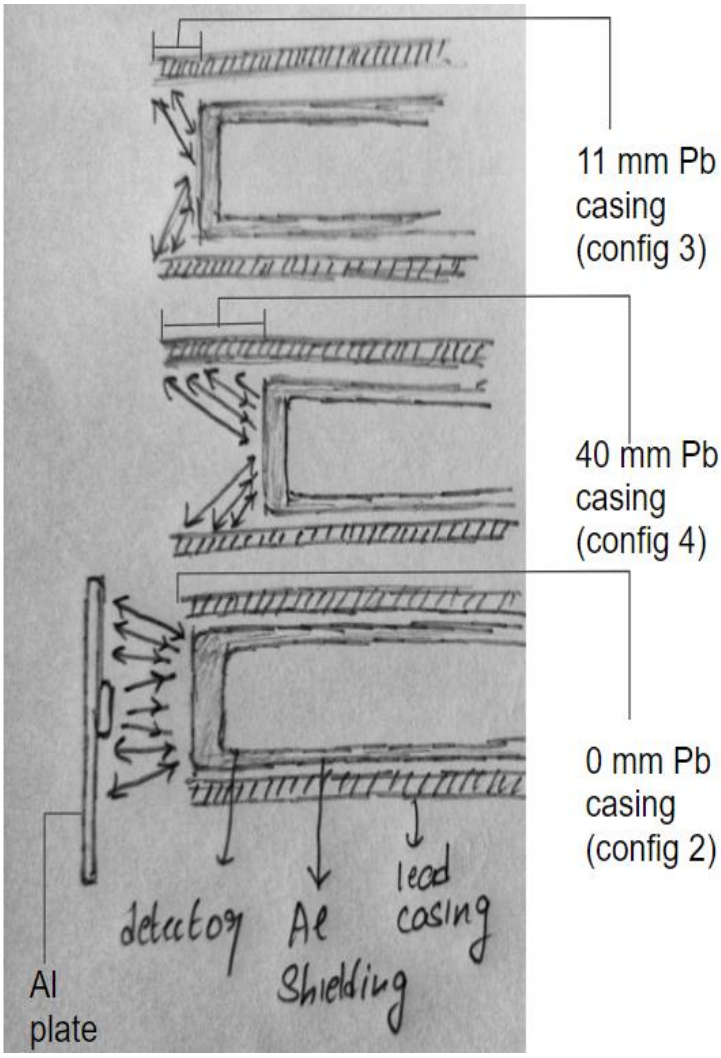
Sodium iodide

Config 1

0 mm from the front of the detector without Al plate behind the source.

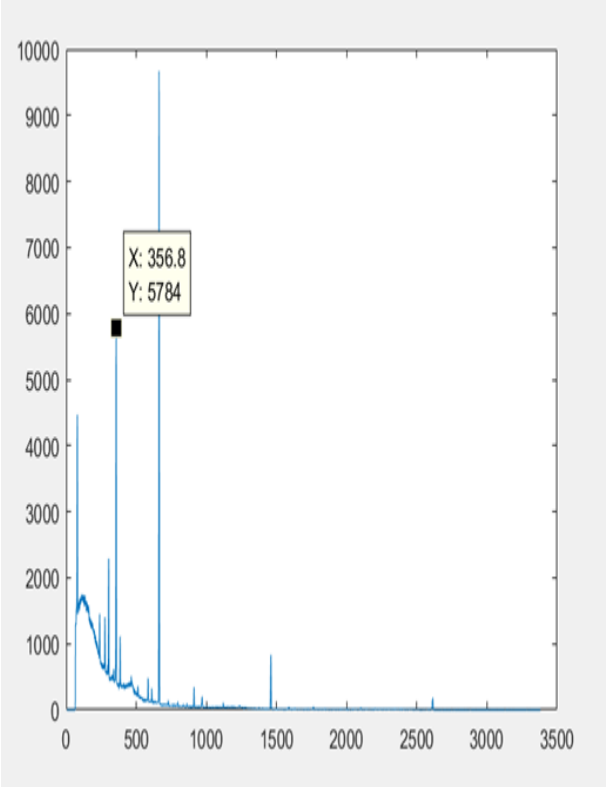
Config 2.

