Nuclear Physics #1

Gamma Ray Spectroscopy with NaI(Tl) and HPGe Detectors

Introduction:
In this experiment you will use both scintillation and semiconductor detectors to study γ-ray energy spectra. The sodium iodide (NaI) scintillator detector provides high efficiency γ-ray detection at moderate energy resolution. The high-purity germanium (HPGe) semiconductor detector gives high resolution energy spectra but at the cost of low efficiency. You will use a Multichannel Analyzer (MCA) to measure these spectra.

The NaI detector has other advantages. It can be made large and be machined to arbitrary shape. It is simple and reliable. One drawback of NaI detectors is that NaI absorbs water from the atmosphere which destroys the crystal thus the crystal must be kept sealed. Another drawback of any scintillation counter is that the light is detected using a photomultiplier tube (PMT). This PMT is a vacuum tube and is susceptible to gain instabilities and non-linearities.

The HPGe detector is a solid state device. It has the advantage that the γ-ray interaction produces electrons that are directly collected and amplified. This property provides gain stability and good linearity. The HPGe detector, like most solid state detection devices, has very good energy resolution, typically around 2 keV for 1.33 MeV γ-rays. On the other hand, HPGe detectors must be kept at liquid nitrogen temperatures which requires that the counter be mounted on a large, insulated reservoir of liquid nitrogen. This reservoir is called a dewar. HPGe detectors are constructed from single crystals which limits their practical size and thus their overall efficiency as well as restricting the shape of the detector.

Gamma rays interact with matter in three main ways: The photoelectric effect, the Compton effect, and pair production. In the photoelectric effect, the entire energy of the γ-ray is converted to kinetic energy of a bound atomic electron. In the energy spectrum, the peak resulting from the photoelectric effect is referred to as the "photopeak." In the Compton effect, the γ-ray scatters from an electron. In the collision, the γ-ray gives up less than 100% of its energy to kinetic energy of the electron. The resulting lower energy γ-ray then may interact with another electron or escape the detector. The kinetic energy of the electron will be largest when the γ-ray scatters through 180°. For γ-rays with energy greater than 1.02 MeV, it is possible to produce an electron-positron pair (the rest mass of an electron is 0.511 MeV) in the field of the atomic nucleus. The resulting positron and a second electron annihilate to produce two more γ-rays each with an energy of 0.511 MeV. One or both of these two γ-rays may interact or leave the detector.

In each of these processes, moving electrons are produced and cause ionization of the atoms in the detector material. In the NaI crystal, the moving electrons also ionize impurity atoms in the NaI crystal that are deliberately placed in the crystal during its fabrication. This impurity is thallium (Tl). These impurity atoms de-excite by emitting

photons. NaI detectors are sometimes referred to as NaI(Tl) detectors for this reason. The photons emitted by the NaI(TI) crystal are detected by a photomultiplier tube which consists of a photocathode and several stages of electron multiplying surfaces called dynodes. At the photocathode, the photons interact and produce electrons that are accelerated to a dynode that produces many electrons for each electron striking it. Up to twelve stages of dynodes multiply the number of electrons to produce an electronic signal from the photomultiplier tube. This electron multiplication can exceed 10^7. For ^{137}Cs, the emitted γ-ray has energy 662 keV. In NaI(Tl) the scintillation efficiency is about 13% for this γ-ray (the fraction of the 662 keV energy γ-ray converted into photons in the photopeak), causing 86 keV of photons to be emitted. The energy per emitted photon in NaI is about 4 eV, giving about 21,000 emitted photons. When these emitted photons strike the photocathode of the PMT, only about 15% of them cause photoelectrons to be ejected from the photocathode and detected. Thus for each 662 keV γ-ray, only about 3200 photoelectrons are produced at the photocathode of the PMT.

For the HPGe detector, the ionization electrons are collected by applying an electric field across the semiconductor that has been fabricated as a diode, which conducts an electric current only in one direction and not the other. This current is very small and must be boosted by a preamplifier that is mounted close to the detector to minimize electrical noise. In HPGe it only takes about 3 eV to produce an electron-hole pair in the semiconductor. Thus each 662 keV γ-ray produces about 220,000 electron-hole pairs that are swept across the diode by the electric field and then measured.

Energy Resolution: For both detection devices, the energy resolution is related to the number of electrons that are detected. Of course, this number is proportional to the γ-ray energy. Assume that N electrons are detected. Then from Poisson statistics, one has that the standard deviation (σ) of the population obeys $σ = \sqrt{N}$. Since energy resolution (ΔE) is measured in term of the full width at half maximum of the photopeak at energy E, one has $ΔE/E ≈ 2σ/N = 2/\sqrt{N}$. For the 662 keV γ-ray, a NaI(TI) detector [with N ≈ 3200 electrons] gives ΔE/E ≈ 4% (~ 30 keV), and a HPGe counter [with N ≈ 220,000 electrons] gives ΔE/E ≈ 0.4% (~ 3 keV). Thus the HPGe counter has roughly an order of magnitude better resolution than a NaI(TI) detector.

