Contents

1 Introduction

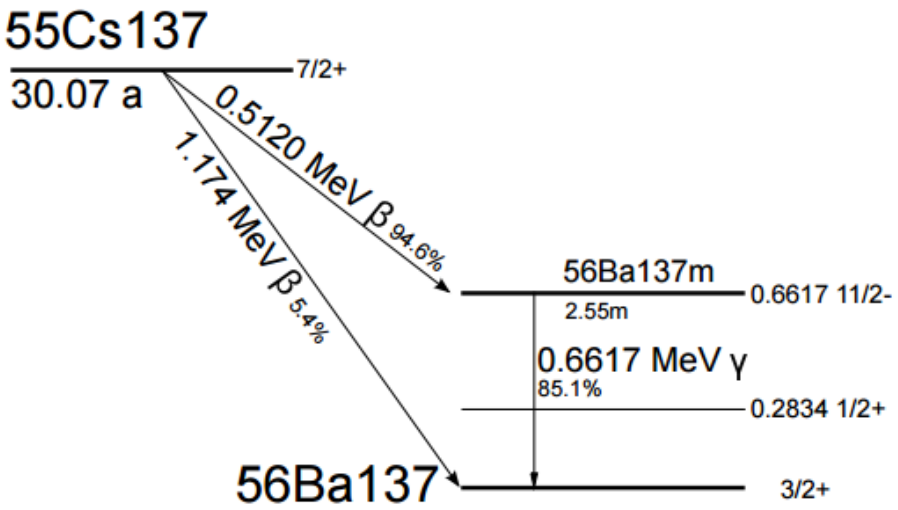
1.1 Aim

To detect γ radiation produced by CS^{137} with a scintilator counter using a single channel analyzer.

- Energy spectrum is obtained and analysed.
- Resolution of the SCA instruement is meassured.

1.2 Sources

γ-ray source used in this experiment are Cs^{137} (one peak)



2 Theory

In this experiment we study about detection of gamma(γ) by scintillator detector. It is a multi-step process: the gamma ray enters a NaI:Tl scintillator crystal where it produces a rapidly moving free electron that, in turn, loses its energy by excitation of the ions in its path as it travels through the crystal. This excitation energy is given off in various ways, one being emission of visible light (fluorescence). Thus a single high energy gamma ray entering the scintillator produces a flash of low energy photons. These photons are directed to the photosensitive surface of a photomultiplier tube(PMT), where they eject electrons via the photoelectric effect. The electrons are collected in the photomultiplier and amplified to yield a current pulse, which is converted to a voltage pulse whose height is proportional to the number of photoelectrons and is thus proportional to the number of photons reaching the tube, which in turn is proportional to the initial energy of the fast electron.

Thus the amplitude of each pulse is related to the energy of the electron freed by the gamma ray.The energy signal from the photo multiplier is usually quite weak; therefore it must be amplified before analyzing it. The output pulses of the PMT are amplified and then recorded. Therefore the output pulse is proportional to the energy deposited in the scintillator. The proportionality constant has to be determined experimentally. This process is called calibrating the detection system.

