Gamma Spectrometry using Semiconductor Detectors

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Abstract

The precise measurement of high energy photons is of paramount importance in many fields of both basic and applied sciences. In this sense, the high resolution gamma ray spectroscopy performed using semiconductor detectors, where transitions with very similar energies can be precisely discriminated, is a very powerful tool.

In this experiment, students will learn the basic concepts on the measurement of photons using semiconductor detectors, then will have a hand-on experience on the use of a high-resolution high purity germanium detector (HPGe), from the initial calibration of the system to actual measurements of standard sources and also of real-world samples, where the high complexity of the spectrum presents an additional challenge. Additionally, the ubiquitous gamma-ray background will be discussed, and students will be offered the possibility to perform a thorough analysis of the transitions found in the environmental radiation.

1 Introduction

As photons have no charge, the detection of photons in general, and of gamma radiation specifically, rely on the absorption of the photon by matter, followed by the detection of the transferred energy.

1.1 Interaction of high-energy photons with matter

In the specific case of gamma rays (and high-energy x-rays), three main processes dominate their interaction with matter:

Photoelectric effect The photon transfers all its energy E_γ to a bound electron in the medium (binding energy = E_b), which is then ejected with a well-determined kinetic energy $E = E_\gamma - E_b$;

Compton effect The photon transfers part of its energy to a bound electron, and the remainder of the energy is emitted in the form of a second gamma-ray with an energy $E_{\gamma 2}$ (which may, or may not, then escape the medium);

in this case, the electron energy will have a continuous distribution, with a maximum energy of [1]:

$$E_e^{max} = \frac{E_\gamma}{1 + \frac{511keV}{2E_\gamma}} \tag{1}$$

Pair Production In this case, a photon with an energy greater than 1022 keV (or twice the rest energy of the electron) interacts with the electric field around an atomic nucleus, producing an electron-positron pair, and the excess energy is then transferred to these particles as kinetic energy; in this case, each of these particles may then either be absorbed in the medium or escape.

1.2 Gamma-ray detectors

As seen, the detection of gamma-rays rely on the conversion of that energy to electrons, which may then be registered. In practice, there are several ways to build a detector for gamma-rays, for example:

Gas detectors If one subjects a gas reservoir to an electric field, the electrons and positive ions produced when radiation interacts with the gaseous medium will be collected and then registered as an electric current; these detectors have low detection efficiency for gamma-rays, due to the low density of the sensitive medium, but are often used for specific cases, as general radiation monitors, sensitive also to gamma radiation (*Geiger counters*) or as detectors for very high radiation fields (*ionization chambers*, often used for medical purposes);

Scintillators A scintillator is a material where the interaction with ionizing radiation results in the emission of light close to the visible range; these detectors can often be produced as high-density solids composed by high-Z materials as Be, I, Lu, etc., which results in improved efficiency for photon detection, with an energy resolution around 5-10 % – commonly used detectors of this type are NaI, CsI, BGO or LYSO, all of which are very commonly used when high energy resolution is not required;

Semiconductor detectors In a semiconductor medium, the passage of ionizing radiation may promote valence electrons to the conduction band, thus producing an electric signal; these detectors offer excellent energy resolution (0.15–0.5 %), at the expense of some detection efficiency, as they are usually produced with lower-Z materials as Ge or Si. These are the detectors we will use in this practice, specifically the HPGe (*High Purity Germanium*) ones.

2 Experimental Procedure

This laboratory session will be essentially a practical introduction to HPGe detectors and their use. In this sense, students will be presented to an HPGe detector, perform an energy calibration so that the energy of the incoming radiation can be determined, perform a quick efficiency calibration, observe some intrinsic spectral defects that hamper the performance of these detectors, and then proceed to analyze a radioactive sample of sand rich in uranium and thorium. Some additional background spectra will be provided so that interested students may, if they want, observe and analyze the ubiquitous gamma-ray background.

2.1 Knowing the detector

Students will be presented to a detector, use an oscilloscope to observe the output signal, and see how the signal is processed to be transformed in a radiation spectrum.