Multichannel Analyzer (MCA)
In addition to the pulse height distribution caused by the interaction of γ-rays with the detectors, the sources themselves also emit a spectrum of γ-ray energies. The question then becomes, how can one quantitatively measure the distribution of γ-ray energies that emerge from a radioactive source. The answer is the MCA, a device that sorts signals according to the voltage amplitude of the pulses presented to its input. In our case, the pulses come from the output of a linear amplifier. The input of this linear amplifier is connected to the output of a preamplifier for either the NaI detector with its PMT or the HPGe detector. An MCA is the combination of an analog to digital converter (ADC), a digital histogrammer, and a visual display. The ADC converts the height of the input pulse into a digital value. The histogrammer adds a count in a channel corresponding to the digital value of the pulse height. When the next pulse is digitized, the channel corresponding to its digital value is incremented. In this way a histogram is constructed

consisting of a series of channels, each with a certain number of counts corresponding to the number of times the MCA was presented a pulse with a given pulse height. This histogram is referred to as an energy spectrum. You will be using a versatile Spectech ICS-PCI MCA that is made into a PCI card installed in the computer. The acquired γ-ray spectrum will be displayed on the computer monitor using the software provided by Spectech.

Procedure

The equipment

First you need to become familiar with the use of the oscilloscope, the various components of your NIM bin (Nuclear Instrument Module), how the various signals propagate and how the MCA operates.

1. Familiarize yourself with the controls on the oscilloscope.
2. Observe the output of the Ortec 480 Pulser with the oscilloscope. Set the pulse to a positive amplitude of ~ 0.1 V.
3. Connect the pulser to the Ortec 571 Spectroscopy Amplifier (SA) input and observe both the unipolar and bipolar outputs of the amplifier (Fig. 1). Sketch the pulses (or photograph the 'scope screen) for the extremes of the shaping time. Now set the shaping time to 2 μs.
4. Now connect the "Direct In" port (a BNC connector) of the Spectech MCA to the bipolar output of the SA, as shown in Fig. 1. Starting the software, and select 'PHA Direct In' as the input mode. Having pulses of fixed height allows you to
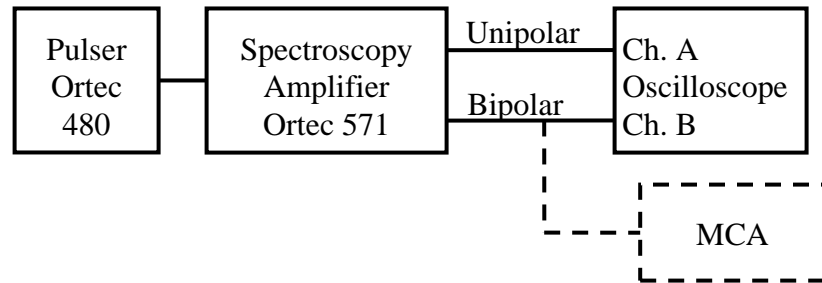

Figure 1

explore the features of the MCA. Using the Pulse Height Analysis mode, vary the gain of the SA and note what the MCA displays. (Note that you can set a clock on the MCA so it counts for a fixed period of time and then stops.) For fixed SA gain, vary shaping time and see if the width of the peak on the MCA display varies. At this point, you should learn what the Regions Of Interest (ROI) feature does, and try to measure the Full Width at Half Maximum (FWHM) of a peak using this ROI feature. Also vary the Upper Level and Lower Level Discriminators (ULD & LLD) to record only the signal for a particular pulse height. Now you are ready to take γ-ray spectra.
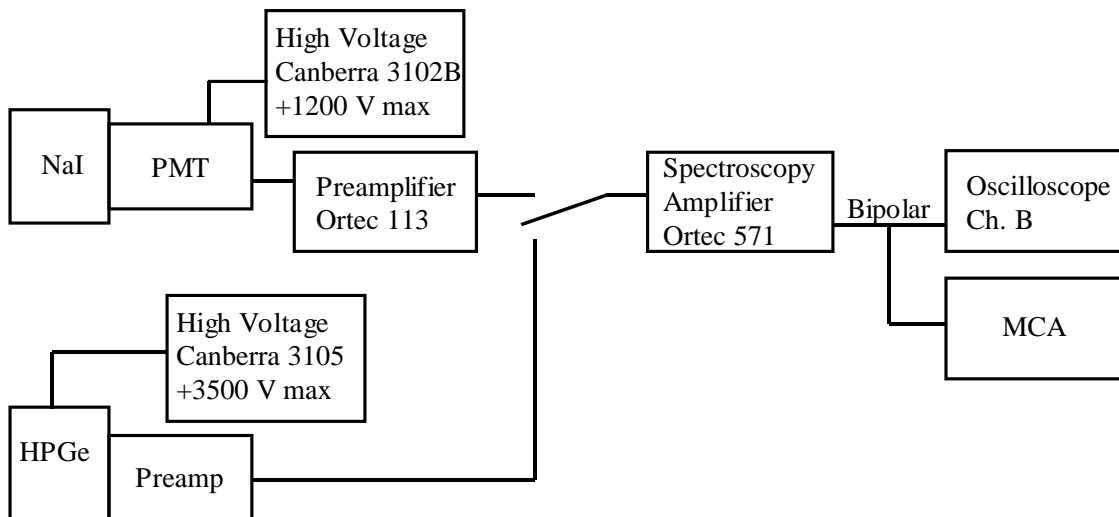
Figure 2: Setups for spectroscopy with NaI and HPGe detectors.

