

University College London
Lab 3 Experimental Physics PHAS0051

HPGe Detector for Nuclear Spectroscopy

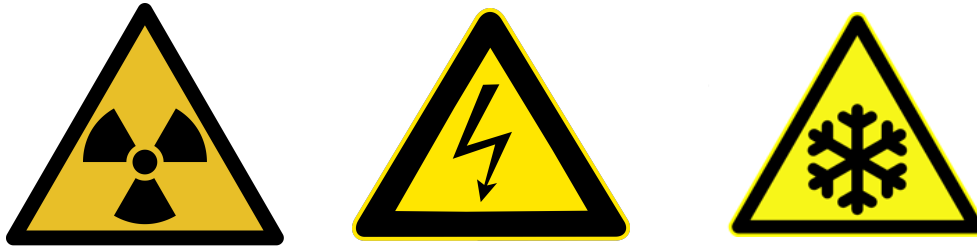
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1 Matters of Safety

High Purity Germanium (HPGe) detectors work at cryogenic temperatures so need to be constantly cooled by Liquid Nitrogen (LN). The Canberra Dewar holds approximately 30L of LN with a maximum boil off rate of 2L per day. The Dewar must be topped up regularly to avoid wasting LN and warming up the HPGe crystal. Applying a high voltage to a warm crystal will cause damage. Each student should consider the following:

- LN has a temperature of 77K and is therefore dangerous. Students should not fill up the detector nor touch any of the experimental apparatus that will be cold due to the LN.
- Students should not need to change any of the cabling from either of the Lynx or DSPEC LF boxes to the HPGe detectors. If something seems wrong, seek out a demonstrator.
- On the Mirion detector, the red LED indicates the temperature of the HPGe crystal. The temperature monitor on the ORTEC detector is displayed on the DSPEC LF display screen - see figure 3. Check this temperature status and the LN log book regularly to ensure the detector has been cool for a minimum of 8 hours. ***Safe conditions for turning on the detector are: (i) the red LED is off or the DSPEC LF display screen does not display OVERLOAD or SHUTDOWN and (ii) the Dewar was last filled more than 8 hours ago. If in doubt, ask a demonstrator before turning on the instrument.***
- The Lynx and DSPEC LF data acquisition boxes supply high voltage to the detectors. Whilst the HV is on, do not touch the cables behind the box.
- For each radioactive source used the exposure should be calculated and considered before use. ***A demonstrator must check your calculations and be present for the introduction of radioactive sources.*** When handling a source, plastic gloves must be worn and tweezers must be used. The 3D printed lid should be tightly secured with the screws then placed lightly onto the detector.

Important sources of information for this project include the following :

- **Documentation.** A folder `Documentation` can be found on the HPGe computer desktop. It contains relevant documentation, including a manual for the `Lynx` or `DSPEC LFdata` acquisition system.
- **Log books.** A folder `Logbooks` can be found on the HPGe computer desktop. It contains a spreadsheet `Detector_Cold_Status`, which is a record of the Dewar liquid nitrogen refills and other observations relevant to the cryogenic status of the instrument. You should append your own observations to this spreadsheet.

If you cannot access any parts of this information, ask a demonstrator.

2 Experimental Aims and Objectives

- Understand the basic principle of operation of an HPGe detector.
- Calibrate the HPGe detector.
- Obtain a spectrum of background radioactivity and identify significant features.
- Obtain spectra for known radioactive sources.
- Quantitatively describe the resolution of the HPGe as a function of gamma-ray energy.
- Investigate the efficiency of the detector.
- Investigate and understand the raw signal output from the HPGe detector
- Identify unknown sources from measured spectra.
- Identify radio-impurities in selected samples.

3 Introduction

Gamma ray spectroscopy describes the quantitative examination of the photon energy spectra in radioactive sources. Each radioactive nuclide has a characteristic gamma spectrum which can be used to identify impurities of samples. This technique is used in various disciplines such as nuclear physics, geology and environmental sciences. The UCL High Energy Physics group are particularly interested in the use of HPGe detectors to “assay” (carefully measure) materials for very low-levels of radioactive impurities which can disturb sensitive neutrinoless double-beta decay and direct dark-matter detection experiments. We help to run a suite of such detectors in the Boulby underground laboratory.

