PH3105: Nuclear Physics Laboratory

Experiment 3

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1 Aim

To Study of γ-ray energy spectrum using a scintillation counter with Single Channel Analyzer (SCA). Then we plot the γ-ray spectrum $^{137}_{55}$Cs and identify the prominent phenomenons that leads to these emissions.

2 Experimental Set Up

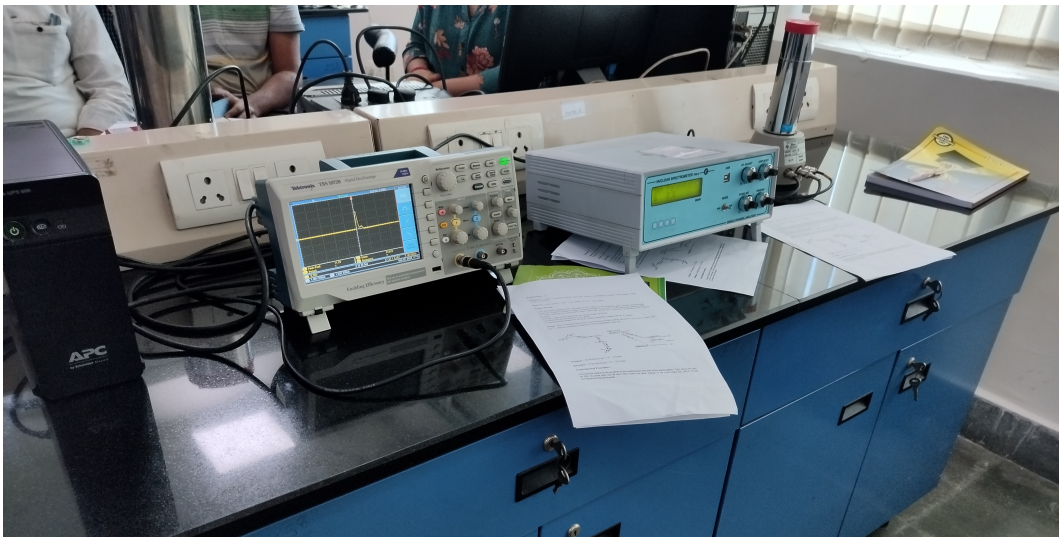


Figure 1: Experimental setup of the instruments at the laboratory

In our experiment, we set up with the following parameters-

High Voltage(HV)	600 V
Amplifier Gain	2.64
Window	20 mV

Before starting the experiment to measure the gamma ray spectrum of Cs-137 using a scintillator detector and PMT, the Cathode Ray Oscilloscope (CRO) was used to set the appropriate gain. We

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proceeded in the following way- first we connect the output of the amplifier to the oscilloscope and look at the signal pattern. Then we adjusted the gain so that no pulse gets cut off and noted down the peak voltage of the most bright line, which corresponded to the photopeak.

We started with baseline of 20 mV and moved up in steps of 40 mV, till we reached 3500 mV (i.e., 3.5 V), and took each reading for 20 seconds. We took two readings for each configuration and took their average to avoid any incidental errors.

3 Working Principle

Scintillation Detector

A scintillation detector is a device used to detect and measure ionizing radiation. It operates based on the principle of scintillation, which is the process of light emission by certain materials when they absorb high-energy particles or photons.

Scintillator Material: The core component of a scintillation detector is the scintillator material. Common scintillator materials include sodium iodide (NaI), cesium iodide (CsI), or organic scintillators like plastic scintillators. When radiation (such as gamma rays, X-rays, or alpha particles) strikes the scintillator, it transfers energy to the atoms or molecules within the material, causing them to become excited.

Light Emission: The excited atoms or molecules return to their ground state by emitting photons, typically in the ultraviolet or visible light range. This light emission is known as scintillation. The amount of light produced is proportional to the energy of the incoming radiation.

Photocathode and Focusing Electrode: The emitted photons are collected and guided towards a photosensitive device, often using a light guide (for example, a Photocathode and Focusing Electrode) to maximize light collection.

