# Lab report 5: Gamma rays

Name: Benjamin Stott, ID: 18336161
Lab Partner= None(Virtual lab)
JS Physics

March 12, 2021

---

## Declaration concerning plagiarism

I have read and I understand the plagiarism provisions in the General Regulations of the *University Calendar* for the current year, found at http://www.tcd.ie/calendar

I have completed the Online Tutorial in avoiding plagiarism 'Ready, Steady, Write', located at http://tcd-ie.libguides.com/plagiarism/ready-steady-write

STUDENT NUMBER: 18336161

SIGNED: Benjamin Stott

## Contents



## List of Figures

## List of Tables



### Abstract

This lab deals with Gamma rays, the acquisition of the data and in particular how the quality of the data is affected by certain parameters of the device.

The first experiment involved analysing the effect of the PM tube voltage upon the spectrum of a $Cs^{137}$ sample. As the voltage was increased so too did the position $H_0$ of the total energy peak according to an exponential relation $H_0 \propto V^n$. "n" was found to be $(7.57 \pm 0.12)$ which is around 8. This corresponds to the number of dynodes within the system.

The second experiment involved measuring 3 separate spectra of $Co^{60}$, $Na^{22}$ and $Cs^{137}$ at a supply voltage of 600V. Data such as the FWHM, the resolution and position of these peaks was tabulated. It was found for all of these spectra that the resolution increased as the counts increased as to be expected(thereby decreasing the limit resolution).It was also possible to measure the detection efficiency of some of these peaks by using the relations between total energy peaks and sum peaks(in further detail in the experimental method). The efficiency of the detector at 511Kev for the $Na^{22}$ sample was found to be $(31.5 \pm 0.01)\%$. The efficiency of the first and second large photopeaks of $Co^{60}$(at energies $(1172.9 \pm 2.8)KeV$ and $(1332 \pm 2.8)KeV$ ) were found to be $(8.57 \pm 0.01)\%$ and $(11 \pm 0.02)\%$.

Finally, the activity of a weak KCl sample was measured. Specifically, the $K^{40}$ ions within the sample which produced Gamma rays. The theoretical activity of the sample(given its mass, half life, abundance and how many gamma rays are produced) was calculated to be 6.158Bq. The obtained activity of the sample(dividing counts by runtime i.e counts per second) was returned as 0.189Bq. There is a large disparity between these two values which is likely due to only allowing the spectrometer to run for 0.9897days. If the counts had been collected for a longer amount of time, a greater signal to noise ratio would likely have been obtained and thus more trustworthy data.

note: references to the bibliography are denoted by |**x**| where x corresponds to the index number of the bibliography entry.

:

# I. Theory

## I. General derivation of useful equations

### I.1 Effect of PM tube voltage|3|

The overall amplication factor or gain of a PM depends on the number of dynodes in the multiplier section and the secondary emission factor 0, which is a function of the energy of the primary electron. the energy of the electrons incident on each dynode is clearly a function of the potential difference, Vd , between the dynodes so that we can write.

$$\delta = KV_d$$

, where K is a proportionality constant. The gain of the PM tube is then

$$G = \delta^n = (KV_d)^n$$

The constant "n" here is the number of dynodes(a piece of equipment that collects secondary electrons multiplied in the cascade process through multi-stage dynodes and outputs the electron current to an external circuit).Below a diagram of the gain vs voltage can be found for various materials, detailing the exponential relationship present.

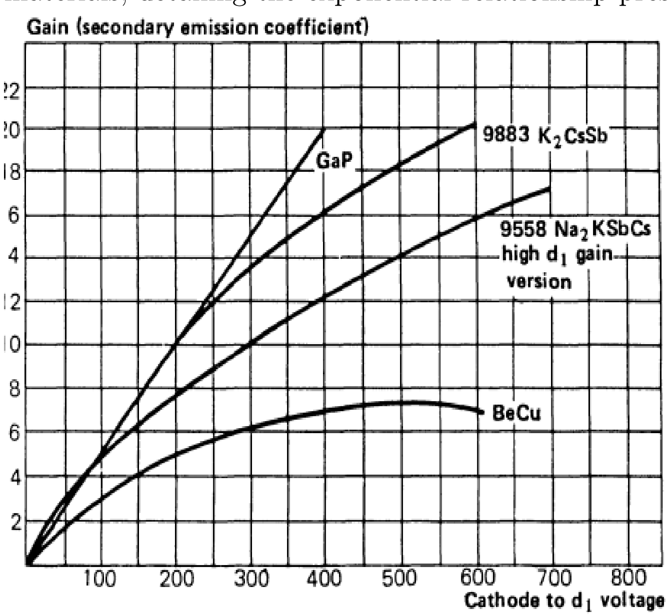



Figure 1: . Secondary emission factor for several dynode materials (from EMf Catalog |3|

### I.2 Resolution|2|

The resolution of a peak can be found by utilising the equation

$$R = FWHM/H_0$$

Peaks can also be fitted as gaussian functions in the form

$$G(H) = \frac{A}{\sigma\sqrt{2\pi}}exp(\frac{-(H-H_0)^2}{(2\sigma)^2})$$

The poisson limit of this is found to be

$$R = \frac{2.35}{\sqrt{N}}$$

In other words, what we should expect is that the greater the number of counts obtained, so too the greater the resolution obtained.

### I.3 Activity of a sample|1|

The activity of a sample is given by

$$A = \lambda N$$

where

$$\lambda = \frac{ln(2)}{t_{1/2}}$$

and

$$N = Totalcounts$$

These things can all be arrived at with the relevant specifications of the machine and the appropriate dimensional analysis.

### I.4 Photoelectric absorption

In photoelectric absorption, a photon interacts the absorpant material and excites it so that it ejects an electron from its surface. This is given by the equation

$$E_{e^-} = h\nu - E_B$$

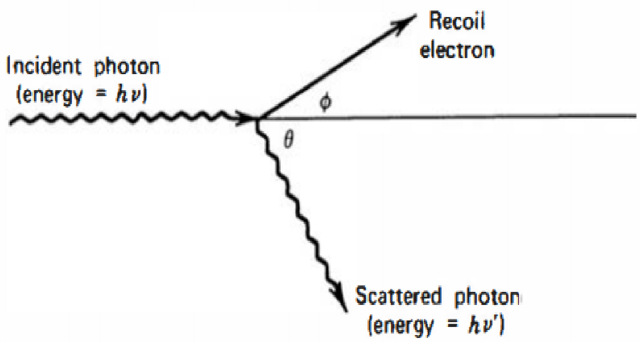
where $E_B$ is the binding energy of the electron.

### I.5 pair production

Pair production occurs when the energy of a gamma ray is high enough such that an electron and a positron are produced.

### I.6 Compton scattering|2|

The interaction below is between the incident gamma ray and an electron in the absorbing material. Energy is transferred to the electron which is scattered at an angle corresponding to the equation also detailed below.




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

Figure 2: compton scattering diagram and equation |2|

## II. Experimental procedure

### .1 Experiment 1:Effect of PM tube voltage

.

The aim of this experiment was to determine the effect of the pm tube voltage on the gamma ray spectrum. For this purpose a $Cs^{137}$ sample was utilised. The maestro software was setup, making sure that reading are appearing. The PM tube voltage was set at 400V and the $Cs137$ spectrum was recorded. This was repeated for voltage readings of 480V,500V,525V,550V,575,600,625 and 700V.The position $H_0$ of the total energy peak was recorded and a gaussian fit was performed using the origin software, where the "w" parameter in the fit corresponds to the FWHM. These values were tabulated and values of resolution were also calculated.

It is known that $H_0$ should be proportional to $V^n$. "n" is determined by taking the natural log of both PM tube voltage and $H_0$ and plotting them in a line. The resulting slope will then return "n" with the y intercept c also being relevant for accuracy.

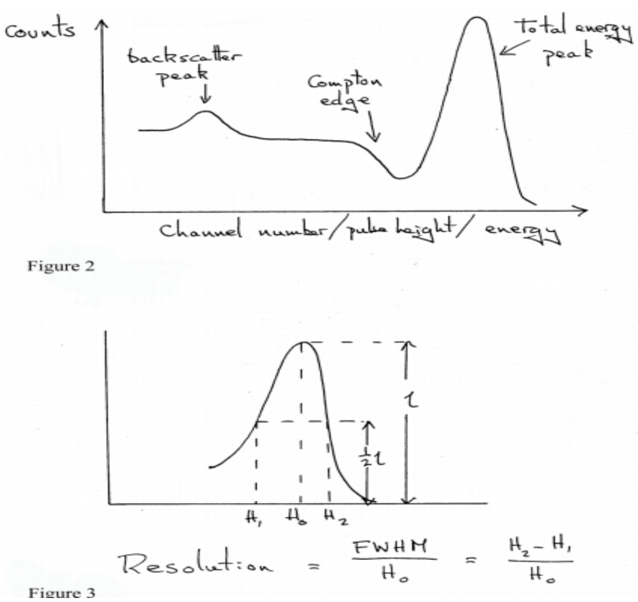



Figure 3: FWHM calculation and spectra characteristics

### .2 Experiment 2:Energy dependence of spectral resolution R

.

