Imperial College London

E1. The Compton Effect

Head of Experiment: Prof Alex Tapper

The following experiment guide is NOT intended to be a step-by-step manual for the experiment but rather provides an overall introduction to the experiment and outlines the important tasks that need to be performed in order to complete the experiment. Additional sources of documentation may need to be researched and consulted during the experiment as well as for the completion of the report. This additional documentation must be cited in the references of the report.

3rd Year Lab Module
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Alex Tapper

The Compton Effect

1. Overview

The key objectives for this experiment are:

- Calibrate and use a scintillating detector to measure ionizing radiation.
- Verify the Compton effect.
- Further investigate sources of radiation or characteristics of the detector.

2. Gamma Ray - Electron Scattering

The collision of a photon and an electron is depicted in Figure 1. Due to this interaction, there is a change in the photon's energy, as well as its direction. This phenomenon is known as the Compton effect, and historically, its discovery played an important role in understanding the particle-like characteristics of light. In the present day, the Compton effect remains a fundamental aspect of light-matter interaction studies, and it is integral to many technical and scientific applications of X-rays and gamma rays.

To derive an equation to describe the Compton effect, we consider a collision in which an electron is initially at rest. In this case, the conservation of energy and momentum results in the following relationship between the initial photon energy $E_{\gamma 0}$, final photon energy E_γ, and scattering angle θ:

$$E_\gamma(\theta) = \frac{E_{\gamma 0}}{1 + \frac{E_{\gamma 0}}{m_e c^2}(1 - \cos\theta)} \tag{1}$$

where $m_e c^2$ = 511 keV is the rest energy of the electron.

- Why is the Compton effect typically disregarded when considering visible light?
- When is it justified to approximate an electron as free and at rest, as assumed for Eq. (1)?

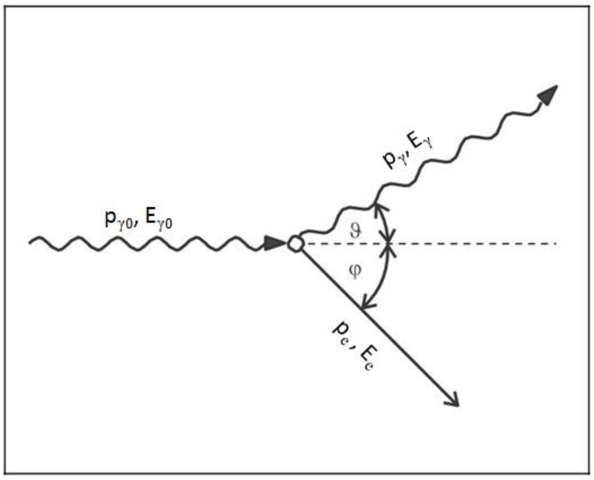


Figure 1. An idealised picture of the collision of a photon with an electron at rest.

Safety notes:

When radioactive items are handled, specific regulations must be observed. The radioactive substances used in this experiment are approved for teaching purposes at schools in accordance with the UK HSE guidelines. Since they produce ionizing radiation, the following safety rules must be obeyed:

- Prevent access to the preparations by unauthorized persons.
- Before using the preparations make sure that they are intact.
- For the purpose of *shielding*, keep the preparations in their safety container.
- To ensure *minimum exposure time* and *minimum activity,* take the preparations out of the safety container only as long as is necessary for carrying out the experiment.
- To ensure *maximum distance,* hold the preparations only at the upper end of the metal holder and keep them away from your body as far as possible.
- The radioactive samples are in sealed containers. However, do not consume food or drink whilst handling radioactive samples. Wash your hands after handling radioactive samples.

3. Instrumentation

An idealised sketch of a typical experimental setup used to observe the Compton effect is shown in Figure 2. The main elements are:

(a) A radioactive sample and sample holder.
(b) Aluminium scattering target.
(c) Lead shielding.
(d) Entrance aperture of detector with shielding.
(e) NaI(TI) scintillator and photomultiplier tube.
(f) Power and signal connections.
(g) High voltage power supply.
(h) Multi-channel analyser (MCA) for pulse height analysis.