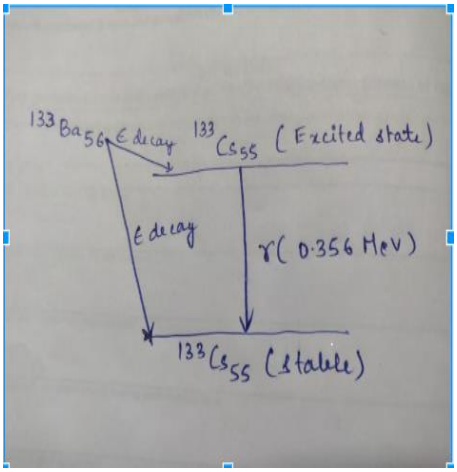
0 mm from the front of the detector with Al plate behind the source.



Plots of INTENSITY v/s ENERGY for Radioactive Isotopes.(Energy is in KeV.)

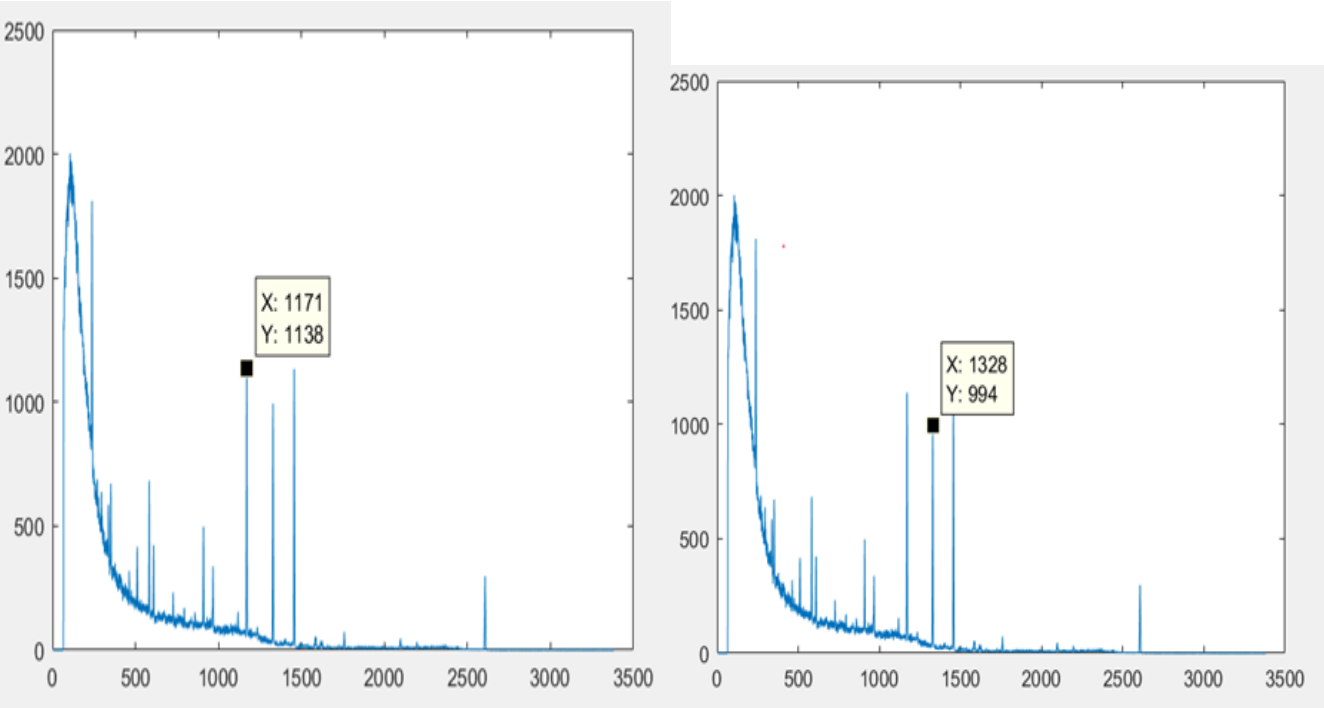
Plot of Ba-133(Half life 10.51 years)

