

# GRIDS 2018

## $\gamma$ -ray Emission Spectroscopy

Lise Wills and Alan Robinson

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### 1 Introduction

$\gamma$ -ray emission spectroscopy (GES) uses precise measurements of the energies and flux of  $\gamma$ -rays generated by a sample, reaction, or the environment to identify nuclear processes. The radiation's energy allows a properly calibrated detector to identify the radionuclide, since each radioactive decay from each element corresponds to a different energy difference.

Some applications of GES include:

- The precise measurement of nuclear structure, for example with the GRIFFIN apparatus. See: <http://griffin.triumf.ca/>
- Environmental monitoring. See: <https://arxiv.org/abs/1806.10070>
- Radionuclide identification in activated samples
- Non-destructive radiopurity assays.  
See: SNOLAB facility <https://www.snolab.ca/users/services/gamma-assay/>

What characteristics of  $\gamma$ -rays make GES useful for non-destructive radioassays?

How does the sensitivity of radioassays compare to that of chemical techniques, which are sensitive to part per billion contamination?

## 2 Apparatus

While a variety of technologies may perform GES assays, high-purity germanium (HPGe) detectors are most commonly used today. Semiconductors detect sharper peaks in comparison to materials such as NaI. Sharper peaks are an advantage, as overlapping peaks make source identification difficult. HPGe detectors are single-crystal germanium PiN diode-based ionization calorimeters using high-purity germanium in its bulk and implanted ions for the P and N contacts. Such detectors provide very good resolution, precisely measuring the energy of gamma-ray radiation incident on it.

A PiN detector is a set of P-type and N-type contacts connected by an intrinsic region, which is sensitive to ionizing radiation.

### 2.1 Detection Principle

Detection functions within the “depletion region,”  $d$ , which is a neutral space between the N and P sides, created by both electrons and holes migrating across the junction. This space then has no charge carriers for current and has only charged impurities left, creating an electric field to dispel any remaining holes or electrons. You can increase the size of this space (Eq. 1) by using a bias voltage,  $V$ :

$$d = \left( \frac{2\epsilon V}{eN} \right)^{\frac{1}{2}}, \quad (1)$$

for  $N \sim 10^{10}$  impurity  $\text{cm}^{-3}$  concentration, dielectric constant  $\epsilon$ , and electron charge,  $e$ . Either reducing source impurity or increasing voltage (for a reverse bias) (see Fig. 2.1), will make a larger depletion region. What happens if you reverse the bias? Ionizing radiation creates electrons and holes in the depletion region proportional to the energy deposited; in germanium, 3 eV of energy will produce an electron-hole pair. The pairs are then propelled to the P and N electrodes by the electric field. In this lab, we can only control the voltage, and not crystal purity. Larger  $d$  is generally better. Why? Where does the 3 eV value come from? Would you expect it to take more or less energy in a NaI detector, if such detectors have poorer energy resolution?

Each detector type creates a different number of electron-hole pairs following a modified poissonian distribution, where the modification depends on

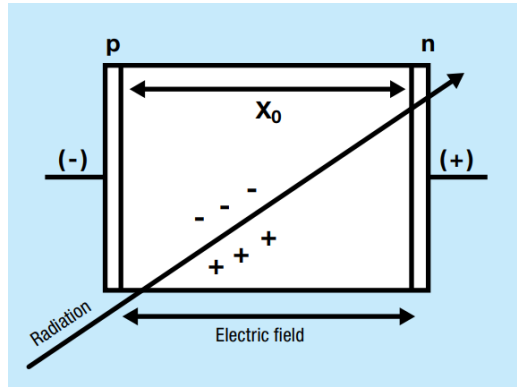


Figure 1: PiN Detector, with reverse bias, demonstrating response to a photon ionization energy.

the detector and is called the Fano Factor. The Fano Factor alters the width of the distribution and is unique to each detector material. For germanium, the value is  $\sim 0.129$ .

The shape of this particular detector is coaxial, so it is oriented as shown in Fig. 2.1. This diagram is for an n-type detector. What is different for your detector, which is p-type?