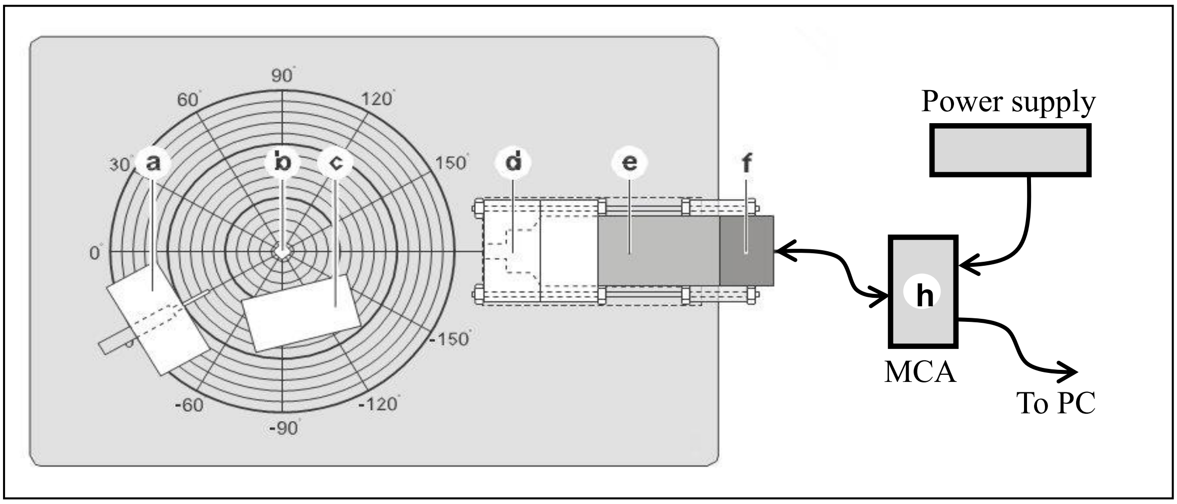


Figure 2. Experimental setup for measuring the Compton effect.

- How do the scintillating crystal and photomultiplier tube work? What are the likely maximum and minimum detectable gamma ray energies with such a system?
- Try to measure signals from the detector with an oscilloscope. What can you learn from this?
- What does the MCA unit do?

4. Recording a detection spectrum

Pre-built software on the desktop computer provided can be used to record a histogram from the MCA for a specified scan time once the PMT is powered on and detecting events.

- Connect the MCA to the computer via USB.
- Launch the counting software Cassy Lab.
- Run an experiment.

Data can be analysed using Cassy Lab, copied into a spreadsheet program, or exported for analysis using another program. A sensible physicist will make sure that data copying and backup processes work as expected and that the files you create actually contain the information you "think" they should contain before moving on with the experiment. This "book keeping and filing" aspect of experiments that generate large data sets is typically a dull but very necessary aspect of laboratory work. Make sure you use sensible file names and record these in your lab book along with preliminary plots of data as you go. This ensures you can use them to illuminate discussions with demonstrator, and properly identify the limited number of "golden" data sets you eventually use in your report.

5. Calibrating the detector

A calibration is needed to express the detector output as an energy. This can be achieved using radioactive samples from which the dominant emission energies are known, for example 662 keV for Cs-137, 122 keV for Co-57, and 59.6 keV for Am-241.

- Place multiple radiation sources of known type individually in front of the detector.
- Determine a power supply voltage for which the dominant peak from each source can be seen at the same time in the histogram recorded in Cassy Lab.
  Typical voltages are 400-700 V. **Do not exceed 1000V PMT drive voltage**.
- Use this voltage setting to measure the peak position for each source separately.
- Develop a scheme to find a calibration relation from your measurements that allows you to convert a position on the histogram to a specific gamma ray energy. Can this be improved (e.g. to identify a non-linearity) using additional sources of known energy?

An example spectrum of Cs-137 from a calibrated detector is shown in Figure 3 below to give you a general sense of the "look and feel" of the data. Different sources will produce traces with a range of features which may be interesting points for discussion with a demonstrator.