It should be noted that subsequent data analysis of these experiments were performed using python, the code of which can be found in the appendix. The spectra of $Cs^{137}$,$Na22$ and $Co^{60}$ were all recorded at a supply voltage of 600V. FWHM data aswell as resolution and peak location were recorded with their subsequent errors noted and calculated. The calibration for these spectra was around 2.8, varying slightly depending on the sample used. The variation of resolution R with energy was then obtained by observing the relevant data.

### .3 Detection efficiency from graphs

.

The detection efficiency of certain peaks at specific energies can also be calculated. The total energy peak's count rate is equal to the activity of the sample A multiplied by twice an effiency constant $\varepsilon$. The sum peak which is at a location further down in the spectrum, normally twice the previously mentioned peak should theoretically have a count rate equal to A$\varepsilon^2$. The samples for which the efficiency was measured were $Na^{22}$ and $Co^{60}$. Since the activity of these samples were not known, equations were divided by each other and a more useful relation was found in the following fashion|1|.

$$\frac{2A\varepsilon}{A\varepsilon^2} = \frac{countratetotalenergy}{countratesumpeak}$$

The activities cancel and with a little rearrangment we find something more useful

$$\varepsilon = \frac{2 \times (countratesumpeak)}{countratetotalenergy}$$

This is then multiplied by 100 in order to convert the data into a %.

### .4 Experiment 3: weak source activity data acquisition

A weak KCl source was placed in the container and a gamma ray spectrum pertaining to the $K^{40}$ within the sample was obtained. The scan was allowed to take place for 86311s(nearly a day). The longer the scan is left for, the greater the signal to noise ratio obtained and the more trustworthy the data for a weak emitting source is.

### .5 Calculating and comparing theoretical and experimental values of $K^{40}$ sample activity

We can compare the activity of the sample detected by the scintillator to that observed by the theory. The activity of the sample is merely calculated by diving the counts obtained by the runtime, thereby obtaining the correct units of counts/second or bequerels(Bq). The theoretical activity was calculated by taking various parameters of the device and sample in question into account, the full calculations of which are explained once the data analysis is done.

# III. Results and discussion

## .1 Experiment 1:Effect of PM tube voltage

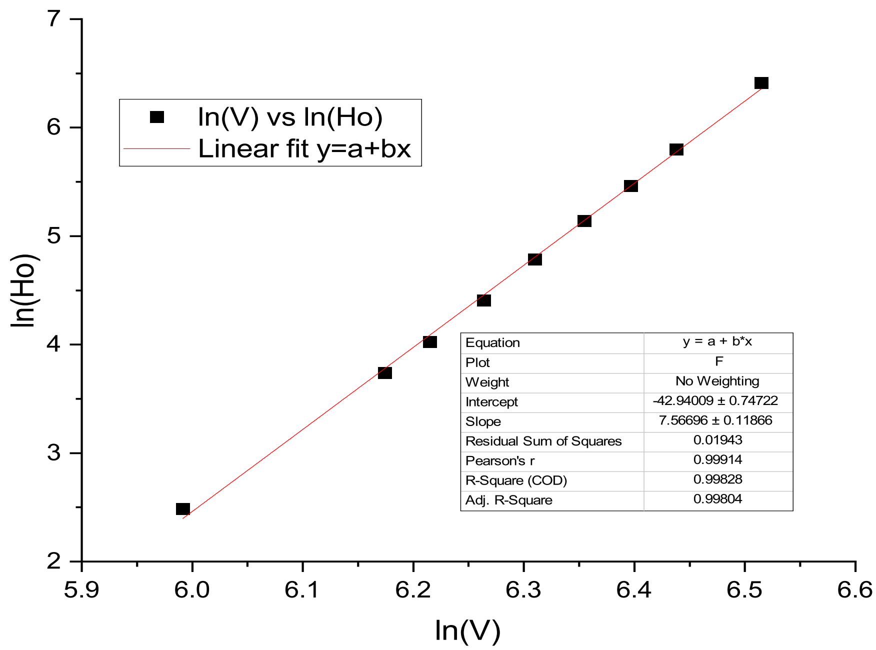



Figure 4: ln(V) vs ln($H_0$) to determine n where $V^n = H_0$

| V(volts) | $H_0$ | FWHM | R | $\delta V(\pm)$ | $\delta H_0(\pm)$ | $\delta FWHM(\pm)$ | $\delta$R($\pm$) |
|---|---|---|---|---|---|---|---|
| 400 | 12 | 4.15 | 0.35 | 1 | 1 | 2 | 0.19 |
| 480 | 42 | 3.41 | 0.08 | 1 | 1 | 2 | 0.05 |
| 500 | 56 | 4.48 | 0.08 | 1 | 1 | 2 | 0.04 |
| 525 | 82 | 6.36 | 0.08 | 1 | 1 | 2 | 0.03 |
| 550 | 120 | 8.92 | 0.07 | 1 | 1 | 2 | 0.02 |
| 575 | 171 | 12.41 | 0.07 | 1 | 1 | 2 | 0.01 |
| 600 | 236 | 16.87 | 0.07 | 1 | 1 | 2 | 0.01 |
| 625 | 330 | 22.98 | 0.07 | 1 | 1 | 2 | 0.01 |
| 675 | 610 | 38.85 | 0.06 | 1 | 1 | 2 | 0.005 |

The graphs from which the values of $H_0$ were extracted can all be found in the appendix. It is known that the dependence on voltage is given by the equation $H_0 = V^n$. Taking the natural log of both sides we find $ln(H_0) = nln(V)+c$ in the form $y = mx+c$. Thus n is determined to be $(7.57\pm0.12)$ and c is $-42.94\pm0.74$ according to the origin linear regression above. We can also find from the data corresponding to the total energy peak above that the resolution decreases in proportion to the voltage of the power supply.

To prove that this is indeed effective, I shall calculated the resolution at 600V and compare with the obtained value.

$$ln(H_0) = (7.57 \pm 0.12)ln(600) - 42.94 =$$

$$(48.43 \pm 0.2) - (42.94 \pm 0.74) = 5.49 \pm 0.12$$

$$H_0 = 242.26 \pm 30.09$$

The obtained value was 236 which is within experimental error range. These would then have the same resolution of we take the FWHM to be the same for both of them.

$$R = FWHM/H_0 = (16.87\pm2)/(242.26\pm30.09) = 0.069\pm0.017$$

. The obtained value of resolutin is 0.07 which this is approximatley equal to this.

