Performance and Characteristics of a Low-Background Germanium Well Detector for Low-Energy Gamma-ray Nuclides

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1 INTRODUCTION

Many environmental samples are low activity and small, typically a few grams, with the typical nuclides of interest emitting gamma rays in the range of 10 to 50 keV. These samples are most efficiently counted with a well-type detector, where the sample is inserted into a well or hole in the detector. This geometry almost surrounds the sample with active detection volume giving a subtended solid angle of 4-π steradians. A Hyper Pure Germanium (HPGe) well detector has been constructed with a well tube of carbon fiber material. The carbon fiber is naturally low background, mechanically strong, and has good transmission (65%) down to 10 keV. Previously, low-background aluminium was used for the well tube, but the transmission is less than 1% at 10 keV for the thicknesses required for mechanical strength. The IEEE 325-2010 standard describes the method to characterize detectors for efficiency and resolution, including the well detector, over the energy range from 50 keV to 2 MeV. The source-detector geometry defined in IEEE 325 for well detectors is the most common geometry for small samples. The HPGe detector was installed in a low-background shield of 15 cm of lead, 1 mm tin, and 6 mm OFHC copper. The shield is approximately 275 m above sea level. The 4- π solid angle increases cascade summing (TCS) which reduces the net areas of the full energy gamma ray peaks for all nuclides with cascade decays, such as ^{60}Co and ^{88}Y. These nuclides are commonly used for calibration. To correct for the cascade summing, the efficiency calibration was done using the TCC methods of GammaVision. The efficiency, both uncorrected and corrected for TCC, and resolution from 50 keV to 2 MeV are presented. The background from 10 keV to 3 MeV will be shown. The minimum detectable activities for common nuclides based on the measured efficiency, background, and different counting times will also be presented.

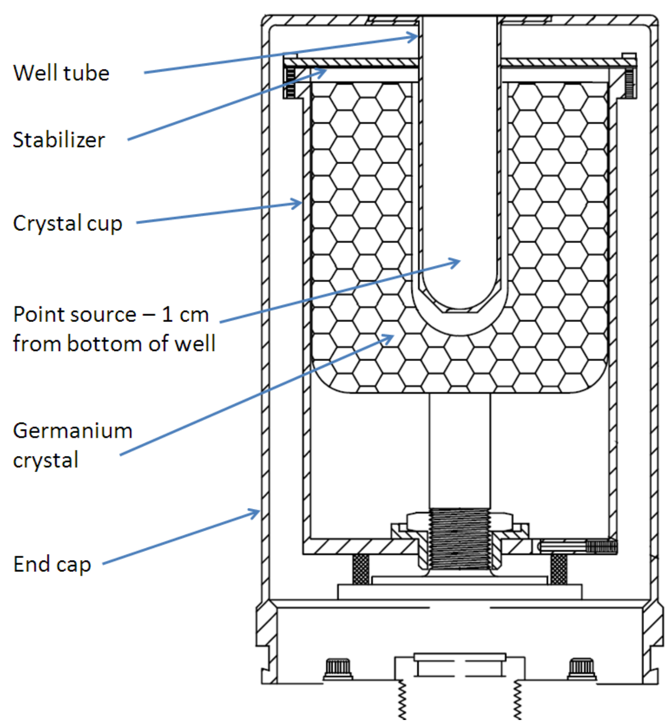

Figure 1 ***Cross Section of Well Detector***

2 EXPERIMENTAL

The HPGe detector has a crystal with 150 ml active volume with an outside diameter of 6.17 cm and a length of 6.49 cm with an internal bore of 2.22 cm. This gives a germanium "wall" thickness of 1.97 cm, which corresponds to 40% absorption of the 1.33 MeV gamma rays. The cross section of a typical crystal and cryostat is shown in Fig.1. The inner contact is ion-implanted boron and the outer contact is diffused lithium. The boron has a thickness of less than 0.3 microns and the lithium thickness is about 600 microns. The endcap and detector mounting cup are made of OFHC copper. The total thickness of copper is less than 3 mm on the sides and 2.4 mm on the front face. The well tube is made of carbon fiber material bonded with epoxy. The carbon fiber thickness is nominally 0.8 mm which has an attenuation of about 15% at 15 keV (that is, 85% of the full energy gamma rays are transmitted). The inside diameter of the well tube is 15.5 mm.