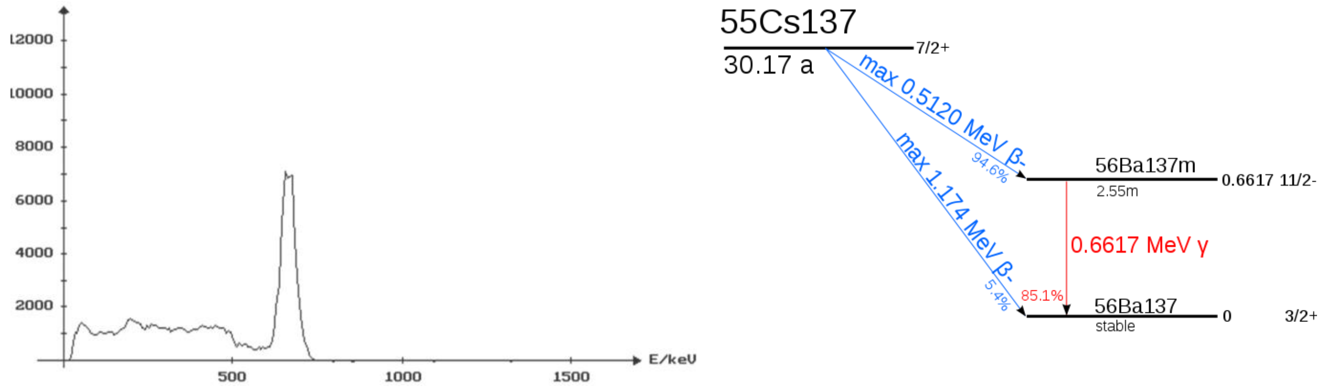


Figure 3. Example spectrum from Cs-137 and an idealised nuclear energy level diagram.

You will need to identify expected gamma emission energies from a range of radioactive materials (known and unknown) and there are many useful sources for this information available on line and in the literature. A useful starting point (including some data taken with research grade NaI scintillator detectors for reference) can be found at:

https://gammaray.inl.gov/SitePages/catalog_nai.aspx

6. Verifying the Compton effect

Once the detector is well calibrated, the Compton effect can be verified using an experimental arrangement similar to that shown in Figure 2 to measure the energy of photons scattered at different angles. Be aware that if you change your PMT voltage your calibration process may need to be repeated.

First, qualitatively observe the Compton effect by comparing a $\theta = 45°$ spectrum to that from no scattering target.

- Position the source, aluminium scattering target, detector, and additional lead shielding as desired to measure the spectrum corresponding to a specific scattering angle θ.
- The additional lead shielding might be needed to block any direct path from the source to the detector.

Once the basic effect is observed, undertake a precise, quantitative verification of angular dependence in Equation (1). This will require some thoughtful experimental planning and analysis. Here are some things to consider:

- What radiation source should you use?
- How should lead shielding be positioned? Note that it may cause additional scattering that adversely affects your measurement. For each experimental geometry, record a spectrum with and without the scattering target in place. (What

can be learned from the data with no target? Why is the differential spectrum useful to analyse?)

- Save each data set along with pertinent details for further analysis.
- What measurement time should be used at each angle? How does the measurement time relate to how precisely the energy peak can be determined?
- Large distances between the scattering target and the source or the detector enhance the angular resolution and decrease the counting rate.

7. Evaluating the Compton effect measurements

Compare the measured values with the energies of the scattered photon calculated according to Eq. (1).

How well do the measured values agree with those expected theoretically? Are you able to verify the Compton effect?

Analyse the experimental procedure and results to produce a full error analysis. Discuss the error in finding the peak signal position and how this relates to the background signal and noise in the measurement with your demonstrators, they may point out subtleties that invite further investigation. What other experimental limitations are significant?

8. Further investigations and Extensions

Once the Compton effect is studied and you have gained a clear understanding of the instrumentation, you are encouraged to further explore the gamma ray spectrometer and its applications.