In this experiment, you will learn how to set up, operate and calibrate a High Purity Germanium (HPGe) solid state detector. You will then obtain gamma spectra of different isotopes of varying activities and identify the composition of samples by comparing your spectra to tabulated gamma-ray lines.

4 Background Theory

4.1 Background Research

Before you begin this experiment you should make sure you understand the following in the context of gamma-ray spectroscopy:

- the different types of radioactive decay;
- the different methods used in gamma ray spectroscopy (scintillation counters, HPGe, etc) and their differences;
- different p-n and p-i-n semi conductor materials;
- ADC counting methods.

You should also familiarise yourself with the different distributions used to describe radioactive decay and associated spectra (Poisson, Binomial, Gaussian, etc.) and be able to quantify a goodness of a fit to the data (via a Chi^2 test for example).

4.2 Radioactive Decay

Gamma decay normally occurs after other forms of decay, such as in alpha or beta decay, where the daughter nuclei are produced in an excited state. These can then

decay to a lower energy state by emitting a gamma-ray photon. The gamma-ray emission is usually prompt, although sometimes has a longer half-life¹, depending on the spin and parity of the parent and daughter nuclides.

Other, typically rarer, decay modes also exist. Particularly useful as a source of mono-energetic electrons is the “internal conversion” decay mode whereby the nuclear excited state that produces gamma-rays in its de-excitation, can instead impart the same decay energy to an inner atomic electron which is subsequently ejected from the atom.

Each radioactive isotope has a known decay scheme which details the nuclide’s emissions (types & energies) and relative intensities. There are many nuclear decay databases which can be found online, for example [1].

4.3 Semiconductor Detectors

Within a doped semiconductor movable charge carriers between the materials will diffuse away or can be forced to move by an electric field. This creates a depletion region which contains only the ionised acceptor and donor impurities.

Under reverse bias, where the p node would be negative with respect to the n node, the potential within the depletion region increases. This forces out more charge carriers leaving more ionised impurities hence creating a larger depletion region. This is ideal for gamma ray spectroscopy (GRS) as we want to maximise the charge collection within the semiconductor and the detection efficiency.

The thickness of the depletion region is given by equation 1 :

$$d = \sqrt{\frac{2\epsilon V}{eN}} , \tag{1}$$

where d is the thickness, ϵ is the dielectric constant, V is the reverse bias voltage, N is the net concentration of impurities within the semiconductor material and e is the elementary charge unit.

To ensure a large depletion region for a given reverse bias voltage, N needs to be minimised. The HPGe detector can provide impurity concentrations as low as 10^9 atoms/cm³, making them ideal for gamma-ray spectroscopy².

In semiconductors, the band gap between the valence band, which is fully occupied, and the conduction band, which is completely empty, is small. An increased temperature, incident charged particles, or an applied electric field can give the electrons

¹Such isotopes are very useful, for example in medical imaging. Do you know of any?

²Does this sound very pure? Compare with other purity standards you may be familiar with.

enough energy to move from the valence band to the conduction band. This leaves a hole in the valence band which acts like a particle with positive charge. These holes then contribute (along with the electrons) to the conductivity of the semiconductor.

4.4 HPGe Detectors

High Purity Germanium (HPGe) detectors are semiconductor diodes which have a $p-i-n$ structure which is similar to a standard $p-n$ diode but with an intrinsic region between the p and n electrodes. This intrinsic region is sensitive to ionizing radiation. When photons interact with the material within the depleted region, under a reverse bias, holes and electrons are produced. These charge carriers are moved by the electric field towards the p and n electrodes. The charge, the number of carriers, is proportional to the energy deposited in the detector by the incident photon. This is converted into a voltage by a pre-amplifier.

The HPGe detector used here is *p-type coaxial*. In general for such detectors an n^+ electrode on the outer surface of the cylindrical volume will be formed by depositing lithium which diffuses into a thin layer of germanium³. The other electrode is formed on the inner surface of the coaxial detector. For further details of common HPGe configurations, consult [2].

