Advanced Laboratory

Gamma Ray Spectroscopy — University of Colorado Boulder

Measurement of Gamma Ray Energies

(updated October 3, 2025)

Abstract

This experiment gives you the opportunity to study high energy photons through analysis of radioactive decay. These photons have energies characteristic to specific initial and final state nuclear energy levels (similar to the use of optical photons to study electronic energy levels in atoms), providing a means to study nucleus energy levels, nuclear reactions, and also to provide a way to identify radioactive nuclear species in different test samples. The experiment allows for open-ended investigation of gamma ray spectroscopy and typically requires three weeks of lab work.

I. Introduction

Nuclei can change their state in a variety of ways. They can split up (fission) or they can decay and emit a variety of particles. The different types of particles are as follows; α particles contain two neutrons and two protons, β particles are either an electron (β-) or a positron (β+), and high energy photons known as γ rays. If the nucleus emits an alpha or beta particle, the number of protons and neutrons must change. In your lab notebook, explain why the number of protons and neutrons remains the same during gamma decay but must change during alpha or beta decay When a nucleus emits a gamma ray the number of protons and neutrons remains the same. However, the energy state of the nucleus will change. Each of these particles can be detected, but they interact with matter in very different ways (see references). Alpha particles can only penetrate a very small amount of material before losing all their energy. Beta particles can penetrate moderately thick materials, though this depends on their energy. Gamma rays can penetrate most materials. Because of this, they are more dangerous as it is difficult to prevent them from reaching a researcher's body. On the other hand, they are easier to study since they can easily escape a radioactive source and reach a detector. Examples of radio decay can be seen in **Figure** 1.

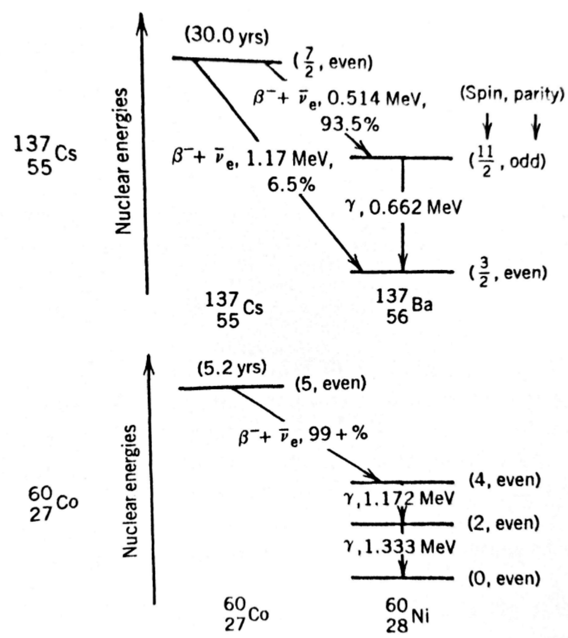

Figure 1 Decay scheme of Cs-137 and Co-60

Most of the radioactivity you will encounter in this experiment will be in gamma ray form. Due to gamma rays being produced by a nucleus changing energy states, there will be characteristic energies for each nucleus associated with the observed gamma rays. By measuring the energy of the emitted gamma rays, we can determine which nuclei are in a sample.

II. Compton Scattering

The primary physical interactions of interest in this experiment are the photoelectric effect and Compton scattering. Compton scattering is an inelastic scattering process that occurs when a high-energy photon, such as a gamma-ray (γ-ray), interacts with a quasi-free, loosely bound electron in a material. In this interaction, the incident photon is not absorbed; instead, it transfers a portion of its energy to the electron, causing it to recoil, and scatters at a lower energy and different angle. The principles of the conservation of momentum and energy govern this interaction and yield the following equations:

$$\frac{hv}{c} = \frac{hv\prime}{c} cos\theta + Pcos\,\phi \qquad [kg \cdot \frac{m}{s}] \qquad \text{(Eq.1)}$$

$$0 = \frac{hv\prime}{c} sin\, \theta - Psin\, \phi \qquad [kg \cdot \frac{m}{s}] \qquad \text{(Eq.2)}$$

