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Measurement of the Photo-Peak Efficiency of HPGe Semiconductor Detector using ^{22}Na, ^{60}Co &^{137}Cs

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Abstract: ***We have measured the full energy photo-peak efficiency of High Purity Germanium (Ge) detector which is very important tools in the measurement of γ-rays and γ-ray's spectroscopy. These Ge detectors are the detectors of first choice for γ-ray studies due to their high energy resolution. This article has presented a brief but very important and effective description on the basic properties of Ge detector. We have studied the emission of gamma rays from the standard radioactive sources (^{22}Na, ^{60}Co, ^{137}Cs) using the High Purity Ge detector at Nuclear Astrophysics laboratory of Okayama University in Japan. We have measured the photo-peak efficiency and energy resolution using the standard radioactive sources (^{22}Na, ^{60}Co, ^{137}Cs) successfully. This result will help us to understand details in Ge detector with more accuracy.***

Keywords: Ge detector, Radioactive sources, Photo-peak efficiency calculation

1. Introduction

The energies of nuclear radiations i.e. γ rays are emitted by atomic nuclei in between 0.1~20 MeV. Ge detectors are mainly used in this energy range when we need high energy resolution. γ rays come out from an atomic nucleus by radioactive decays or other nuclear reactions. It is very important to detection these γ rays accurately and this detection process will give the basic information on the nuclear energy level. The position of the energy levels is determined by their energy and intensity and the lifetime of the levels are measured by the γray's emission times.

2. Ge detectors and its basic properties

A semiconductor detector is kind of device which is usually uses a semiconducting material to measure the energy loss of ionization from effect of incident charged particles or photons. These detectors are the detectors of choice for the γ-ray's studies. Silicon (Si) and Germanium (Ge) based semiconductor detectors are usually used as a semiconductor detector. The Ge detector are mainly used in an experiment where high resolution is required and it has a long history. In 1962 the Ge detector was first introduced. These types of detector directly collect the charges produced by the ionization of the semiconductor material, when a charged particle passes through. The energy required to produced one electron-hole pair is about 3 eV energy[1].

A p-n junction is created in such a way that no current can pass through the junction unless the ionizing radiation fall on it. The standard method of forming a p-n junction is to change the impurity concentration of one side of the material so that both sides can leave opposite configurations, which is known well as doping.

This depletion region or zone will work as a radiation detector shown in Figure 1. The thickness of the depletion region is very small, that is why only a small volume of the crystal acts as a radiation detector, which needs to enlarge. The p-n junction semiconductor detector operates much better as a radiation detector in a reverse condition because this reverse biasing make the depletion layer larger. The performance of the p-n junction semiconductor detector depends on the thickness of the depletion region and which is inversely proportional to the net impurity concentration of the detector material.

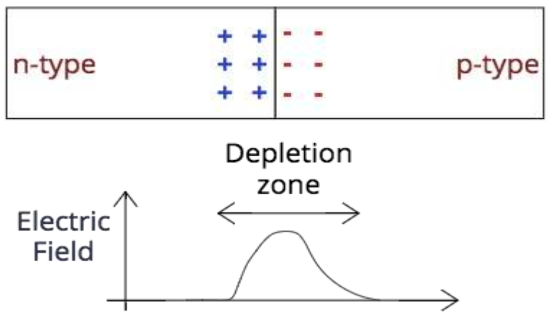


Figure 1: p-n junction semiconductor

2.1 HPGe detectors

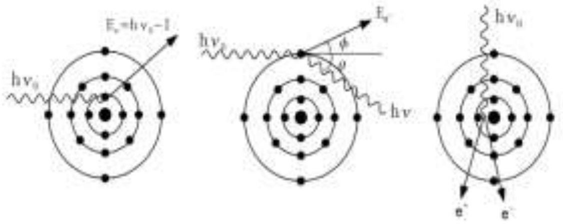
The high purity Ge (HPGe) detectors are created by purifying the germanium element heavily and growing it into a crystal. The techniques were first established in the mid 1970s for the production of ultra-pure Ge with impurity levels as low as 10^{10}atoms/cm^3[2]. It has a higher resistivity, which is proportional to the square of the depletion layer's thickness.

Characteristic of HPGe detector:
1) High atomic number
2) Low impurity concentration
3) Large depletion depth
4) Low ionizing energy required to produce an electron-hole pair
5) High resolution

2.2 γ ray interaction with the crystal of the detector.

