Gamma–ray Spectroscopy

I. Objectives

The ultimate goal of this lab is for you to understand how scintillation detectors can be used as tools for nuclear spectroscopy, that is, to study the energy levels of atomic nuclei. To gain this understanding, however, you must first become familiar with the various processes by which energetic electro-magnetic radiation, or “gamma-rays,” can interact with matter. You will then examine how an inorganic scintillator responds to these interactions and, via electronic processing, can provide information on the γ-ray, and hence the nucleus, of interest.

II. Physics background

In elementary modern physics, you probably 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, we will be interested primarily in processes involving high-energy photons, or γ-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.

Before starting the lab, you should become thoroughly familiar with the physics involved in these three processes. There are many excellent references. Some of the better (and more readily available) ones are [KNO79, LE087, MEL66, PRE91, SEG77]. You might want to read through two or more of these, and then pick one that seems most useful to you.

In several of the above references ([KNO79] and [LE087] in particular), there is also some discussion of how an inorganic scintillator responds to these interactions of γ-rays with matter. You must also understand this aspect of the physics in order to be able to interpret, or connect, what you will observe on the multi-channel analyzer (MCA) with the physical processes occurring within the scintillator. The key point—and one that is often not stated explicitly in many texts—is that the amount of light collected, and hence the size of the current pulse sent to the electronics, is related to the kinetic energy of the electrons involved in the electromagnetic interaction, and not that of the photons themselves. Thus, in a photoelectric process, the size (voltage) of the amplified signal is directly related to the
full photon energy; hence, the full-energy peak is often referred to as a “photo-peak.” More subtly, in a Compton scattering event, the signal recorded reflects the energy of the recoiling electron, rather than that of the scattered photon. If \( E_\gamma > 1.022 \text{ MeV} \), so pair production can occur, one detects only the kinetic energies of the electron and positron as they slow down. Once the positron stops, however, it will annihilate, creating a pair of 0.511 MeV \( \gamma \)-rays. These, in turn, may initiate photoelectric processes, Compton scatterings, or one or both may escape from the scintillator entirely. All of these lead to distinct features in the observed pulse height spectrum.

As part of this lab, you will become familiar with several new types of modular electronics, in addition to the scintillation detector itself and its associated photomultiplier tube (PMT) and base. Once the basic features of the energy spectra are understood, you will investigate quantitatively the linearity of the detector response and measure the energy resolution of the entire detection system. With the measurement apparatus thus calibrated, studies of \( \gamma \)-ray attenuation through various materials, or a determination of the relative activity of two radioactive sources, or even identification of an unknown radioisotope are possible.

**III. Experimental Equipment**

Some components of the equipment associated with this lab may be unfamiliar to you. In addition to reading several of the references mentioned above, you may find it useful to look through the material in the binder kept near the apparatus, especially the manuals provided by Harshaw and ORTEC, manufacturers of the scintillation crystal and the modular electronics, respectively. The primary pieces of equipment for this lab include:

- **Scintillation detector** This is a small piece of thallium-doped sodium iodide, or NaI(Tl), that is optically attached to a photomultiplier tube (PMT). The PMT voltages are established by the PMT base, which is connected to a HV supply. The integral of the current pulse leaving the PMT (the total charge) is proportional to the amount of scintillation light, and hence to the energy deposited in the scintillator by the various electromagnetic processes. The scintillator/PMT system needs to be shielded from stray magnetic fields (using a mu-metal wrap) and sources of background radiation (hence the small ‘house’ of lead bricks surrounding the crystal and the radioactive source of interest).