2.2 Detector calibration

Students will receive a set of standard sources ($^{57+60}$Co, ^{137}Cs, ^{241}Am, ^{166m}Ho, ^{152}Eu and/or ^{133}Ba) and will then count each of them individually for 300-600 s (depending on the intensity of each source), saving and analyzing the resulting spectra to obtain the centroid and area of each peak. Using these data, we will perform both calibrations.

2.2.1 Energy Calibration

To know the energy corresponding to each position or peak in the spectrum, the peaks observed in the $^{57+60}$Co source will be associated with the expected emission energies E_γ (122, 136, 1173 and 1332 keV - the precise energies will be given in a separate datasheet), and this will then the plotted, and a linear function (*energy calibration*) will be fitted – P is the centroid of each peak:

$$E_\gamma = a + b \times P \tag{2}$$

To verify the accuracy of this fit, the centroid of the peaks found in the other sources will be converted to energy and compared to the expected emission energies.

2.2.2 Efficiency calibration

In order to understand the energy dependence of the detection efficiency, students will then take the nominal activity of each source (A_0), correct it for the decay since they were measured (dT) – see eq. 3 – and use these results, together with the intensity of each transition (I_γ, also given in the datasheet) and the experimental results obtained for the peak areas (C) and the counting time (t_c)

to determine the experimental detection efficiency for that energy ($\varepsilon(E)$), as shown in equation 4.

$$A = A_0 \times e^{\lambda \times dT} \tag{3}$$

$$\varepsilon(E) = \frac{C}{A \cdot I_\gamma \cdot t_c} \tag{4}$$

These results will then be plotted as a function of the gamma-ray energy, and the results will be fitted to a special function developed specifically for this purpose (equation 5, where energies should be written in MeV [2]).

$$\varepsilon\left(E_\gamma\right) = \left(P_1 \cdot e^{-P_2 \cdot E_\gamma} + P_3 \cdot e^{-P_4 \cdot E_\gamma}\right) \cdot e^{-P_5 \cdot \left(0.05757 \cdot E_\gamma^{-0.416} + 0.000465 \cdot E_\gamma^{-2.943}\right)} \tag{5}$$

2.3 Exploring secondary effects in the spectrum

Using the spectra obtained so far, and new quick measurements of rather strong ^{137}Cs and ^{60}Co sources, students will identify the Compton borders, as well as note the pile-up peaks formed when the system cannot separate two almost-simultaneous gamma rays. Students will also compare the energy resolution obtained with these strong sources to the ones obtained with the weaker ones, to see how very high count rates can negatively affect the energy resolution. Finally, other issues that may appear in the spectra shall be discussed, including the interference of x-rays, dead time, annihilation, etc.

2.4 Gamma-ray analysis of an environmental sample

Guarapari, a coastal city in the Espírito Santo state, is known for the high concentration of U and Th in its sands [3]. In this experiment, a sample of sand from one of Garapari's beaches will be counted in the HPGe detector for $\sim$1h, then the resulting spectrum will be analyzed, the peaks will be identified and assigned to the respective emitter, allowing also for a discussion on the most common NORMs (*Naturally Occurring Radioactive Materials* [4]) and their progeny.

2.5 Analysis of the gamma background (optional)

Additionally, students will be given two spectra of the background radiation that they may analyze at home, if interested. In this case, one spectrum will be from a detector inside a usual Pb/Cu shield, while the other has been taken with an unshielded detector – with these, students will be able to identify the most important radionuclides found in the background of our laboratories.

References

[1] Glenn F. Knoll, "Radiation Detection and Measurement," Wiley (1989);

[2] J.Y. Zevallos-Chávez et al., "Study of the inactive layer of a germanium detector: experimental and Monte Carlo simulation treatment," Proceedings of the 2005 International Nuclear Atlantic Conference, Santos, 28 August to 2 September (2005).

[3] Danilo C. Vasconcelos et al., "Natural Radioactivity In Sand Beaches Of Guarapari, Espírito Santo State, Brazil – A Comparative Study,", Proceedings of the 2011 International Nuclear Atlantic Conference, Belo Horizonte, 24-28 October (2011);

[4] International Atomic Energy Commission - IAEA, "Naturally occurring radioactive material Factsheet", available at https://nucleus.iaea.org/sites/orpnet/resources/posters/Shared%20Documents/NORMFactsheet.pdf