Germanium has a relatively low band gap so thermally generated charge carriers are easily created. These produce a leakage current which is a noise that will reduce the resolution of the detector. Therefore, the detectors must be cooled to low temperatures to reduce the thermal activity and reducing the noise. This cooling is achieved by using liquid nitrogen, which has a temperature of 77K.

4.5 Gamma Ray Efficiency

The number of photons detected in the HPGe detector (N_{measured}) will always be less than the photons emitted by the radioactive source (N_{emitted}). The ratio between these two numbers is called the detection efficiency (ϵ) and is shown in equation 2 :

$$\epsilon = \frac{N_{\text{measured}}}{N_{\text{emitted}}} \quad (2)$$

The number of counts observed in a detector, for a incident photon, depends on the size, atomic number and density of the detector. It also depends on the activity of the radioisotope, the distance the source is from the detector and the medium through which the photons traverse.

³The superscript + in the designation n^+ indicates a stronger concentration of n -type impurity.

In general, the number of gamma photons produced by a source does not equal the number of disintegrations within the radioisotope (1 Becquerel equivalent to 1 disintegration per second) due to the various decay channels available to the nucleus. Gamma decays often involve the cascade emission of several gamma-rays; by contrast internal conversion serves to reduce the number of gamma rays produced. The total number of gamma ray emissions per disintegration can be described in terms of an intensity parameter as shown in equation 3 :

$$N_{\text{emitted}} = AYt, \quad (3)$$

where A is the activity of the source, Y is the gamma ray yield and t is the exposure time.

The activity of a source is quoted at a specified calibration date. The activity will fall according to the standard half-life equation :

$$A = A_0 e^{\frac{-\ln(2)t}{t_{1/2}}}, \quad (4)$$

where A_0 is the activity on the reference date and $t_{1/2}$ is the half-life of the nuclide under consideration.

There are two efficiencies that are important for this detector; *absolute* and *intrinsic*. The absolute efficiency is the ratio of the total number of photons detected to the number of photons emitted by the source. The intrinsic efficiency is the ratio of the number of photons detected to the number of photons incident on the detector medium itself. Note that one should be careful to define a detection - typically it would be defined as a photon whose energy is fully absorbed (i.e. contributes to the count-rate given by the full energy peak).

5 Experimental Procedure

5.1 Apparatus

The following list is the description of each part of the detector labelled in figure 1. Note - the ORTEC is very similar in design:

1. HPGe Crystal
2. Pre-Amplifier
3. LED (Mirion ONLY)
4. Dewar

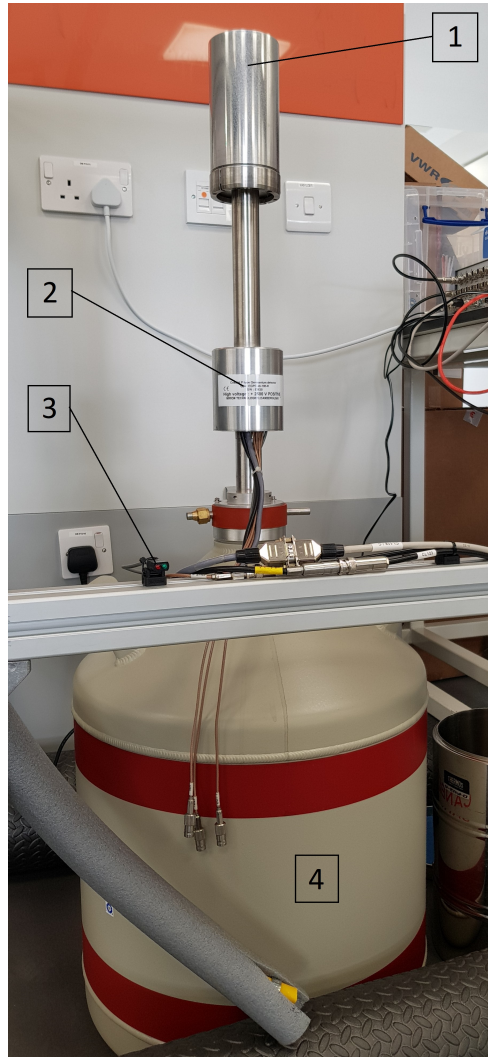


Figure 1: Major components of a HPGe detector.