If an elastic collision occurs, then through the conservation of energy, we have the following equation:

$$hv = hv' + K \qquad [J] \qquad \text{(Eq.3)}$$

These concepts are illustrated in **Figure** 2

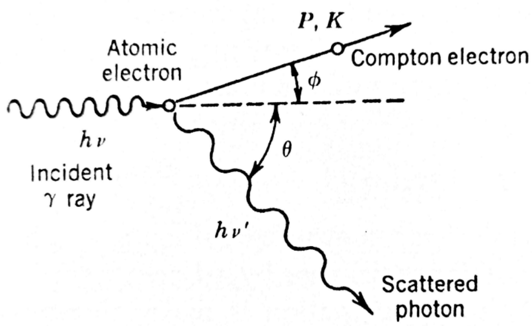

Figure 2 Elastic collision conservation of energy

To detect the emitted gamma rays, we will be using a NaI crystal as a scintillator (see the next section). When the gamma rays pass through the crystal, the photon energy will be either scattered (through Compton scattering) or directly transmitted. In the case of Compton scattering, the gamma ray photon transfers its energy and momentum to the electrons and then recoils with reduced energy, according to (Eq. 3). In one case of transmission, electron-positron pairs can be created, which give up an amount of energy equal to the rest mass of the pair. In the other case, the photon can just give up all of its energy in the crystal through scintillation (direct release of lower energy photons). In both cases, the lost energy is converted into pulses of light (seen by the lower energy photon) within the crystal which is then detected by a photomultiplier tube (PMT).

III. Scintillation, Photomultiplier, and Multichannel Analyzers

Detection of the Compton scattering is facilitated through a scintillator. A scintillator is a material that converts the energy of a charged particle to photons in the visible light spectrum, which is multiplied in the photomultiplier tube. In this experiment, NaI crystal with 0.1% of Tl impurity is used for the scintillator (see Fig. 3), where some or all of the gamma rays' energy is converted to the kinetic energy of electrons through Compton scattering, the photoelectric effect, or pair production. Then this kinetic energy is transferred to emit a photon from Tl impurity sites, and its intensity is proportional to the absorbed kinetic energy. The photomultiplier converts this light into a voltage pulse, and the multichannel analyzer creates a histogram for the different pulse heights.

The scintillator materials vary depending on the energy range of the charged particles of interest. For more information about the scintillation process, see chapter **5.4** in Experiments in Modern Physics by Melissinos.

IV. Goals of the experiments

This section outlines the primary learning objectives for the experiment. Upon completion, you will be able to:

- Understand the process of gamma ray generation from radioactive decay. This will be achieved by analyzing the energy spectra of at least four known radioactive sources: Co-60, Ba-133, Cs-137, and Na-22.
- Become familiar with the operation of the scintillator, photomultiplier tube (PMT), and Multi-channel Analyzer (MCA) system. A key component of this objective is to understand the requirements for calibrating this equipment.
- Use the known radioactive sources to calibrate the MCA, establishing a linear relationship between the detector's channel number and the corresponding gamma ray energy (in MeV). This calibration will then be used to characterize a Europium source and identify an unknown radioactive sample.

V. Hazards and Dangers

The power supply can operate in the **kilovolt (kV)** range, which is considered **high voltage**, and requires careful handling to ensure safety. As a critical precaution, you must ensure that the power supply is switched off before connecting or disconnecting any cables to the photomultiplier tube (PMT).

Applying too large a voltage or the wrong polarity of voltage to a PMT will generally destroy it. For this experiment, the polarity of the tube will be **positive,** and the potential should not exceed 1000V. The polarity and voltage limits should be listed on the PMT, however, if you have any doubt, check with the instructor **before** turning on the power supply. See the references (Moore, Davis, Coplan pg. 247) for a more extensive discussion of PMTs.

All students participating in this experiment need to take the radiation safety training course for teaching labs. If you've not taken this course yet, please stop and check with your instructor immediately.

A large, cylindrical lead tube is placed around the Photomultiplier Tube (PMT) to reduce background radiation and improve signal quality.

As you will need to handle this lead shielding, you must follow proper safety protocols. Lead is a toxic heavy metal, and the primary risk from handling it in its solid form is accidental ingestion from residue transferred via hand-to-mouth contact. To mitigate this risk, please adhere to the following procedures:

- **Protective Gear:** Always wear the protective gloves provided when handling the lead shielding.
- **Skin Contact:** If you make direct skin contact with the lead, promptly wash the affected area thoroughly with soap and water.
- **Hygiene:** As standard laboratory practice, always wash your hands after the experiment is complete, especially before eating or drinking.
- **Damage Reporting:** If you notice that the lead shielding is damaged or flaking, do not handle it further and inform your instructor or lab technical staff immediately.

