Radioactive isotopes are commonly used in medical physics in diagnostics, imaging (e.g., $^{22}$Na), and radiation treatment (e.g., $^{60}$Co). It is important to understand the interaction of the different types of radiation in matter, and a first handle on this can be determined by how a scintillating crystal responds to charged particles (as well as to photons that subsequently produce or interact with electrons). Spectroscopy is a technique that has long provided insight into atomic, nuclear, and hadron structure. In this lab you will learn techniques for measuring the spectrum of $\gamma$-rays emitted from various radioactive isotopes.

**Introduction**

In elementary modern physics, you learned of several different ways in which quanta of electromagnetic energy, or photons, can interact with matter. The three dominant processes include: the photoelectric effect, in which all of the photon’s energy is transferred to a single electron; Compton scattering, in which the photon scatters from an electron, transferring some of its energy, but re-emerging as a lower-energy photon; and pair production, whereby the photon converts to a positron-electron ($e^+e^-$) pair. In this lab, you will investigate processes involving high-energy photons, or $\gamma$-rays, where in this context “high energy” means on the scale of nuclear energy level spacings, i.e., several MeV or so. Note that an MeV is many thousands of times larger than typical atomic energies, so the fact that the struck electrons are bound in matter is usually not important. These processes are described in more detail in Refs. [1, 2].

The key tools in this experiment will be a Thallium-doped Sodium Iodide crystal, which is a scintillating crystal often used as an electromagnetic calorimeter. Light produced by the crystal will be collected with PMT and analyzed with a multi-channel analyzer. More information about photon detection and multi-channel analyzers is available in Ref. [2].

**Setup and Equipment**

- scintillation detector: this is a small piece of thallium-doped sodium iodide, or NaI(Tl), that is optically attached to a photomultiplier tube (PMT).
- PMT base, which is used to distribute high voltage (HV) to the PMT
- HV supply
- NIM Ortec amplifier used to amplify PMT pulses as needed
- NIM Ortec multi-channel buffer (MCB) and associated multi-channel analyzer (MCA) software
- oscilloscope
- various radioactive sources

Connect the HV supply to the PMT base and power up the PMT. Be certain to check that the polarity of the HV supply matches that required by the base before turning on the supply. Do not apply more than 1200 V to the PMT. Signals from the PMT can be studied on the oscilloscope or amplified and analyzed by the MCB. When collecting data, shield the detector from stray background (and shield yourself from the source) by using several lead bricks. The MCB can be read out using the Ortec Maestro-32 software installed on the PC at the experimental station. At its core, the MCA effectively generates a histogram of pulse heights that it observes on its input.
Exercises

Conduct the following experiments. Document your work in your logbook. *For this lab prepare a formal lab report, that details the results of your investigations.* In your lab report you do not need to discuss results of introductory steps done to familiarize yourself with the equipment or the behavior of the MCA. Focus on the study of the γ-ray spectrum for the various radioactive isotopes. Be sure to include some discussion of the detector and its calibration.

- Familiarize yourself with the equipment: obtain a $^{137}\text{Cs}$ source from your instructor and use the PMT to examine how the detector responds to the source. Try varying the distance from the source to the detector. Use the amplifier to amplify the signal from the PMT and examine the output on the scope. Explore how the amplifier setting affect the output.

- Study the γ-ray spectrum of $^{137}\text{Cs}$ using the MCA. Label and understand the important features: photopeak, Compton edge, etc. How do the amplifier settings affect the measured spectrum? Try taking data with the source removed to study the background – how significant is it? Make small variations in the PMT HV (±50 V) and examine changes in the spectrum. It should be clear that the amplifier settings and PMT HV need to remain fixed to the same values throughout your measurements.

- Repeat your studies with $^{22}\text{Na}$ and $^{60}\text{Co}$. Also measure the spectrum of an unknown source that your instructor will provide.

- Using the ROOT scripts provided, load your data into ROOT and fit the photopeaks of the known sources with a Gaussian plus a suitable background function (polynomial of some order). Use the photopeaks to calibrate the your the energy scale of your detector by plotting the expected photopeak energy $E$ versus the mean of the Gaussian (in channels) $\mu$ and fitting to the form

$$E = a\mu + b.$$  \hfill (1)

- Using the energy calibration derived from the photopeaks, predict the locations of other features in the spectra such as Compton edges and annihilation peaks. Comment on how your measured spectra agree with the predictions. Label as many features as possible in the spectra. (Labels and arrows can be easily added to PDF files with Adobe Illustrator.)

- Discuss the features of the unknown source and identify it.

- Optional: From your fits to the photopeaks, plot the fractional resolution of the detector $\sigma/E$ as a function of energy $E$. It is common to characterize detector performance using the equation

$$\frac{\sigma}{E} = \frac{A}{\sqrt{E}}.$$  \hfill (2)

Understand the motivation for the functional form. What is the parameter $A$ for our detector and how does it compare with other typical calorimeter materials? You may find discussion of this in Ref. [2].

References