The well tube is held in place by the endcap and an additional stabilizer. The stabilizer is constructed of Mylar and thin copper which reduces the efficiency for low-energy gamma rays originating outside the well in front of the detector.

The detector was placed in the center of a shield constructed of low activity lead bricks in a rectangular shape and lined with tin and copper on all internal surfaces. The internal cavity is 30 cm wide by 51 cm tall by 71 cm long. The lead walls and bottom are nominally 15 cm thick. The lead top is supported by a thin steel sheet and is nominally 15 cm. The copper is 6 mm thick and the tin is 1 mm thick. The shield is located in a building constructed mainly of concrete. It is at an altitude of 275 m.

The background spectrum was collected for 2×10^6 s and is shown in Fig. 2. The average count rate in the energy range of 15 keV to 3 MeV is 5.6×10^{-4} counts/s/keV. The three largest peaks are 511 keV (0.022 c/s), 1461 keV (2.4×10^{-3} c/s), and 2614 keV (8.6×10^{-4} c/s). The cosmic neutron inelastic scattering peaks are also clearly visible.

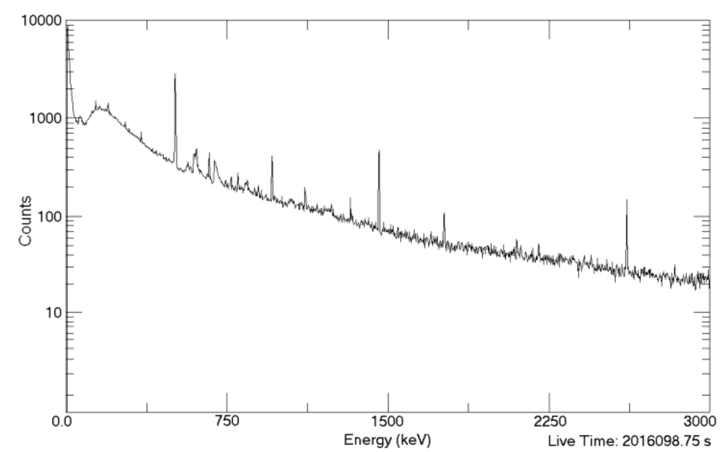

Figure 2 ***Background in Shield, Live Time of 2,000,000 s***

The source was a point source in a recessed cavity 2 mm from the end of an 8 mm diameter plastic rod. The source was positioned at 1 cm from the bottom of the well tube by inserting the source in a thin wall plastic tube such that the plastic tube rested on the bottom of the well tube and centered horizontally in the well. This is the position for the efficiency measurement of a well detector specified in IEEE 325-2010 (draft).[1] Blaauw[2] suggested the use of an absorbing layer in well detectors to reduce the effects of X- and gamma-ray self-absorption. Measurements were made with the unshielded source and with the source surrounded by 0.25 mm of copper or 0.065 mm of aluminum.

The source is traceable to NIST and contained ^{109}Cd, ^{113}Sn, ^{139}Ce, ^{203}Hg, ^{134}Cs, ^{137}Cs, ^{88}Y, ^{54}Mn, and ^{241}Am. The nuclides ^{134}Cs and ^{88}Y have cascade summing (true coincidence summing) and were included in order to make the summing correction calibration in GammaVision. The correction is necessary for small source-detector distances (less than 10 cm)[3] and the well-detector geometry is very close.

The efficiency was calculated using GammaVision with and without consideration of true coincidence summing using the same spectrum. The carbon fiber cup and the thin contact make the detector sensitive to low-energy gamma- and X-rays, which can be in coincidence with the gamma rays used in the calibration. In addition, the high efficiency of the detector can cause considerable random summing which distorts the full-energy net peaks of the gamma rays needed for the efficiency calculation. The normal rise time setting is 12 μs, but at this setting, the random summing was too severe to produce usable spectra. The amplifier rise time was then set to 1 μs (shaping time of 0.5 μs) to reduce random summing, but the summing with X-rays is still evident. The bare source spectrum is shown in Fig. 3. This shows the background under the peaks is not able to be determined which means that the efficiency will not be correctly calculated.

