Experiment 3

Gamma-ray scintillation spectroscopy and the Compton effect

This experiment uses several sources of ionizing radiation. You must have completed your radiation safety training before you start.

The experiment is in two parts: first we calibrate the spectrometer by measuring the spectra of several sources of known γ energy, and then use it to precisely measure the way photons scatter off of an Al target, as a function of the scattering angle, and thus to identify the Compton scattering mechanism.

3.1 The scintillation spectrometer

The spectrometer is designed to record and display the spectrum of γ-rays emitted by radioactive sources. The energies it can detect cover the range from about 10 KeV (X-rays) to nearly 10 MeV. The use of energy units, rather than the wavelength or frequency of the EM waves, for the classification of the emissions from radioactive materials, emphasises the particle-like interaction of γ-rays with matter.

There is no dispersive element, such as a grating or a prism, in the spectrometer; there are no slits, lenses or mirrors. The detector is a crystal of thallium-doped sodium iodide, NaI(Th). When radiation, in the form of an X-ray or γ-ray photon, or an energetic electron, interacts with the crystal a certain fraction of the energy deposited in the crystal is transferred to the thallium activation centres and subsequently emitted as visible light. Other fractions of the deposited energy are dissipated as heat or through re-radiation in the invisible portions of the spectrum. The total energy deposit is itself proportional to the incident photon energy. The number of visible light photons emitted by the activation centres is directly proportional to the amount of energy deposited and, hence, to the energy of the incident radiation.

Each group of photons emitted by the centres appears as a short flash of light, or scintillation. The photons are detected by a photomultiplier tube (PMT) which produces a voltage pulse with height proportional to the number of photons that entered the tube. Hence, the height of the voltage pulse is proportional to the energy deposited in the crystal. If the dimensions of the crystal are such that the incident radiation is completely absorbed (*i.e.*, the probability of absorption approaches 1), the height is proportional to the energy of the incident radiation. The number of voltage pulses per second with heights lying between V and $V + dV$ (this defines a single "channel" of voltage and, therefore, of energy) is counted electronically. This measures the intensity (number of photons) as a function of energy, *i.e.* the energy spectrum of the radiation. The device that performs the counting and recording function is called a multi-channel analyzer (MCA). The MCA, the detector crystal, and the photomultiplier form the γ-ray spectrometer.

If a source of monoenergetic γ-rays, such as Cs^{137}, is examined with the spectrometer it is found that the recorded spectrum contains a fairly well-defined peak at some channel number, and a broad continuum of smaller peaks that extends from the main peak toward lower channel numbers (lower energies). The origin of these features of the spectrum is found in the nature of the interactions of γ-rays with the crystal, which can occur in one of the following three ways:

1. Photoelectric Absorption. The γ-ray is annihilated and the energy of the photon is transferred to an electron bound to an atom or ion of the crystal. The kinetic energy of the electron (KeV to MeV), plus its binding energy to the atom or ion (eV), is equal to the energy of the γ-ray photon. This

photoelectron then transfers, on average, a certain fraction of its energy to the thallium activation centres as it moves through the crystal. In crystals of the sizes used in practice the photoelectron loses all its kinetic energy within the crystal. The number of photons emitted by the thallium centres is proportional to the γ-ray energy. The voltage pulse at the output of the PMT that collects the light from the NaI(Th) crystal is proportional to the γ-ray energy.

2. Compton Scattering. The γ-ray transfers momentum to an electron and is thereby "scattered" with lower energy and momentum. The scattered electron will excite some thallium centres and cause a voltage pulse to appear at the PMT output. The scattered gamma photon may then interact by photoelectric absorption (see 1.) and produce a PMT voltage pulse. The height of this pulse, as well as that produced by the interaction of the scattered electron with the crystal, will be less than that produced when the gamma photon energy is deposited as in the previous case. Since the loss of energy by the gamma photon depends on the scattering angle, there will be a range of pulse heights detected.