- What else can be deduced from your data, and how might the instrument be improved? What role does Compton scattering play in the detector itself?
- Can the precision with which the Compton Effect is tested be improved? What systematic errors arise in this experiment, and how can they be accounted for?
- Can the apparatus be used to measure the differential cross-section for Compton scattering?
- Can this type of spectrometer be used to study cosmic rays?
- Can Monte Carlo simulations be used to model the detector, study its performance, and design improved instruments?
- Can the Compton Effect be used to build an imaging instrument? (see next page)

9. Optional extension: Imaging using the Compton Effect

The following guide describes an optional extension developed in Summer 2019 by undergraduate students Michaela Flegrova and Timothy Marley.

Overview

X-ray imaging devices, such as the ones used in hospitals or at airports, rely on measuring the transmission and attenuation of light rays that pass through an object of interest. This however means that you must have access to both sides of the item, which makes the technique unsuitable for some purposes. Since Compton scattering causes some photons to backscatter, it has been suggested that it could be utilised to design imaging devices for items or areas with access restrictions where you can't be on the other side of what you're imaging; those devices could be used for example in geology, for landmine detection, or to simply "look behind a wall".

In this experiment you will investigate whether it would be feasible to design a Compton effect-based device that could be used to **image the contents of a sealed steel shipping container**.

As a starting point, show that you can detect an object behind a steel wall using the Compton effect. Next, go on to investigate the possibilities and limitations of this potential technology. Questions to get you started:

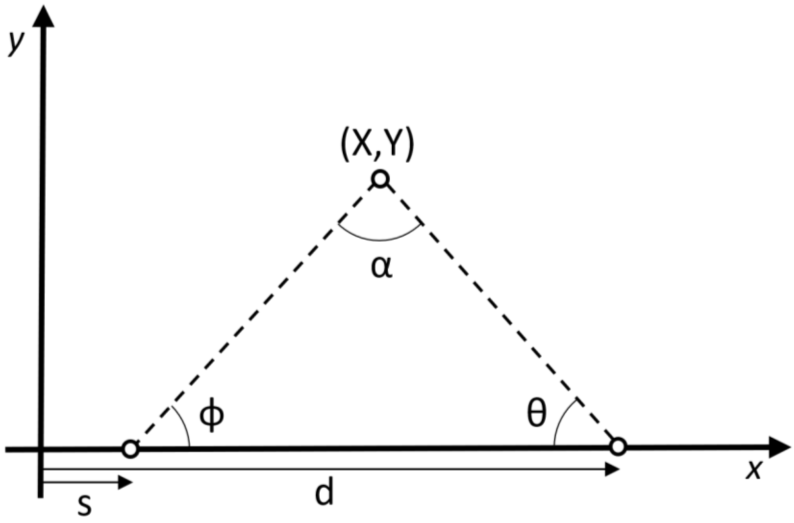
- How precisely can a single object be located?
- What is the optimal position of the source and detector? What is the optimal protocol for using multiple measurement positions?
- For how long do you need to collect data?
- Can the method be extended to multiple or more complex objects?
- Is this technology practical? In what scenarios? What improvements might be made?

Suggestions for analysis

To be able to determine the position of the scatterer based on the scattering angle, you will need to take at least two different measurements with different source and/or detector positions. The diagram below shows the source, detector and scatterer that are positioned in the x-y plane. The distances of the source and detector from the origin along the x-axis *s* and *d* respectively are known, and the angle α can be determined from the measured scattering angle. The angles θ and φ are then given by

$$\theta = \arctan\left(\frac{Y}{X - s}\right), \qquad \varphi = \arctan\left(\frac{Y}{d - X}\right),$$

where *X*, *Y* are the (unknown) coordinates of the scatterer.