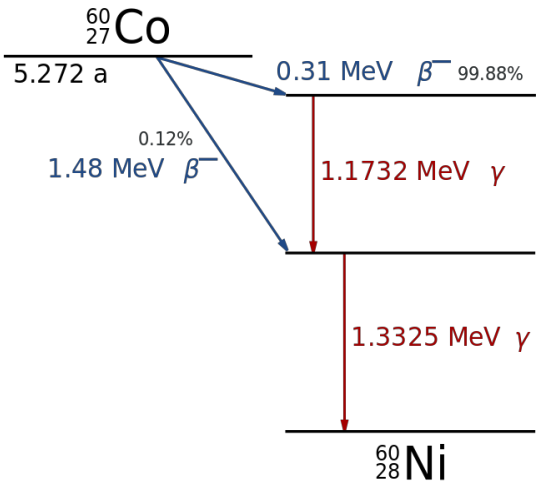




This plot is for the isotope of barium with atomic mass 133. It undergoes an electron capture and converts into isotope of Cesium of atomic mass 133. Since Cesium formed is in higher nuclear state, it radiates Gamma radiation of characteristic energy 356.8 KeV to come to the ground state.

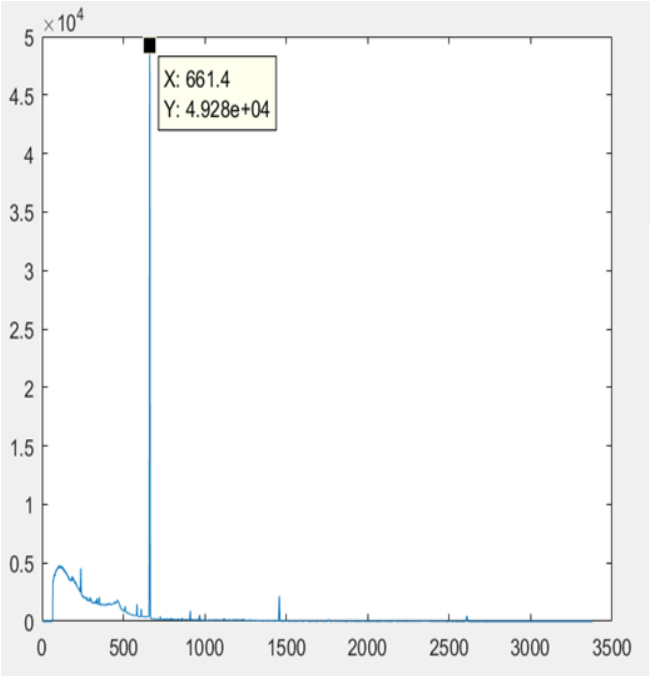
Plot of Co-60(Half life 5.26 years)

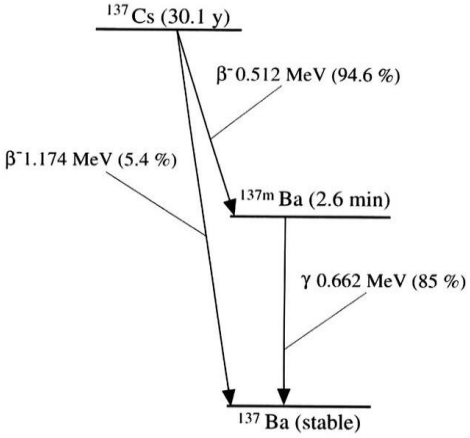




These plots are for the isotope of Cobalt with atomic mass 60. It undergoes a beta radiation reaction by releasing an electron and converts into isotope of Nickel of atomic mass 60. Since Nickel formed is in 2 different higher nuclear states, it radiates Gamma radiation of 2 different characteristic energies 1.17 MeV and 1.3 MeV to come to the ground state.