3. Pair Production. When a photon of energy greater than or equal to twice the rest energy of an electron interacts with matter it may be annihilated. The photon energy appears as a positron electron pair. When the positron meets another electron a gamma photon (annihilation radiation) appears. For our purposes this effect may be ignored because the gamma sources used do not have a sufficient energy.

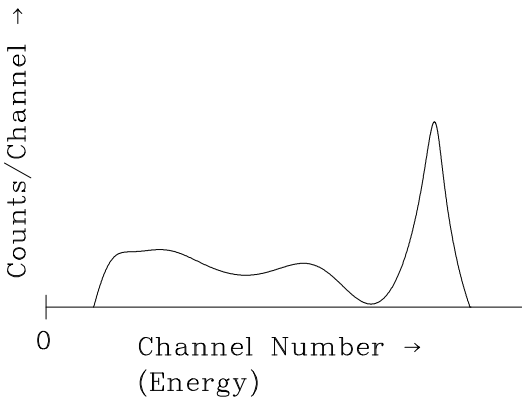

Figure 3.1: A sketch of a ^{137}Cs spectrum

A typical spectrum for a cesium ^{137}Cs source is shown schematically in Fig. 3.1. The large peak at high energies (channel numbers, pulse heights) arises from mechanism 1. It is called the Full Energy Peak. The energy corresponding to the maximum intensity is the energy of the gamma photon. The "shoulder" of the peak on the lower-energy side is the so-called Compton Edge. It is produced by the most energetic electrons arising from the Compton scattering process. The secondary peak at still lower energy arises from the full energy peak of the back-scattered photons in the Compton process. Other lower energy peaks may arise from X-rays produced in the PMT shielding or from background effects, and they can be quite strong. However, the spectrometer can be set to ignore the peaks of energy below a certain limit, to focus on the high-energy γ-ray peaks: note the region of zero intensity near the zero of the energy axis in Fig. 3.1. Identifying the channel number of the full-energy peak and knowing its true energy from reference sources provides a way to calibrate the spectrometer.

Spectrometer calibration checklist

The scintillation crystal and PMT are housed in a protective lead shield. The signal output from the PMT is a pulse where the peak voltage is proportional to the photon energy absorbed by the crystal.

The XIA Saturn hardware incorporates the MCA electronics as well as a programmable-gain PMT amplifier and a PMT voltage source, in a single compact box, so all controls are in one place. The anode voltage of the PMT has been set to the optimum value of 1,000 V and is not adjustable. The gain of the pre-amplifier that connects the PMT to the spectrometer (ORTEC model 113) sets the range of voltages

Figure 3.2: Main and Plot menu windows of EPICS

(pulse heights) for the energy spectrum. If the gain setting is altered, the spectrometer will require a re-calibration.

The software that controls the spectrometer (EPICS) is the same software used at large nuclear physics laboratories, and is capable of controlling dozens of sensors and mechanical and electronic actuators simultaneously. In our lab, only a small subset of the available parameters will be used, and each of the data acquisitions ("scans") will contain only a single spectrum. XIA Saturn MCA has 2048 energy channels, sufficient for the energy resolution of our detector.

- Turn on the XIA Saturn, then press the red button. The PMT voltage will slowly ramp from 0 to 1,000 V. At the end of the experiments you will press this button to turn the high voltage off; please wait until the voltage actually ramps down before turning off the power switch.

- Collect a set of calibration sources from the instructor; they are kept in the vault and must be returned at the end of the experiment. The following steps must be performed for each of the sources in turn.

- Place a calibration source near the crystal end of the detector. The active end is the blackened end of a plastic rod. You can simply lay it down in the lead shielding surrounding the PMT.

- Invoke the software; and icon called "XIA Saturn" should be on the desktop. The main control window appears, as shown on the left in Fig. 3.2. During the experiment you will make use of additional sub-menus that will open up as separate windows; the two most important ones are the `Scans` and `Plots` sub-menus. Click on `Plots` to open the MCA display window shown on the right in Fig. 3.2 and on `Scans` to open the scan control window shown on the left in Fig. 3.3. The spectrometer console has an extended display, you will find it helpful when multiple windows are open. While you wait during data acquisitions, you may want to perform other tasks, such as preliminary data analysis on already acquired partial data.