## .2 Experiment 2: Energy dependence of spectral resolution R

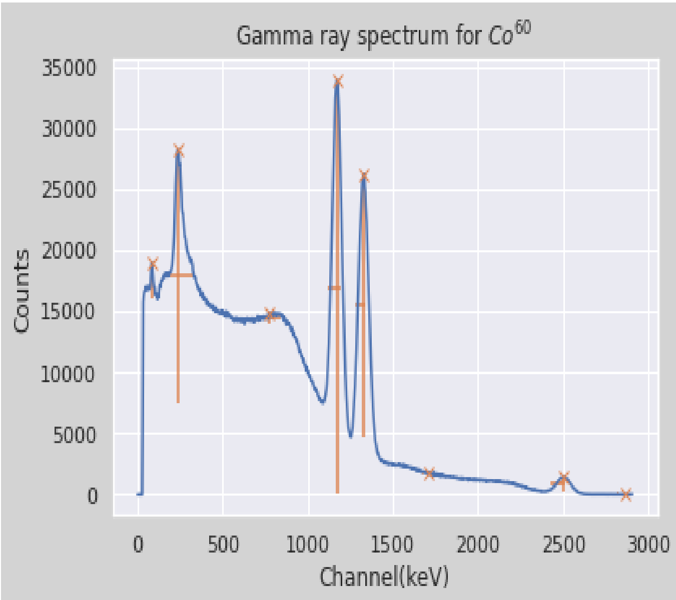



Figure 5: Counts vs channel(KeV) $Co^{60}$

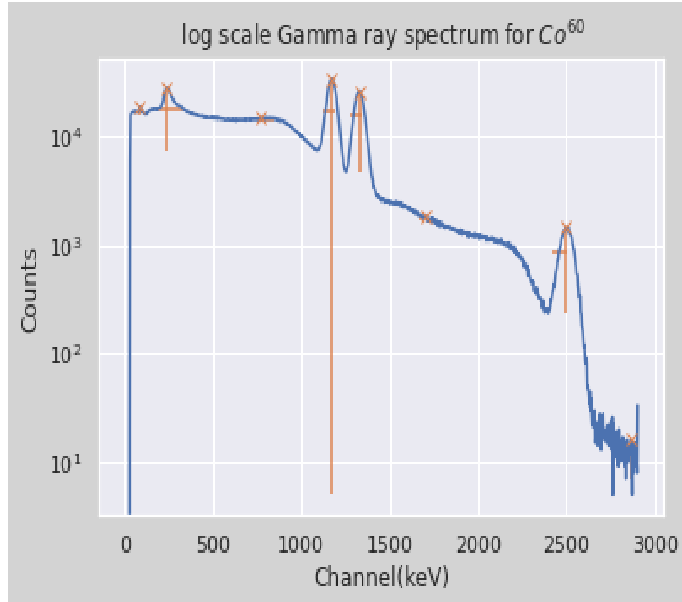



Figure 6: Counts vs channel(KeV) $Co^{60}$ log scale

$Co^{60}$ Gamma Ray spectrum data

| | $H_0$(KeV) | FWHM(KeV) | R | Counts | $\delta H_0$(KeV) ± | $\delta$FWHM(KeV) ± | $\delta R$ ± |
|---|---|---|---|---|---|---|---|
| 0 | 85.2 | 16.0 | 0.191 | 19041.0 | 1.0 | 2.0 | 0.026 |
| 1 | 238.6 | 151.0 | 0.633 | 28284.0 | 1.0 | 2.0 | 0.011 |
| 2 | 769.6 | 88.0 | 0.115 | 14928.0 | 1.0 | 2.0 | 0.003 |
| 3 | 1172.9 | 72.0 | 0.062 | 33995.0 | 1.0 | 2.0 | 0.002 |
| 4 | 1332.0 | 65.0 | 0.049 | 26248.0 | 1.0 | 2.0 | 0.002 |
| 5 | 1706.8 | 16.0 | 0.01 | 1858.0 | 1.0 | 2.0 | 0.001 |
| 6 | 2499.2 | 88.0 | 0.035 | 1458.0 | 1.0 | 2.0 | 0.001 |
| 7 | 2865.6 | 16.0 | 0.006 | 16.0 | 1.0 | 2.0 | 0.001 |

Table 1: $Co^{60}$ relevant spectrum data

The compton edge was corresponds $H_0 = 769.6KeV$, while the backscatter peak and sum peaks are respectively located at $H_0 = 238.6KeV$ and $H_0 = 2499.2KeV$. The data for all peaks, including the two photopeaks in the middle are tabulated above. The calibration value utilised was 2.8(i.e the x axis values were simply scaled by a factor of 2.8).

## .3 detection efficiency of $Co^{60}$

It is possible to calculate the detector efficiency for each peak here using the equation(please refer to the experimental method to know more)

$$\varepsilon = \frac{2 \times (countsofsumpeaks)}{countsofrelevantphotopeak}$$

. For the photpeak at $H_0 = 1172.9 \pm 2.8KeV$, this corresponds to

$$\varepsilon = \frac{2 \times (1458 \pm 1)}{33995 \pm 1}$$

$$\varepsilon = 0.0857 = 8.57 \pm 0.01\%$$

For the second photopeak at $H_0 = 1332.0 \pm 2.8KeV$, this corresponds to

$$\varepsilon = \frac{2 \times (1458 \pm 1)}{26248 \pm 1}$$

$$\varepsilon = 0.11 = 11 \pm 0.02\%$$

## .4 experiments upon $Na^{22}$

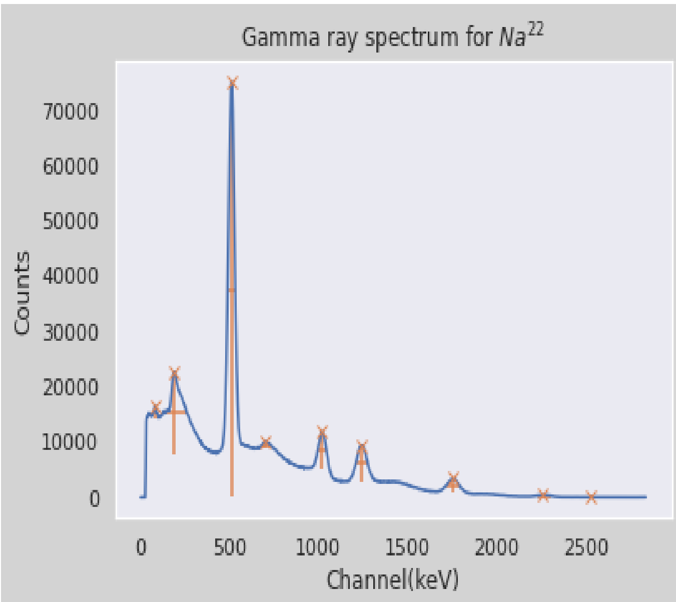



Figure 7: Counts vs channel(KeV) $Na^{22}$

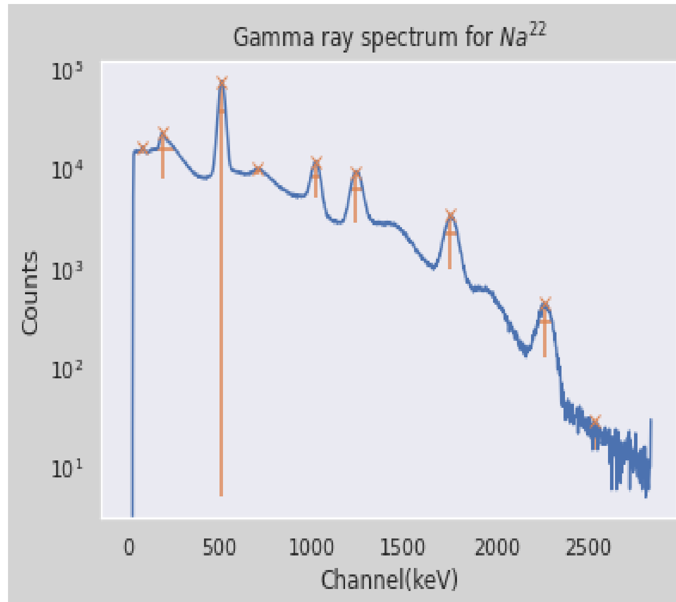



Figure 8: Counts vs channel(KeV) $Na^{22}$ log scale

$Na^{22}$ Gamma Ray spectrum data

| | $H_0$(KeV) | FWHM(KeV) | R | Counts | $\delta H_0$(KeV) ± | $\delta$FWHM(KeV) ± | $\delta R$ ± |
|---|---|---|---|---|---|---|---|
| 0 | 83.3 | 15.0 | 0.179 | 16582.0 | 2.8 | 2.0 | 0.026 |
| 1 | 188.8 | 124.0 | 0.658 | 22723.0 | 2.8 | 2.0 | 0.0141 |
| 2 | 511.0 | 43.0 | 0.085 | 75148.0 | 2.8 | 2.0 | 0.0041 |
| 3 | 702.6 | 49.0 | 0.069 | 10014.0 | 2.8 | 2.0 | 0.0029 |
| 4 | 1022.0 | 49.0 | 0.048 | 11832.0 | 2.8 | 2.0 | 0.002 |
| 5 | 1241.4 | 67.0 | 0.054 | 9376.0 | 2.8 | 2.0 | 0.0017 |
| 6 | 1755.2 | 73.0 | 0.042 | 3399.0 | 2.8 | 2.0 | 0.0012 |
| 7 | 2260.6 | 76.0 | 0.034 | 455.0 | 2.8 | 2.0 | 0.0009 |
| 8 | 2532.8 | 17.0 | 0.007 | 29.0 | 2.8 | 2.0 | 0.0008 |

Table 2: $Na^{22}$ spectrum relevant data

The backscatter peak, sum peak and total energy peak are respectively located at $H_0 = 188.8 \pm 2.8KeV$, $H_0 = 1022 \pm 2.8KeV$, and $H_0 = 511 \pm 2.8KeV$. The data for all peaks, including the two photopeaks in the middle are tabulated above. The calibration value utilised was 2.8(i.e the x axis values were simply scaled by a factor of 2.8).