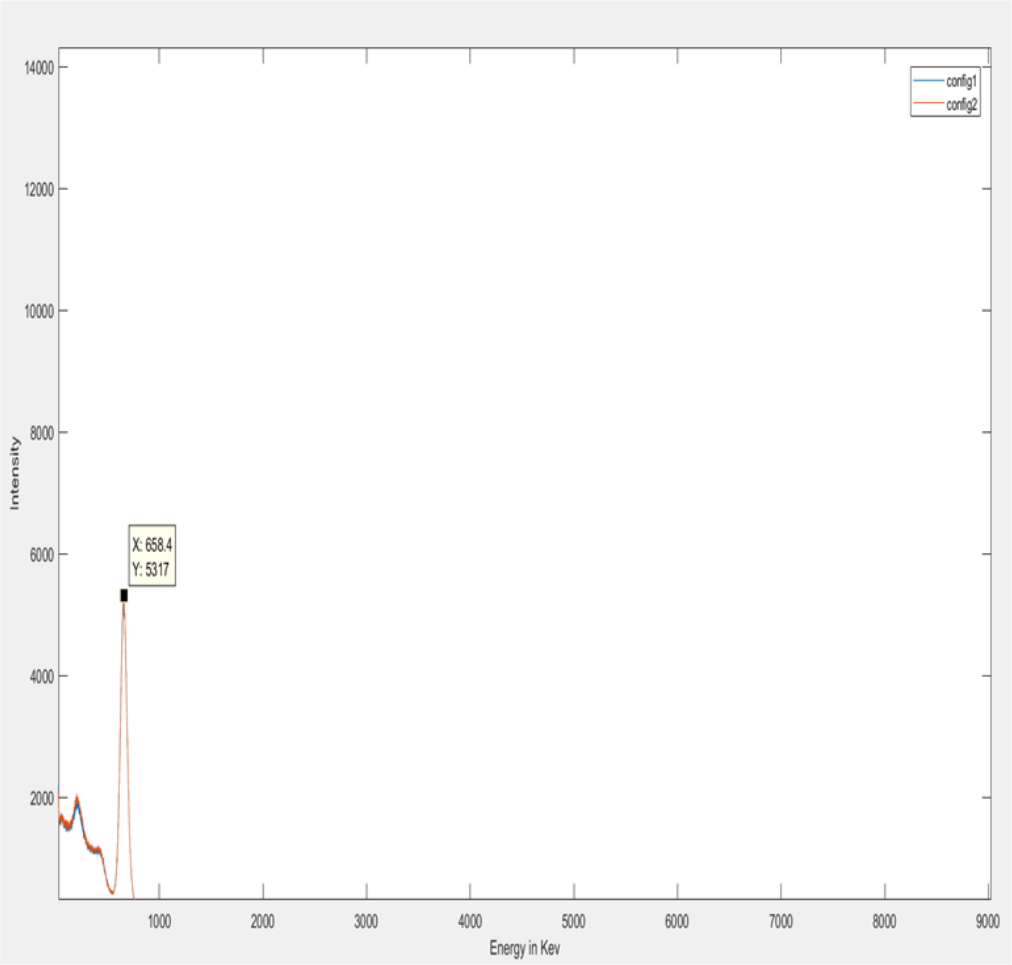
Plot of Cs-137(Half life 30.17 years)