Photomultiplier Tube (PMT)

The Photomultiplier Tube (PMT) is a highly sensitive light detector used in combination with the scintillation detector. It amplifies the weak light signal produced by the scintillator.

Photocathode: The PMT contains a photocathode, a thin layer of material that emits electrons when struck by photons (due to the photoelectric effect). When the scintillation light reaches the photocathode, it releases electrons proportional to the light intensity.

Dynodes: These electrons are directed towards a series of electrodes called dynodes. Each dynode is maintained at a progressively higher positive voltage. As the electrons strike each dynode, they cause the emission of secondary electrons. This process repeats across multiple dynodes, resulting in a multiplication of electrons.

Anode: Finally, the electrons are collected at the anode, producing a measurable current pulse. The current is proportional to the number of photons initially emitted by the scintillator, and thus to the energy of the incident radiation.

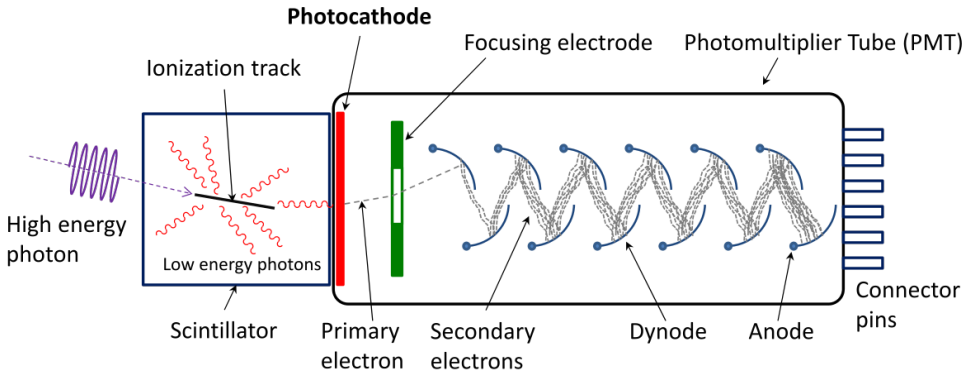


Figure 2: Scintillation Detector and Photomultiplier Tube. Source: Internet

Single Channel Analyzer (SCA)

A Single Channel Analyzer (SCA) is an electronic device that processes the pulses from the PMT. It functions as a pulse height analyzer to select pulses of specific amplitude ranges, allowing only those within a set window to be counted.

Pulse Height Selection: The SCA is configured with a lower-level discriminator (LLD) and an upper-level discriminator (ULD) to set the desired amplitude window. Only pulses with amplitudes between the LLD and ULD thresholds are passed through; others are rejected. This selection helps in discriminating against noise or unwanted signals and allows for the measurement of specific types of radiation based on their energy.

Output Pulse Generation: The SCA generates an output pulse (often a logic pulse) each time a pulse from the PMT falls within the set amplitude window. This output pulse can then be counted or used for further processing.

How Do They Work Together?

The gamma rays enter a NaI(Tl) scintillator crystal. This incident γ-ray photon excites an electron in the valence band of the lattice. This excited electron has large amount of energy ($E_\gamma - E_{band}$), so in this process it collides with other sites and excites other electrons similarly to conduction band. When these electrons de-excite they release a large number of lower energy photons. Thus a 10 MeV γ ray will produce more photons from scintillation than a 1 MeV photon (in this way we can distinguish the energies of photon). These photons travel through the crystal to the photocathode of a photomultiplier tube, where they are converted into electrons by means of the photoelectric effect. The photoelectrons are sent through a series of electrodes where the number of electrons is multiplied. The PMT amplifies this signal through the dynode chain, resulting in a significant electrical pulse at the anode. The number of lower energy photons produced in the scintillator is proportional to the deposited energy of the incident gamma ray, and the number of electrons produced is proportional to the number of photons incident on the photocathode. Therefore, the pulse height of the signal from the photomultiplier tube is proportional to the energy of the incident gamma ray. A pulse height analyzer is used to display the spectrum of pulses from the photomultiplier tube. The output from the PMT is sent to the SCA, which analyzes the pulse height. The SCA allows only pulses within a specified range (those corresponding to the desired radiation energy) to pass through.

