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High purity germanium detector in gamma-ray spectrometry

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ABSTRACT

We measured full energy peak efficiency of High-Purity Germanium detector which is important for gamma-ray spectrometry experiments. A brief but very effective description on the basic formation of detector crystal and creation of signal pulse has been presented here. This article is furnished in such a way that the contents find useful and interesting to physics and electronics students, educators, and also researchers who are generally reading outside their specialties to broaden their understanding of physics and to expand and enhance their pedagogical toolkits at the undergraduate and graduate levels.

Key words: HPGe detector, Radioactive sources, Efficiency calculation

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INTRODUCTION

The energies of electromagnetic radiations span eighteen orders of magnitude, from10^{-6} eV used in radio and telecommunications, to10^{6} MeV produced in cataclysmic events in galactic nuclei. The natural range for γ-rays emitted by nuclei is 0.1~20 MeV. Germanium (Ge) semi-conductor detectors are most commonly used in this energy range when high energy-resolution is needed.

Gamma rays are emitted in nuclear processes during radioactive decay or in nuclear reactions. Detection of these γ rays gives basic information on the nuclear energy levels: their energy and intensity determine the position of the levels; the γ -ray emission times measure the lifetime of levels which, in some cases, can give deformation parameters; their polarization gives the parity of levels; and their angular distributions and correlations provide information about spins, magnetic moments, and static quadrupole moments, among other things (Lee et al., 2003). In the last 10–15 years, large improvements in efficiency and sensitivity of high energy-resolution detectors have led to important discoveries in nuclear structure.

Generally, nuclear reactions occur when an energetic beam of nuclei impinges on fixed target nuclei. In the beam-energy range used in nuclear structure studies, the two nuclei may fuse to form a 'compound nucleus' which can have a range of excitation energies and angular momenta. Typically, these nuclei de-excite by emitting a few nucleons (which remove much of the energy) and then by γ -ray cascades which remove most of the angular-momentum. In order to isolate the interesting cascades, two basic requirements must be met: (i) Two γ rays close in energy should be distinguishable. This means that the peak associated with γ rays of a given energy in a spectrum should be as narrow as possible. This characteristic is called high energy-resolution. This is fulfilled in Ge semiconductors because of the small band gap between the valence band and the conduction band. (ii) The detection of full-energy peaks should be as efficient as possible, i.e. we need high full-energy efficiency. This requires large Ge crystals.

The typical large detectors are cylinders approximately 7 cm in diameter and 8 cm in length (7 × 8). Still only 20% of incident 1 MeV γ rays deposit their full-energy in such a detector. The present study was performed to measure the full energy photo-peak efficiency of HPGe-detector so that a reliable data could possible to measure in gamma-ray spectrometry experiment.

THE SEMICONDUCTOR GE DETECTORS

Germanium semiconductor detectors were first introduced in 1962 (Tavendale and Ewan, 1963) and are now the detectors of choice for high energy-resolution γ-ray studies. These detectors directly collect the charges produced by the ionization of the semiconductor material. One electron-hole pair is produced on the average for every 3 eV absorbed from the radiation. These pairs drift under an external electric field to the electrodes where they generate the pulse. The high number of information carriers leads to a small percentage fluctuation and this is the reason for the high energy-resolution of Ge detectors. However, the detector cannot simply consist of the semiconductor material and two electrodes because there are inherent impurities in these materials. Both Si and Ge have a valence 4 and when an impurity of valence 3 (acceptor) or 5 (donor) exists in the crystal, it lowers the energy necessary to create electron-hole pairs and this tends to create too much noise. The Ge crystal with acceptor impurities is called p-type (Ge) material and the same with donor impurities is called n-type (Ge) material. The solution (Knoll, 2000; Goulding, 1966; Haller, 1982) is to create a p–n junction at one electrode and to polarize it so that no current passes through when there is no ionizing radiation (this is called reverse biasing or using non-injecting or blocking electrodes). This creates a region called the depletion layer (Fig. 1) where few charge carriers remain, resembling a pure semiconductor. With a sufficient voltage, the electric field can create a large enough depleted volume to make a viable detector. The intrinsic region (depleted volume) is sensitive to ionizing radiation particularly X-rays and γ-rays. The performance of a detector depends on its depletion depth, which is inversely proportional to the net impurity concentration in the detector material.