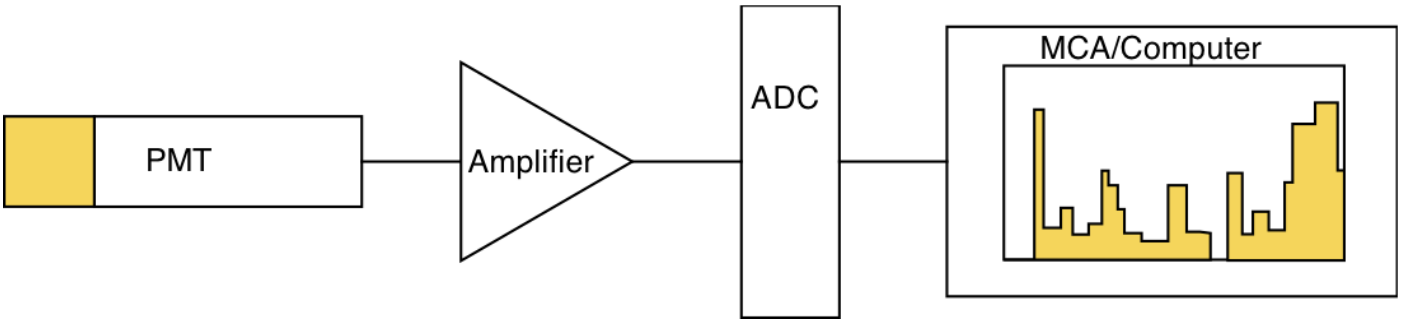


Figure 1: Schematic of the data acquisition with PC

The amplified pulses are analyzed by an Analog to Digital Converter (ADC) which determines the pulse height and converts it into a number between 0 and 1023. "Number of times a particular ADC value is observed" is counted. So We have a total of 1024 counters. Each ADC value is called a channel and the counter value is called the channel contents. If we take data for a while we will see that some values occur more frequently than others. The total set of counter values and the corresponding ADC values is called a spectrum. When we plot the graph x-axis corresponds to the ADC value and the y-axis represents the corresponding counter values or channel contents. The process described above is performed by a Multi Channel Analyzer (MCA). Voltage pulses are studied using either a single- and multi-channel analyzer. A single channel analyzer (SCA) counts the number of voltage pulses whose height falls within a given (adjustable) window of values, while a multichannel analyzer (MCA) sorts the pulses according to height and counts the number in each window to give a spectral (energy) distribution of the fast electrons.

Figure-2 shows a typical MCA spectrum. In order to relate this spectrum to the nuclear decay, we need to understand how gamma rays interact with matter.

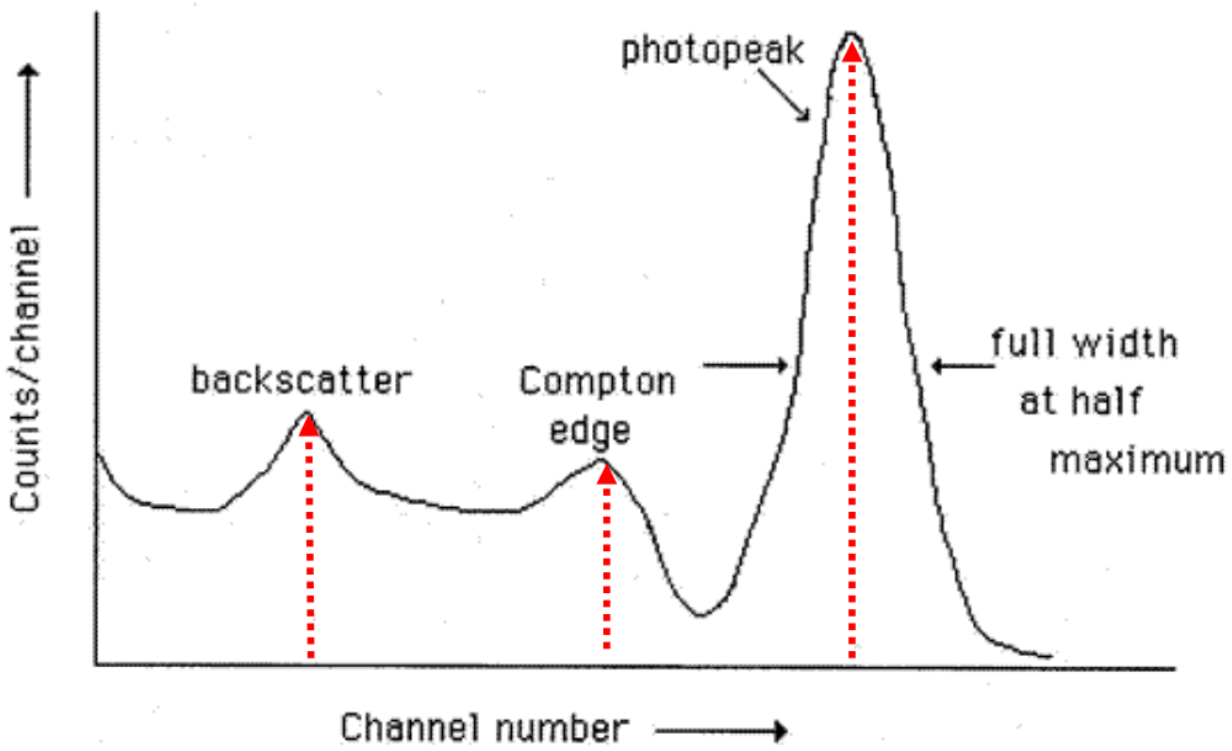


Figure 2: NaI:Tl Spectrum for Cs^{137}

2.1 Interaction of γ rays with matter

Gamma rays are high-energy photons. Photons have no mass and no electrical charge, therefore they cannot directly ionize matter, neither gamma rays. Despite this fact, gamma rays ionize matter via indirect ionization. Although a large number of possible interactions are known, three key interaction mechanisms with matter are as following.

