MIDDLE EAST TECHNICAL UNIVERSITY

Compton Effect

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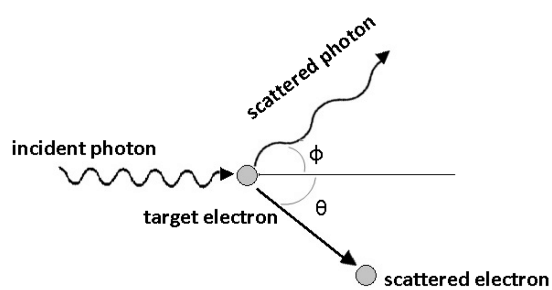


Contents

1 Introduction

1.1 Goal

The goal of this experiment is to observe the particle properties of light and to analyze the experimental observations to validate the wave-particle duality, bridging the gap between classical and quantum physics.

1.2 Theory

1.2.0.1 Thomson Scattering - Classical Electromagnetic Theory

Thomson scattering is an example of elastic scattering of electromagnetic radiation. The electric and magnetic fields components of an electromagnetic field exerts a Lorentz force on a particle, which sets it into motion that is periodic in time. Since the particle is now accelerated, it emits radiation.

The electric field component of a linearly polarized, monochromatic, plane wave incident on a particle of charge **q** can be written as

$$E = eE_0 exp(i(k.r - wt)) \tag{1}$$

The particle undergoes oscillations with small amplitude, therefore its velocity is assumed to be non-relativistic, enabling us to neglect the magnetic component of the Lorentz force. Then the EOM of the charged particle can be written as

$$F = qE = m\ddot{s} \tag{2}$$

where **s** is the displacement from the origin.

Then the time averaged power radiated per unit solid angle becomes

$$\frac{dP}{d\Omega} = \frac{q^2 < \ddot{s}^2 >}{16\pi^2\epsilon_0 c^3} sin^2\theta \tag{3}$$

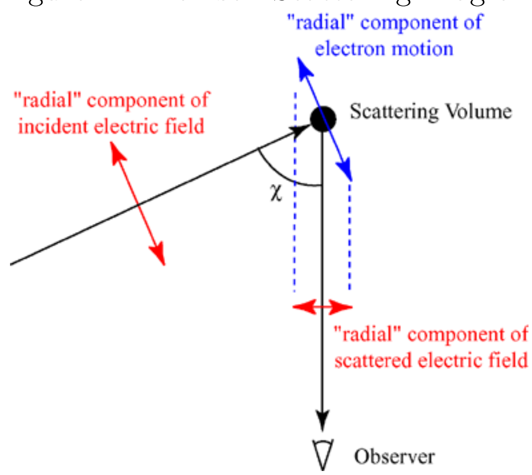
and

$$< \ddot{s}^2 >= \frac{q^2}{m^2} < E^2 >= \frac{q^2 E_0^2}{2m^2} \tag{4}$$

Which essentially means that the oscillating particle acts as a short antenna.

The resulting radiation will be perpendicular to the acceleration of the particle and be polarized along its direction of motion.

Figure 1: Thomson Scattering Diagram



1.2.0.2 Compton Scattering - Particle Properties Of Light

Compton scattering is an example of inelastic scattering of electromagnetic radiation. Collision between a photon γ with wavelength λ and an electron e that is at rest causes the electron to recoil, which in turn results in a new photon γ' with wavelength λ' at angle θ from the incident photon's path. Using the conservation of energy, we have

$$E_\gamma + E_e = E_{\gamma'} + E_{e'}. \tag{5}$$

Compton postulated that photons carry momentum and used the conservation of momentum as well