## .5 Detection efficiency of $Na^{22}$

It is possible to calculate the detector efficiency for each peak here using the equation(please refer to the experimental method to know more)

$$\varepsilon = \frac{2 \times (counts of sum peaks)}{counts of relevant photopeak}$$

. For the photpeak at $H_0 = 511 \pm 2.8KeV$, this corresponds to

$$\varepsilon = \frac{2 \times (11832 \pm 1)}{75148 \pm 1}$$

$$\varepsilon = 31.5 \pm 0.01\%$$

## .6 Experiments upon $Cs^{137}$

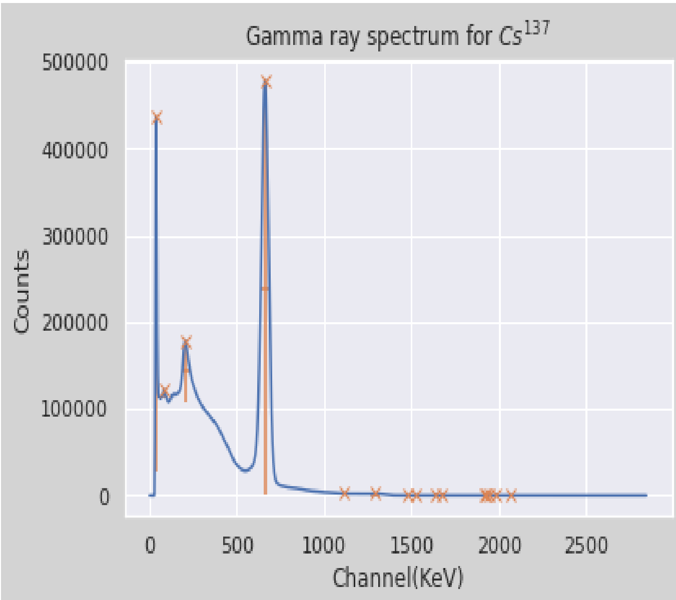



Figure 9: Counts vs channel(KeV) $Cs^{137}$

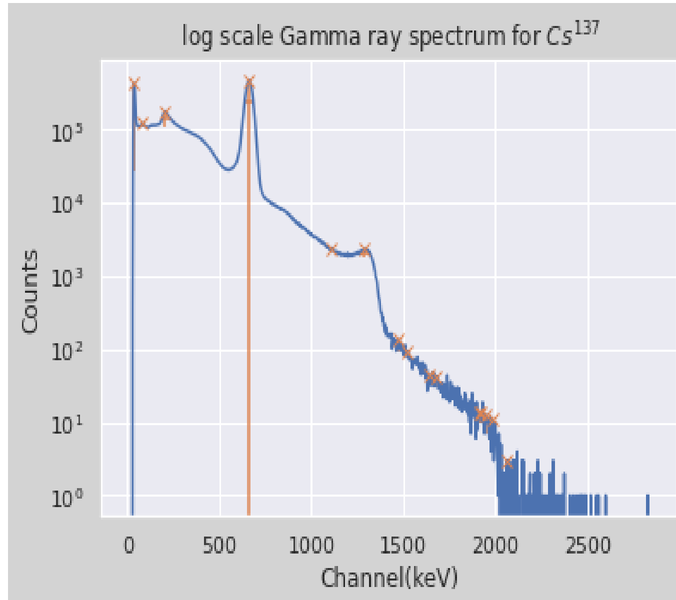



Figure 10: Counts vs channel(KeV) $Cs^{137}$ log scale

$Cs^{137}$ Gamma Ray spectrum data

| | $H_0$(KeV) | FWHM(KeV) | R | Counts | $\delta H_0(KeV) \pm$ | $\delta FWHM(KeV) \pm$ | $\delta R \pm$ |
|---|---|---|---|---|---|---|---|
| 0 | 36.1 | 10.0 | 0.289 | 437099.0 | 2.78 | 5.56 | 0.08 |
| 1 | 83.4 | 12.0 | 0.142 | 122503.0 | 2.78 | 5.56 | 0.028 |
| 2 | 202.9 | 45.0 | 0.222 | 179078.0 | 2.78 | 5.56 | 0.013 |
| 3 | 661.6 | 48.0 | 0.073 | 478927.0 | 2.78 | 5.56 | 0.003 |
| 4 | 1112.0 | 9.0 | 0.008 | 2423.0 | 2.78 | 5.56 | 0.002 |
| 5 | 1289.9 | 52.0 | 0.04 | 2338.0 | 2.78 | 5.56 | 0.002 |
| 6 | 1473.4 | 10.0 | 0.007 | 135.0 | 2.78 | 5.56 | 0.001 |
| 7 | 1520.7 | 10.0 | 0.007 | 94.0 | 2.78 | 5.56 | 0.001 |
| 8 | 1640.2 | 13.0 | 0.008 | 45.0 | 2.78 | 5.56 | 0.001 |
| 9 | 1676.3 | 16.0 | 0.009 | 43.0 | 2.78 | 5.56 | 0.001 |
| 10 | 1912.6 | 15.0 | 0.008 | 14.0 | 2.78 | 5.56 | 0.001 |
| 11 | 1921.0 | 15.0 | 0.008 | 14.0 | 2.78 | 5.56 | 0.001 |
| 12 | 1946.0 | 9.0 | 0.005 | 13.0 | 2.78 | 5.56 | 0.001 |
| 13 | 1982.1 | 9.0 | 0.004 | 11.0 | 2.78 | 5.56 | 0.001 |
| 14 | 2062.8 | 8.0 | 0.004 | 3.0 | 2.78 | 5.56 | 0.001 |

Table 3: $Cs^{137}$ spectrum relevant data

It is evident from the data pertaining to resolution obtained here that resolution increases as counts increases. This has been evident for all datasets calculating R as FWHM/$H_0$. The calibration for the device was 2.78 as specified above.

## .7 Experiment 3: weak source efficiency

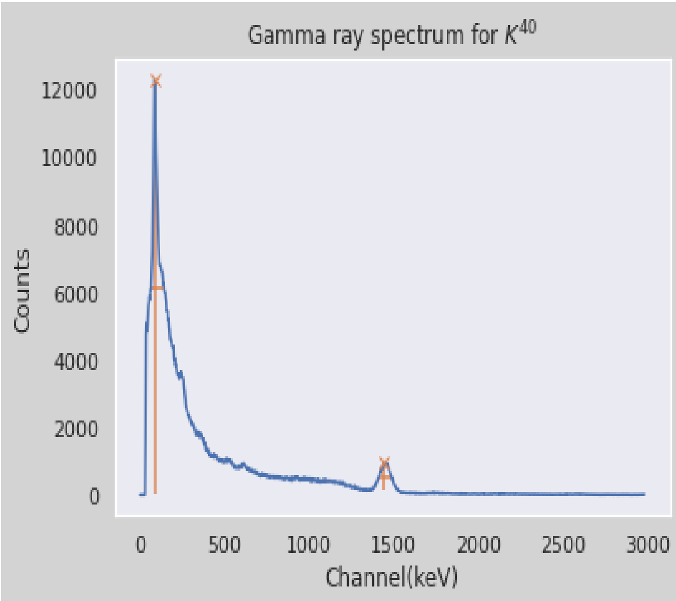



Figure 11: Counts vs channel(KeV) $K^{40}$

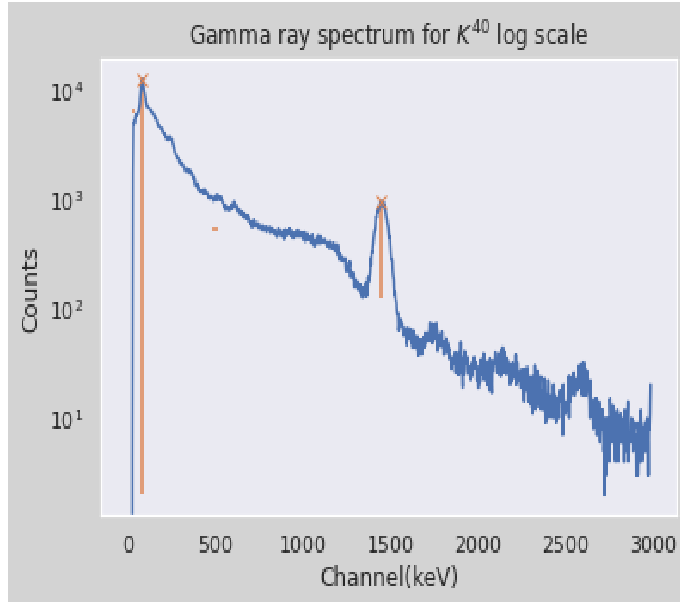



Figure 12: Counts vs channel(KeV) $K^{40}$ log scale

$K^{40}$ Gamma Ray spectrum data

| | $H_0$(KeV) | FWHM(KeV) | R | Counts | $\delta H_0$(KeV) ± | $\delta FWHM$(KeV) ± | $\delta R$ ± |
|---|---|---|---|---|---|---|---|
| 0 | 80.5 | 76.0 | 0.95 | 16300.0 | 2.9 | 5.83 | 0.1073 |
| 1 | 1377.5 | 74.0 | 0.054 | 2833.0 | 2.9 | 5.83 | 0.0044 |