VI. Equipment/Setup

The equipment that you will need for this experiment are as follows:

- Photomultiplier tube (PMT) attached with a Tl-doped NaI crystal
- SHV (Safe High Voltage) cable
- Multiple BNC cables
- High voltage power supply
- Multichannel Analyzer (MCA)
- Amplifier
- Shielding
- Gamma sources

The detection system consists of a thallium-activated sodium iodide (NaI(Tl)) crystal scintillator coupled to a photomultiplier tube (PMT). When a gamma ray interacts with the NaI(Tl) crystal, it deposits energy, causing the crystal to scintillate—that is, to emit a brief flash of light. A crucial principle of this process is that the intensity of the light produced is directly proportional to the energy deposited by the incoming gamma ray.

This faint light is then detected by the PMT, a highly sensitive light detector that converts the light into a measurable electrical signal. It accomplishes this through a series of electrodes called dynodes, which create a cascade of electrons, effectively multiplying the initial signal.

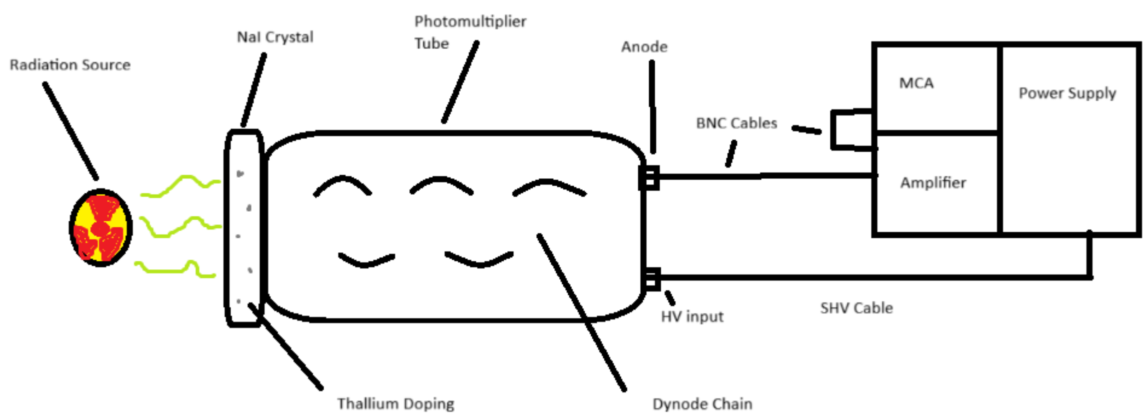

Figure 3. A graphic representation of the experimental setup

The NaI(Tl) crystal is housed within a silver-colored can made of thin aluminum, which is designed to minimize energy loss as gamma rays pass through it into the detector. This housing is mounted directly onto the front of the PMT, so the two components appear as a single, integrated unit. Please handle this detector with care, as the thin aluminum casing can be easily damaged. For a more detailed discussion of inorganic crystal scintillators and their application in gamma-ray detection, refer to the text by Melissinos.

The MCA, amplifier, and high voltage power supply are contained within the same unit for ease of access. This unit **can produce high voltages** so be aware of this when using this bit of equipment to avoid accidental electrocution. For a picture of the experimental setup, refer to **Figure** 3.

Equipment Setup and Connection Procedure

Before acquiring data, the components of the detection system must be correctly assembled and powered on. Follow these steps in the specified order to ensure proper setup and prevent equipment damage.

1. **Initial System Check:** Verify that all cables, with the exception of the main power cord, are disconnected from the Canberra Portable Bin/Power Supply (Model 1000).

2. **Power On the MCA:** Power on the MCA using the primary switch located directly above the power cable inlet.

3. **Verify Polarity:** Confirm that the High Voltage (H.V.) power supply is set to **Positive (+)** polarity.

4. **Voltage Safety Check:** Temporarily toggle the H.V. switch to the 'On' position and verify that the digital display reads **0.00 kV**. Once confirmed, immediately return the switch to the 'Off' position. This step ensures the voltage is at zero before connecting the sensitive detector.

5. **Power Down for Connections:** Power down the Canberra power supply before proceeding with the cable connections.