- **Detector electronics** The current pulse must be amplified, shaped, and converted to a voltage pulse, all of which is performed by a combination preamp and spectroscopic amplifier. This same module also contains a Single Channel Analyzer (SCA), which generates a TTL (+5V) logic pulse if the size of the linear signal falls within a set voltage range. The voltage window is established using dials for the lower and upper levels. The TTL pulse is then used to open a linear gate, whose input is the delayed linear signal from the spectroscopic amplifier. The output of the linear gate, then, is a stream of signals whose amplitudes are constrained to fall within a chosen voltage range.
• Multi-channel analyzer (MCA)  With the lowest energy ‘noise’ eliminated by the SCA/linear gate combination, the signal can be sent to the Quantum 8 MCA. A manual for this complex piece of equipment is available, and you should read through the basic operating procedures. Note that pulse height spectra can also be transferred to the PC nearby, then copied to a disk. This allows you to use other, more sophisticated software to produce hard copies of the spectra, perform peak sums, etc. Some of these manipulations (such as integrating the counts over a range of channels) can also be carried out using the MCA itself.

IV. Suggested Measurements (but feel free to use your imagination!)

1. Obtain a $^{137}$Cs source from the instructor. Make sure you understand the precautions necessary when dealing with a radioactive source. Place the source within the lead house, 5-10 cm from the end of the detector.

2. Apply a bias of about 1100 V to the PMT base. Use an oscilloscope to measure the shape and size (in V and t) of the signals coming from the PMT.

3. Connect all of the electronics discussed in the preceding section. Again, use the scope to examine quantitatively the relationship between the input(s) and output(s) of each component as you add it to your circuit. Adjust the relevant settings of the amplifier, SCA, and linear gate while observing the effects on the signals produced. Ask the instructor for help if something doesn’t make sense or if you can’t understand the function of specific dials or settings.

4. Adjust the MCA until a reasonable pulse-height spectrum is obtained. Sketch the main features in your logbook, and explain the origin of each; in particular, discuss the photopeak, Compton edge, and backscatter peak. Be as quantitative as possible, noting the channel numbers that correspond to or define each feature.

5. Using several sources, check the linearity of the system response. From the reference material at hand (especially [LED78]), calculate the relevant energies, and make a graph showing the relationship between energy and channel number. Comment on the linearity of your result, the meaning of a possible non-zero intercept, etc. You should not change the detector bias, amplifier gain, and MCA settings during this study.

6. Each photopeak also has a finite width. Devise a scheme to estimate the width $\Delta E$ in a reproducible way (such as determining the full width at half maximum, or FWHM), and examine the resolution function $\Delta E/E$. How does this depend on $E_\gamma$?

7. Obtain an ‘unknown’ source from the instructor. As before, note the primary features of this source, and use your calibration to determine the energies of these features. Be sure to include a reasonable error estimate for your extracted $\gamma$-ray energies. Using the reference material at hand, you should be able to identify the radio-isotope contained in the source.
8. Due predominantly to interactions with atomic electrons, the intensity of a photon 'beam' decreases approximately exponentially as it passes through matter. Test this idea using both aluminum and lead as absorbers. Estimate the mass absorption coefficients for each. Do these depend on the energy of the photon?

9. Obtain two different radioactive sources of the same isotope. Determine the relative activities of the two sources. Note the initial activity of each at the time of purchase. If the purchase date of one is known, can you determine the purchase date of the other?

V. Analysis Ideas

- Plot and discuss the correlation between $E_{\text{meas}}$ and channel number. Estimate the slope, $x$- or $y$-intercept, and the degree of linearity. What are the main sources of error in the calibration? Which features of the spectrum (photopeak, Compton edge, ...) are most useful and why?

- Discuss the resolution function of the detector system. Which component of the system contributes most to this non-zero width? What are the physical mechanisms that produce this spread in the measured energies? Specifically, what would you expect due to purely statistical fluctuations in the number of optical photons emitted? To estimate this, you will need to look up the energy typically required to produce a single photon in NaI. Note also that only a fraction of these photons actually reach the photocathode, and only some of these will produce a photo-electron.

- Describe the effects of placing material in the path of the photon 'beam.' Is the attenuation truly exponential? If not, what are some possible reasons for deviations? Some clues may lie in the changing shape of your pulse-height spectrum as more material is added. How do your estimates of the mass absorption coefficients compare to those found in the literature? Can you offer an explanation for why they may differ? How could you improve the experimental setup to obtain more reliable values? (Hint - think about the mechanism that gives rise to the back-scatter peak in your spectrum.)

References


