High Purity Germanium Gamma-Ray Spectroscopy

Kevin Choe, Will Johnston, Nicholas Quartemont

***Abstract*— Semiconductor detectors enable high resolution spectroscopy of gamma-ray radiation. A sample can be identified based on the emission lines. A high purity germanium (HPGe) semiconductor detector was calibrated for energy with a multinuclide source. The associated energy calibration equation is $\mathbf{Energy\ [keV] = 0.0413 + 0.2583 * Channel}$. The detector efficiency equation from the calibrated multinuclide source was determined to be $\mathbf{-0.0012E^2 + 0.26E - 7.4756}$, under 160 keV and $\mathbf{5.3516\exp(-0.001}E\mathbf{)}$ over 160 keV, where E is the energy in keV. An ash sample source from a coal plant was tested and characterized. The sample characterization showed quantities of Ac-228, Bi-212, Bi-214, K-40, Pb-212, Pb-214, and Th-227.**

***Index Terms*—HPGe, Semiconductor, Statistics, Efficiency, Calibration, Resolution, Multinuclide**

I. Introduction

SEMICONDUCTOR detectors can be used in a large amount of nuclear science experiments and have excellent energy resolution for gamma-ray spectroscopy. Semiconductor detectors produce a large amount of information carriers per source radiation and are not as impacted by the Compton effect, as the cross section is low [1]. High purity Germanium (HPGe) is a popular type of solid state semiconductor detector. The detector requires substantial cooling to reduce thermal noise and prevent electron transitions over the semiconductor bandgap [2].

HPGe detectors can be used to perform nuclear forensics on a sample to determine radioactive sources present by the gamma-ray emission lines in the spectrum. A sample's radioactive components can be analyzed based on the detector efficiency and recorded spectrum.

II. Theory

HPGe detectors produce an information carrier as an electron-hole pair for every 3 eV of energy deposited in the detector [2]. Gamma radiation spectroscopy can be used to identify radioactive sources based on the pulse height amplitude produced in the detector for a proportional detector. Gamma radiation interacts with matter though the photoelectric effect, Compton effect, and pair production. Scattered photons have a continuum of energies under the FEP [1].

An energy calibration curve can be constructed to map channel to incident energy using a least square fitting technique. A linear distribution is appropriate for an HPGe. Non-linearities will may introduce errors up to five percent at lower energies near 100 keV [2]. The full energy peak (FEP) centroid can be used to determine the radioactive source by the emission energy.

The resolution for a FEP is a measure of how well two sources can be distinguished from each other. The resolution of a FEP is given as a function of the full width at half maximum (FWHM) and energy as:

$$Resolution\ [\%] = \frac{FWHM}{Energy} \tag{1}$$

The HPGe efficiency as a function of energy can be calibrated with a known multinuclide source and measurements of the experimental setup. The intrinsic efficiency can be obtained by:

$$e_{int} = \frac{\#\ Events\ Recorded}{\#\ Events\ on\ Detector\ Surface} \tag{2}$$

A calibrated efficiency curve can be used to find the source strength of samples, scaled by the distance to the detector.

III. Experiment

The HPGe detection system can be streamlined compared to a traditional nuclear counting experiment. An ORTEC HPGe is connected to a DSA1000. The DSA1000 functions to replace many components necessary for a nuclear detection system. The DSA1000 is connected to a computer, which has a multi-channel analyzer (MCA) data acquisition software. Genie 2000 is used for this experiment . The bias voltage is set to 4,000 V. The gain must be set so that the dynamic range of gamma ray energies of interest is measurable on the MCA.

A multinuclide source is used to calibrate the MCA for energy. The source used is composed of the isotopes and characteristics shown in Table 1. The multinuclide source is acquired 9 cm from the HPGe with a gain course gain of 20 and a fine gain of 1.5. This portion of the experiment is also used to determine the detector efficiency curve.