The addition of the thin aluminum foil showed minimal improvement in the random summing or pileup. The use of the copper foil showed enough improvement for the spectrum to be used for energy and efficiency calibration. Figure 4 shows the spectrum with the addition of the copper foil around the source. The 750 to 900 keV region of the two spectra is shown

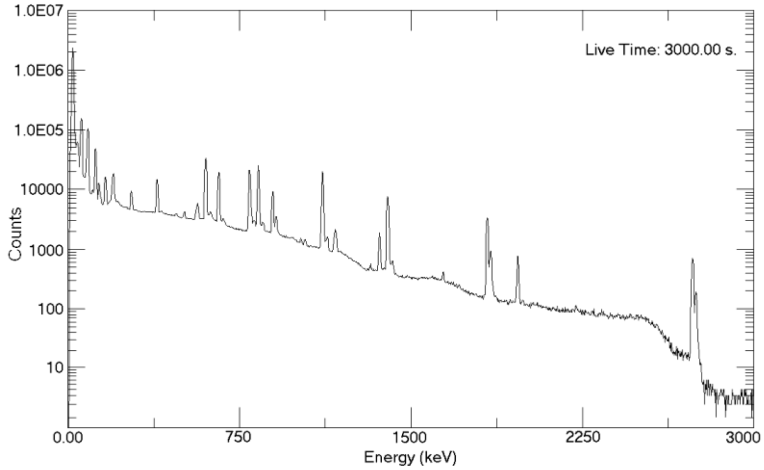

Figure 3 ***Calibration Source Spectrum with no Absorber***

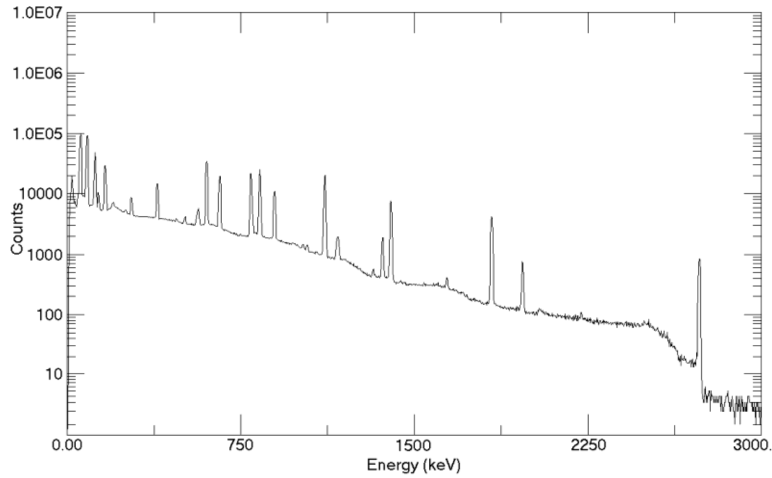

Figure 4 ***Calibration Source Spectrum with Copper Absorber***

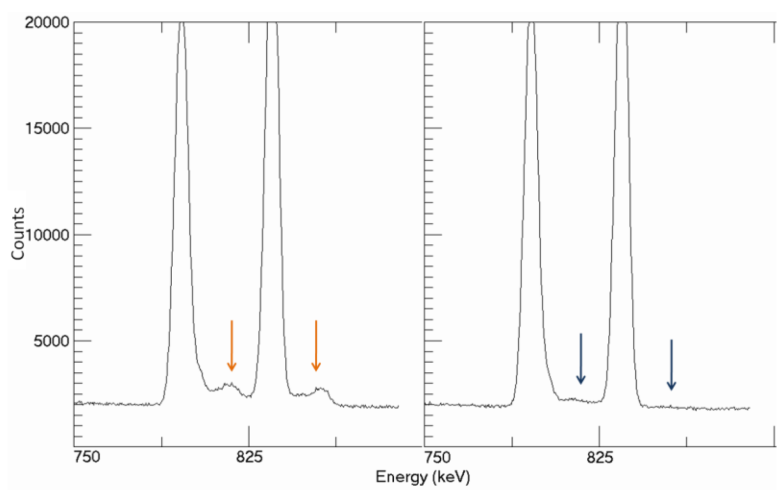

Figure 5 ***Comparison of Spectrum Region with and without the Copper Foil Absorber***

in Fig. 5. Comparing these two spectral regions shows the reduction in the pileup is enough to enable the software to accurately define the background and the net peak area.