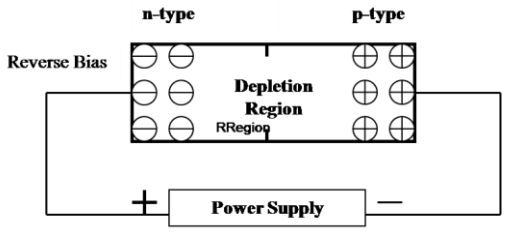

Figure 1: Creation of depletion region in the Ge semiconductor crystal. With negative bias is applied, the charge carriers are drawn away from the junction, creating a region depleted of charge carriers that acts as a solid-state ion chamber.

THE HIGH PURITY GERMANIUM (HPGE) DETECTORS

A step forward was achieved when higher purity Ge material could be fabricated (Hall and Soltys, 1971; Hansen, 1971), with impurity concentration of 10^{10} atoms cm^{-3} instead of 10^{13} atoms cm^{-3}, eliminating the need for Li compensation. This means that the material has a higher resistivity which is proportional to the square of the depletion layer's thickness. This paved the way for the manufacture of larger and much more efficient detectors (Fig. 2). The major characteristics of the HPGe detector are high atomic number, low impurity concentration (large depletion depth), low ionizing energy required to produce an electron-hole pair, high conductivity, compact size, first time response, high resolution and relative simplicity of operation.

For the purpose of decay counting, a closed end co-axial dipstick detector is used. These types of detector present a more uniform, efficient cross-section of the active detector volume to samples that are counted at a short distance from the detector.

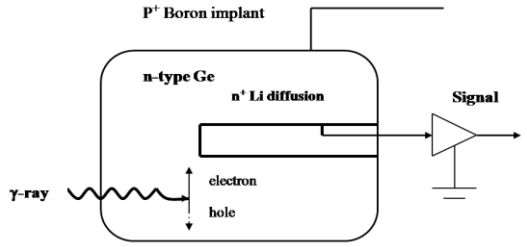

Figure 2: Configuration of an n-type intrinsic germanium closed-end co-axial detector. When a γ-ray interacts in the active volume, it creates electrons which are collected on the n+ contact, while the holes are collected on the p+ contact, and the current that occurs as the electrons and holes move toward the electrodes, once integrated, constitutes the γ-ray energy signal.

INTERACTIONS OF GAMMA RADIATION WITH DETECTOR CRYSTAL

Gamma-ray detection is based on the effect of a γ-ray interacting with matter (Siegbahn, 1965; Evans, 1955). For our purposes there are only three important types of interaction of a γ-ray with matter. These are called (i) the photoelectric effect, (ii) the Compton Effect, and (iii) the pair-production. The characteristics of these effects are important in detector design and we made a brief review on these interactions. In the photoelectric process, the γ- or X-ray gives all of its energy to the recoil electron. As a result, the recoil electrons ejected from the shell of atoms and hence produces the electron-hole pairs in the detector that yield the output pulse. This output pulse from the detector is proportional to the energy of the γ- or X-ray that made the interaction. In the spectrum, these events will show up as full-energy photo-peaks. The Photo electric effect is significant for the incident gamma energy of 0-150keV**.**

The Compton cross section is the dominant one for all energies except the very lowest ($E_\gamma \leq$ 150 keV) and the very highest (E_γ=8.5 MeV). The Compton Effect too contributes strongly to the full energy peak by multiple Compton scattering under the condition that the last interaction is a photoelectric one and that all the preceding Compton interactions take place in the Ge crystal. In large-volume detectors the probability of multiple Compton scattering increases. 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 contribute to the Compton continuum.The pair-production process can also provide a total absorption of the γ-ray energy. The gamma enters in the detector and creates an electron-positron pair. From the law of conservation of mass and energy, it follows that the initial

gamma must have energy of at least 1.02 MeV because it takes that much energy to create both the negative and positive electrons. Figure 3 illustrates what happens in the detector in the pair-production process. In Fig. 3, the *e* (ordinary electron) will produce a pulse whose magnitude is proportional to the energy of $e-$ (E_{e-}).