Table 4: $K^{40}$ spectrum relevant data

The activity of the sample obtained from the experimental data can be measured. Since activity is in units of counts/second we need only divide the maximum counts by the runtime of the spectrometer. This returns

$$A = \frac{16300(counts)}{86311(seconds)} = 0.18885(counts/second) = 0.189Bq$$

The theoretical value of the sample activity can also be calculated and compared with the obtained value. The half life of $K^{40}$ is given as $1.26 \times 10^9 years$, in other words, $3.9735 \times 10^{16}$seconds. The abundance of $K^{40}$ in KCl is 0.011% of which only 11% produce gamma rays. The molar mass of KCl is 74.5513g/mol. We are now ready to calculate the activity of the sample.

$$N = \frac{3.625g}{74.5513g/mol} \times \frac{6 \times 10^{23} particles}{mol} \times \frac{0.011\% K^{40}}{particle} \times \frac{11\% counts}{K^{40}} = 3.53 \times 10^{17} counts$$

$$\lambda = \frac{ln(2)}{3.9735 \times 10^{16} seconds} = 1.7444 \times 10^{-17} \frac{1}{seconds}$$

$$A = \lambda N = 6.158 \frac{counts}{seconds} = 6.158Bq$$

This is considerably different from the value obtained in the experiment. The half life of the sample is far too large for the sample's date to be relevant. Its activity will not change in our lifetime. It is possible that the signal to noise ratio was not large enough to obtain trustworthy data. The sample was left to run for 86311seconds which is

$$86311 seconds \times \frac{1 minute}{60 seconds} \times \frac{1 hour}{60 minutes} \times \frac{1 day}{24 hours} = 0.9897 = \ 1 day$$

If the sample had been allowed to run for more than a day it is likely that a better signal to noise ratio would have been obtained and that experimental data would be consistent with the theoretical data.

## IV. Conclusion

In conclusion, the relation between $H_0$ and V was returned by $H_0^{(7.57 \pm 0.12)}$ i.e 8 dynodes.It was found that for the $Cs^{137}$,$Na^{22}$ and $Co^{60}$ spectra, the resolution decreases as energy of the channel increased. The efficiency of the $Na^{22}$ photopeak was found to be $(31.5 \pm 0.01)\%$. The efficiency of the first and second peaks large photopeaks of $Co^{60}$ were respectively found to be $(8.57 \pm 0.01)\%$ and $(11 \pm 0.02)\%$.The activity of the KCl sample recorded in the experiment did not match the activity that was calculated through the theory. The obtained value was 0.189Bq while the calculated value was 6.158Bq. These answers are far off and can probably be explained by simply not leaving the spectrometer enough time to calculate a good signal to noise ratio.

## V. Error Analysis

The error in all parts here was calculated by taking the fractional errors of equations and multiplying them by the obtained value to determine the $\pm$ shift. The error along the x axis corresponds to what calibration is used as shown in the tables above and the y axis error is always $\pm 1$ count.

## References


[1] TrinityCollegeDublin/Schoolofphysics/JSlabs[*"Gamma ray Spectroscopy" 2013*]

[2] [*"Radiation Detection and Measurement Fourth Edition"*] Glenn F. Knoll, Professor Emeritus of Nuclear Engineering and Radiological Sciences University of Michigan Ann Arbor, Michigan

[3] [*"Techniques for Nuclear and Particle Physics Experiments "*] William R Leo

# A. Appendix

## I. Code for data analysis:experiments 2 and 3

```python

import matplotlib.pyplot as plt
import numpy as np
import scipy as scp
import pandas as pd
from astropy.io import ascii
from scipy.signal import find_peaks
data = ascii.read("/home/Benjamin/Desktop/Gamma ray data/exp2_spectra_from_different_sources/exp2_co60_6
channelCo,countCo=np.array(data['col1']*2.84),np.array(data['col2'])
data2=ascii.read("/home/Benjamin/Desktop/Gamma ray data/exp2_spectra_from_different_sources/exp2_cs137_6
channelCs,countCs=np.array(data2['col1']),np.array(data2['col2'])
data3=ascii.read("/home/Benjamin/Desktop/Gamma ray data/exp2_spectra_from_different_sources/exp2_na22_60
#data3=data3*(511/184)
data4=ascii.read("/home/Benjamin/Desktop/Gamma ray data/exp3_KCL_activity/exp3_KCL_600V.txt")
channelKCL,countKCL=np.array(data4['col1']),np.array(data4['col2'])
channelNa,countNa=np.array(data3['col1']*(511/184)), np.array(data3['col2'])
import seaborn as sns
sns.set_theme()
#import relevant libraries
#import datasets from text files
# also sort them into columns and names to be called

peaks, properties = find_peaks(countCo, prominence=3, width=5)
#using the scipy peaks analyser we identify peaks
#the FWHM and height of each peak is contained in properties
properties["prominences"], properties["widths"]
plt.plot(channelCo,countCo)
plt.yscale("log")
plt.plot(channelCo[peaks], countCo[peaks], "x")
plt.vlines(x=channelCo[peaks], ymin=countCo[peaks] - properties["prominences"],
           ymax = countCo[peaks], color = "C1")
plt.hlines(y=properties["width_heights"], xmin=properties["left_ips"]*2.8,
           xmax=properties["right_ips"]*2.8, color ="C1")
#plots horizontal and vertical lines to denote FWHMs on relevant peaks
plt.xlabel('Channel(keV)')
plt.ylabel('Counts')
plt.title(' log scale Gamma ray spectrum for $Co^{60}$')
plt.gcf().set_facecolor('lightgrey')
plt.show()
r=2.8*properties["widths"]/channelCo[peaks]
#2.8 is the calibration scaling constant

df=pd.DataFrame({'$H_0$(KeV)':channelCo[peaks],


                 'FWHM(KeV)':properties["widths"]*2.8
                 ,'R':r})
#start sorting data into a dataframe
df['FWHM(KeV)'] = df['FWHM(KeV)'].astype(float).round(0)
df['R'] = df['R'].astype(float).round(3)
df['$H_0$(KeV)']=df['$H_0$(KeV)'].astype(float).round(1)
df['Counts']=countCo[peaks]
df['$\delta H_0(KeV)\pm$']= 1
df['$\delta FWHM(KeV)\pm$']= 2
df['$\delta R \pm$']=((1/df['$H_0$(KeV)'])+(2/df['FWHM(KeV)']))*df['R']
#specify all relevant values and their errors
df['$\delta R \pm$'] = df['$\delta R \pm$'].astype(float).round(3)
#round to significant figures
#The data is now ready to be tabulated
print(df)
from pandas.plotting import table
```

```python
fig, ax = plt.subplots(figsize=(10, 2)) # set size frame
ax.xaxis.set_visible(False)  # hide the x axis
ax.yaxis.set_visible(False)  # hide the y axis
ax.set_frame_on(False)  # no visible frame, uncomment if size is ok
tabla = table(ax, df,loc='upper right', colWidths=[0.3]*len(df.columns))  # where df is your data frame
tabla.auto_set_font_size(False) # Activate set fontsize manually
tabla.set_fontsize(20) # if ++fontsize is necessary ++colWidths
#df.round(decimals=4),
tabla.scale(1.4, 1.9) # change size table
#all data obtained in the dataframe is tabulated in a more portable manner as a png
plt.title('$Co^{60}$ Gamma Ray spectrum data',size=20)
plt.savefig('table.png', transparent=True)
plt.show()
#This code was repeated for all non log plots and varying samples
#returning a total of 6 graphs and 3 tables
#KCL was then analysed in a similar fashion.
```