The characteristic small band gap of semi-conductors is also important for detection - just a small amount of temperature, charge, or electric field will induce electrons to transition from the valence to conduction band. The band gap of germanium is 0.7 eV. This leaves holes which increase the conductivity of the semiconductor. Why might we need to run germanium detectors at liquid nitrogen temperatures?

Germanium detectors' crystal purity requirements and need for nitrogen cooling contribute to the continued use of other detectors, such as NaI, despite their worse resolution. Requiring lesser crystal purity also means NaI crystals can be made larger for much cheaper. On top of that, detectors that are cooled to liquid nitrogen temperatures are run in a vacuum. Is this detector being pumped? Is there a vacuum? What happens if there isn't one?

Once the ionizing radiation creates charge in the depletion region, a preamplifier (preamp) converts this to a voltage pulse. Preamps function to increase signal strength at the sensor itself, so that it is easier to read above noise gathered from electronics, wiring, and other sources between the

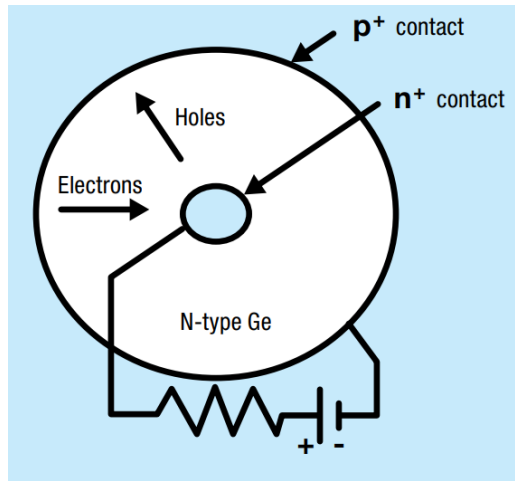


Figure 2: PiN Detector, n-type coaxial detector.

detection and the readout.

The specific germanium detector you will be using is an Ortec GEM80. The bias of 4000 V is applied across the detector, depleting the interior under a strong electric field. Liberated charges from radiation ionization rapidly drift towards the electrodes and are collected. An amplification chain is followed by a Multi-Channel Analyser that bins each pulse by its size.

## 2.2 Multi-Channel Analyser (MCA)

An MCA counts and sorts events in real time, by event characteristics. Here we will be binning by size of the pulse. These bins are called channels, and such analyses are called multi-channel. This experiment will be a pulse-height analysis (PHA). Pulse height is proportional to the event's voltage, which is in turn proportional to the incoming photon's energy. These pulses are converted to channel numbers by an analog-to-digital converter (ADC), with each number representing a narrow range of voltages. When the distribution of pulses is arrayed in increasing energy, a spectrum is achieved, binned into a histogram with energy on the x-axis and number of hits on the y-axis. This histogram is uncalibrated - the values are arranged with respect to one another, but do not have intrinsic values to help us establish our sources. To establish our x-axis values, we must calibrate by using sources with a known peaks at certain energies.

The MCA can record data in a variety of formats. The simplest, plain text, format available is the `.spe` format. You may use a spreadsheet program or a code of your choice to analyse these spectra. However, we recommend the use of the Radware package and the `gf3` program within it which is specifically designed for GES analysis. This code is available for Unix based systems at <https://radware.phy.ornl.gov/download.html> . A set of useful commands are found here: <https://radware.phy.ornl.gov/gf3/>.

How linear is the energy response? Can you think of an equation to describe it? What are gain and offset?

### 3 Set Up

This detector requires at least 72 hrs to cool, and another 24 hrs for the preamp to stabilize. Under such circumstances, the detector has been pre-cooled for you. The germanium crystal in this detector is quite large, which contributes to the cooling time. The detector comes with several fail-safes to keep the system from being run when it is too warm. What do you foresee as an issue should the detector run when too warm?

The system is set up with a the temperature sensor on the side of the germanium that is closer to the nitrogen. Why might this not give reliable readouts? Why is the sensor here, and not on the other side of the crystal? This sensor will turn off the system should it the crystal warm up too much, or if we attempt to run while the crystal is still warm. What happens to noise if the detector is too warm? What happens to the detector itself? Are any of these effects permanent?