6. **Connect High Voltage to PMT:** Connect the SHV (Safe High Voltage) cable from the H.V. output port on the rear of the MCA to the H.V. input port on the Photomultiplier Tube (PMT) assembly.

    - **Handling Precaution:** To prevent damage, lift the PMT assembly only by its aluminum base. Do not lift or support it by the upper section marked with yellow caution tape.

7. **Connect Signal Cables:** Establish the signal path to the MCA by making the following connections with BNC cables:

    - Connect the 'Anode' output port on the PMT to the input port on the Amplifier.

    - Using a short BNC cable, connect the output port on the Amplifier to the 'Channel 1' input port on the MCA.

8. **Connect to Computer:** Connect the USB cable from the data port on the rear of the MCA to an available USB port on the provided laptop to establish a data link.

Signal Processing and Data Acquisition

The electrical pulse generated by the PMT is transmitted to a signal amplifier. This device serves two primary functions:

1. **Amplification:** It increases the amplitude of the pulse via an adjustable gain control. You will need to optimize this gain setting for your measurements.

2. **Pulse Shaping:** It modifies the temporal shape of the input pulse to one that is compatible with the input requirements of the Multichannel Analyzer (MCA). The pulse shaping controls have been pre-set and should not be adjusted.

The shaped and amplified pulse is then sent to the Multichannel Analyzer. The MCA is an interface card that, in conjunction with its dedicated software on the laptop, digitizes the incoming pulses and sorts them by amplitude to build an energy spectrum. The software provides several essential functions for data acquisition and analysis, including the ability to:

- **Acquire and Display Spectra:** Collect and plot pulse height spectra. A spectrum taken without a radioactive source present should be recorded to measure the background radiation.

- **Save and Export Data:** Save acquired spectra to a file for subsequent analysis.

- **Perform Spectrum Subtraction:** Subtract a background spectrum from a source spectrum to isolate the signal from the radioactive decay.

- **Calibrate the Energy Axis:** Perform an energy calibration using the known photo peaks from standard sources.

A variety of radioactive sources are available for this experiment. The standard calibration sources (e.g., Co-60, Cs-137) are sealed within brightly colored, labeled plastic discs. Each label indicates the isotope, the initial activity, and the date of manufacture. In addition to these standards, you will be provided with environmental samples containing naturally occurring radioactive material for characterization and identification.

VII. Data Acquisition Procedure

With the equipment set up, you are ready to acquire data.

1. Begin by opening the **Gamma Acquisition and Analysis** software on the computer. From the file menu, select the option to open a data source. A pop-up window will appear; first select the **detector** option, then choose the **MC2_MCA1** file.

2. Once the detector is connected, acquire a background radiation spectrum for a duration of **10 minutes**.
3. After the acquisition is complete, save the file using either the .IEC or a Toolkit file format, and label it clearly as the background measurement.
4. Next, request access to the radioactive sources from your instructor or the lab staff. A Geiger counter may also be provided.
5. When handling the samples, measure one source at a time. After acquiring data for a sample, return it to the storage container before retrieving the next one.
6. Each source measurement should be acquired for **10 minutes**. Save each file with a name that corresponds to the specific radioactive sample being measured.
7. After you have finished taking data, ask your instructor or the technical staff to properly store the radiation samples.

You should become familiar with the operation of the data acquisition program and the nature of the spectra from the sources. Your objective is to find the optimal settings for the PMT voltage and the amplifier gain. In doing this, you will use the various radioactive samples to calibrate the MCA spectrum and evaluate sources of error, including detector saturation or other non-linearities, drift in the gain of system components, and resolution limits due to noise or an insufficient number of data points in the spectrum. An example of a typical spectrum is shown in Fig. 4.

You will need to develop a strategy for data acquisition that evaluates and reduces these sources of uncertainty. You may encounter spectral lines that are present even when all sources are removed. Information regarding these background lines can be found in the Melissinos text. You should consider if and how these lines might affect your results and what steps can be taken to mitigate such effects.

In addition to calibrating the energy scale, you must obtain a calibration of the detection efficiency versus energy. This can be accomplished by using the given activity of the calibration sources and determining the best method to interpolate between the calibration points.

After establishing these calibrations, investigate your unknown source and your Eu-152 source. Check to see if their measured energy peaks are consistent with your calibration line.