$$p_\gamma + p_e = p_{\gamma'} + p_{e'} \tag{6}$$

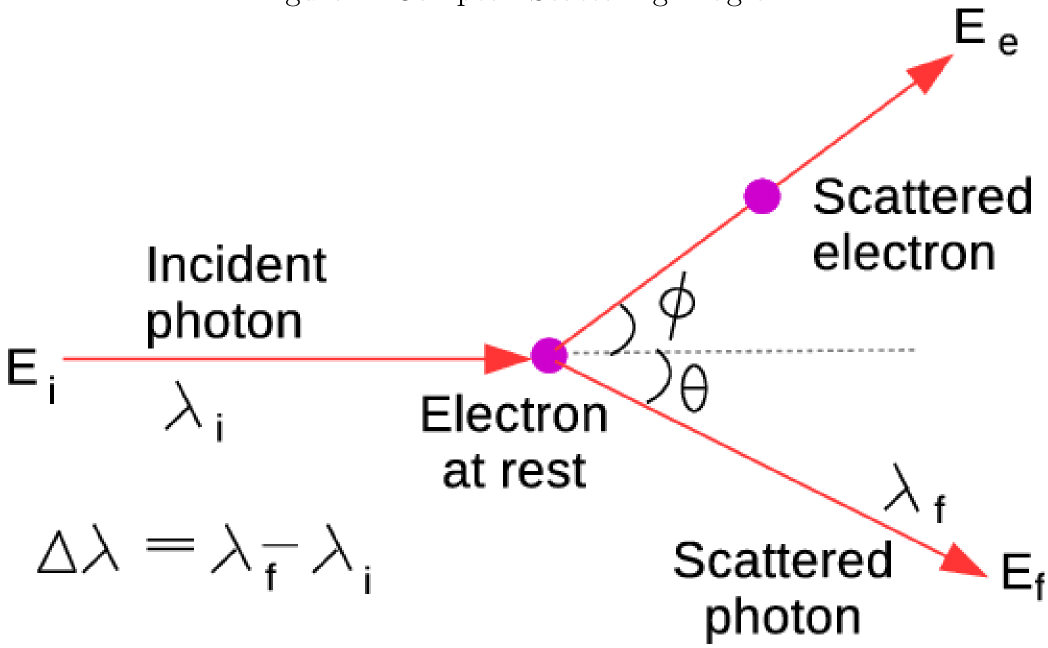
Knowing that,

$$E_\gamma = hf,\ E_{\gamma'} = hf' \tag{7}$$

and that,

$$E_e = m_e c^2,\ E_{e'} = \sqrt{(p_{e'}c)^2 + (m_e c^2)^2} \tag{8}$$

Figure 2: Compton Scattering Diagram



We expect the electron to be accelerated to a relativistic speed after the collision, thus we used the relativistic energy and momentum relation. Substituting these variables in the conservation relations, we get

$$hf + m_e c^2 = hf' + \sqrt{(p_{e'}c)^2 + (m_e c^2)^2} \text{ and } p_{e'}^2 c^2 = (hf - hf' + m_e c^2)^2 - m_e^2 c^4. \tag{9}$$

Solving the equation for the conservation of momentum,

$$\begin{aligned}
p_{e'}^2 c^2 &= p_\gamma^2 c^2 + p_{\gamma'} c^2 - 2c^2 p_\gamma p_{\gamma'} cos\theta, \\
p_{e'}^2 c^2 &= (hf)^2 + (hf')^2 - 2(hf)(hf')cos\theta, \\
2hfm_e c^2 - 2hf'm_e c^2 &= 2h^2 ff'(1 - cos\theta), \\
\frac{c}{f'} - \frac{c}{f} &= \frac{h}{mc}(1 - cos\theta).
\end{aligned}$$

And finally, after rigorous derivation, we arrive at the famous Compton Shift expression

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}(1 - cos\theta). \tag{10}$$

Where λ is the wavelength of the incident photon, λ' is the wavelength of the scattered photon, m_e is the rest mass of the electron, θ is the scattering angle and the expression $\frac{h}{m_e c}$ is the Compton wavelength.

1.2.0.3 Bridging The Gap

As it is clear from the derivations, Thomson scattering is the low-energy limit of Compton scattering, where the photon energy is much smaller than the resting energy of the electron $\mu << mc^2/h$. Since classical electrodynamics fails to explain the wavelength shift between the incident and scattered photons, realization of this phenomena had important implications on physicists' understanding of light since light clearly behaves as if it consists of particles in this experiment.