Listing 1: Python example

## II. Graphs for experiment 1

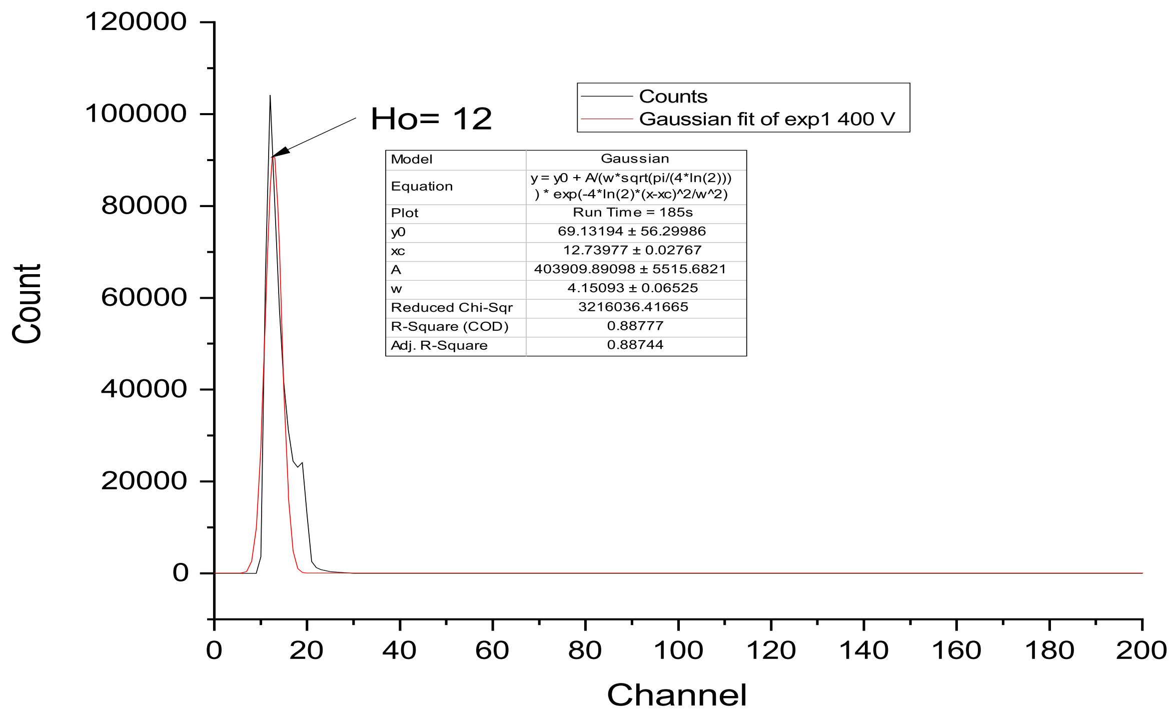



Figure 13: Counts vs Channel V=400V $Cs^{137}$

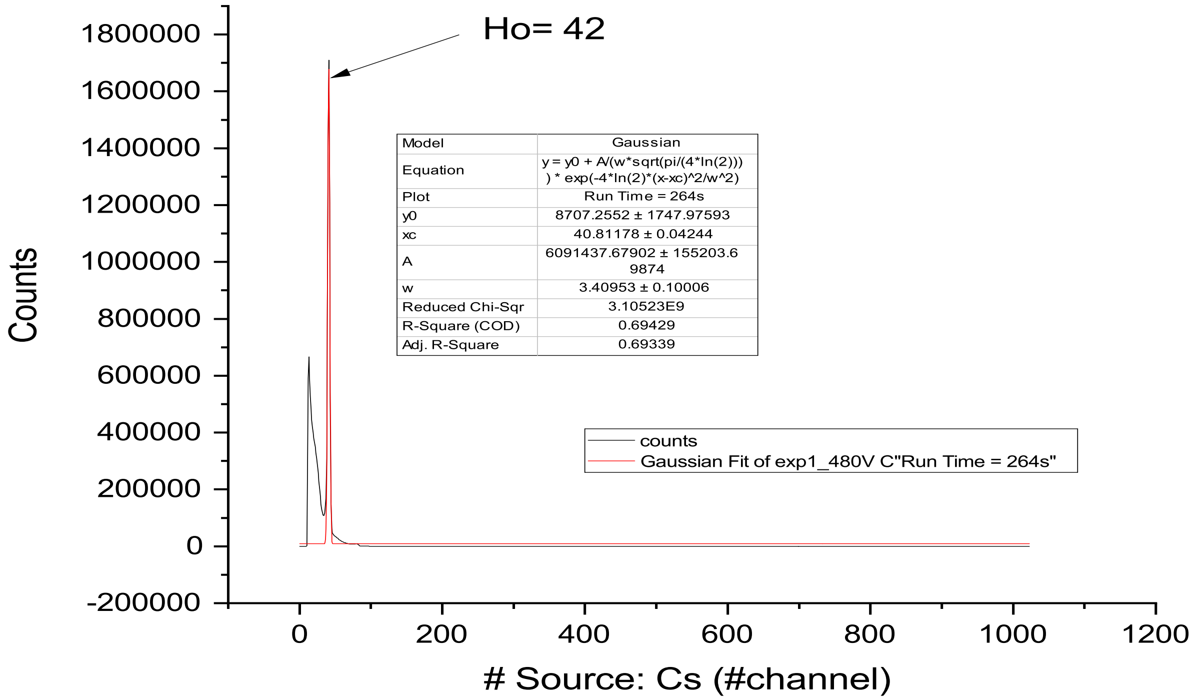



Figure 14: Counts vs Channel V=480V $Cs^{137}$

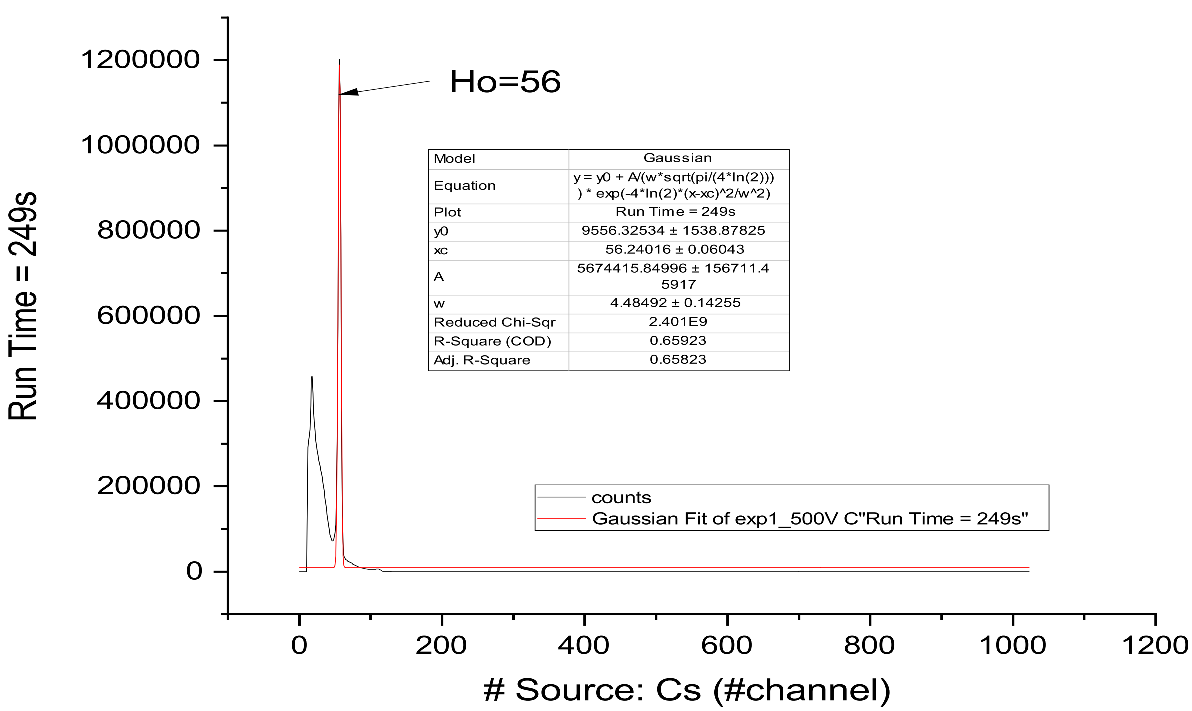