The Lynx DAQ box and the DSPEC LF are ADC signal processors and can be seen in figure 2. After turning on the box at the mains, the power LED will flash for a minute. Wait until the LED is fully lit before using the box. When the HV is turned on via the Lynx user interface (UI), the HV LED will turn on.

5.2 Set up and Calibration

Before doing anything with the detector, ensure that the DAQ box is turned on at the mains, check the log book to see the cold status of the instrument, and check the cold status.

For the Mirion detector -



Figure 2: Photograph of the Lynx DAQ box

Figure 3: Photograph of the DSPEC LF DAQ box

On an internet browser connect to the Lynx box network which can be achieved by typing 10.0.0.3 into the URL. This will load the Lynx UI with the blank spectra on the right and the settings on the left. Under hardware, select the HV power supply which brings up the dialogue box for controlling the HV. It is important to check that the LED has been off for at least 8 hours before applying a HV. This information should be logged in the log book. ***Check with a demonstrator before applying HV to the instrument.*** It is good practise to ramp up the voltage (to its maximum) in incremental steps. The maximum voltage that should be applied is 2500V so do not change this setting. Ensure the polarity (and inhibit polarity) settings are set to positive. Select the voltage you wish to apply (relatively low) and tick the box to supply the HV.

For the ORTECdetector -

Maximum voltage is 3000V.

With no source on the detector, ramp the HV to maximum. Begin the acquisition of data by clicking the start button at the top of the screen. To the right you will see a progress bar and a time counter. It will be worthwhile to investigate whether the UI records the actual time or takes into account the dead-time of the detector. Note that before calibration, the output channels of the Lynx ADC do not correspond to the true energies being detected. ***Ensure that the voltage is turned off when not collecting data and before you leave the lab.***

For ^{60}Co , deduce the dosage you will be exposed to during your experimentation and update your risk assessment (for details of this procedure, see Section 6.2 below). Place the ^{60}Co source within the container and secure using the screws. Place the holder onto the detector and ramp up the voltage. Collect a ^{60}Co spectrum and open the corresponding .csv file in the BASSLite software. The first objective is to calibrate the output channels of the ADC to an energy scale. This can be achieved by adjusting the parameters m and c . m is the gradient which controls the number

of channels per unit of energy (keV in this case). Set m to one and compare the ^{60}Co photopeak positions to the ones found on the database. Obtain the channel per energy/keV ratio, which for a good calibration is close to 1. The calibration can be improved by altering m and c , the offset. This should be done analytically and not by trial and error.

5.3 Efficiency Investigation

You should determine the resolution of the detector and see how this varies with energy across the spectrum. Does the resolution change with voltage? By calculating the number of photons emitted by the source, determine the efficiency of the detector. Investigate how this efficiency changes with energy and distance from the detector.

You can replace the source with another source (to be discussed with a demonstrator). Test your calibration on the new source by collecting a spectrum and analysing it. Test the activity of the source using the efficiency of the detector, at a particular distance, that you have determined and compare this to that calculated using equation 3.

6 Data Analysis

6.1 BASSLite

One of the main software packages we will be using for this project is **BASSLite**, which is installed on the desktop computer next to the HPGe experiment. This software has been written by colleagues at the Boulby Underground Germanium Suite (BUGS). You can familiarise yourself with this software by using the ^{60}Co `test_data.csv` file in the HPGe data folder.

To zoom in on a section, click and drag along the axis in question. To plot a quick Gaussian, hold shift and drag across the section you want to plot. Note that this calculates the counts in the peak, the peak position and the FWHM but does not calculate the errors.

6.2 Radioactive Exposure Calculations

In this experiment you will be working in close proximity to radioactive sources. Over the experimentation time period you will receive a dose of ionising radiation which depends on the activity of the source, your distance away from it, the exposure

time and the shielding. Before any work is done with any radioisotope, a full risk assessment must be completed.

For each radioisotope, you need to find the absorbed dose constant at the average distance that you will be working. Using this, you can calculate the equivalent dose using the SI unit for dosage, Sievert, by using the activity and the time for which you will be using it. This dose should then be checked against the statutory dose limits for the UK.