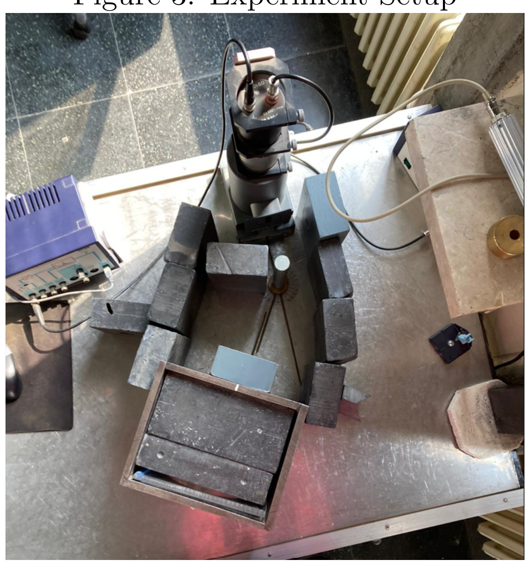
2 Experimental Details

The experiment was carried out with utmost care, following the radiation safety guidelines. The surroundings of the path of the photons radiated from the gamma radiation sources were carefully obstructed and the experiment area was checked with a Geiger counter before anyone interacted with the setup.

The procedure consisted of two parts that will be explained individually later in this section. The experiment took approximately two hours including the two procedures, discussion about the experiment with the TA and necessary calculations.

The experiment setup used can be seen in the figure below, the equipment will be explained individually.

Figure 3: Experiment Setup

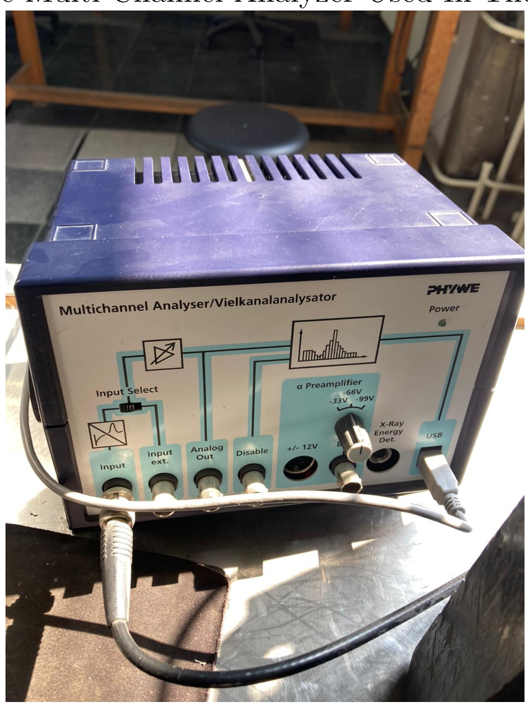


2.1 Equipment

2.1.1 Multi Channel Analyzer

A multichannel analyzer is an instrument that uses a fast analog to digital converter to analyze incoming input pulses and is a popular instrument used in gamma spectroscopy. The data taken from the MCA will be presented in the next section.

Figure 4: The Multi Channel Analyzer Used In The Experiment



2.1.2 Radioactive Source

Two radioactive sources were used during the experiment.

2.1.2.1 CS - 137, 37 kBq

This source was encased in a small lead block and used during the calibration process. Its small size allowed it to be around safely without much effort. When the calibration process was over, this source was carefully removed from the setup and left adjoining the wall.

2.1.2.2 CS - 137, 18.5 MBq

This source was encased in a large lead block, had wheels attached to it and used during the experiment procedure. A thick lead block was present in front of this source during the calibration process for safety reasons, the block was only removed briefly for the experiment procedure. The source is encased in the large lead block which can be seen in Figure 3.

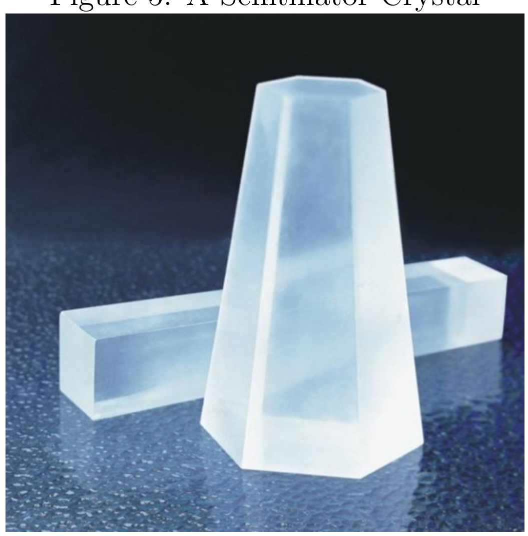
2.1.3 Gamma Detector

The gamma detector used in this experiment is a scintillation counter, which consists of a scintillator crystal and a photomultiplier tube connected to it.