- Photoelectric effect
- Compton effects
- Pair production

Which of these processes contributes the most is mainly dependent on theatomic number (Z) of the material and the energy (E) of the photon. Figure-3 shows that At low energies and with high Z materials the photoelectric effect is main interaction process. At intermediate energies and in low Z materials, the Compton scattering is dominating. At very high energies pair production is the most dominant interaction process.

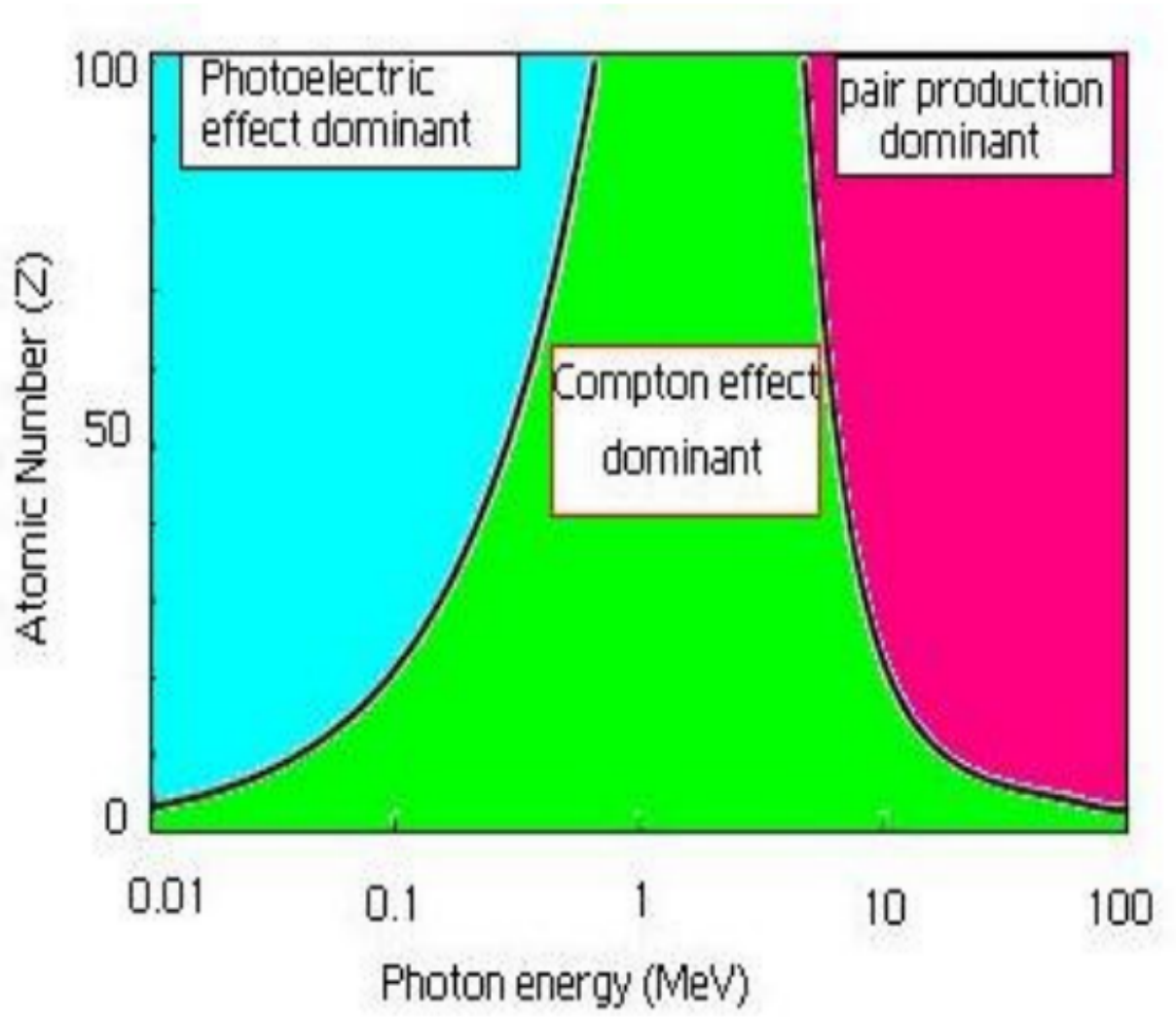


Figure 3: Z-E diagram

2.1.1 Photoelectric effect:

When the photon collides with an atom, it may impinge upon an orbital electron and transfer all of its energy to this ejecting it from the atom. When the incident photon energy $h\nu$ exceeds the electronic binding energy (or ionization energy) E_B, the electron is ejected with a kinetic energy

$$E_{kin} = h\nu - E_B \tag{1}$$

This process, in the course of which the photon disappears completely, takes place exclusively in the direct vicinity of the nucleus because the impulse the photon has due to its energy and velocity can be transferred to an electron for a small part only as mass of the electron is low. The rest of the impulse must therefore be transferred to the nucleus. So, the process only takes place with K or L-electrons and occurs more often with substances with a high atomic number (Z). When the photon energy is too high, a nucleus with a high Z cannot handle the surplus of impulse either,that is why the photoelectriceffect only occurs up to a limited energy value.