4 Theory

Interaction of γ-ray with matter

In nature, all type of radiations can be broadly categorised as *Charged particle interactions* or *uncharged radiations*. Gamma ray and X-rays fall under the second category. A gamma ray can transfer all or part of its energy to electrons within the medium. The resulting secondary electrons are similar to the fast electron radiations (such as the β particle). Devices designed to detect gamma rays are tailored to promote such interactions and to fully stop the resulting secondary electrons so that their entire energy may contribute to the output signal.

Although a large number of possible interaction mechanisms are known for gamma rays in matter, only three major types play an important role in radiation measurements: *photo- electric absorption*, *Compton scattering*, and *pair production*. All these processes lead to the partial or complete transfer of the gamma-ray photon energy to electron energy. They result in sudden and abrupt changes in the gamma-ray photon history where the photon either disappears entirely or is scattered through a significant angle. This behavior is in contrast to the charged particles, which slow down gradually through continuous, simultaneous interactions with many absorber atoms.

Photoelectric Absorption

In photoelectric absorption process, a photon undergoes an interaction with an *absorber atom* in which the photon completely disappears. In its place, an energetic photoelectron is ejected by the atom from one of its bound shells. These liberated electrons lose energy quickly and the γ-ray is detected through

the energy loss of these electrons in the material. It is to be noted that, the interaction is with the atom as a whole and cannot take place with free electrons. For gamma rays of sufficient energy, the most probable origin of the photoelectron is the most tightly bound or K shell of the atom. From photoelectric equation, we have the energy of photoelectron:

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

where E_b denotes the binding energy of the photoelectron in its original shell. For gamma-ray energies of more than a few hundred keV, the photoelectron carries off the majority of the original photon energy.

In addition to the photoelectron, the interaction also creates an ionized absorber atom with a vacancy in one of its bound shells. This vacancy is quickly filled through capture of a free electron from the medium and/or rearrangement of electrons from other shells of the atom. Therefore, one or more characteristic X-ray photons may also be generated.



Figure 3: The figure shows the differential distribution of electron kinetic energy for a number of photoelectric events. For monoenergetic γ-ray it will be a delta function at the incident γ-ray energy (broadening may come from the distribution of binding energy of the electrons).

The photoelectric process is the predominant mode of interaction for gamma rays (or X-rays) of relatively **low energy**. The process is also enhanced for absorber materials with high atomic number Z. Empirically, we have a rough relationship for the probability of photoelectric absorption per atom over all ranges of E_γ and Z,

$$\tau \simeq \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

where the exponent n can vary between 4 and 5 over the gamma-ray energy spectrum of interest. E_γ is the gamma ray energy.

Compton Scattering

The interaction process of compton scattering takes place when the incident gamma-ray photon interacts with an electron in the absorbing material. It is most often the predominant interaction mechanism for gamma-ray energies typical of **radioisotope sources.**

In Compton scattering, the incoming gamma-ray photon is deflected through an angle θ with respect to its original direction. The photon transfers a portion of its energy to the electron (assumed to be initially at rest), which is then known as a *recoil electron*. Because all angles of scattering are possible, the energy transferred to the electron can vary from zero to a large fraction of gamma ray energy. This is why, there is a distribution of energy of the scattered electrons over many compton scattering events. The following graph illustrates it

The variation of scattered γ-ray energy with scattering angle θ can be easily deduced as:

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

The angular distribution of scattered gamma rays is predicted by the **Klein–Nishina** formula for the differential scattering cross section $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$