γ ray detection depends on the effects of a γ ray interactions with matter. A γ ray can interact with matter in different ways. The main interaction types of γ rays with matter are: (a) the photo effect both in its photoelectric and photo-nuclear forms (b) Compton scattering and (c) Electron positron pair production is shown in Figure 2. In a small margin, photo-fission, Rayleigh scattering and Thomson scattering are also occurred.

The γ ray can be interacted with the entire atom (as in the photoelectric effect), or with one electron in the atom (as in the Compton effect), or with the atomic nucleus (as in pair production). The characteristics of these interaction are important in detector design.



(a) **(b)** **(c)**

Figure 2: Testing data- load current (amperes)

2.2.1 Photoelectric Effect

In the photoelectric effect, a photon undergoes an interaction with a detector (absorber) atom which is absorbed the γ rays completely a photo-electron is ejected by the atom from its bound shells.

In the photoelectric effect, the γ ray transfers all of its energy to the recoil electron. That is why the recoil electron is ejected from the shell of the atom and hence creates the electron-hole pairs in the detector that generate the output pulse in semiconductor detector. The output pulse produced by the detector is proportional to the energy of the γ ray which made the interaction. This γ ray energy is shared between the kinetic energy of the knocked-out electron and the characteristic transition radiation according to the conservation of energy equation as

$$E_\gamma = E_r + E_a + E_B \dots\dots\dots\dots\dots\dots (1)$$

where, E_γ is the kinetic energy of the initial gamma γ ray, E_r is the kinetic energy acquired by the knocked-out electron, E_a is the kinetic energy of the recoiling atom. E_B is the binding energy of the electron in the atom, equal to the excitation energy of the atom after electron ejection. The photoelectric interaction cross section is inversely proportional to the gamma photon energy and proportional to the atomic number Z.

2.2.2 Compton Scattering

The Compton effect is dominant for all energies except the very lowest and very highest energy. It also contributes to the full energy peak by multiple Compton scattering in such a way that the last interaction is a photoelectric one and the preceding Compton interactions take place in the Ge crystal. In large-volume detectors, the probability of observable multiple Compton scattering increases. For the case if the last interaction does not occur by the photoelectric effect or if one of the multiple Compton interactions takes place outside the sensitive volume of the detector, the pulse will definitely contribute to the Compton continuum.

2.2.3 Pair Production

The pair production is a type of process in which the total energy of the γ ray is fully absorbed. In this type of interaction, a γ ray enters into the detector material and creates an electron positron pair. From the law of conservation of mass and energy, it is known that the initial γ ray have to have an energy of at least 1.02 MeV because it takes same amount energy to create both an electron and positron.

3. Experiment with HPGe detectors

3.1 Experimental Set up

We have carried out an experiment with High Purity Ge detector for studying its basic properties by using the standard radiation sources (^{22}Na, ^{60}Co, ^{137}Cs) at Nuclear Physics Laboratory, Department of Physics in Okayama University. Figure 3 shows the experimental set up for Ge detector characteristic experiment.

Figure 3: Experimental Set-up for Ge detector

Properties of the Ge-detector: We have studied three different properties of Ge semiconductor detector and those are: (1) High voltage experiment (voltage dependency of peaks position). (2) Photo-peak efficiency. (3) Energy resolution. The γ source (^{22}Na, ^{60}Co and ^{137}Cs) was placed 115mm away from surface of the Ge detector. The γ rays from the ^{60}Co source was detected at different voltages. The high-voltage experiment was performed using different voltages. We carried the experiment for the voltages of 500 V, 700 V, 900 V, 1100 V, 1300 V and 1500 V.

3.2 Data Acquisition System

Data Acquisition System (DAQ) is very important for γ ray's detection because it has to handle so may signals from Ge semiconductor detector. It is required to have high time resolution and high speed. At the same time, it is also required to have good energy resolution at wide rage for analysis of discrete γ rays to effectively apply energy gates on them. Figure 4 shows the block diagram of DAQ system.

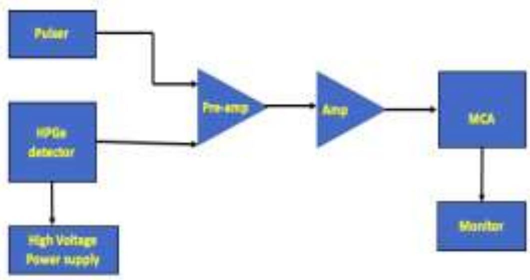


Figure 4: Data acquisition system for Ge detector [3]

In DAQ system, there has a High Voltage Power supply, a Pulser or Analog to Digital Converter (ADC), an Amplifier, a Multichannel Analyzer (MCA) and a computer monitor.