If for example an atomic K-electron is ejected as a result of the photoelectric process Very shortly after, another bound atomic electron will "fall" into the K shell vacancy (or cascade down sequentially) with the subsequent emission of X-rays. These X-rays will have a large probability of producing light

pulses in the scintillator by exciting other loosely bound electrons. These processes (initial photoelectron ejection and subsequent X-ray production and interaction with the crystal) will usually happen within the resolution time of the counter, so that these successive light pulses add and can not be distinguished from one another. Therefore in the end the photomultiplier output pulse will correspond to the full gamma ray energy, if the photoelectron stops in the crystal and if no light escapes the crystal. **Thus the photoelectric effect results in a peak, called the photopeak, at an energy equal to that of the incoming gamma ray**.

2.1.2 Compton scattering

In this case the gamma ray is not absorbed, but rather scattered through an angle θ by an electron, which recoils and carries away some of the gamma rays energy E. The scattered electron energy is then detected in the photomultiplier. The scattered gamma ray escapes from the scintillator because the probability that a gamma ray Compton scatters in a typical size scintillator is quite small (0.01 to 0.1), which means we are unlikely to detect a gamma ray that has undergone two Compton scatterings.The energy of the Compton-scattered gamma ray $E_\gamma^{'}$ as a function of the scattering angle θ and the initial energy E_γ is given by

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

Where c is the speed of the light and m is the mass of the electron. From equation(2) we see that the energy of the scattered electron, which is the energy loss of the gamma ray, will vary from zero (when $\theta = 0^\circ$) to a maximum of $\frac{2E_\gamma^2}{2E_\gamma + mc^2}$ (when $\theta = 180^\circ$). This maximum energy is called the **Compton edge.** The energy distribution of Compton scattered electrons is essentially a constant. So the Compton spectrum produced by a photomultiplier tube is an almost flat plateau from zero energy up to the **Compton edge** where it drops off sharply (at a rate limited by the energy resolution of the tube).

The discussion above refers to gamma rays that are Compton scattered by electrons within the scintillator. It is also possible for a gamma ray to be Compton scattered into the scintillator from an interaction outside the scintillator. In this case the observed signal is from the scattered gamma and not from the recoiling electron. The scattered gamma ray could then be detected through the photoelectric effect. However, because of the geometry of the detector, most of the gamma rays scattered into the scintillator will have been scattered through a large value of θ (almost 180°). But cosθ varies only slowly with θ for θ near 180°, which means [see equation(2)] that these gamma rays will have energies close to $\frac{mc^2 E_\gamma}{2E_\gamma + mc^2}$ resulting energy peak is called the **backscatter peak**. It can be enhanced by placinga sheet of lead around the outside of the scintillator.

2.1.3 Pair production

If the incoming gamma ray energy is above $1.02MeV = 2mc^2$,the rest mass of an electron-positron pair, the gamma ray can spontaneously create an electron-positron pair and be totally absorbed. If both the electron and positron lose all of their kinetic energy while still in the scintillator, they would produce a photomultiplier pulse corresponding to an energy $2mc^2$ below the gamma ray energy ($E - 2mc^2$).

2.2 Scintillator

In this experiment, scintillator detector with NaI:Tl crystal is used to detect gamma ray. As described in previous section, that photoelectric effect will dominate, which depends on the atomic number of

the interacting matter. Thus NaI is grown with some heavy nuclei (e.g. Thalium;Tl). The resolution of such detector is about 10%. High purity Germanium may be used as detector to obtain greater resolution, but is also highly expensive. Depending on the size of the NaI crystal, occasional escape of electrons, X-rays or γ rays.