- You should not need to make any adjustments to the default settings with the exception of the following:

  1. the `Elapsed Mode` sets the duration of the data acquisition to end after a set time or to continue until the user manually stops the process. Set the mode to perform a Real Time acquisition of

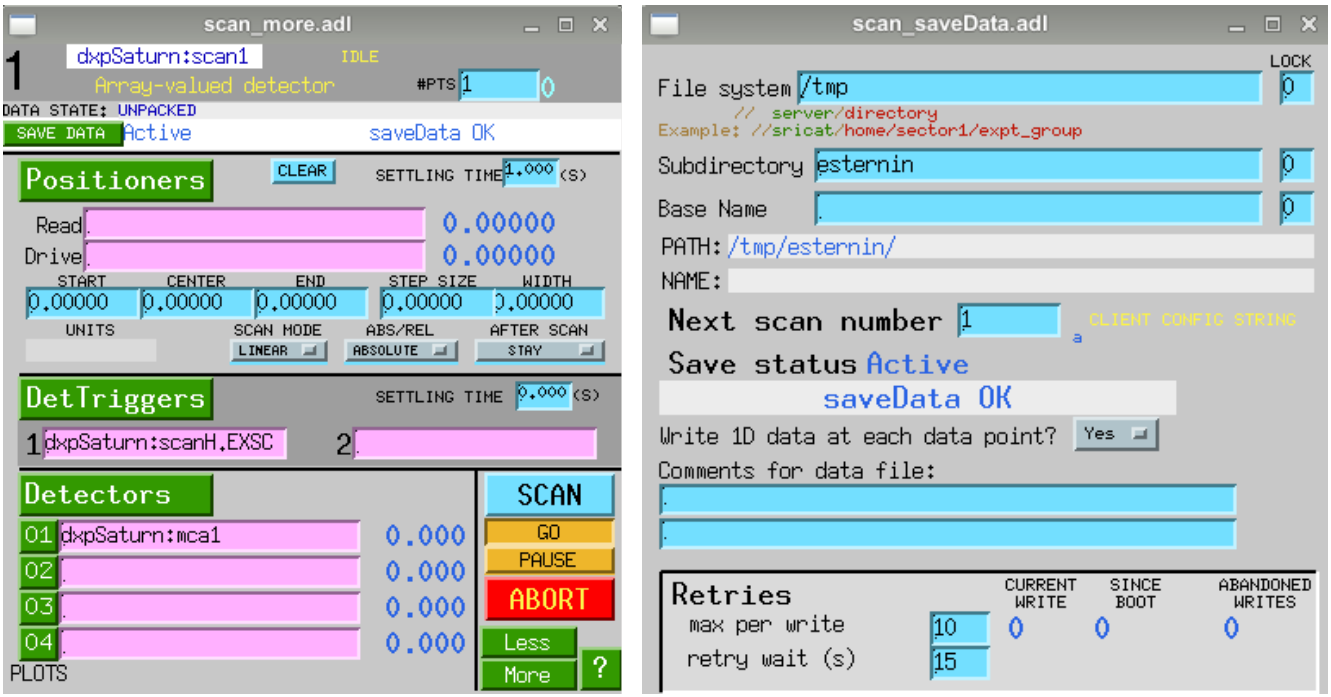

Figure 3.3: Scan and file save windows

20 seconds;

2. the `Max. energy (keV)` adjusts the energy/channel scaling of the 2048-point MCA and must be set to cover the range that includes the full energy peak of the most energetic of your calibration sources. Once set, it should not be changed, or a re-calibration will be required;
3. the `Energy Threshold` can be adjusted to ignore low energy channels near zero where significant background noise can be present.

- Within the scan control window click on `SAVE DATA` to open the settings window for data file management, shown on the right in Fig. 3.3. You should change the default save directory to a new folder; something like `/work/3P91/2020-2021/G1/` is a good choice, as it will allow you to access your data from any workstation in the Physics cluster. Make sure that the directory you are specifying here actually exists, create it if necessary.