Figure 15: Counts vs Channel V=500V $Cs^{137}$

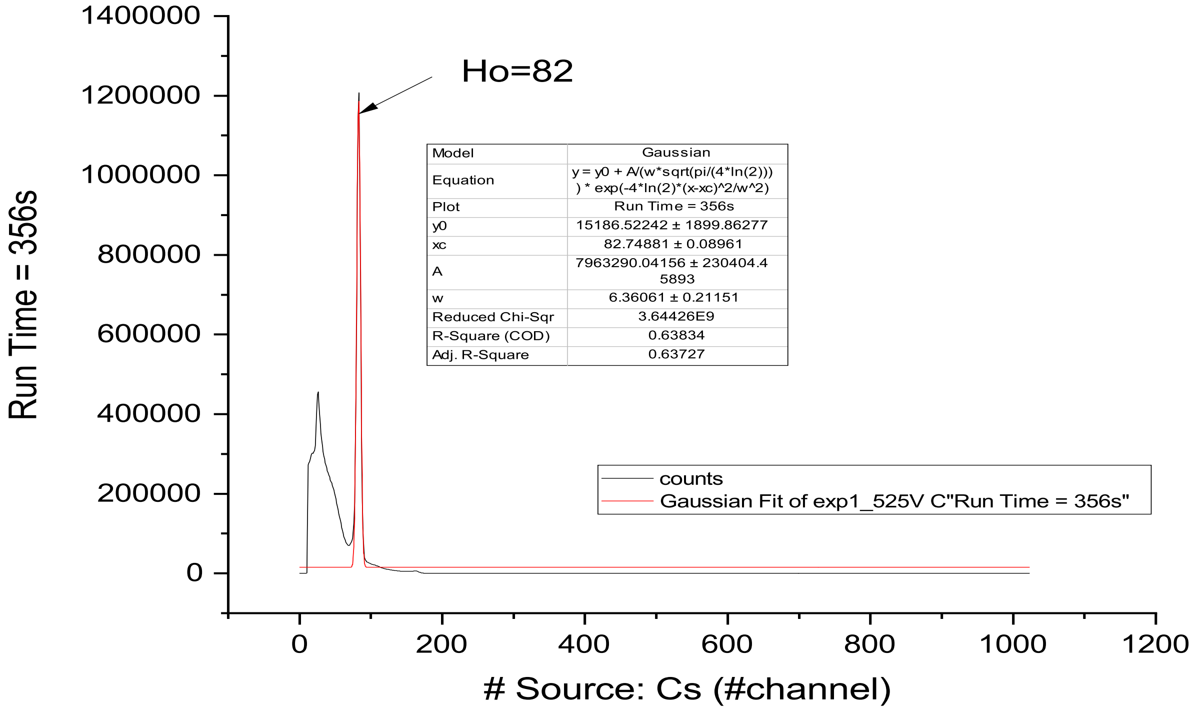



Figure 16: Counts vs Channel V=525V $Cs^{137}$

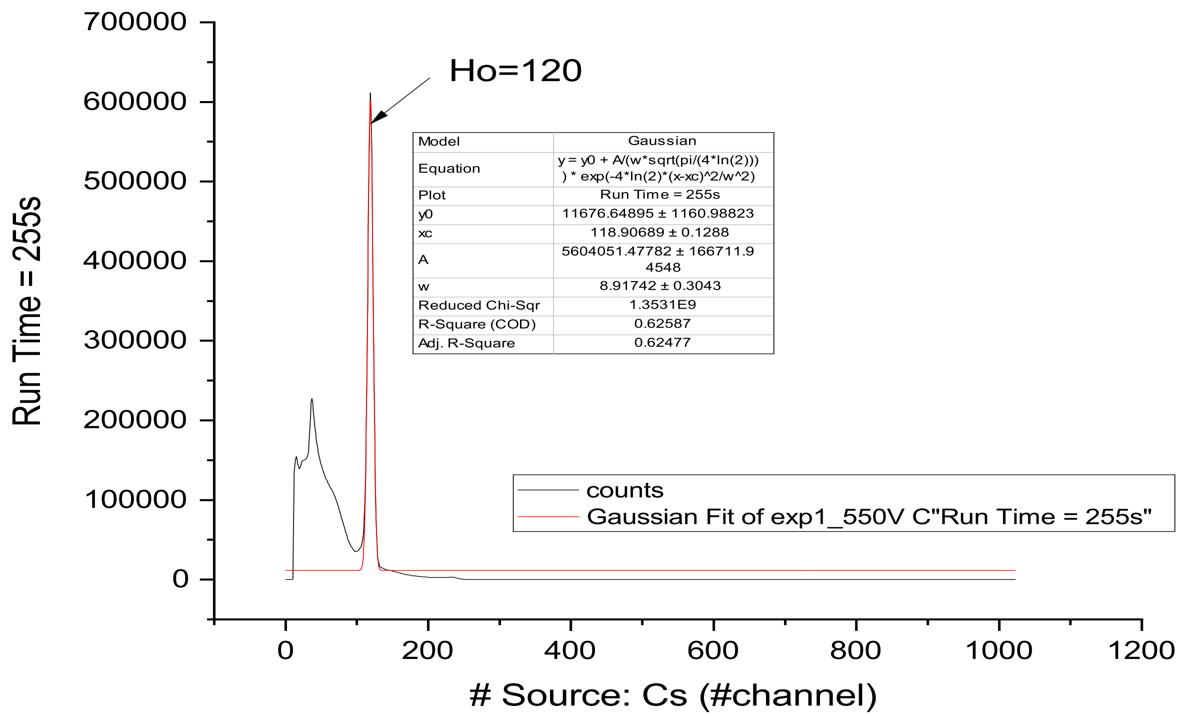



Figure 17: Counts vs Channel V=550V $Cs^{137}$

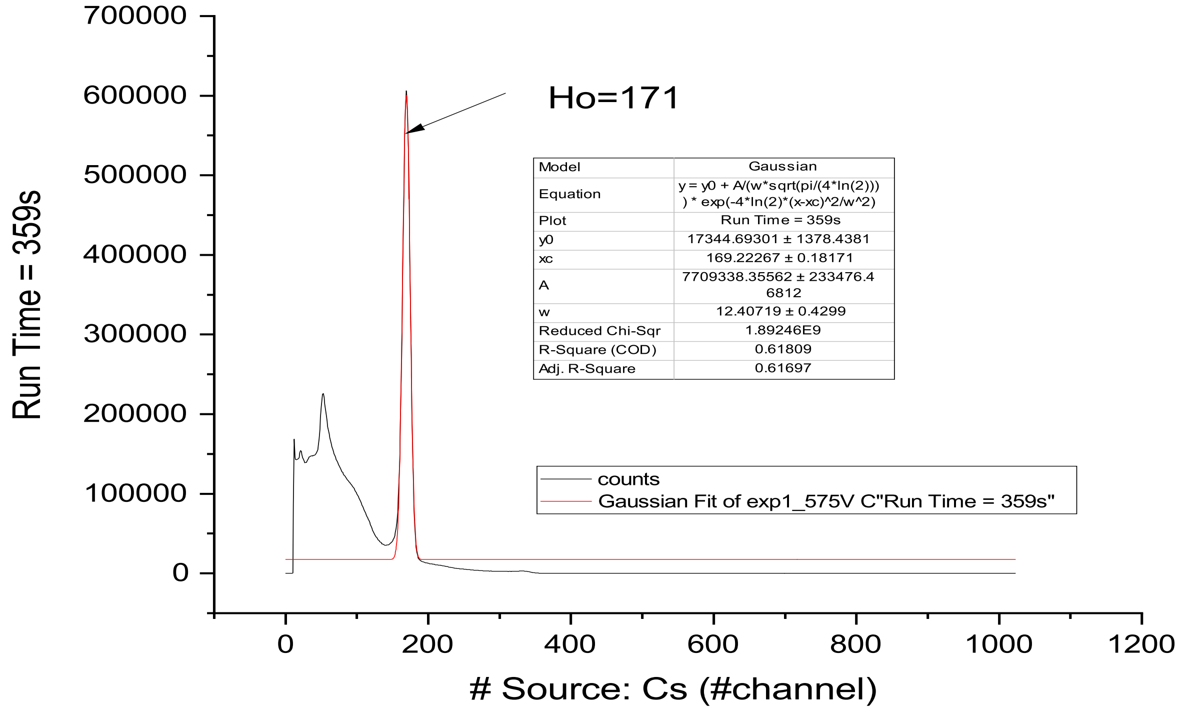



Figure 18: Counts vs Channel V=575V $Cs^{137}$