2.3 Photomultiplier tube (PMT)

After generation of secondary photons, they hit the photo-cathode of PMT, releasing electrons by photoelectric effect. These electrons are then focused to a series of Dynodes, each of which are at positive potential than the previous (can be achieved by a voltage divider). From each dynode, by positive potential, electrons are accelerated, which striking the next dynode, releases more electrons. In this way, up to the anode, a large number of electrons are produced, which leads to a current, which is then converted into a voltage pulse. The height of the voltage pulse is proportional to the initial energy of the photons, hence accounts for the energy of the γ ray. The efficiency of a PMT tube is about 30%

2.4 Single channel analyzer

In single channel analyzer gamma rays having energy between E to $E + \Delta E$ are recorded others are ignored. Hence the name single chanel analyzer. In our experiment E is specfied by baseline voltage and ΔE is specified by window voltage. We keep window voltage to be fixed at 40 mV and and vary the baseline from 40mV to 3500mV in the step size of 40mV. Note that step size and window voltage must be same otherwise e will miss some energy interval (if step size is greater than window voltage) or overcount some energy interval (if step size is less than window voltage). By doing this we measure gamma rays having energy coresponding to 40mV to 80 mV then 80mV to 120mV then 120mV to 140mV and so on upto 3500mV to 3540mv. Thus relavant part of the energy spectrum data is obtained. We will plot this energy spectrum. Which we expect to be similar to the graph in figure-2. From this spectrum data we will also determine the resolution of SCA instrument at photopeak energy. Correspondance between energy of the gamma ray and volatge selected can be found if the value of the gain setted is known.

3 Data

3.1 Raw data

PMT voltage: 750V
Gain:9
For baseline knob: 10 full rotation is 10V. Each rotation has 50 devision hence least count is 20mV.
For window knob: 10 full rotation is 2V. Each rotation has 100 devision hence the least count is 2mV.
After setting PMT voltage and window volatge we measure count for time interval of 30 Sec for diffrent baseline voltage and this data is presnted in table-1.

Table 1: Count for different basline voltage

Baseline Voltage	Counts for 30 Seconds		
	Reading-1	Reading-2	Average
40	8571	8582	8576.5
80	8601	8481	8541
120	8494	8485	8489.5
160	8482	8511	8496.5
200	8788	8834	8811
240	9025	9164	9094.5
280	8648	8662	8655
320	8275	8312	8293.5
360	7940	7874	7907
400	7562	7635	7598.5
440	7388	7380	7384
480	7182	6979	7080.5
520	7054	6966	7010
560	6921	6821	6871
600	6655	6729	6692
640	6643	6618	6630.5
680	6408	6341	6374.5
720	6271	6236	6253.5
760	5733	5722	5727.5
800	4613	4668	4640.5
840	3504	3490	3497
880	2574	2494	2534
920	2384	2370	2377
960	5102	4953	5027.5
1000	4846	4855	4850.5
1080	4027	4100	4063.5
1120	3303	3265	3284
1040	4610	4631	4620.5
1160	2379	2263	2321
1200	1965	1912	1938.5
1240	1793	1782	1787.5
1280	1733	1782	1757.5
1320	2002	1924	1963
1360	2422	2310	2366
1400	3070	3171	3120.5
1440	3754	3716	3735
1480	4608	4651	4629.5
1520	6130	6137	6133.5
1560	9255	9405	9330
1600	14497	14664	14580.5
1640	21616	21533	21574.5
1680	25109	24599	24854

Baseline	Counts for 30 seconds		
Voltage	Reading-1	Reading-2	Average
1720	22199	22270	22234.5
1760	14252	13939	14095.5
1800	7158	7117	7137.5
1840	2361	2405	2383
1880	1105	1099	1102
1920	685	696	690.5
1960	549	561	555
2000	515	498	506.5
2040	503	461	482
2080	502	462	482
2120	419	409	414
2160	422	441	431.5
2200	408	363	385.5
2240	273	280	276.5
2280	233	243	238
2320	177	184	180.5
2360	187	183	185
2400	213	167	190
2440	208	281	244.5
2480	292	226	259
2520	250	263	256.5
2560	278	223	250.5
2600	225	184	204.5
2640	174	179	176.5
2680	139	134	136.5
2720	54	97	75.5
2760	58	187	122.5
2800	195	201	198
2840	200	197	198.5
2880	184	196	190
2920	190	182	186
2960	172	193	182.5
3000	161	192	176.5
3040	156	150	153
3080	141	140	140.5
3120	15	10	12.5
3160	140	29	84.5
3200	8	3	5.5
3240	4	5	4.5
3280	9	6	7.5
3320	5	3	4
3360	5	5	5
3400	9	11	10
3440	7	11	9
3480	7	6	6.5
3520	6	11	8.5

3.2 Analysing the data

As presented in table-1 for each baseline voltage two data for number of counts is taken. We consider average of these two data to be the actual count. With this avergae value we plot histogram using Matlab. This histogram is presented in figure-4