2.1.3.1 Scintillator

Scintillators absorb incoming particles (or ionizing radiation, ie. gamma radiation used in this experiment) to emit the absorbed energy as light. Scintillators themselves work on the principle of Compton effect, which is a nice correlation.

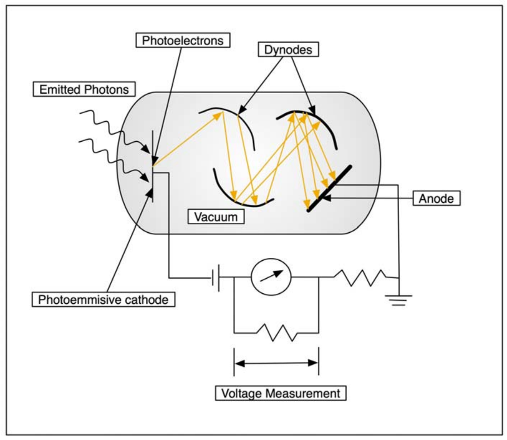
Figure 5: A Scintillator Crystal



2.1.3.2 Photomultiplier Tube

A photomutiplier tube allows the incoming photons to hit the photocathode material inside, allowing electrons to eject its surface because of photoelectric effect. The ejected electrons are then directed over to the electron multiplier where secondary emission allows the electrons to be multiplied.

Figure 6: Photomultiplier Tube Schematic



2.1.3.3 Operating Unit

The operating unit of the detector is rsponsible for supplying the appropriate voltage in a stable way to the photomultiplier tube. It operates between 600 Volts and 1100 Volts.

During the experiment, the voltage knob was at the scale 8.00, which corresponds to 1000 Volts.

2.1.4 Iron Rod

An iron rod is used as an electron source in this experiment. The photons radiated by the gamma source hit the iron rod and scatter photons to be detected by the detector.

2.1.5 Lead Block

Several lead blocks are used in the experiment for safety reasons. Everywhere except the direct path of the incident radiation is obstructed by lead blocks, which in turn has consequences in the measured result which will be discussed in the discussion section.

2.2 Procedure

2.2.1 Calibration Procedure

The calibration process was performed as follows:

- The MCA was turned on and its proprietary software was set up to make measurements.
- The voltage knob of the operating unit of the detector was adjusted to the scale value of 8.00 to supply the necessary voltage to the detector.
- Cs - 137, 37kBq, which is the source encased in the smaller lead block, was carefully inserted in front of the detector, adjoining it.
- The calibration process was started in the software.
- Waited around 15 - 20 minutes for the measurements.
- Analyzed the resulting spectra with the TA.
- Identified the two sharpest peaks corresponding to two different types of radiation from the source and marked them.
- Assigned known peak values for Cs - 137 to the marked peaks, completing the calibration process.
- The calibration was saved on the software and the radiation source was carefully removed.

2.2.2 Experiment Procedure

The experiment procedure was performed as follows:

- The software was set up to make measurements again.
- The iron rod, which acts as an electron source, was inserted in front of the larger gamma source and its angle was arranged with an old and worn down instrument.
- The direct path of the radiation was blocked by a lead block to ensure that we mostly measure the radiation due to Compton scattering.

- The lead cover of the Cs - 137, 18.5 MBq source was carefully removed to let radiation hit the iron rod.
- The measurements was started with the software.
- Waited around 15 - 20 minutes one again for the measurements.
- After we had enough data, the lead cover of the radiation source was carefully inserted in front of it once again and the measurement process was done.
- The resulting spectra was analyzed with the TA and had verbal discussion on it.
- Performed smoothing on the measured data and saved the plots for the laboratory report.