VIII. Calibration and Compton Edge

While analyzing your data, you will notice that spectral features have different shapes; some are sharp, high peaks, while others are broad, plateau-like structures. What is the physical significance of these two different feature types? The plateaus are associated with the Compton effect. To fully understand the spectrum, however, you must consider the different physical interactions involved. In your analysis, explain what processes lead to these distinct features.

What is the energy of the "Compton edge" in terms of the incident gamma-ray energy? Estimate the theoretical energy of the Compton edge for the primary Cs-137 photopeak and compare it to your measured value. A discussion of the Compton effect can be found in Melissinos (pg. 252).

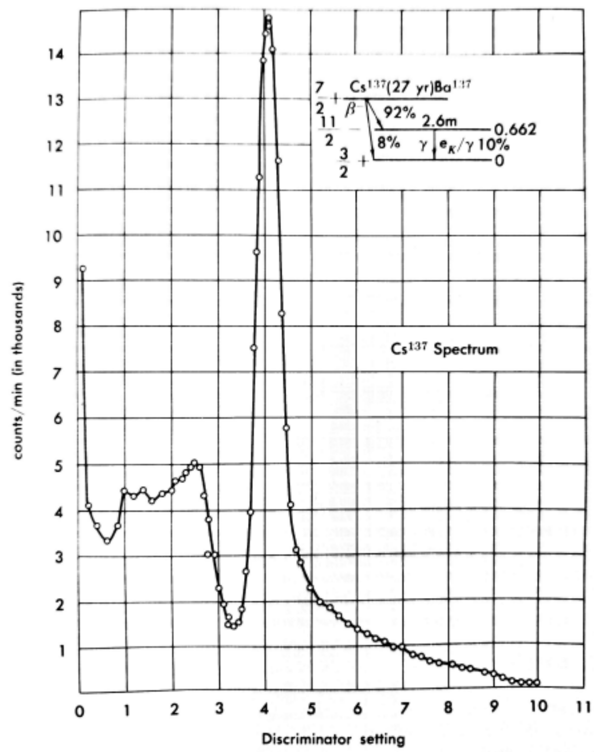

Figure 4 An example of a Cs-137 spectrum as a function of the channel number. Adapted from Melissinos book.

X. Important Questions to answer in your lab notebook

1. How does one calibrate the detector efficiency given sources of known radioactivity?
2. What is the difference between Compton scattering and the photoelectric effect?
3. By applying the principles of conservation of energy and momentum, determine the scattering angle at which the recoiling electron receives the maximum possible energy from the incident gamma ray. In the MCA plot, how does the data collecting time make a difference in your result?
4. Propose a modification to the experimental setup that would allow for the simultaneous measurement of both the scattered gamma-ray energy and the recoil electron's energy. Sketch your proposed design and explain how it would allow you to experimentally verify the conservation of energy as stated in Equation 3.
5. Each radiation source indicates the radioactive strength in the nanocuries (nCi) per gram. In this setup, how do the different nCi numbers affect your result?
6. Assuming one has a calibrated detector, how do you find the gamma ray energy of an unknown sample?

7. For each of your acquired spectra, compare the energy of the Compton edge to the energy of the primary photopeak. Is the Compton edge energy consistently lower or higher? Explain this observation using the physics of Compton scattering.

8. Earlier, three mechanisms of detecting gamma ray using the scintillator-PMT-MCA setup: (1) Photoelectric effect, (2) Compton scattering (3) pair formation. In this experiment, which ones do you observe? If there is anything you do not observe, why is that?

9. How might the single and/or double escape peaks be used to improve your calibration and accuracy in the measurement of E_γ?

Some useful numbers:

Proton (^{1}H) mass energy: m_Hc^2 = 938.272MeV

Deuteron (^{2}H or D): m_Dc^2 =1875.618MeV

^{1}H: m_H = 1.00782522 atomic mass units (amu)

^{2}H or D: m_D = 2.01410222 amu

Electron mass energy: m_ec^2 = 0.5110045 MeV

MeV/amu = 931.49432

XI. References

1. A. Melissinos Experiments in Modern Physics pp. 194-208, 252-265
2. Ferway, Moses & Moyer, Modern Physics (1989), C Chapter 13, pp. 372-396. This gives a good basic introduction to nuclear processes
3. D. Preston and E. Dietz, The art of experimental physics, see experiments 18 and 19, and Appendix B for a discussion of apparatus.
4. J. Moore, C. Davis, and M. Coplan, Building Scientific. Apparatus, pg 242-257 on PMTs