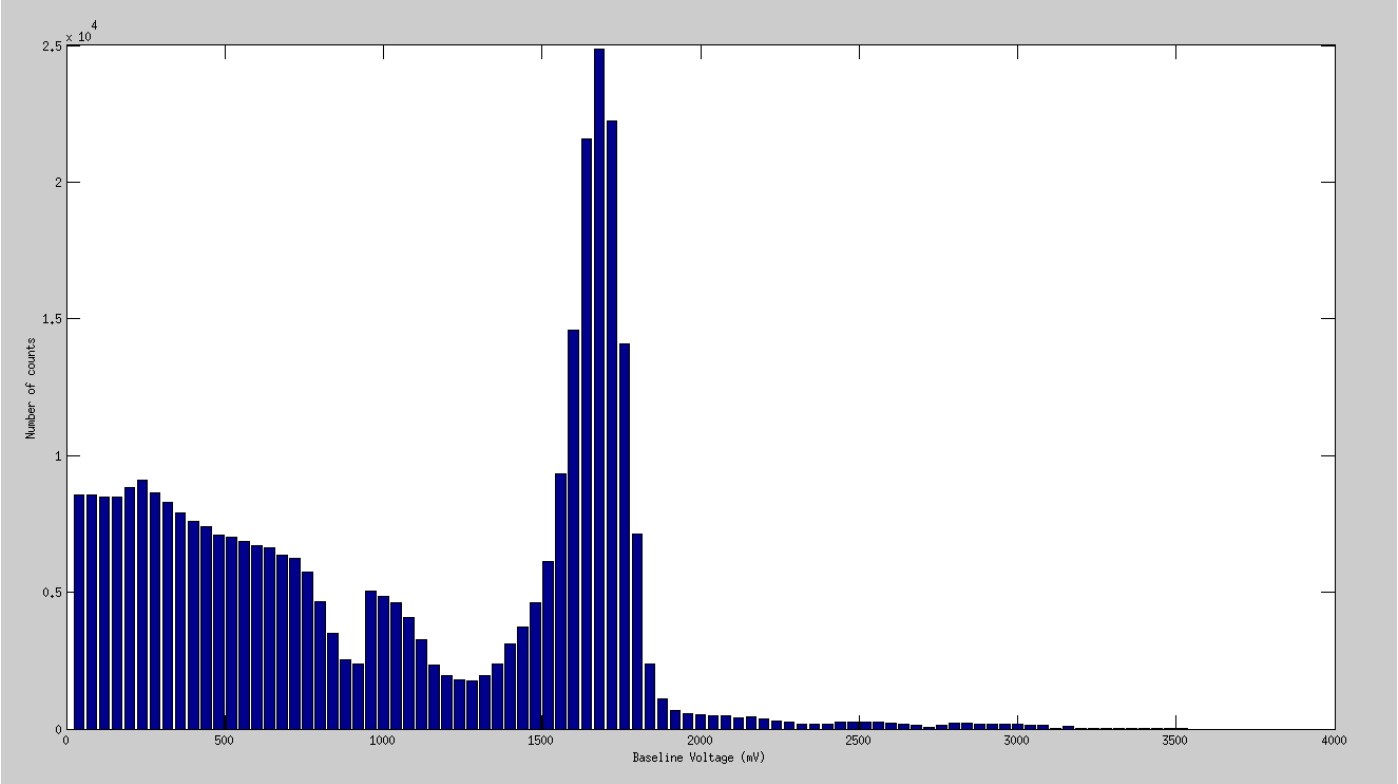


Figure 4: Histogram of number of counts vs Baseline Voltage

As it can be seen from above data photopeack is near 1600mV. We plot the number of vounts vs baseline voltage for data near the photopeack baseline voltge. Plot of the data and it's fit with guassian function is presented in figure-5. As it can be seen from the fitting data in figure-5 the the point of maximum (parameter X_c) is 1675.8 mV with an error of 3.34 mV. Full width at half maxima is 176.6 mv with an error of 9.36 mV.