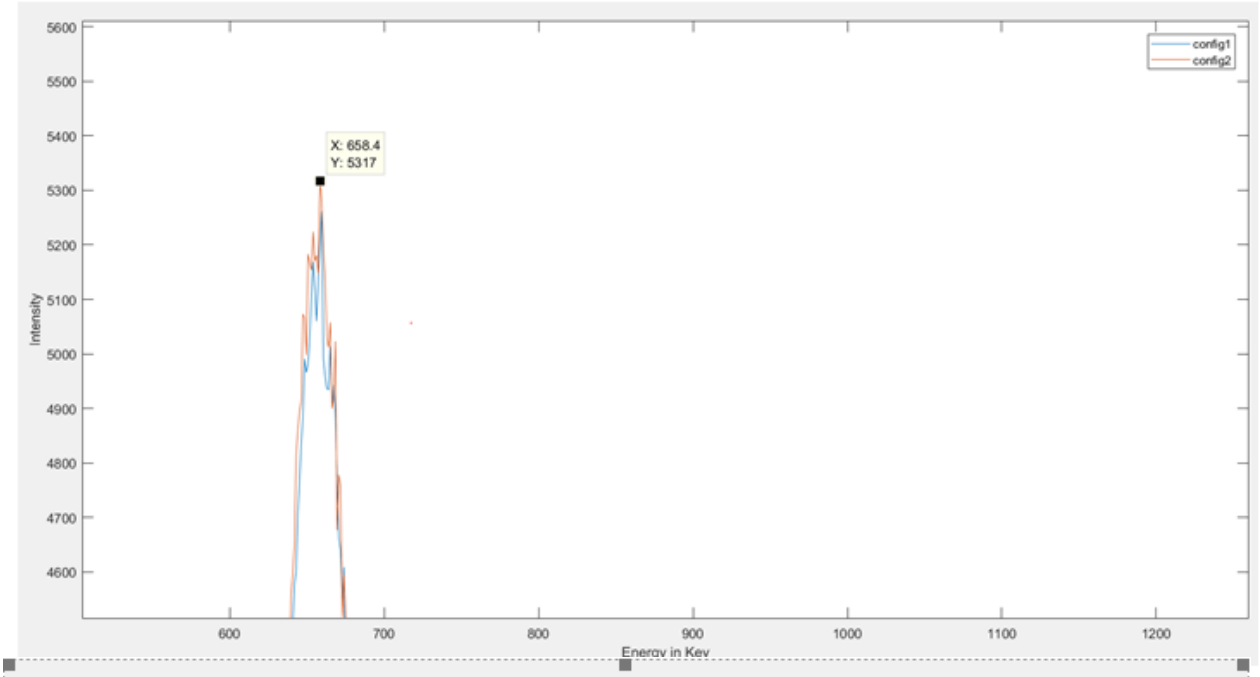


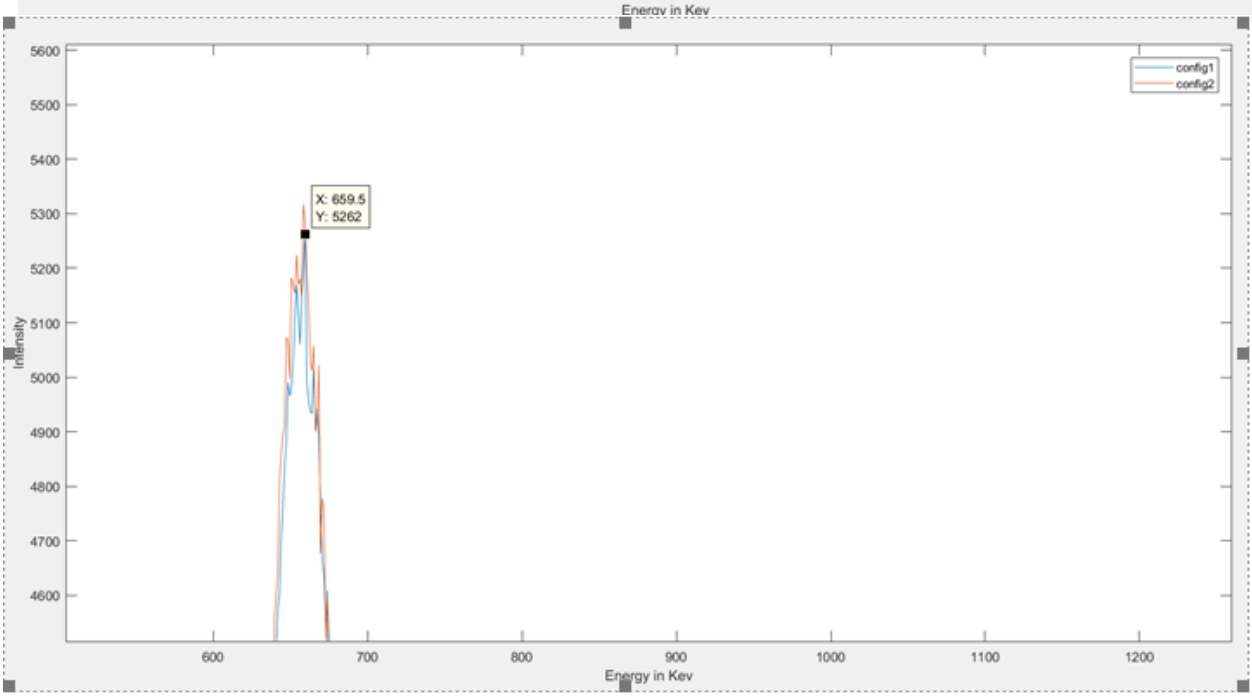
This plot is for the isotope of Cesium with atomic mass 137. It undergoes a beta radiation reaction by releasing an electron and converts into isotope of Barium of atomic mass 137. Since Barium formed is in higher nuclear state, it radiates Gamma radiation of characteristic energy 661.4 KeV to come to the ground state.

Plots of INTENSITY v/s ENERGY for Cs-137 with lead shielding on detector. (Energy is in KeV.)