- Press `Start` to accumulate a trial spectrum. This can be achieved from any of several windows, as the buttons are duplicated for convenience.

- When you have a good estimate of the time it would take to get a clean-looking spectrum, with a clearly identified peak that can be used for calibration, adjust the acquisition time and press `SCAN` to record and save the spectrum. Depending on the strength of the signal (calibration sources become weaker with age, as they radioactively decay) you may need anywhere from 30s to 300s. Note the isotope and its γ-energy, the file name (the file names contain an index number that is incremented after each run, automatically) and the approximate channel number for the full energy peak.

  Repeat these steps for all the sources in the calibration set.

- Use fitting and plotting software (such as `physica` or `extrema`) to fit a Gaussian lineshape to each full-energy peak, and obtain an error estimate. You may start by using the prototype scripts in `/work/3P91/Compton/Demo/`; copy them into your filespace and copy the data you have acquired into the same location, using `mda2ascii` command. You may work on your data analysis while waiting for the next data scan to complete, by using `ssh -Y ab00cd@localhost` command without

Isotope	γ-energy, MeV
^{109}Cd	0.088
^{57}Co	0.1222
^{133}Ba	0.356
^{22}Na	0.5110034
^{137}Cs	0.66164
^{54}Mn	0.834827
^{60}Co	1.1732, 1.3325

Table 3.1: A selection of well-known gamma energies.

leaving the spectrometer console, or you may log onto a second workstation to access the data being saved into `/work/3P91/2020-2021/G1/` directory.

The data files saved by EPICS (`.mda`) are binary files, for reasons of compactness. To extract a readable set of numbers, suitable for plotting and analysis, a small utility, `mda2ascii`, is available on every workstation in the Physics cluster. Here's a self-explanatory sequence of steps, to perform from a terminal window, using the above example names:

```
$ ssh -Y ab00cd@localhost
Password:
$ mkdir -p 3P91/Compton
$ cd 3P91/Compton
$ mda2ascii -i 1 -o Ba-131 /work/3P91/2020-2021/G1/dxpSaturn_0001.mda
```

This places a readable data file `Ba-131_1.asc` into your directory `/home/ab00cd/3P91/Compton/`. You can now read this data file into `physica`, or `extrema`, or `gnuplot`, or another plotting/analysis software. If you are using `physica`, the two files `/work/3P91/Compton/Demo/*.pcm` will prove a handy starting point, and can be copied into the same directory. `gamma.pcm` is the top-level script; it in turn calls a subroutine in `gfit.pcm`. You can also make use of this subroutine in your own scripts.

- Plot a graph of known gamma energy *vs.* the full-energy peak channel number and fit a straight line through the data; this is your calibration curve that can be used to correctly display and analyze the spectra from the next part of the experiment.

  Some of the known gamma energies you may need are listed in Table 3.1. Additional values may be obtained from sources listed in References.

? Discuss in your lab report: why is the full energy peak not sharp?

3.2 The Compton effect

The Compton effect can be studied and the scattering relationship verified. The apparatus has been set up as shown in Fig. 3.4. You will measure the energy, E', of the scattered gamma photons as a function of their scattering angle θ. The experimental arrangement is shown in Fig. 3.4.

> Note: The 25-millicurie source (inside a yellow-coloured lead brick) produces an intense collimated beam. **DO NOT** stand in the direct line of the beam **E**. **DO NOT** tilt or drop the yellow lead brick, as the high-intensity source may fall out of it. If this happens, leave the area immediately and inform the instructor.