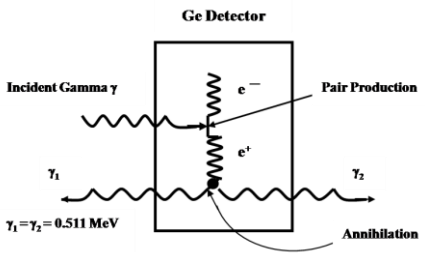

Figure3. Process of pair production in germanium, image reproduced from EG&G Ortec.

The positron will produce a pulse proportional to E_{e+}. Since these two pulses are produced simultaneously, the output pulse from the detector would be the sum of the two pulses. When the positron annihilates in the detector, the annihilation radiation γ_1 and γ_2 is produced. If both γ_1 and γ_2 escape from the boundaries of the detector without making further interactions, then energy of exactly 1.02 MeV escapes from the detector and is subtracted from the total energy that entered in the detector. Sometimes only one of the gammas, make a photoelectric interaction in the detector while the other escapes. In such cases, the total energy absorbed by the detector is 0.511 MeV less than the original incident γ-energy. It is also possible that both gammas make photoelectric interactions without escaping, leaving all of the incident γ-energy in the detector. Therefore, in the measured spectrum three peaks can be obtained for each γ-energy. These peaks are called full-energy peak, single-escape peak, and double-escape peak, and they will be separated by 0.511 MeV increments (Debertin and Helmer, 1988). Of course, the full energy peak represents those events where there was a combination of pair-production and photoelectric effect in which all the energy was absorbed in the detector. Pair Production process becomes predominant for the incident gamma energy of ≥5000keV. The plotted absorption cross-section (Fig. 4) is a measure of the relative probability that an interaction will take place in a germanium detector. These probabilities of relative interactions, for the most part, determine the shape of the observed spectrum. As an example, a photon with energy of 100 keV has an absorption cross-section of ~55 barns/atom for the photoelectric process where as the corresponding Compton cross-section is ~18 barns/atom. There is no pair production. This indicates that at 100 keV, there are 3 times as many photoelectric interactions as Compton interaction. That means, the sum of counts under the photopeak, Σpp would be ~3 times the sum of counts under the Compton distribution Σc. For larger crystals, the ratio $\Sigma pp/\Sigma c$ would be larger than 3 as some of the scattered gammas from the Compton interaction would make photoelectric interactions before escaping from the crystal. For an infinitely large crystal, there would be no Compton distribution since the crystal would totally absorb all of the incident gammas. But the shape of the spectrum changes drastically from 100 keV to 1 MeV, in this energy range the ratio of Compton cross-section to photoelectric cross-section becomes approximately ~90.

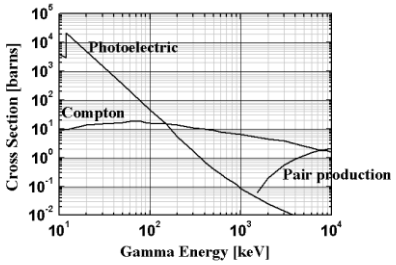

Figure4. Compton, photoelectric, and pair production cross section of Ge for high energy γ-rays (ElBaradei and Burkart, 2003).

EXPERIMENTAL SET UP OF HPGE DETECTOR WITH ASSOCIATED ELECTRONICS

The HPGe detector and the below electronics were arranged according to the Fig. 5.