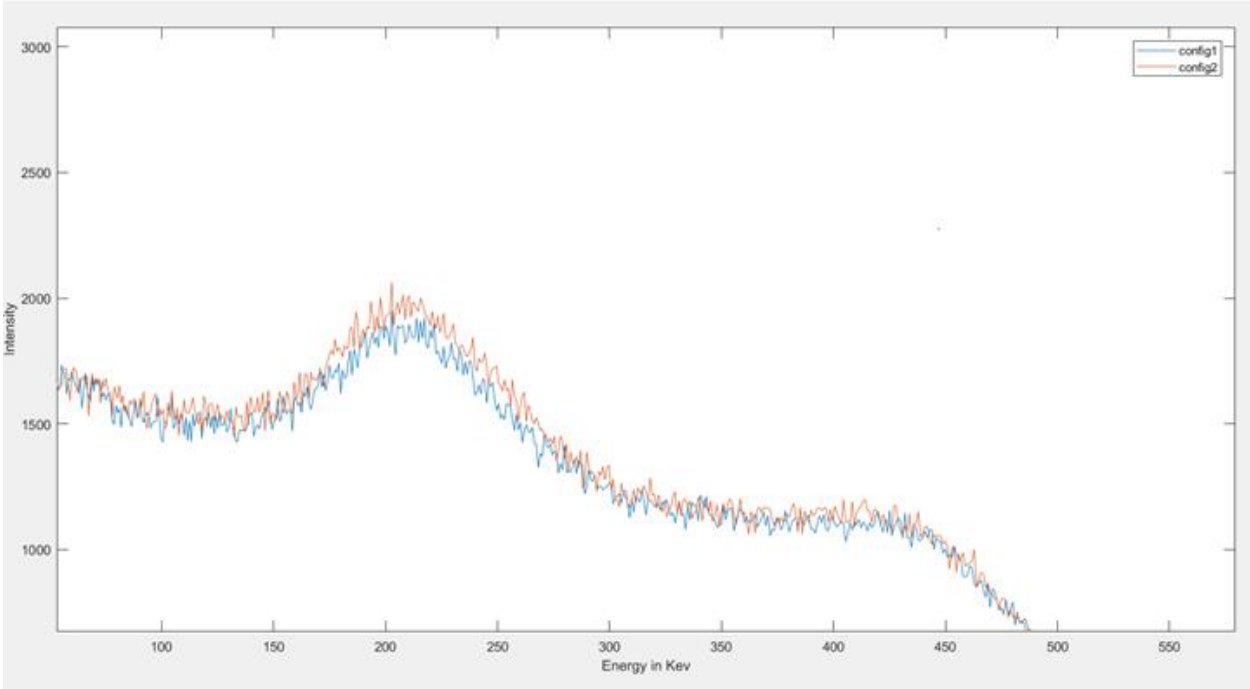


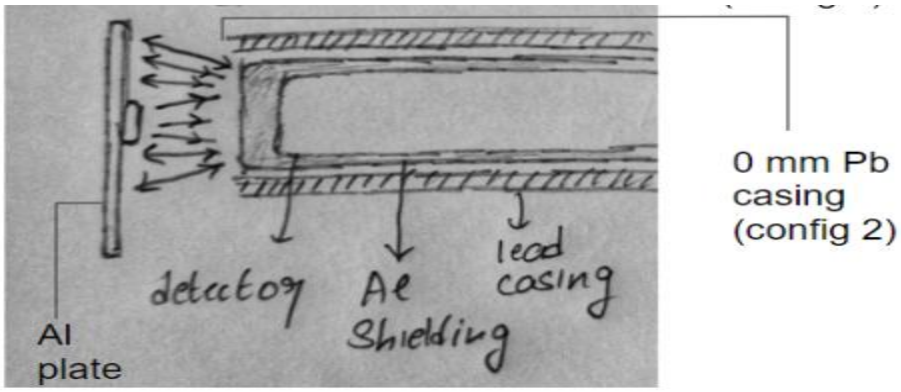
This plot is of Cs-137 in 2 different conditions. In config 1 ,the detector is covered with lead encasing and there is no Aluminum plate behind the source. In config 2 the detector is covered with lead encasing and there is a aluminum plate behind the source. Lead encasing helps in reducing background radiation in both the cases. In both the cases intensity is calibrated for 1200 seconds.





