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γ-ray Emission Spectroscopy

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1 Introduction

γ-ray emission spectroscopy (GES) uses precise measurements of the energies and flux of γ-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`
- Radionucleide identification in activated samples
- Non-destructive radiopurity assays.
  See: SNOLAB facility `https://www.snolab.ca/users/services/gamma-assay/`

Ask yourself

What makes GES different to other radiological monitoring and assay techniques:

- What characteristics of γ-rays make GES useful for non-destructive radioassays?

- How many atoms can be detected by radioassays as compared to chemical techniques, which are often sensitive to part per billion contamination?

2 Apparatus

Amongst the technogies available, high-purity germanium (HPGe) detectors are the most commonly ones used today for GES. These detectors provide the best energy resolution for ionization produced by /*sim*MeV photons. Sharper peaks provide multiple advantages in identifying and caracterizing ionizing radiation.

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.

The specific germanium detectors 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.

Ask yourself

What makes germanium useful:

- How is the band structure of Ge different than that of other common semi-conductors?
- How do γ-rays interact in Ge as compared to other semi-conductors?

2.1 Inside the germanium

The conversion of deposited energy into a measurable collected charge occurs within the depletion region, d in the figure. This neutral insulating space between the N and P sides of the diode is created by electrons and holes migrating to opposite sides of the junction under the applied electric field. This space then has only thermally generated charge carriers and immobile charged impurities left. The use of High-Purity Germanium (HPGe) minimizes these concentrations of charge impurities that would degrade the electric field, allowing for a thick depletion region to form. The length of the depletion region along the electric field can be controlled (Eq. 1) by a bias voltage, V:

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

for $N \sim 10^{10}$ impurity cm^{-3} concentration, dielectric constant ϵ, 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.

Ask yourself

- What happens if you reverse the bias?
- Why does a large depletion region generally improve the performance of the detector?

Ionizing radiation, such as a rapidly moving electron, creates conduction electrons and holes in the depletion region proportional to the energy deposited by the radiation; in germanium, this ratio is measured to be one electron-hole pair per 3 eV of energy. The electron-hole pairs are then propelled to the P and N electrodes by the electric field.

Ask yourself

- Is there a reason to expect an electron-hole pair per 3 eV instead of an electron-hole per 0.3 eV or 30 eV?
- Would you expect it to take more or less than 3 eV to produce a photon in a NaI detector, given that such detectors have poorer energy resolution than HPGe?

Each detector type creates a different number of electron-hole pairs following a modified Poisson distribution with the number of electron-hole pairs produced as the random variable. In a Poisson distribution, the variance is equal to the expected value. For the number of electron-hole pairs produced in an HPGe detector, the variance is multiplied by a Fano Factor which is unique to each detector material for a given type of incident radiation. For fast electrons in germanium, the value is ~ 0.129.

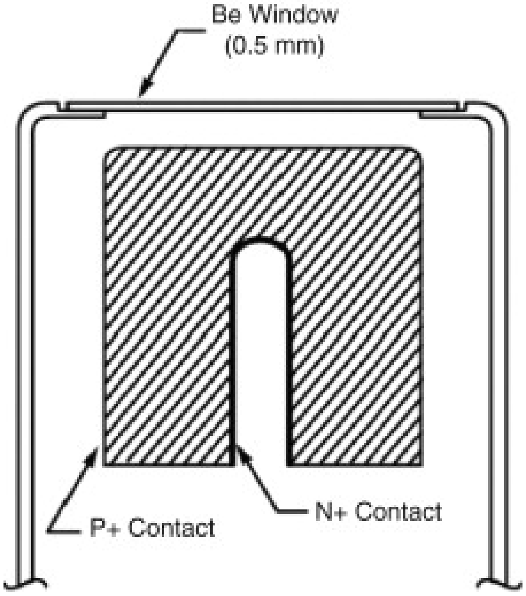

Figure 1: Cut-away diagram of an n-type HPGe detector. The boron implated forms a thinner doped region than the lithium diffused p-region. The n-type detectors thus have enhanced x-ray sensitivity vs the p-type we are using.

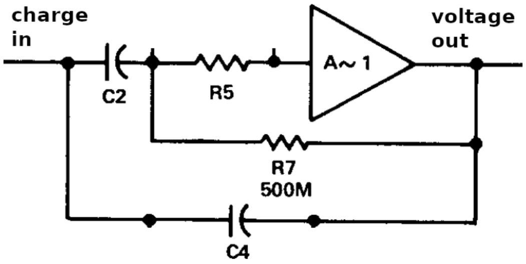

Figure 2: Simplified wiring diagram of a typical charge preamp (Ortec 142A). What is the pulse shape generated by this amplifier following an instantaneous injection of charge? Which element in the amplifier determines the amplifier gain?