Look at the placement of the detector in relation to the table and the nitrogen dewar - what other things should you be thinking of as you're filling the dewar? Why do you think all newer versions of this system have the detector attached at the top, instead of near the bottom, of the detector?

### 4 Instructions

You will be provided with a sample of green tea. Attempt to determine whether any man-made radioactivity is present in this sample. What does it mean if you detect radioactivity? What does it mean if you don't? What does your detector, or your set up, have to do with your detection or lack thereof?

Why might Japanese tea be radioactive? Could you get a publication out of that? (Load the paper from bullet 2 in Section 1).

For you to run this experiment, the voltage must be slowly ramped up to not destroy this equipment. This is usually done over the course of 30 min to an hour by a computer system that controls the pace to avoid such issues. It can also be done patiently by hand. To save time, this has been done before you, but there is some good theory in determining an appropriate rate to increase voltage. Increasing the voltage bias should drop noise - each time the voltage is increased, you should wait for the baseline to return and noise to reduce. Does this involve changing the voltage scale on the oscilloscope, or leaving it alone? Why does this happen? What does it tell you? How does any of this relate to capacitors?

## 4.1 Safety

- The HPGe operates with 4000V of high voltage applied across the crystal. Do not adjust the high-voltage power supply or cables as they may cause a fatal shock. This is 1000 V higher than the largest voltage given by an AED, and more voltage than is required to jump a car. We're not messing around.
- The HPGe is operated at cryogenic temperatures. Do not touch or block the vent at the neck of the HPGe's dewar, or tip the dewar, due to risk of frost-bite or overpressurization.
- As you hopefully determined, the HPGe is under vacuum. Do not hit or apply force to the thin can surrounding the crystal due to the risk of breaking this seal. Does this harm you, the detector, or both?
- Weak radioactive sources will be used to calibrate this detector. The instructor is solely responsible for handling and tracking the location of these sources. Do not move the sources on your own.

A variety of radionuclide sources for calibrating the detector will be made available. Please ask the instructor to place these sources. You will be provided with information on the sources that allow you to calibrate the detector.

## 4.2 Time

There are three kinds of time for most detectors; real time ( $T_R$ ), live time ( $T_L$ ), and dead time ( $T_D$ ), which share the following relationship:

$$T_L = T_R - T_D \quad (2)$$

Real time is time as it passes, whereas livetime is the amount of time that the detector is available to respond to an incoming ray. The time in which the detector cannot respond is called dead time; any event in this time is lost. Is this an effect of the germanium, or the processing equipment? Are other events lost? Do all gammas interact in the detector? What influences whether or not they do? Do you have dead time in this detector? Why? How does this affect what you measure? Can you do anything about it? How, if you should, should you alter your results? Can an experiment have no deadtime?

## 4.3 Analysis

To learn about the HPGe and determine the radioactivity (or lack thereof) of your tea, the following steps should be followed. The instructions are purposely sparse. While the instructor is always present to guide you, see how much you can explore on your own with the information in this manual.

1. Use source to calibrate the spectrum.
  - Do this calibration for varying time lengths
  - How do they affect your calibration?
2. Identify unknown peaks in your spectrum, if any
  - What does the presence, or absence, of these peaks signify?
3. Is there anything you can see in your set-up that might be increasing your noise? (Hint: why do you trust a set up someone else prepared?)
4. Calibrate detector resolution to measured peaks and fit it to a functional form:

$$\text{var} = A + (B * E) + (C * E^2) \quad (3)$$

- Try this for varying time lengths and see how the fit changes.
  - How do you determine a good enough interval?
  - Why do you care? Binning almost cost a Nobel Prize ( $J/\psi$ )
  - What are gain and offset? How do they apply to your fit?
5. Fit relative strength of peaks for certain isotopes.
  6. Determine what a baseline is, and how it affects your calibration.
  7. Perform a dead time calibration.
  8. Detector efficiency is the ratio between detected and emitted photons. How would you calculate it? Can you?
  9. Is your tea radioactive? How might shielding help?
  10. Did anyone hide a source in your tea? How can you tell?
  11. Should you have done a background calibration run? Could you? How long after a source is present do you have to wait, if at all?
  12. Discover how much harder it is to run your detector than get a physics result.