3.3 Data Analysis

Raw data was collected by Ge detectorby MCA as counts per channel. This raw data from Ge detector were analyzed by two different ways: (1) Background subtractions (2) Energy calibration.

(1) **Background Subtraction**: We have collected data without radioactive sources i.e. empty source.

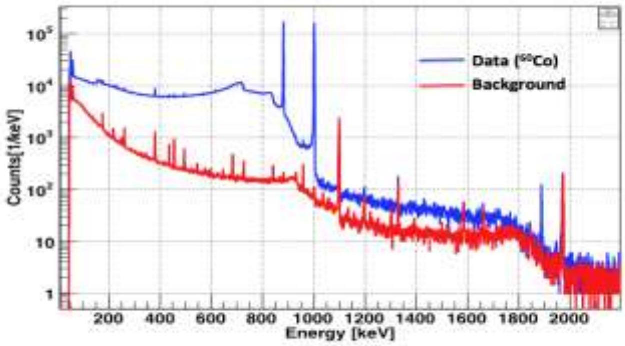


Figure 5: γ ray's energy spectrum of ^{60}Co.

Figure 5 shows the γ ray spectrum of ^{60}Co source and background data. There are large number of background that have come from some other radioactive sources which have been used earlier for different experiment. So, we have subtracted the background data from the total data. Figure 6 shows the background subtracted data of the γ ray spectrum of ^{60}Co source.

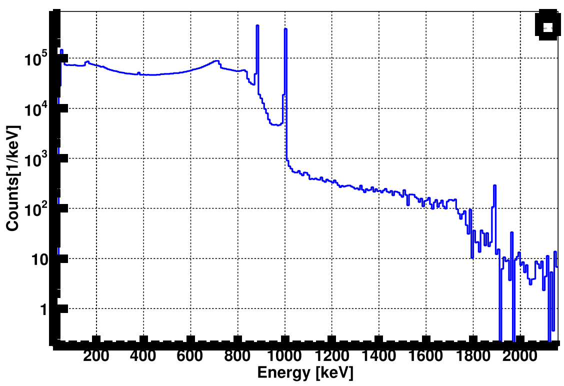


Figure 6: Background subtracted γ rays energy spectrum of ^{60}Co.

(2) **Energy Calibration:** Energy calibration was done with the help of the below

$$E = a \times ch + b \quad \ldots\ldots\ldots\ldots\ldots(2)$$

where ch is the channel, a is the linear scale (keV/channel) or slopes, b is the intercept and E is the energy. The calibration sources information is shown in Table 1.

Table 1: Calibration sources information

Source	*Peak energy [keV]*	*I_g [%]*
^{22}Na	511 1274.58	90.30 99.94
^{60}Co	1173.24 1332.51	99.85 99.99
^{137}Cs	661.66	85.1

We have calibrated and Figure 7 is the energy calibrated γray's spectrum for ^{60}Co.

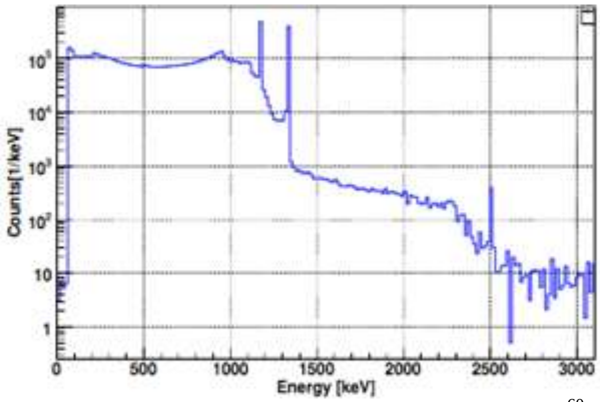


Figure 7: Energy calibrated γray's energy spectrum of^{60}Co.

3.4 Measurement of the Photo-peak Efficiency

For ^{60}Co:

Radioactive source ^{60}Co emits two γ rays which are 1173keV and 1332keV. And their coincidence γ is at 2505keV.

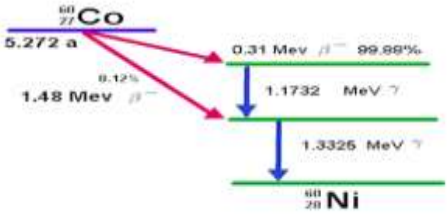


Figure 8: γ rays decay scheme of ^{60}Co.