We can determine resolutio (R) using the formula

$$R = \frac{\delta E}{E} \times 100\% \tag{3}$$

where,
δE = The full width of the peak at half of the maximum count level
E = The photopeak voltage.
Note Energy and voltage are related by a constant factor so $\frac{\delta V}{V} = \frac{\delta E}{E}$ Using equation(3) we get

$$R = \frac{176.6 \pm 9.36}{1675.8 \pm 3.34} \times 100 \approx \frac{176.6 \pm 9.36}{1675.8} \times 100 = 10.35 \pm 0.56\%$$

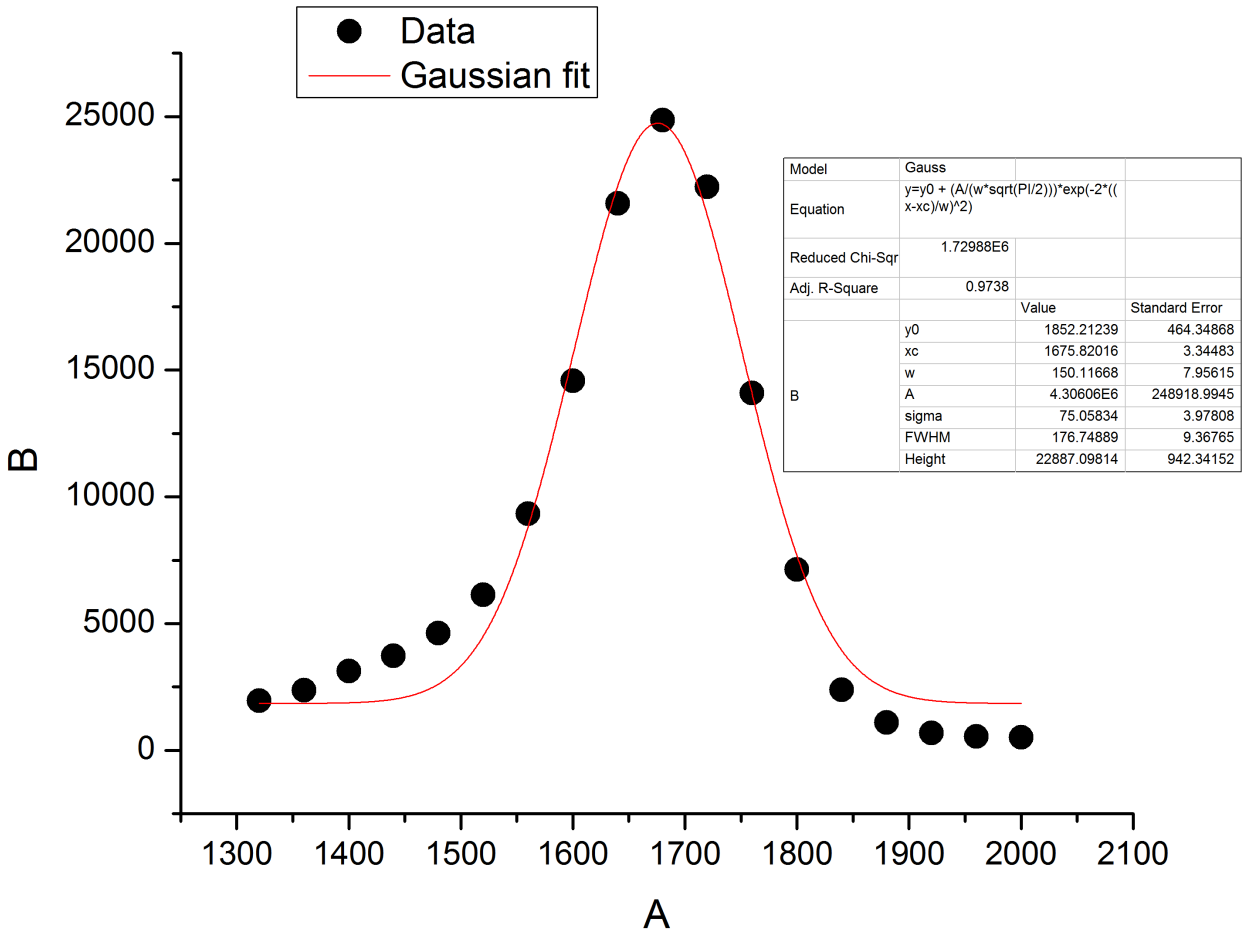


Figure 5: Plot of number of counts vs Baseline Voltage in the vicinity of photopeack voltage.

As shown in section 1.2 the gamma emission of CS^{137} happens via decay of a metastable nuclear isomer of barium: barium-137m (^{137m}Ba, Ba-137m) to stable a stable barium isotope Ba-137 with emission o gamma rays of energy 0.6617 MeV. Aso as discuused in section 2.1.1 the photopeack corresponds to actual energy of gamma radiation. Therefore 1675 mV (which is photopeack baseline voltage) is equivalent to 0.6617 MeV (which is actual energy of the gamma rays.)