An unknown sample is then tested with the same settings as the multinuclide source. The unknown sample is in a cylindrical plastic container with an inner radius of 10.5 cm and an outer radius of 14.5 cm. The height of the inner cylinder is 9.5 cm, and the height of the outer cylinder is 16.5 cm. The sample effective surface area to the detector is taken as the ratio of the surface areas of the inner and outer cylinder divided by two, 0.218. The sample is analyzed to determine isotopes, activity, and photon energies. The MCA software can aid in determining

.

the isotopes present based on the gamma-ray energy.

The geometric efficiency is a function of the detector surface area and the distance to the source. The detector surface from the bottom is 210 square centimeters and the source distance is 9 cm. The geometric efficiency is:

$$e_{geo} = \frac{SA_{detector}}{4\pi R_{source}^2} \quad (3)$$

TABLE I
MULTINUCLIDE SOURCE CURRENT CHARACTERISTICS

Nuclide	Gamma-ray Energy [keV]	Activity [Bq]	Branching Ratio [%]
Am-241	60	391	36
Cd-109	88	181	3.6
Co-57	122	102	85.6
Te-123m	159	30.0	84
Cr-51	320	75.0	9.86
Sn-113	392	15.5	64.9
Cs-137	662	1323	85.1
Y-88	898	163	94
Co-60	1173	1595	99.86
Co-60	1333	1595	99.98
Y-88	1836	172	99.4

IV. RESULTS AND DISCUSSION

The energy calibration curve was created for 8192 channels on the MCA using the multinuclide source. Not all gamma-rays were detectable because of low activity or being below the Compton edges of the higher activity sources. The energy calibration curve is shown in Figure 1. The R^2 value is unity; however, there is uncertainty in the channel fit, equal to the width of the channel, which is 0.2583 keV. The associated equation for the energy calibration is:

$$Energy\ [keV] = 0.0413 + 0.2583 * Channel \quad (4)$$

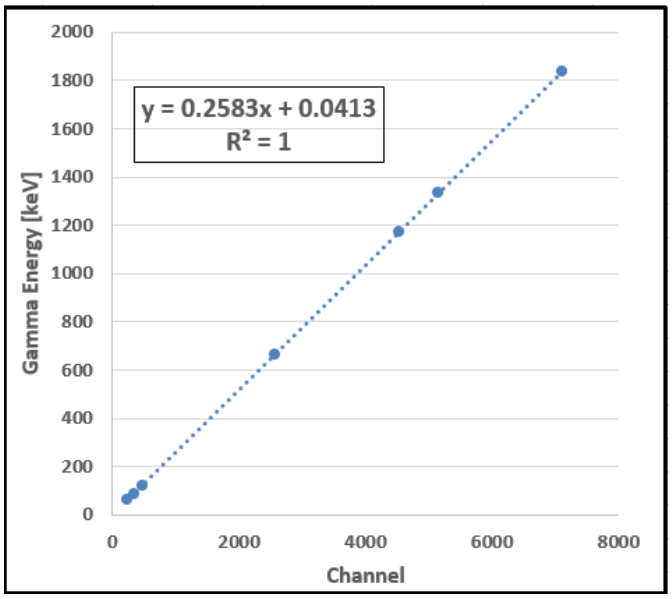

Fig. 1. HPGE energy calibration curve using a multinuclide source.

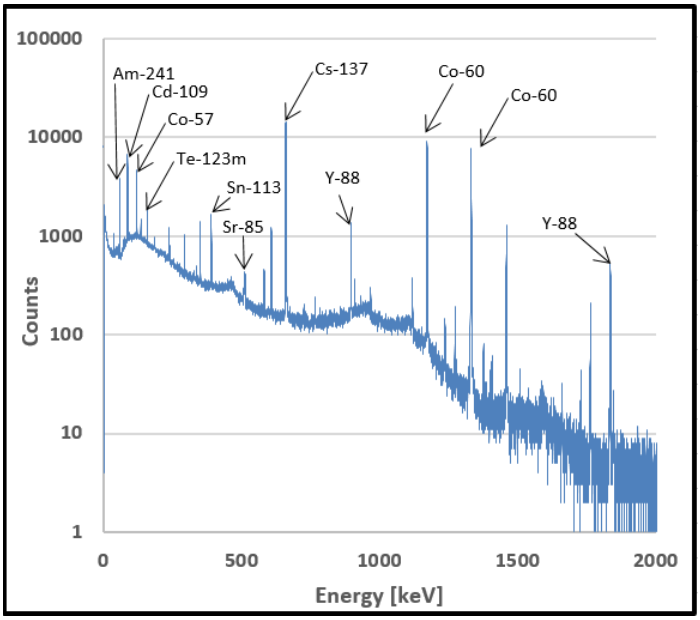

Fig. 2. Calibrated multinuclide source spectrum with radioisotopes identified.