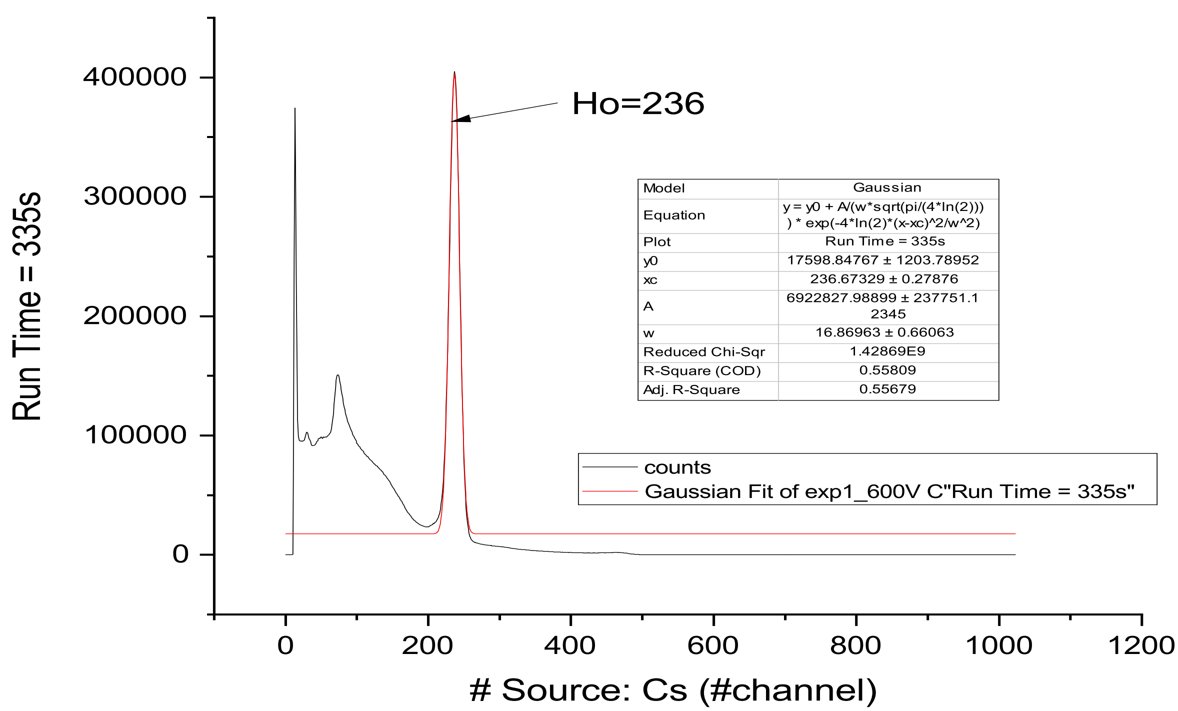



Figure 19: Counts vs Channel V=600V $Cs^{137}$

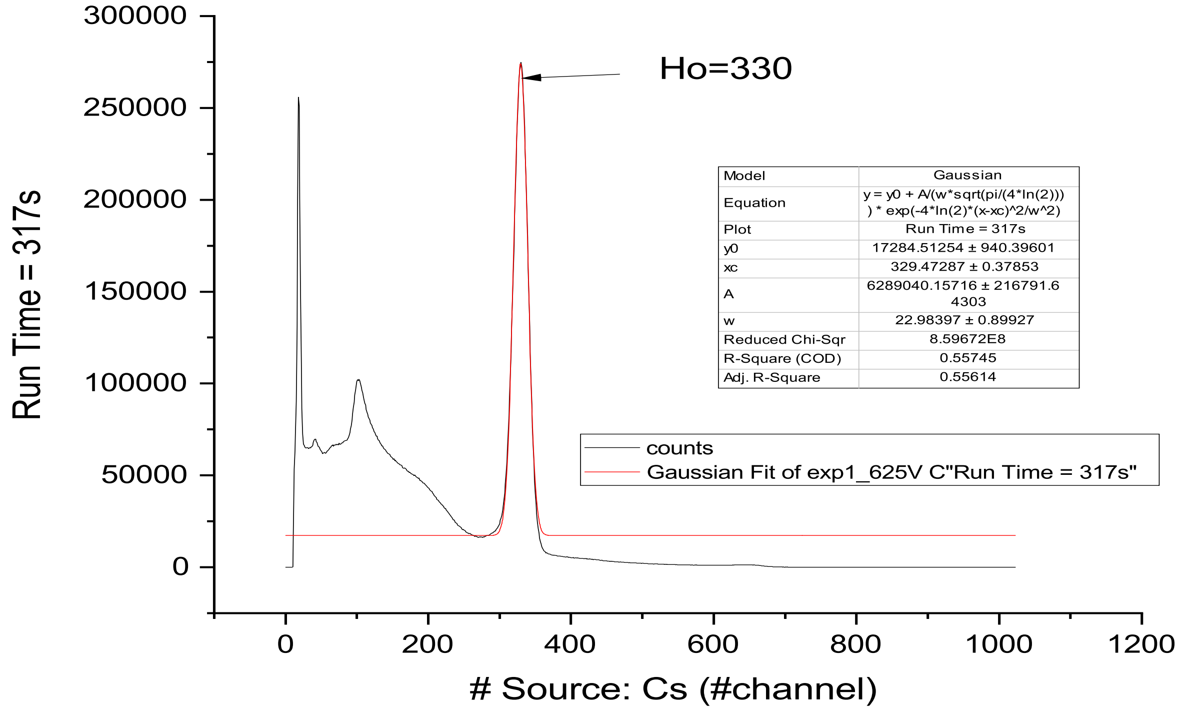



Figure 20: Counts vs Channel V=625V $Cs^{137}$

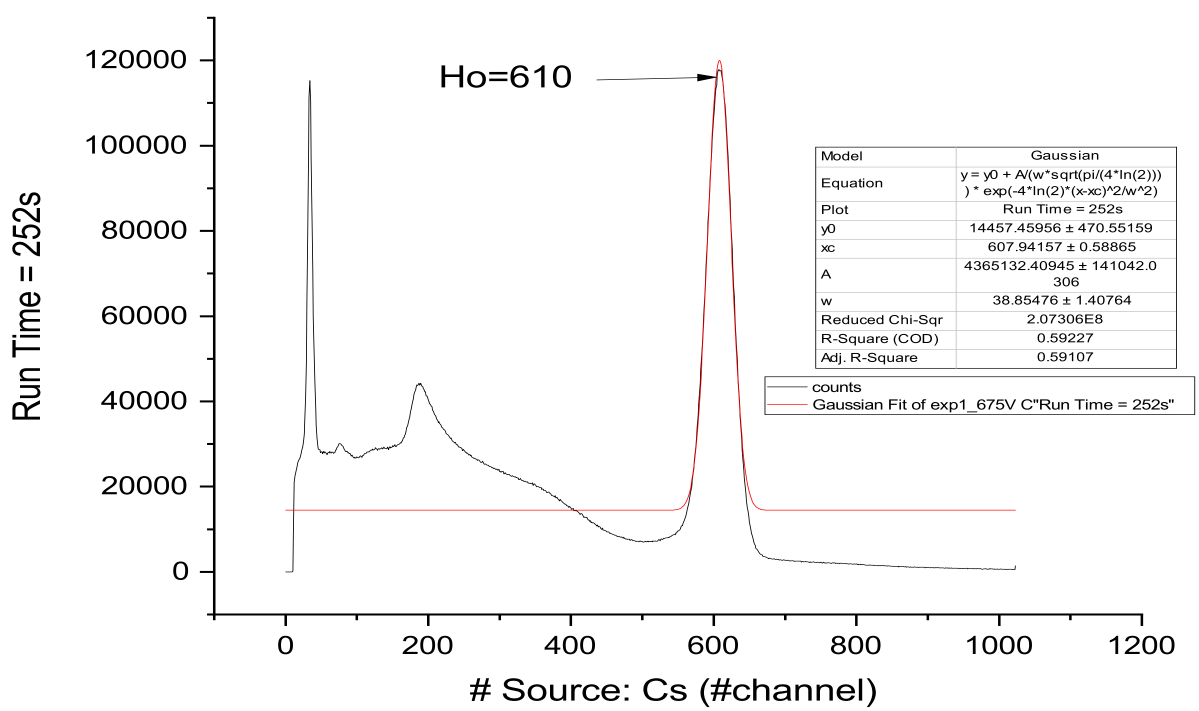



Figure 21: Counts vs Channel V=675V $Cs^{137}$