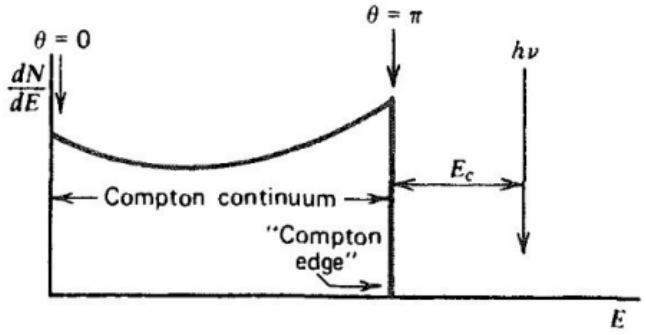


Figure 4: A graph of differential energy distribution of the compton recoil electrons. The maximum energy of the recoil electron is known as **Compton edge**.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = Zr_0^2 \left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2 \left(\frac{1+\cos^2\theta}{2}\right) \left(1 + \frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right)$$

where $\alpha \equiv \frac{h\nu}{m_0c^2}$ and r_0 is the classical electron radius. The distribution when plotted in polar coordinates illustrates the strong tendency for forward scattering at high values of the gamma-ray energy.

Coherent Scattering

In addition to Compton scattering, another type of scattering can occur where the γ-ray photon interacts coherently with all the elctrons of an absorber atom. This coherent scattering or **Rayleigh scattering** process neither excites nor ionizes the atom, and the γ ray retains ts original energy after the scattering event. The probability of coherent scattering is significant only for low photon energies and is most prominent in high-Z absorbers.

Pair Production processes

If the gamma-ray energy exceeds twice the rest-mass energy of an electron (1.02 MeV), the process of pair production becomes energetically possible. However practically, the probability of this interaction remains very low until the gamma-ray energy approaches several MeV and therefore pair production is predominantly confined to high-energy gamma rays. In the interaction (which must take place in the coulomb field of a nucleus), the gamma-ray photon disappears and is replaced by an electron-positron pair. All the excess energy that is carried in by the photon above the 1.02 MeV required to create the pair, goes into kinetic energy shared by the positron and the electron.

To, summarize the relative importance of the 3 major types of gamma-ray interactions are illustrated in the graph below.

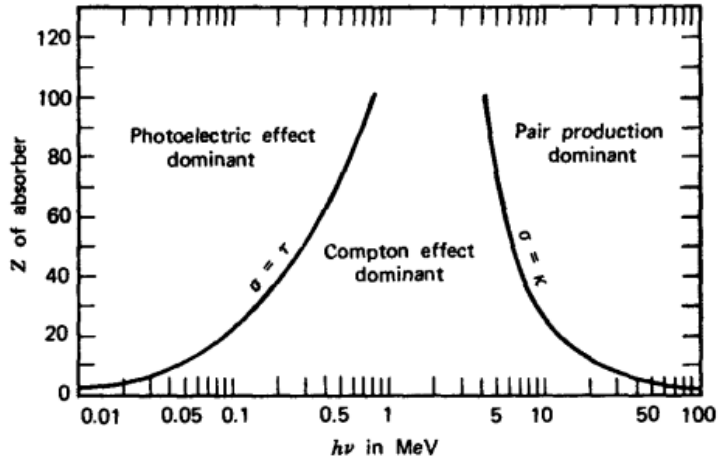


Figure 5: Energy range of 3 major types of gamma-ray interactions.

5 Data analysis

5.1 Graphical Inference of Data

We proceed to plot our data (in Fig 6) , to get a view of the entire spectrum.