3 Measurement And Data Analysis

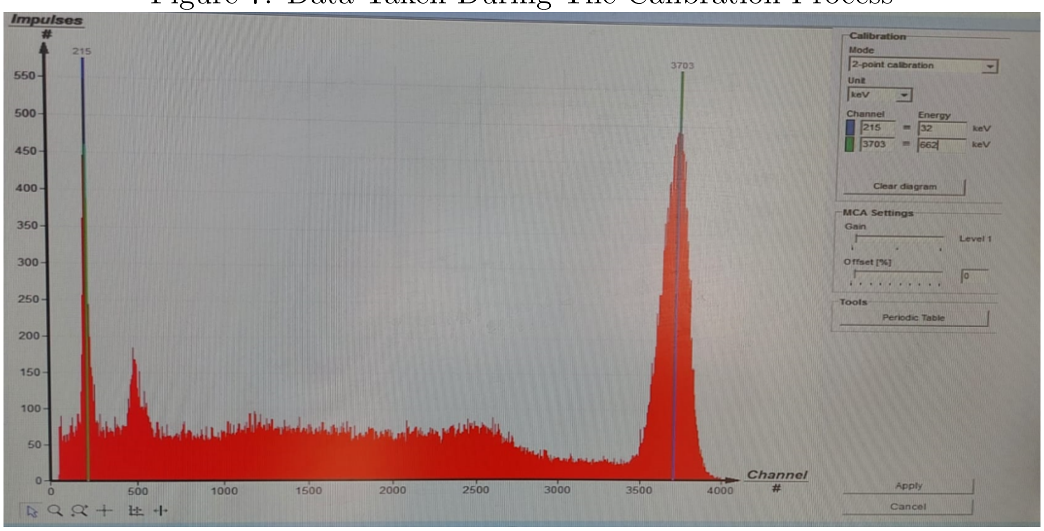
3.1 Presentation Of Data

Since we are only interested in the peak values for our calculations and the general shape of the spectra to draw conclusions, the data is taken as photographs from the laboratory computer.

3.1.0.1 Calibration

The calibration spectra data is presented below, the significance of the peaks and their values will be discussed in the discussion section.

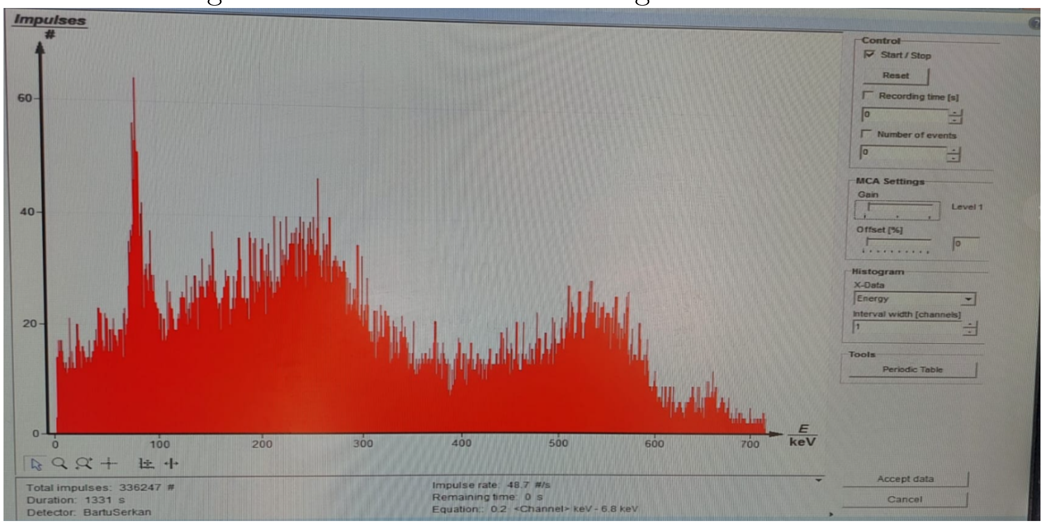
Figure 7: Data Taken During The Calibration Process