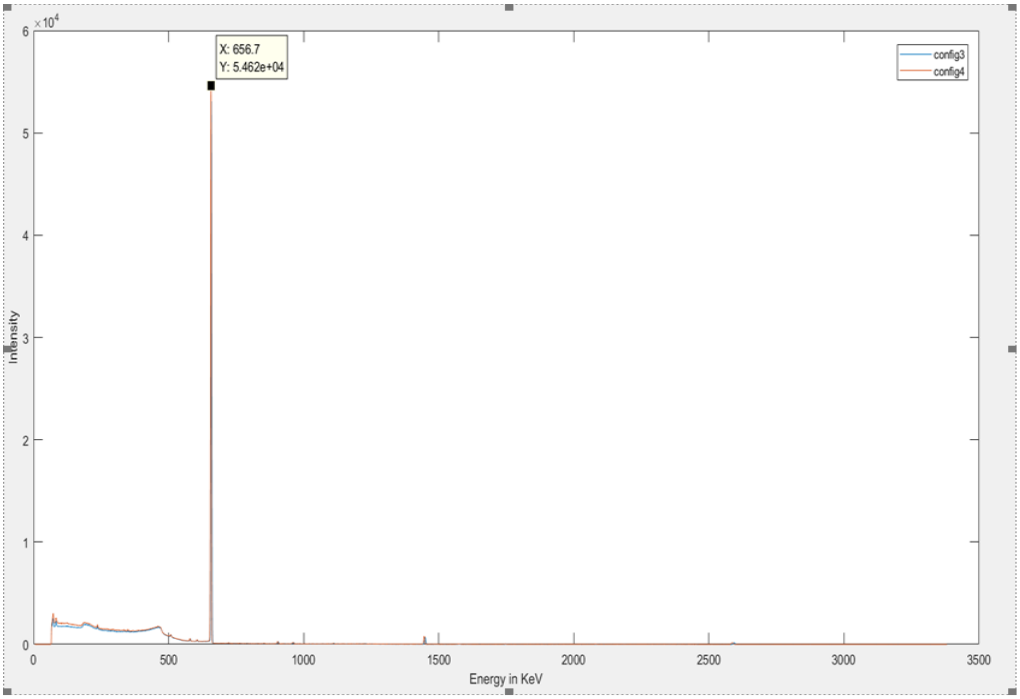
These plots are the zoomed in versions of the previous plot at the photoelectric peak. It can be seen here that in config2 , intensity is 5317 and in config1, intensity is 5262. This is because some of the gamma radiation from the source gets reflected by the Aluminum plate toward the detector. That is why intensity is more in config2.





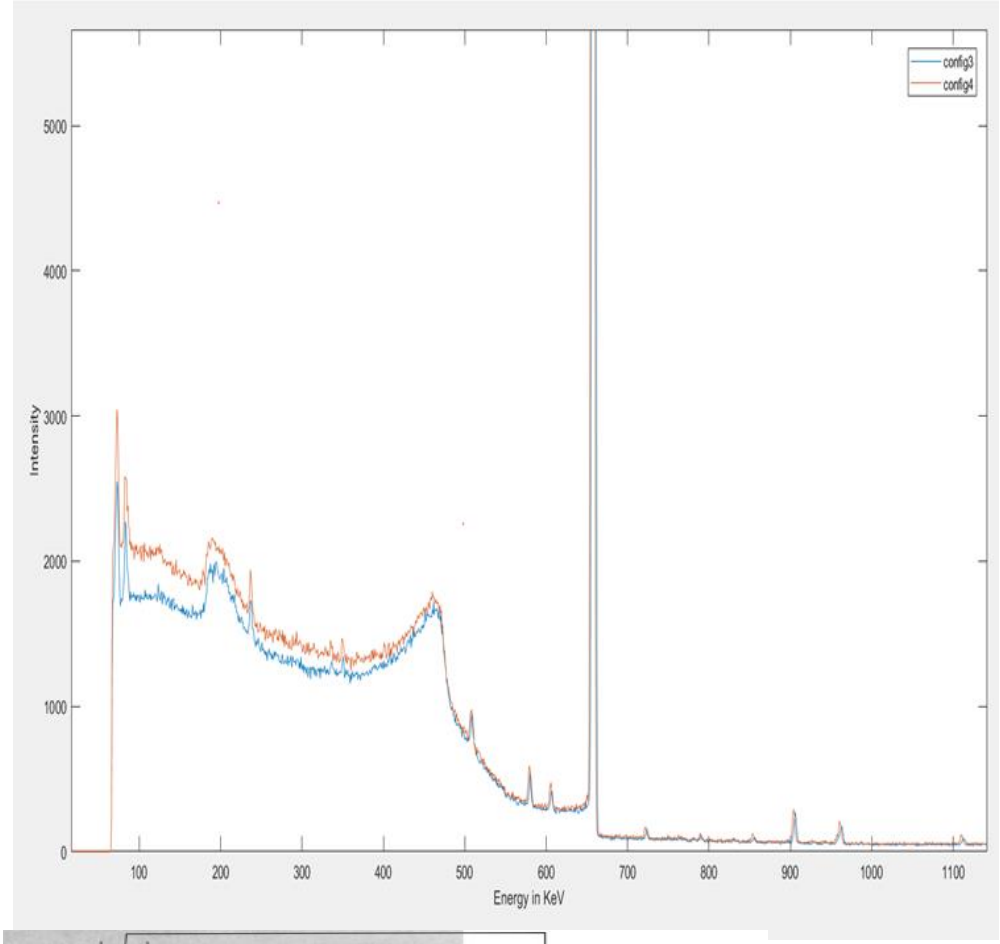
This plot is zoomed in at lower energy part of the same plot. In this plot, it can be seen that intensity is more in the case of config 2. This is because gamma rays that gets backscattered by the Na-I crystal in the detector is again reflected towards the detector by the Aluminum plate.