Both **S** and **D** are well shielded with lead. The source shielding minimizes the radiation intensity in all directions except within a small solid angle centred on the beam direction, **E**. The detector shielding

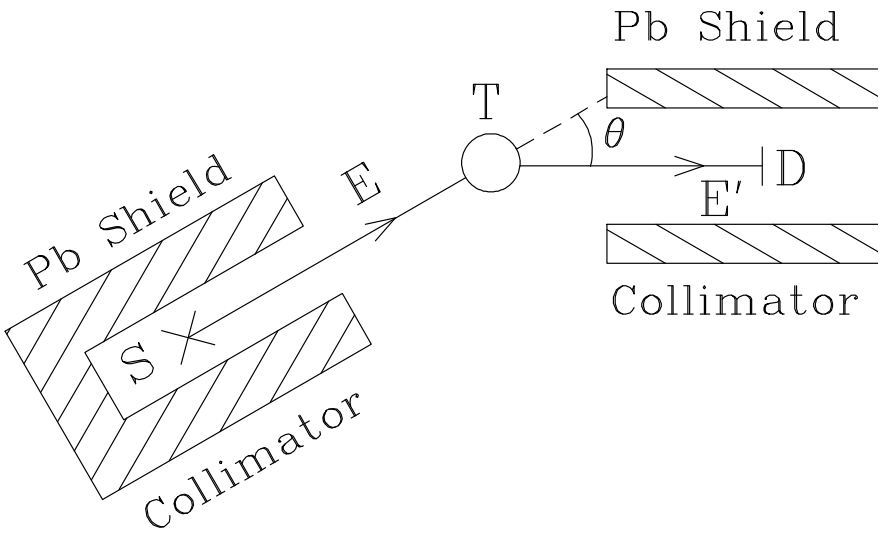

Figure 3.4: The Compton scattering apparatus. Here **S** is a ^{137}Cs γ-source, energy 0.66164 MeV, strength 25 millicuries; **E** is the collimated γ-photon beam of energy E; **T** is the Al target that contains the free electrons from which the γ-rays scatter; **E′** is the scattered beam of photons of energy E'; **D** is NaI γ-ray detector.

is designed to admit the scattered photons, **E′**, and to exclude entrance to photons incident from other directions. The scattering angle, θ, is varied by rotating the source assembly, **S**, about the target position, **T**. To measure **E′** use the energy calibration that you completed in the first part of the experiment.

The Compton experiment checklist

- Accumulate a series of spectra of the scattered photons as a function of the scattering angle and so determine $E'(\theta)$. The Compton formula is usually given in terms of incident wavelength λ and scattered wavelength λ':

$$\lambda' - \lambda = \frac{h}{m_0 c}\,(1 - \cos\theta). \tag{3.1}$$

  Show that in terms of photon energies E' and E this formula becomes

$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_0 c^2}\,(1 - \cos\theta) \tag{3.2}$$

- Plot your experimental data as $1/E'$ versus $(1 - \cos\theta)$ and from the results determine E and the electron rest mass energy m_0c^2.

  The minimum value of the scattering angle θ at which the Compton scattering energy shift is observable will be determined by the energy resolution of the detector and the effectiveness of the lead collimator which defines the solid angle of emergence of the cesium photon beam. If the scattering angle is made too small, the direct beam of the cesium gamma photons into the detector will completely mask the small Compton energy shift. In practice it means that scattering angles below 10° are not detectable in our apparatus.

  Remember that only a small fraction of the photons are scattered in the target. The intensity of the scattered beam is much less than that of the incident beam, and thus the recording time required to obtain a satisfactory spectrum may be many minutes. A direct beam into the detector would produce an intense spectrum in seconds rather than minutes!

References

- A discussion of the scintillation detector is given in: *Radiotracer Methodology in Biological, Environmental and Physical Sciences*, C. H. Wang, D. L. Willis and W. D. Loveland (Prentice-Hall), Chapters 4, 6, 7, 12. Call Number QC 795.42 W36 1975.
- A useful online source of select gamma energies is `https://www.cpp.edu/~pbsiegel/bio431/genergies.html`.
- A comprehensive searchable database of nuclear data is maintained at Lund University, Sweden, `http://nucleardata.nuclear.lu.se/toi/`.
- EPICS software has a home here: `https://epics-controls.org/`, and the technical documentation for the XIA Saturn driver for EPICS, by Mark Rivers at U. Chicago is here: `https://www.physics.brocku.ca/Courses/3P91/References/MCA/`.