3.1.0.2 Main

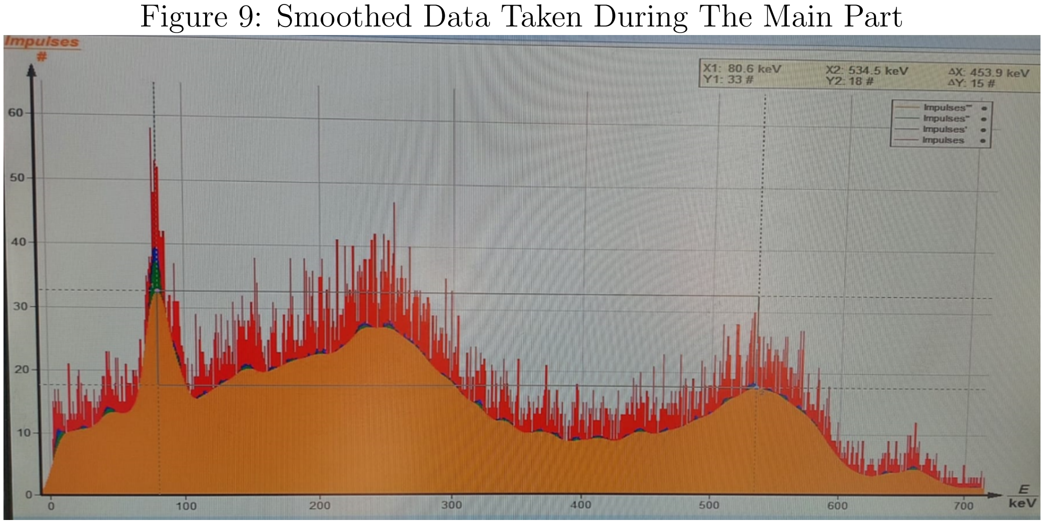
The raw spectra data from the experiment is presented below, this spectra was then smoothed for easier analysis. From the figure, we can see that the measurement was taken for 1331 seconds and there were 336247 total number of impulses.

Figure 8: Raw Data Taken During The Main Part



The smoothed spectra data from the experiment is presented below, the meanings of the three significant peaks will be discussed in the discussion section.

Figure 9: Smoothed Data Taken During The Main Part



3.2 Calculations

For the proof of concept, we needed to calculate the Compton wavelength which we initially knew the value of. The calculations were carried out as follows:

$$\text{incident photon wavelength, } \lambda = 1.873 * 10^{-12} m$$
$$\text{incident photon energy, } E = 661.6 keV$$
$$\text{scattering angle, } \phi = 30^\circ$$
$$\text{rest mass of electron, } m_0 = 0.510998950 MeV/c^2$$
$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_0 c^2}(1 - cos\phi)$$
$$E' = 563.82 keV$$
$$E' = hc/\lambda'$$
$$\lambda' = 0.0219928\text{Å}$$
$$\lambda = 0.0187311\text{Å}$$
$$\lambda_c = \frac{\lambda' - \lambda}{(1 - cos\theta)} = 0.0243457\text{Å, the Compton wavelength}$$