Bin and power supply
High resolution germanium γ-ray detector
Amplifier (Ortec 572 or equivalent)
Detector Bias Supply (Ortec 459 or equivalent)
Pulser (Ortec 480 or equivalent)
Multichannel analyzer (MCA) and personal computer

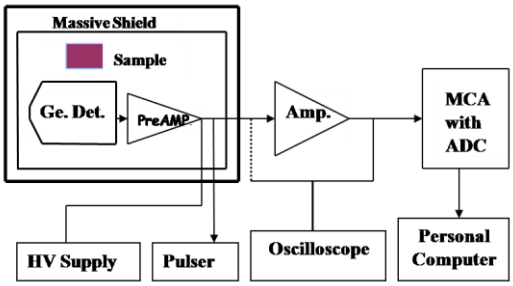

Figure 5: Electronic block diagram of high resolution γ-ray spectrometry system (Mollah et al., 1992).

The experimental set-up and equipment of the gamma ray spectrometry system used in this experiment are summarized in the Table 1.

Table 1: Summary of the experimental set-up and equipments

Detector	Bias	+4000 volts
	HPGe	Closed
	Crystal type	Vertical dipstick
Preamplifier	D-C coupled	CANBERA model 2001
	Charge(energy) sensitive	100 mV / MeV
Amplifier	Spectroscopy amplifier	CANBERA model 2022
Multichannel analyzer (MCA)	Personal computer analyzer	4k (4096 channels) 8k (8192 channels) 16k (16384 channels)
Low background shielding	Material	Lead
	Shape	Square
	Length	14.5 cm
	Height	12.5 cm
	Thickness	4 cm

The radioactive sources used in this experiment have been presented in Table 2. The radioactive source (e.g.,^{60}Co) was placed 8 cm above the surface of the detector. The two pulses from 1.17 and 1.33 MeV gamma-rays were seen on the oscilloscope. The gain of the amplifier was adjusted so that the 1.33 MeV peak has amplitude of 6 V on the oscilloscope. A reasonable output was also seen from the biased amplifier on the oscilloscope. The spectrum was observed carefully on the display of the MCA. The bias level and gain of the bias amplifier and amplifier respectively, were adjusted until the two sharp photopeaks positioned in the spectrum.

A typical spectrum obtained in this experiment is shown in Fig. 6.

Table 2: Gamma-Ray Standards for Detector Calibration (IAEA-TECDOC-619, 1991)

Nuclide	Decay mode	Half-life (d)	Energy (keV)	Emission Probability, P_γ
^{109}Cd	EC	462.6(7)	88.0341(11)	0.0363(2)
^{57}Co	EC	271.79(9)	14.4127(4)	0.0916(15)
			122.0614(3)	0.8560(17)
			136.4743(5)	0.1068(8)
^{133}Ba	EC	3862(15)	80.998(5)	0.3411(28)
			276.398(1)	0.07147(30)
			302.853(1)	0.1830(6)
			356.017(2)	0.6194(14)
			383.851(3)	0.08905(29)
^{137}Cs	β	$1.102(6)\times10^4$	661.660(3)	0.851(2)
^{54}Mn	EC	312.3(4)	834.843(6)	0.999758(24)
^{60}Co	β	1925.5(5)	1173.238(4)	0.99857(22)
			1332.502(5)	0.99983(6)
^{22}Na	EC	950.8(9)	1274.542(7)	0.99935(15)

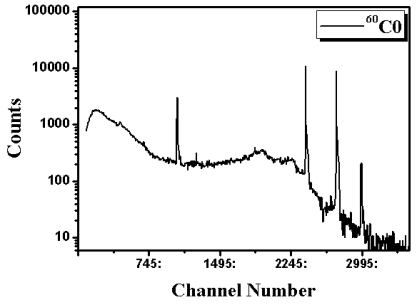

Figure 6: A typical ^{60}Co spectrum obtained in the present work

EFFICIENCY CALCULATION

Efficiency is an important parameter of HPGe detector. The efficiency of a detector is the proportionality constant which relates the activity of the source being counted and the number of counts observed. The true activity of sources can be calculated by the efficiency of the detector. The efficiency of a detector changes with the physical change of counting system and the environment that surrounds it, therefore counting must keep constant throughout the experiment.