The calibrated and characterized multinuclide source spectrum is shown in Figure 2. All spectroscopic lines from the source have been identified.

The multinuclide total energy resolution was calculated for each of the peaks in the multinuclide source. The uncertainty in the resolution the channel width. The large uncertainty comes from the high number of channels. The results of the energy resolution are summarized in Table 2.

TABLE II
ENERGY CALIBRATED MULTINUCLIDE SOURCE RESOLUTION

Nuclide	Gamma-ray Energy [keV]	FWHM [keV]	Resolution [%]
Am-241	60	0.79	1.32±0.43
Cd-109	88	0.78	0.89±0.29
Co-57	122	0.85	0.70±0.21
Cs-137	662	1.06	0.16±0.04
Co-60	1173	1.16	0.10±0.04
Co-60	1333	1.22	0.09±0.02
Y-88	1836	1.40	0.08±0.01

The detector efficiency curve was generated using a piecewise quadratic followed by an exponential decay. The associated equations as a function of energy in keV are presented, and the curve is shown in Figure 3.

$$e_{int} = \begin{cases} -0.0012E^2 + 0.26E - 7.4756, E < 160\ keV \\ 5.3516\exp(-0.001E) \quad , E \geq 160\ keV \end{cases} \quad (4)$$

The ash sample was sampled for 90,168 seconds live time. Various peaks were identified which are shown in Figure 4 and summarized in Table III. A few peaks were not related to known gamma-ray emissions. These peaks and the features in the graph can be attributed to Compton edges, Compton continuums, and backscatter peaks.

The highest count peaks are for Pb-214 at 352 keV with 116,000 counts, Pb-212 at 238.8 keV with 104,000 counts, Bi-

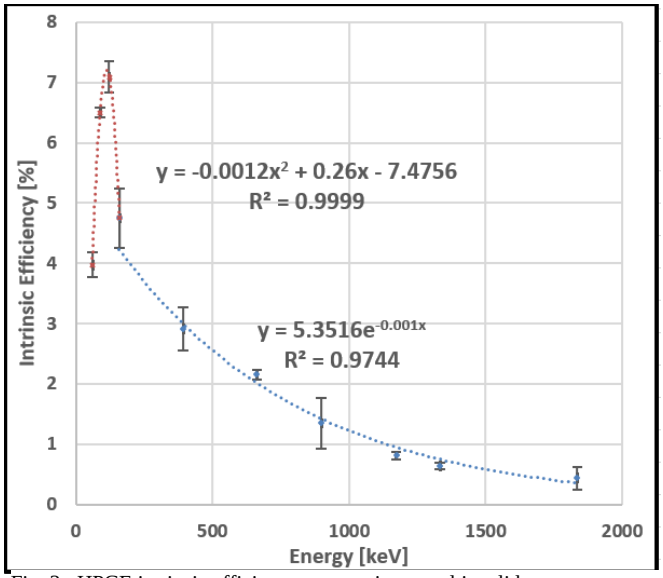

Fig. 3. HPGE intrinsic efficiency curve using a multinuclide source.