The shape of our particular detector is coaxial, oriented as shown in Fig. 2.1 which permits a larger detector volume for a given acheivable intrinsic region depth.

The characteristic small band gap of semi-conductors, the band gap of germanium is only $0.7\,\mathrm{eV} = (8120\,\mathrm{K})k_B$, mandates the cooling of the detectors to prevent damaging currents and diode breakdown. Cooling additionally reduces the detector's shot noise. HPGe detectors are generally cooled to as low a temperature as possible, around 100 K, while still efficiently ionizing doping sites. A liquid nitrogen dewar (77K) provides the cooling power to this cryostat.

Germanium detectors' crystal purity and need for nitrogen cooling imply that they need to be maintained under high vacuum. This vacuum is provided by an initial ultra-high vacuum pumping of the cryostat at elevated temperature which is then sealed and subsequently maintained by cryogenic pumping onto a molecular sieve in the detector cryostat.

2.2 Charge preamplifier

Once the ionizing radiation creates charge in the depletion region, a preamplifier (preamp) converts this to a buffered voltage pulse. The charge preamp for an HPGe is generally, but not always, located within the cryostat, reducing signal loss and pickup, and taking advantage of the cryogenic temperatures to reduce the first stage amplifier noise.

Ask yourself

The pre-amplifier can be damaged by excess current through the detector. How would this current damage the pre-amp?

2.3 Shaping amplifier or spectroscopy amplifier

The spectroscopy amplifier has three roles.

1. Match the small signals generated by the pre-amplifier to the 0-10 volt signals required by the MCA. This is controlled by the adjustable amplifier gain.
2. Provide a bandpass filter that minimizes sensitivity to sources of noise in the electronics chain. This is controlled by the shaping time.
3. Minimize the effect of progressions of pulses (pile-up) on measurements of the amplitude of each pulse. This is controlled, in part, by the Pole-z adjustment

2.4 Multi-Channel Analyser (MCA)

An MCA counts and sorts pulses in real time, by peak height. Each pulse-height bins is called a channel, and such analysers are called multi-channel. This is in contrast to discriminators, which determine whether a threshold has been passed, and single-channel analysers, that accept pulses within a window of peak-height values.

To determine the energy of gamma-rays striking our detector, we will perform pulse-height analysis (PHA) using the MCA. As described in the above sections, the 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 a measure proportional to 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-scale, 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.

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 a thermal sensor wired to shutoff the high-voltage if the detector was ever too warm.

The 4000V bias voltage is applied slowly to the detector once it is cold. This has been done for you.

Ask yourself

Think through the how the rapid application of this voltage could damage the pre-amplifier.

The shaping amplifier, MCA, and an oscilloscope are all wired and available to help up explore how this detector operates. Please plan on several hours to optimize the detector performance before committing to assaying our radioactive sample.

4 Instructions

You will be provided with a sample of material that may be radioactive. Please determine what radioisotopes are present in the sample, and whether it is man-made. Think about what it means if you detect radioactivity, or if you don't. How do you optimize the sensitivity of your measurement before assaying the sample?

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 connected to a diode large enough to have a significant capacitance, and stored energy. 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. This could harm you and the detector.
- 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 radionucleide 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 and detection efficiency

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:

$$\mathrm{T}_L = \mathrm{T}_R - \mathrm{T}_D \tag{2}$$

Real time is measured by clocks, 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 due to the need to process a previous pulse is called dead time; any event in this time does not contribute to the measured spectrum and affects the detection efficiency.

There are also important geometric and radiation effects that contribute to the detector efficiency.

Ask yourself

- Do all gammas that pass into the detector interact with it?

- Where the photons interacting in the detector come from?
- Can you do anything to maximize, minimize, or calibrate the detector efficiency to different sources of radioactivity?

4.3 Analysis

To learn about the HPGe and determine the radioactivity (or lack thereof) of your sample, 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. Ensure your detector is operating at its peak performance.

   Ask yourself

   - 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?)

2. Calibrate your detector.

   Ask yourself

   - What parameters do you need to calibrate?
   - What does the calibration tell you about detector performance?

3. Plan how to measure your sample to high sensitivity and accuracy.

   Ask yourself

   - Does your calibration match your planned measurement?

4. Identify and quantify any radioactivity from your sample.