There are various (Absolute efficiency, Intrinsic efficiency, Relative efficiency, and Full energy photo peak efficiency) kinds of efficiency, which are in common uses for gamma ray detectors. Full energy peak efficiency is the most significant parameter in practical gamma spectrometry. This efficiency is a basic parameter of the detector and is independent of the detector geometry. In the present experiment, we have calculated Full energy photo peak efficiency using the following relation: Efficiency (%)

$$\varepsilon = \frac{CPS}{A_t \times I_\gamma} \times 100\% \quad (1)$$

Where, *CPS* counts per second, A_t present activity of the source, I_γ gamma ray intensity per decay. In the present experiment, the calibrated sources ^{60}Co, ^{57}Co, ^{137}Cs, ^{22}Na and ^{133}Ba were used to calculate the efficiency of the HPGe detector. Since the sources ^{133}Ba, ^{60}Co and ^{22}Na emit more than one gamma ray; there is a certain probability of coincidence loss of cascade gamma rays when the source is put closer to the detector (Wyttenbach, 1971). In order to eliminate the coincidence loss, all the sources were individually placed at 8 cm above the surface of the detector. As the source ^{137}Cs emits only single gamma peak that is why we were selected it to obtain the normalizing factor. In order to obtain the normalizing factor, the ^{137}Cs source was placed on the surface of the detector. The normalizing factor was then calculated from the ratio of the efficiencies of ^{137}Cs on the surface of the detector to 8 cm above the surface of the detector. The efficiencies of other sources were then normalized at the surface of the detector multiplying by the normalizing factor. The efficiency curve of the HPGe detector has been plotted with gamma ray energy vs. normalized surface efficiency, and it is shown in Fig. 7.

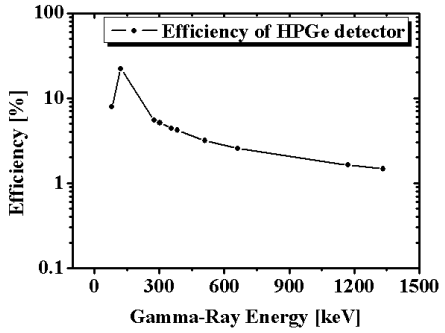

Figure 7: Efficiency curve of the HPGe detector.

RESULTS AND DISCUSSION

The use of germanium detectors has completely revolutionized gamma spectroscopy. The energy resolution of HPGe detector obtained in this measurement is 1.94 keV/ channel. This is a factor of 30 improvement at full-width half maximum compare to NaI(TI) detector (EG&G ORTEC). As a result of the improved resolution, many nuclear energy levels that could not even be seen with NaI(Tl) detectors are identified easily with HPGe detectors. The efficiency of HPGe detector obtained in

this experiment is ~30%, Besides this, because of the lower atomic number of silicon (Z = 14), the Si(Li) detectors are typically 60 times less efficient than Ge detectors for photoelectric absorption (EG&G ORTEC). Therefore, only low-energy γ-rays (~200 keV) are detected with reasonable efficiency by Si(Li) detectors, where as HPGe detector can be used for high energy γ-rays detection with high resolution.

CONCLUSIONS

HPGe (n-type, co-axial) detectors are at present the best γ-ray detectors (in the energy range ~0.1 to ~10 MeV) due to: (i) the high energy-resolution of the semi-conductor Ge material, and (ii) the high full-energy efficiency of large detectors. For typical nuclear structure experiments with high γ-ray multiplicities, such detectors are arranged in large arrays. The basic construction of detector crystal and the methodology on how signal pulse is generated by detector crystal has been demonstrated here. The presented materials in this article will help the undergraduate students of physics and electronics, educators, and also researchers who are generally reading outside their specialties to broaden their understanding of physics and to expand and enhance their pedagogical toolkits at the undergraduate and graduate levels.

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