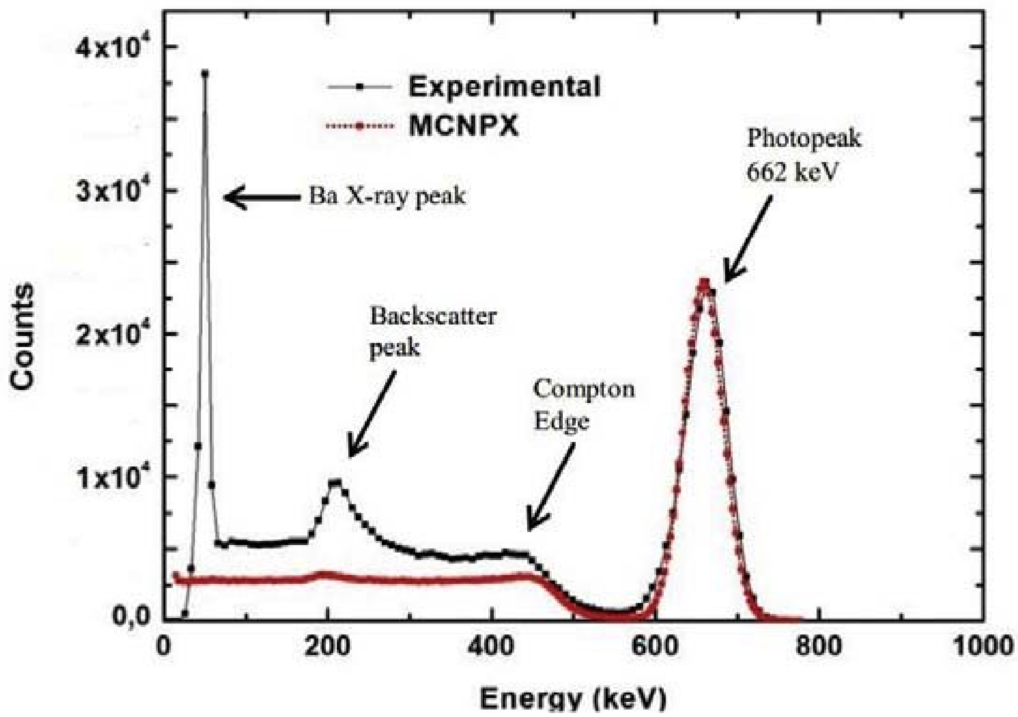
4 Results And Discussion

4.1 Discussion Of Results

The points of discussion for this experiment are the peaks in the measured spectra.

At this point, it can be instructive to look at the spectra for Cs-137, which we knew about while performing the experiment. A gamma spectroscopy measurement of Cs-137 can be seen in the figure below.

Figure 10: Cs-137 Spectra



Looking at the three peaks present in the spectra in Figure 7, since we already know the emission spectra of Cs-137, we can easily identify the rightmost and leftmost peaks as the X-ray photopeak, caused by the excitation of lead atoms and the gamma photopeak. Since we know the values for these peaks, we can select the peaks and assign the appropriate value to them for healthier measurements. The smaller peak is the backcatter peak, most probably caused by Compton effect from the shielding inside the detector.

The three peaks discussed in the previous paragraph are present in the experiment data as well as it can be seen in Figure 9, however they are clearly not as sharp as they were in the calibration spectra in Figure 7 since radiation coming from other sources have populated the spectra as well. The calibration data was measured when the source was completely adjoining the detector, mitigating all other sources of radiation. However there are many other factors effecting the result and they can be listed as follows:

- The shielding between the radiation source and the detector is not perfect since we have used a lead block to block the direct path. We can clearly see the result of direct radiation in the rightmost small peak in Figure 9.
- The second peak from the left is caused by the excitation of the lead block that was encasing the radiation source and this was present in the calibration spectra as well.
- The main peaks that we are interested in are not as sharp as the calibration data peaks because the detector most likely measured radiation scattering from the lead blocks all over the experimental setup. This is not much of a problem as well since we can identify the reason and just ignore it, focusing on the two relevant peaks that indicate Compton Effect.

Smoothing was applied to the data to make it easier to analyze but the results were clear enough in the raw data as well. Compare the figures 8 and 9 to see the difference that smoothing makes.

4.2 Discussion Of Errors

Although some error was present in the measurement, the results were clear enough to draw concrete conclusions. Especially after the smoothing done by the software of the MCA, errors were less prominent.

4.2.1 Main Sources Of Errors

The main sources of error in this experiment are:

Angle Arrangement: The instrument used for angle arrangement was old and worn down which made it harder for us to see the exact values and align the setup. Also since the instrument was ruler-like, there are vision based errors as well as we used our eyes and hands for alignment. These factors played role in the error of the scattering angle value.

Shielding: Shielding is necessary for safety reasons, however, the excessive shielding of the surroundings and the radiation source itself caused an extra peak in the measured spectra. The radiation that scattered from the lead blocks that are used for shielding effected the result a lot, however since we are aware of this unwanted consequence, we are able to just ignore that peak during the analysis of the main experiment. It was also informative to see the clear consequence of shielding in the resulting spectra which allowed us to brainstorm on it.

4.2.2 Error Mitigation

The errors caused by shielding is not very important here since it has little to no effect on the actual peaks that we want to analyze and safety of people in the laboratory is definitely more important than "cleaner data" since the radiation used in this experiment is very dangerous.

The errors caused by the angle arrangement can be mitigated by replacing the current instrument with a better one, or at least a new one. I think the error in the scattering angle doesn't affect our result very much.

References

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