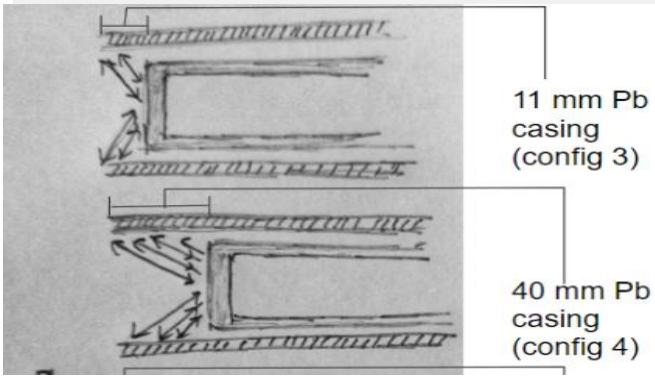
Plots of INTENSITY v/s ENERGY for Cs-137 with lead shielding on HPGe detector. (Energy is in KeV.)



This plot is of Cs-137 in 2 different conditions. In config 3, the detector is covered with lead encasing with 11mm distance

between the face of the detector and the face of the lead encasing as shown in the procedure. In config4, the detector is covered with lead encasing with 40mm distance between the face of the detector and the face of the lead encasing. Lead encasing helps in reducing background radiation in both the cases. In both the cases intensity is calibrated for 1800s.





This plot is the zoomed-in version of the previous plot at the lower energy region. In this plot, it can be seen that in config4 case intensity is more. This is because in the case of config4 there is more lead encasing in front of the detector and because of this more gamma radiation scattered from the germanium crystal at some angle gets reflected again towards the detector than in the case of config3.

CONCLUSION

Using methods of gamma ray spectroscopy, we were able to obtain the spectral analysis of the different isotopes of elements such as Co 60, Ba 133 and Cs 137.

We have studied about the working of HPGe and NaI detectors.

We have studied the kinetics of Compton scattering and obtained experimental results which are in line with the observed theory.

The initial conditions of the experiment were changed to obtain spectral analysis graphs of specialized cases where we used lead encasing positioned at different lengths, and Aluminum plate was also installed behind the source which reflected back the back scattered gamma rays from the Ge crystal again towards the detector.

Thus we have learnt the theories and properties of Compton Scattering and how it can be used in the spectral analysis of elements.

We have also studied the working principles and kinematics of Rutherford backscattering spectrometry and how it is used in the surface analysis of samples.

RBS is a quantitative and non-destructive technique and thus it has become a widely used surface analytical technique

RBS is used to measure the composition, areal concentration, density and thickness of the film

References: Page 49-50 and 323-325 of Radiation Detection and Measurement By Glenn F. Knoll.