We consider N1, N2 and N3 are the number of events of the respectively energy 1173keV, 1332keV and 2505keV shown in Figure 8. N1, N2 and N3 can be written as

$$N_1 = \beta T_L \, \eta\varepsilon_1 (1 - E_2)$$

$$= \beta T_L \, \eta\varepsilon_1 (1 - c\eta\varepsilon_2) \quad \ldots\ldots(3)$$

$$N_2 = \beta T_L \, \eta\varepsilon_2 (1 - E_1)$$

$$= \beta T_L \, \eta\varepsilon_2 (1 - c\eta\varepsilon_1) \quad \ldots\ldots(4)$$

$$N_3 = \beta T_L \, \eta\varepsilon_1 \, \eta\varepsilon_2 \quad \ldots\ldots(5)$$

Where E_1 is the efficiency of Compton due to γ_1 (1173keV), E_1=cηε_1 and $E_2$is the efficiency of Compton due to γ_2 (1332keV), E_2=cηε_2. c is the Compton ratio. The photo-peak efficiency of γ_1 and γ_2 are

$$\eta\varepsilon_1 = \frac{N3}{N2 + cN3} \ldots\ldots\ldots\ldots(6)$$

$$\eta\varepsilon_2 = \frac{N3}{N1 + cN3} \ldots\ldots\ldots\ldots(7)$$

For ^{137}Cs:

From the decay scheme of ^{137}Cs, we get that the branching ratio for decaying γ –ray is 85.1%.

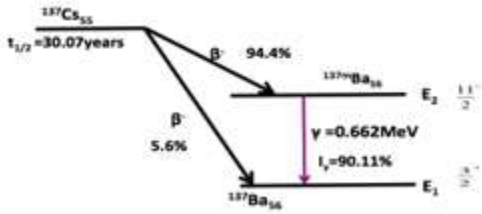


Figure 9: γ rays decay scheme of ^{137}Cs.

Figure 9 shows theγ spectrum of ^{137}Csradioactive source. The number of events $N_i$can be written as

$$N_i = 0.851 \beta T_L \, \eta\varepsilon \ldots\ldots\ldots\ldots(8)$$

where β= activity for ^{137}Cs, ηε= photo-peak efficiency,

T_L=live time =$r_L T$, where T is the measurement time, r_L is the dead time correction factor =0.94 (as dead time is 6%). The efficiency can be written as

$$\eta\varepsilon = \frac{N_i}{0.851 \times \beta T_L} \;\dots\dots\dots\dots (9)$$

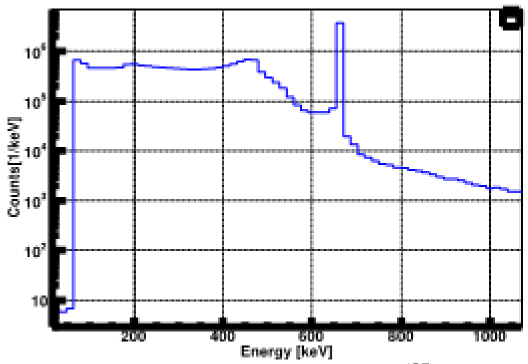


Figure 10: γ ray's spectrum of ^{137}Cs

For ^{22}Na:

The γ ray source ^{22}Nadecays 2 γ rays with energy 511keV, 1275keV and their coincidence is 1786keV.

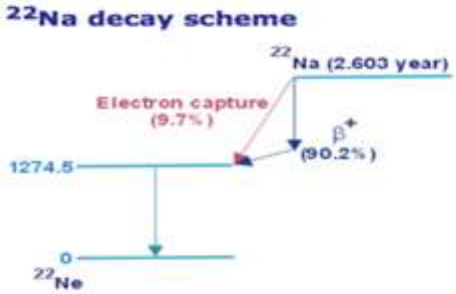


Figure 11: γ rays decay scheme of ^{22}Na

Figure 11 shows the γrays decay scheme of ^{22}Na. N1, N2 and N3 are the number of events of the peaks of 511keV, 1275keV and 1786keV correspondingly. Number of events are given by:

$$\boldsymbol{N_1} = \mathbf{1.8}\beta T_L\, \eta\varepsilon_1 (1 - c\,\eta\varepsilon_2) \;\dots\dots(10)$$

$$\boldsymbol{N_2} = \beta T_L\, \eta\varepsilon_2 (1 - c\,\eta\varepsilon_1) \dots\dots\dots\dots(11)$$

$$\boldsymbol{N_3} = \mathbf{1.8}\beta T_L\, \eta\varepsilon_1\, \eta\varepsilon_2 \dots\dots\dots\dots\dots(12)$$

Then, the photo-peak efficiencies of the two γ rays are

$$\eta\varepsilon_1 = \frac{N_3}{1.8(N_2 + cN_3)} \dots\dots\dots\dots\dots(13)$$

$$\eta\varepsilon_2 = \frac{N_3}{(N_1 + cN_3)} \;\dots\dots\dots\dots(14)$$

where c is the Compton ratio.