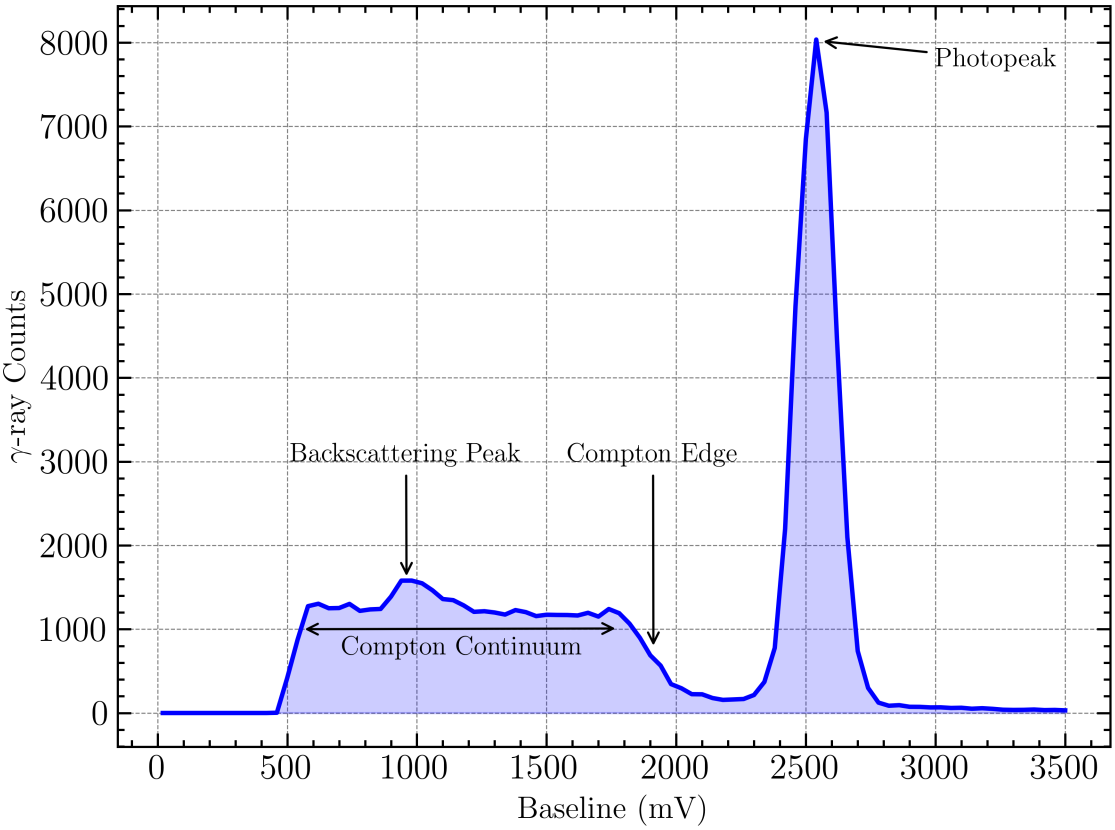


Figure 6: A plot of $\gamma-$ray spectrum of $^{137}_{55}$Cs in $t = 20$s. The prominent parts of the graph have been labelled in the above diagram.

In this plot, we find two major peaks namely *backscattering peak* and the *photopeak*, but they have different heights. The photopeak appears at baseline of 2540 mV, and has a height of about 5.085 times the backscattering peak which appears at 980 mV.

We describe some of the features that are observed from our plot-

Backscattering Peak The fact that electrons often undergo large-angle deflections along their tracks leads to the phenomenon of backscattering. The backscattering peak results from gamma rays that are scattered in the surrounding materials (like walls, detector housing, etc.) and then detected. This peak typically appears at lower energies, around 150-250 keV, depending on the geometry and materials involved.

Compton Continuum The Compton continuum arises from the Compton scattering process, where a gamma photon is partially absorbed, and the rest of the energy is scattered. The scattered photon escapes, leaving behind a range of energies in the detector.

Compton Edge It corresponds to the maximum energy of the recoiled electron during a compton scattering event (i.e at $\theta = \pi$).

Photopeak The photopeak represents the full-energy peak and occurs when the gamma ray transfers all its energy to an electron in the detector through the photoelectric effect. $^{60}_{27}$Co, emits two primary gamma rays at 1.17 MeV and 1.33 MeV, (corresponding to its two major transitions). So would see *two photopeaks* in its spectrum. On the other hand, $^{137}_{55}$Cs emits a gamma ray at 0.6617 MeV (corresponding

to it's only major transition, after a β decay), thus we will see a single photopeak corresponding to this energy.

5.2 Relation with pulse height in CRO

The highest pulse height in CRO corresponds to the maximum energy of incident radiation. The CRO displays the voltage pulses as a series of peaks on the screen, with the height of each peak representing the energy of the detected gamma ray. This height of the highest pulse in CRO corresponds to the baseline in the SCA spectrum at which photo-peak is observed.