We know $mc^2 = 0.511MeV$ and $E_\gamma = 0.6617MeV$ using this we compute

- **Compton edge energy:**

$$E_c = \frac{2E_\gamma^2}{2E_\gamma + mc^2} = \frac{2 \times 0.6617^2}{2 \times 0.6617 + 0.511} = 0.477MeV$$

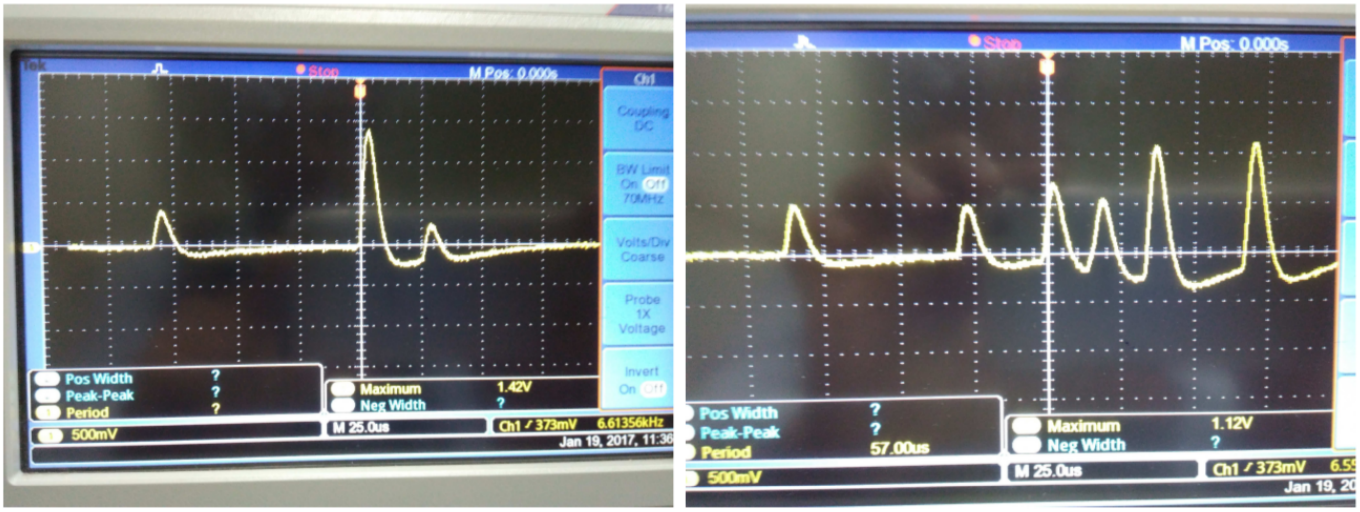
In terms of baseline voltage it should be $1675.8 \times \frac{0.477}{0.6617} = 120mV$

- **Backscatter peak energy:**

$$E_{bc} = \frac{mc^2 E_\gamma}{2E_\gamma + mc^2} = 0.184MeV$$

In terms of baseline voltage it should be $1675.8 \times \frac{0.184}{0.6617} = 188mV$

CRO output is presented in figure-6. When a beam of gamma ray of energy 0.6617 MeV is incident on the NaI:Tl crystal, due to it's different interactions there is a fluctuation in the height of voltage pulses, which lead to broadening of the peak. As decay of radioactive materials is purely probabilistic leading to statistical fluctuation in the number of electrons emitted at the cathode of PMT tube, count rates also vary randomly.



(a) 1^{st} output image

(b) 2^{nd} output image

Figure 6: Images of Voltage pulse heights from CRO.

4 Discussion

We expect the spectrum to of the form as theoretically predicted in figure-2. Our experimentally obesered spectrum as shown in figure-4 is qaulitatively similar to the expected one. It has a small peak near 150 mV which is backscatter peack. We also onserve another peak near 100mV which is compton edge peak. After compton edge we see sudden decrease in count. Ideally it should have been zero but it's not zero because photopeack is nearby and resolution of detector is only 10%. The nonzero count is observed due to spreading of photopeak. If detector had high resolution then photopeak wil be sharp and we shall not see much count between compton edge and photopeak voltage. Calculated value of backscattering peak voltage is 120mV and it's observed near 150mV. However, calculated value of compton edge voltgae is 1200mV and it's observed near 1000mV. This much error is possible because we have selected energy window as 40mV. So our count measurement is for range of energy corresponding to 40mV interval it's not measured at any precise value of energy. So energy correponding to 40mV is kind of our least count. Gievn 40mV least count observed result is possible.

Nuclear decay is probabilistic process so we take data for 30 seconds so that averge count in 30 second does not fluctuate much. After placing the source on top of Scintillator, up to 5 minutes no data is taken to ensure full ionization of the NaI:Tl crystal.