Since the angles α, θ and φ must add up to π, we can write

$$0 = \pi - \alpha_i - \arctan\left(\frac{Y}{X - s_i}\right) - \arctan\left(\frac{Y}{d_i - X}\right).$$

At least two independent measurements of α_i with different s_i and d_i positions are needed to determine the two unknowns *X* and *Y*, giving a minimum of two simultaneous equations. It is difficult to find an analytical solution to this set of equations, but we can find a numerical one. We start by defining a function *f*, a measure of how much a given estimate of *X* and *Y* deviates from the true scatterer position, as

$$f(\mathrm{\alpha_i, d_i, s_i, X, Y}) = |\pi - \alpha - \theta(\mathrm{s_i, X, Y}) - \phi(\mathrm{d_i, X, Y})|^2.$$

We then define the loss function as

$$L(X, Y) = \sum_{i=1}^{N} f(\mathrm{\alpha_i, d_i, s_i, X, Y}),$$

where *N* is the number of measurements taken. With ideal measurements, the correct *X* and *Y* coordinates are those for which the loss function equals zero. With realistic data, the position can be estimated by numerically finding the *X* and *Y* that minimizes the loss function. One approach is to write a computer program that calculates the loss function for many trial positions.

Imperial College London

RISK ASSESSMENT AND STANDARD OPERATING PROCEDURE

1. PERSON(S) CARRYING OUT THIS ASSESSMENT – This assessment has been carried out by the head of experiment.	
Name (Head of Experiment)	Steve Kolthammer
Date	4 Oct 2019

2. PROJECT DETAILS.						
Project Name	E1 The Compton Effect				Experiment Code	
Brief Description Of Project Outline	Measurement of gamma rays emitted from radioactive materials					
Location	Campus	South Ken	Building	Blackett Lab	Room	409

3. HAZARD SUMMARY – Think carefully about all aspects of the experiment and what the work could entail. Write down any potential hazards you can think of under each section – this will aid you in the next section. If a hazard does not apply then leave blank.			
Manual Handling		Electrical	Mains equipment + High Voltages
Mechanical		Hazardous Substances	Radioactive Materials: Sealed sources, Caesium-137, Americium-241, Cobalt-57, Na-22, Ba-133, Cd-109, Co-60, radioactive mineral specimens in sealed plastic containers. Lead blocks (tape wrapped)
Lasers		Noise	
Extreme Temperature		Pressure/Steam	
Trip Hazards	Personal items in narrow walkway	Working At Height	
Falling Objects		Accessibility	
Other	Computer display		

4. CONTROLS – List the multiple procedures which may be carried out during the experiment along with the controls/ precautions that you will use to minimise any risks. Remember to take into consideration who may be harmed and how – other people such as students, support staff, cleaners etc will be walking past the experimental setup even when you aren't around.	
Brief description of the procedure and the associated hazards	**Controls to reduce the risk as much as possible**
Handling sealed radioactive sources	Treat all sources with respect. Emission of gamma and beta rays are at a level that is safe to handle. The alpha particles from Am-241 do not escape the source containers. Do not remove sources from sealed shielding containers. Do not damage the source containers. Take particular care with the mineral containers. Minimize time sources are close to your body. Do not remove radioactive sources from laboratory. Do not consume and food or drink in the laboratory. Do not swallow a radioactive source. Do not scratch or damage the sources. Always return sources to their proper storage (radiation safe) at the end of the laboratory session.
Handling of lead blocks	Wear protective gloves or wash hands immediately after handling sources. Wash hands after laboratory session.
Using High Voltage supply	Prevent any possibility of ingestion by careful handling.
Use of 240 V mains powered equipment	Wear protective gloves or wash hands after handling lead blocks.
Use of Computer display	Check connections and leads for wear and tear before switching on.

Accessibility and trip hazards	Isolate socket using mains switch before plugging in or unplugging equipment. Avoid prolonged sessions. Take breaks. Keep bags, coats, and personal items out of the walkways. Place these under the workbench, or store them in a cupboard or hanger. Keep lab items on the workbench.

5. EMERGENCY ACTIONS – What to do in case of an emergency, for example, chemical spillages, pressure build up in a system, overheating in a system etc. Think ahead about what should be done in the worst case scenario.
Notify member of staff immediately in the event of an accident, including if any of the named controls might have failed. In the event of an evacuation, follow designated escape routes and follow any additional instructions.