6 Sources of Error

1. **Compton Scattering Effects:** Gamma rays scattering inside the detector results in energy loss before detection, leading to a Compton continuum in the spectrum rather than sharp peaks.
2. **Energy Calibration:** If the scintillation detector isn't properly calibrated to detect lower energy signals, such as X-rays (which typically have energies around 10-100 keV), this could cause a discrepancy in the results. Even slight miscalibrations could prevent lower-energy peaks from being resolved.
3. **Environmental Radiation:** Background radiation from the environment, cosmic rays, or other radioactive sources in the surroundings can cause noise and interfere with the gamma-ray peaks.
4. **Scintillator Degradation:** Over time, the scintillation material can degrade, affecting its ability to convert gamma-ray energy into visible photons.

7 Discussion

Lower level discrepancies We do not get any counts at low baseline values. We expect to find a a barium (Ba) X-ray peak in the SCA reading. It is caused by a barium de-excitation gamma ray transferring its energy to a K-shell electron. This process creates a vacancy in the atom, which is then filled by an electron from the top shell. The filling of this vacancy emits a 32 keV X-ray, known as the Ba-$K\alpha$ line. One of the most plausible explanation for this might be

Many detectors have lower-level thresholds (or LLD) set to ignore signals below a certain energy level to reduce noise. If this threshold is set too high, the detector might filter out lower-energy events, like the X-ray peaks, leading to their absence in the graph.

References

- Knoll, Glenn F. *Radiation detection and measurement.* John Wiley & Sons, 2010.

Appendix

Readings from SCA for $t = 20$s

Baseline (mV)	Count 1	Count 2	Average Count
20	0	0	0
60	0	0	0
100	0	0	0
140	0	0	0
180	0	0	0
220	0	0	0
260	0	0	0
300	0	0	0
340	0	0	0
380	0	0	0
420	0	0	0
460	3	3	3
500	423	416	419.5
540	860	893	876.5
580	1273	1276	1274.5
620	1276	1331	1303.5
660	1259	1241	1250
700	1241	1264	1252.5
740	1261	1342	1301.5
780	1225	1212	1218.5
820	1191	1281	1236
860	1207	1276	1241.5
900	1404	1373	1388.5
940	1606	1553	1579.5
980	1573	1587	1580
1020	1501	1594	1547.5
1060	1452	1476	1464
1100	1356	1363	1359.5
1140	1325	1368	1346.5
1180	1267	1302	1284.5
1220	1212	1202	1207
1260	1242	1187	1214.5
1300	1229	1169	1199
1340	1158	1191	1174.5
1380	1237	1219	1228
1420	1182	1225	1203.5
1460	1160	1152	1156
1500	1145	1200	1172.5
1540	1164	1176	1170
1580	1195	1143	1169
1620	1172	1155	1163.5
1660	1187	1204	1195.5
1700	1147	1154	1150.5
1740	1209	1272	1240.5
1780	1185	1197	1191
1820	1086	1046	1066
1860	856	938	897
1900	663	714	688.5
1940	557	574	565.5
1980	357	333	345
2020	295	295	295
2060	211	238	224.5
2100	220	226	223
2140	165	192	178.5
2180	164	149	156.5
2220	165	158	161.5
2260	176	158	167
2300	221	209	215
2340	373	368	370.5
2380	802	750	776
2420	2231	2165	2198

Baseline (mV)	Count 1	Count 2	Average Count
2460	4872	4838	4855
2500	6697	7002	6849.5
2540	7934	8137	8035.5
2580	7196	7134	7165
2620	4437	4479	4458
2660	2172	2024	2098
2700	730	748	739
2740	307	291	299
2780	140	108	124
2820	71	102	86.5
2860	90	97	93.5
2900	70	78	74
2940	74	72	73
2980	57	76	66.5
3020	69	66	67.5
3060	56	64	60
3100	63	62	62.5
3140	53	49	51
3180	51	63	57
3220	50	49	49.5
3260	32	46	39
3300	33	40	36.5
3340	37	38	37.5
3380	34	49	41.5
3420	38	31	34.5
3460	37	36	36.5
3500	32	31	31.5