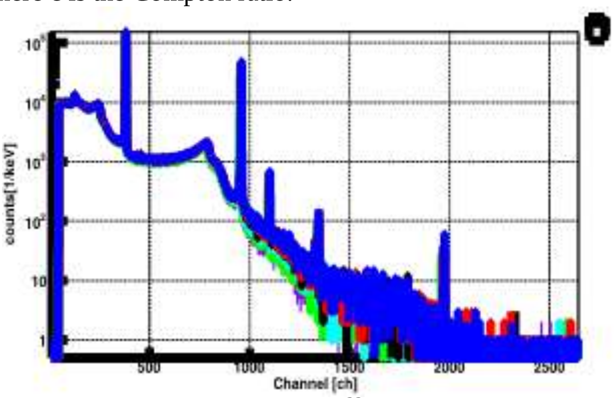


Figure 12: γray's spectrum of ^{22}Na for different volts.

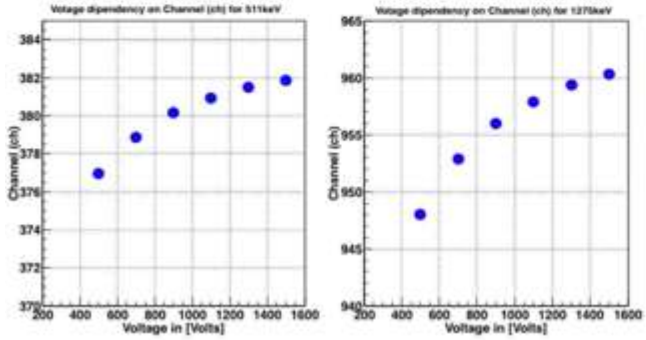


Figure 15: Channel Vs Voltage for ^{22}Na

From Figure 15, we can say that the channel number has increased with respect to the applied voltage and which satisfies the basic characteristics of Ge detector.

We have calculated the number of events of each peak of the radiation sources ^{60}Co, ^{137}Cs and ^{22}Na. The photo-peak efficiencies of each peak of ^{60}Co, ^{137}Cs and ^{22}Na sources. The photo-peak efficiency vs energy graph was plotted. Figure 14 is the photo-peak efficiency vs energy graph. The photo-peak efficiency of ^{60}Co at energy 1173keV is 8.84% and at energy 1332keV is 7.75%. And the photo-peak efficiency at energy 511keV is 18.6%. With this we can calibrate the photo-peak efficiency for the energy 0.1 to 2.0 MeV.

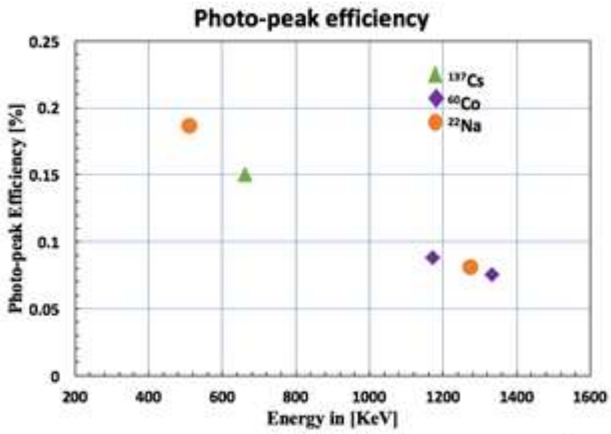


Figure 16: Photo-peak efficiency of ^{137}Cs, ^{22}Na and ^{60}Co

4. Conclusion

We have analyzed the characteristics of Ge semiconductor detector using the radiation source ^{137}Cs, ^{22}Na and ^{60}Co. We have measured the full energy photo-peak efficiency of High Purity Germanium (Ge) detector which is very important tools in the measurement of γ rays and γray'sspectroscopy. We have measured the photo-peak efficiency and energy resolution using the standard radioactive sources (^{22}Na, ^{60}Co, ^{137}Cs) successfully. This result will help us to understand details in Ge detector with more accuracy.

5. Acknowledgement

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Author Profile

Pretam Kumar Das has received his B.Sc. (Hons) and M.Sc. degrees in Physics from Rajshahi University in 2008 and 2009, respectively. During 2014-2017, he stayed at Sakuda Laboratory of Okayama University in Japan for his PhD research. Now he is serving as assistant professor & chairman of the Department of Physics, Pabna University of Science and Technology, Pabna-6600, Bangladesh.