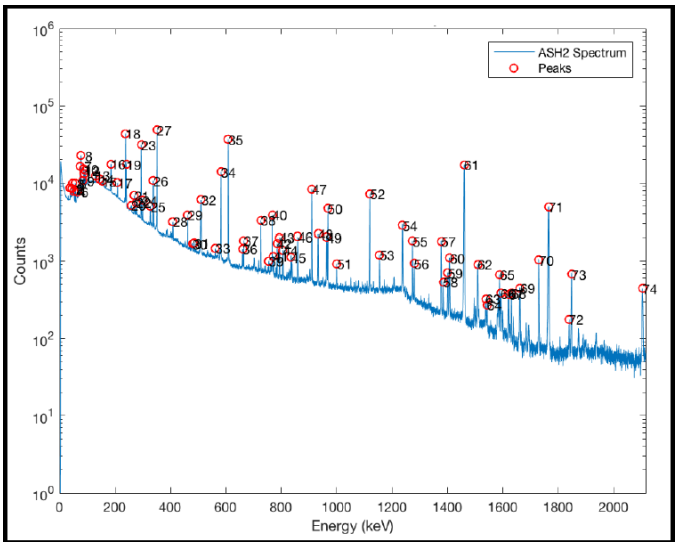

Fig. 4. Ash sample identified radionuclides

214 at 609.2 with 80,800 counts, K-40 at 1461.07 with 46,400 counts, and Ac-228 at 911.1 keV with 20,600 counts. Other peaks have the same nuclide; however, these have larger counts and more statistical certainty behind them. Based on the count rates, branching ratios, and change in geometric efficiency, the source strength in becquerels can be determined. The change is geometric efficiency from the efficiency calibration curve is to multiply the curve by the surface area ratio given in section III, 0.218, and divide by the calibrated geometric efficiency, 0.207.

The characterized analysis sample source strengths are given for Pb-214, Pb-212, Bi-214, K-40, and Ac-228 based on the largest peaks are given in Table IV.

TABLE III
ASH SAMPLE IDENTIFIED PEAKS

Nuclide	Gamma-ray Energy [keV] (Peak Number)
Ac-228	129.3 (13), 209.5 (17), 270.4 (21), 328.1 (25), 352.0 (26), 409.44 (28), 463.0 (29), 794.7 (43), 911.0 (47), 968.9 (50), 1,558.5 (65)
Ac-228 / Eu-152	964.6 (49)
Bi-212	727.2 (38), 768.3 (38), 1,621.3 (67)
Bi-214	609.2 (35), 768.3 (40), 806.0 (44), 933.9 (47), 1,120.2 (52), 1,155.0 (53), 1,281.0 (56), 1,238.3 (54), 1,337.8 (57), 1,385.5 (58), 1,401.7 (59), 1,509.5 (62), 1,661.7 (69), 1,730.2 (70), 1,765.1 (71), 1,848.1 (73)
Bi-212 / Pb-214	785.6 (42)
Bi-214 / Eu-152	1,408.1 (60)
Br-82m	46 (2), 48 (3)
Cs-137	661.6 (36)
K-40	1,461.1 (61)
Kr-89	835.55 (45)
Kr-89 / Na-22	1,274.6 (55)
La-140	487.1 (31), 1,592.6 (66)
Pb-212	238.8 (18)
Pb-214	242.2 (19), 295.4 (23)
Pb-212 / Bi-211	352 (27)
Pb-212/Pb-214	75.1 (7), 77.3 (8), 87.5 (10)
Pb-212 / Th-227	300.3 (24)
Ra-226 / U-235	186.4 (15),
Rb-89	1,538.8 (63)
Th-227 / U-235	90.2 (11), 93.1 (12),
Th-231	84.4 (9)
W-187	480.6 (30), 772.2 (41)
Xe-138	154.4 (14), 259.1 (20)

TABLE IV
ASH SAMPLE IDENTIFIED PEAKS

Nuclide	Ash Sample Activity [Bq]
Ac-228	43.3 ± 0.3
Bi-214	71.3 ± 0.3
K-40	413.8 ± 2.0
Pb-212	74.2 ± 0.2
Pb-214	85.8 ± 0.3

V. REFERENCES

[1] "Lab Manual, HPGe Gamma-Ray Spectroscopy (Weeks 1 & 2)," NENG 650, AFIT, Winter 2018.

[2] G. F. Knoll, Radiation Detection and Measurement, Ann Arbor, Michigan: Wiley, 2010.