Spectroscopy with NaI detector

1. Set up the NaI detector as shown in Fig. 2 and set the shaping time to 2 μs. Observe the spectra of ^{60}Co and ^{137}Cs.

2. Observe the effect of magnitude of the high voltage on the PMT gain. Plot the channel number of the ^{137}Cs photopeak vs. the high voltage. Assuming a functional form of V^χ for the pulse channel number as a function of voltage, determine χ. Note that the response of the PMT can become very non-linear near the highest operating voltage of +1200 V. For best results, operate the PMT at +1000 V, as a compromise where channel number vs. high voltage behavior is not too steep. At higher voltages the channel number at which the photopeak occurs will be more susceptible to voltage drifts with time. Although the preamplifier usually has its input capacitance set at 100 pF, see what happens when this input capacitance is increased.

3. With the PMT at +1000V and the input capacitance at 100 pF, measure the detector resolution R as a function of the amplifier shaping time for the ^{137}Cs photopeak. Choose the optimum shaping time. The resolution of a peak is defined as R=width/position. The width of the peak is defined as its FWHM in number of channels. The position of the peak is the center of the distribution in channel number.

4. With the shaping time now optimized, also determine R for several different γ–ray energies in the range ~0.1 to 1.3 MeV. Suggestion: start with ^{60}Co that has the highest γ-ray energies that you'll measure and adjust the amplifier gain so the two photopeaks appear close to the maximum of the display abscissa. Use the MCA ROI feature with good statistics for these measurements. See if your data obey the expected dependence of R on γ-ray energy.

5. Using your data from part 4, make a plot of energy vs. channel number, **excluding the ^{137}Cs data**, and do a linear fit to these data to establish a calibration curve. Plot an energy spectrum of γ-rays emitted from ^{137}Cs, and use your

calibration curve to determine the energy of the photopeak. How well (within uncertainties) does your calculated value of the ^{137}Cs photopeak energy agree with the accepted value? Also determine the energy of the Compton edge (maximum energy transferred in Compton scattering) from your calibration.

6. Using photopeak areas or peak heights, measure the γ-ray attenuation coefficients in Pb and Al at different energies. Turn the NaI detector over so it's looking downward. Then you can tape the source to the table and place the absorbers on top of it. Don't forget to do a background count with the γ-ray source removed. Compare you results with expectations.

Spectroscopy with the HPGe detector

1. Set up the HPGe detector as shown in Fig. 2 with voltage at 3000 V. Obtain the spectrum of ^{137}Cs and optimize the resolution of the photopeak by varying the pulse-shaping time in the linear amplifier. Record the improved (over NaI) energy resolution based on the photopeak. Obtain the spectra for [60]Co. For both spectra you should label the photopeak and Compton edge, and also look for a back-scattered peak. Also try to find the electron-positron annihilation peaks for [60]Co.

2. Prepare a calibration curve for 0.1 to ~1.3 MeV as done above for NaI. Measure the energies of the photopeak, back-scattering peak and Compton edges for ^{137}Cs and compare with calculated values for these phenomena.

3. For ^{60}Co, try to identify the "coincidence summing photopeak," measure its energy using an extrapolation of your calibration curve in Item #2, and compare its energy with the sum of the energies of the two photopeaks.

4. Enhance the backscattering peaks for ^{137}Cs by placing Pb or W behind the source. See if you can see the characteristic X-rays of Pb and W. Identify their energies.

5. Try [152]Eu to locate as many peaks as possible.

6. Measure the background radiation and try to identify as many peaks as possible.

7. You could repeat the γ-ray attenuation experiments with this detector to see if you obtain better results.

References:
*   G. F. Knoll, Radiation Detection and Measurement.
    NaI(TI) detectors, p. 227 - 234,
    Radiation Spectrometry with Scintillators, p. 287 – 314,
    HPGe detectors, P. 387 – 440,
    Gamma ray interactions, P. 50 – 57.

*   Gamma Ray Spectra of Nuclei.

*   Table of Isotopes, C. M. Lederer et al.

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