You should find that the dosage will be well below that of the legal limit as you will not be using very active sources. However, it is always important to check and also convince yourself that you aren't causing any harm to yourself.

There is an opportunity to add to the experimental set-up to reduce the amount of gamma radiation being emitted into the room via the use of shielding. How much shielding would be needed to reduce the intensity of the emitted gamma radiation by half? This may be a good consideration to make in your risk assessment.

6.3 Spectrum Analysis

When no source is on the detector there are still a significant number of gamma ray photons incident upon it. These photons are from many sources and create a background across a large energy range. This is a problem in all experiments that are sensitive to small amounts of radioactivity as it can often hide features of interest. Reduction of the background and background analysis techniques are therefore important to address the interesting physics which may or may not be there. With the HPGe fully calibrated, can you identify any particular photopeaks within the background that stand out within the spectrum?

Another large part of the background is due to the Compton scattering of gamma photons within the detector. Compton scattering refers to the process when an incident photon collides with an electron in a given material. The energy of the scattered photons can be formulated in equation 5 :

$$E_s = \frac{E}{1 + \frac{E}{m_e c^2} (1 - \cos \theta)}, \quad (5)$$

where E_s and E are the energies of the photon after scattering and before scattering respectively, m_e is the rest mass of the electron, c is the speed of light and θ is the angle through which the photon is scattered. The energy deposited in the material, in this case the HPGe crystal, is a function of θ and is maximum when the photon gets reflected, $\theta = 180$ degrees. The transfer energy E_T is then just the energy difference shown in equation 6 :

$$E_T = E - E_s. \quad (6)$$

As no more energy can be transferred to the electron by the photon at $\theta = 180$ degrees there is a sharp cut off which is known as the Compton edge. This cut-off energy, E_C can be described by equation 7 :

$$E_C = E \left(1 - \frac{1}{1 + \frac{2E}{m_e c^2}} \right). \quad (7)$$

There is also a region between the minimum energy and this cut off known as the Compton Plateau which is characteristic of Compton scattering. Can the Compton Plateau and the Compton Edge be distinguished within the background spectra you have collected? You should also measure the position of any Compton edges that you see.

When analysing the collected radioisotope spectra, compare your measured values to those referred to in online databases such as [1]. You will also find a table of common gamma energies in the experiment folder or in the documents file on the MAC desktop.

The relative intensity of a photopeak is directly linked to the net area of the peak with any background subtracted. The efficiency of the detector for that energy and the gamma ray yield should also be taken into consideration for each photopeak. For each source, the positions of each gamma ray photopeak, the FWHM, the resolution, the efficiency and the relative intensity should be calculated. The energy positions should be checked to ensure the Lynx box is calibrated and the relative intensities compared to known values.

6.4 Energy Resolution

The energy resolution of a HPGe peak can be described by two contributions shown in equation 8.

$$\text{FWHM} = \sqrt{(w_d^2 + w_e^2)}, \quad (8)$$

where FWHM is the the full-width-at-half-maximum, and w_d and w_e are the width of the peak due to detector and electronic effects respectively. w_d is given by :

$$w_d = 2\sqrt{(2 \ln 2) F E w}, \quad (9)$$

where F is the so-called ‘‘Fano’’ factor and w is the energy required to create an electron-hole pair in the depletion region. For HPGe detectors, the value of w is relatively low (a few eV) so the number of pairs created is large. This increases the charge collection statistics, and therefore improves the energy resolution.

The energy resolution is the term that describes the ability to distinguish between two energy peaks. This can be calculated using equation 10.

$$R = \frac{\text{FWHM}}{E_0} \times 100, \quad (10)$$

where E_0 refers to the photopeak energy.

Investigate the value of w_d .

References

- [1] https://www-nds.iaea.org/xgamma_standards/. A list of some common gamma-ray lines is also provided in the `Documentation` folder.
- [2] “Radiation Detection and Measurement” (Fourth Edition), G. Knoll. Chapter 12 is on HPGe detectors, but other sections on the general principles of radiation detection are also useful.
- [3] “Germanium Detectors: User’s Manual”, Canberra Industries Inc. (2003). An electronic copy of this document can be found in the `Documentation` folder on the desktop computer, and a paper copy in the folder.