3 RESULTS

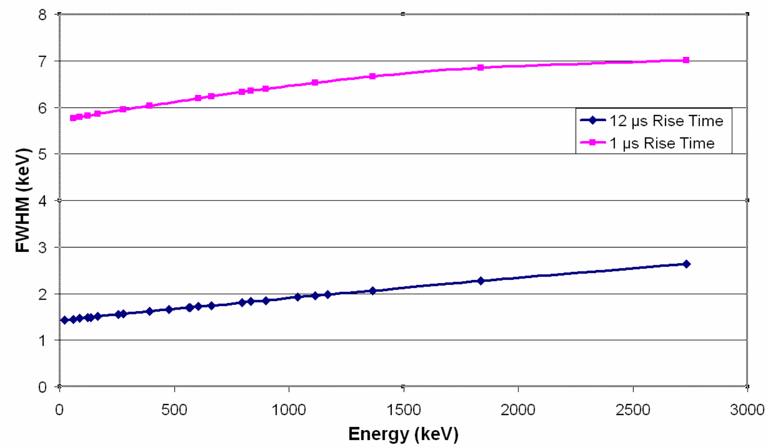

Figure 6 ***Resolution for Different Rise Times as a Function of Energy***

The spectra shown in Figs. 4 and 5 were used to measure the resolution for the two rise times (shaping times). Note that neither of these spectra is in the geometry specified in the IEEE 325 standard, so the resolution values are not comparable to normally specified values. Figure 6 shows the FWHM for both Rise Times for the energy range from 50 keV to 3 MeV.

The spectrum collected with the copper foil was calibrated for energy using all the gamma ray energies from the source. The efficiency calibration was first done without consideration of any true coincidence summing by using only the nuclides in the source that do not have cascade decays. The analysis of the spectrum using this calibration for activity is shown in Table 1 along with the declared activities. Note that the differences between the declared activities and the measured activities for most nuclides are within 2%. The exceptions are ^{134}Cs and ^{88}Y, both of which are subject to cascade summing. The ^{134}Cs result is under reported by 58% (that is, less than half of the actual activity) and ^{88}Y is under reported by 36%, indicating that significant coincidence summing is impacting the results.

Table 1 *Comparison of Calculated and Known Activity without True Coincidence Correction*

Nuclide	Measured	Known	Difference
^{241}Am	5544.4	5571.4	-0.5
^{109}Cd	50471.0	50639	-0.3
^{57}Co	1325.7	1343.2	-1.3
^{139}Ce	1761.1	1749.7	0.7
^{203}Hg	4225.6	4224.5	0.0
^{113}Sn	2768.5	2715.6	1.9
^{134}Cs	2583.1	6183.2	-58.2
^{137}Cs	1482.6	1476.4	0.4
^{54}Mn	3496.1	3521.8	-0.7
^{65}Zn	9292.2	9245.1	0.5
^{88}Y	4177.8	6563	-36.3

The same spectrum was calibrated for efficiency (using the energy calibration above) using the true coincidence correction feature (TCC) of GammaVision. The TCC calibration includes ^{134}Cs and ^{88}Y, as well as all of the other nuclides in the source. With this calibration, it is possible to account for the cascade summing in the calibration and correct the net peak areas for the loss of counts due to cascade summing. The analysis will utilize peaks in the spectrum from the summing of two or more primary gamma rays and escape peaks (where a 511 keV gamma ray leaves the active volume of the detector) thus increasing the accuracy of the results. Table 2 shows the analysis results using this calibration along with the declared activities. Note that the activity of ^{134}Cs and ^{88}Y are much closer to the declared values than the analysis that did not considering coincidence summing. This calibration is valid to the low energy of 59 keV and is extrapolated to energies below that value. The activity of ^{139}Ce is over reported by 9.6% because of the over correction for the summing of the 163 keV gamma ray and the 33 keV X-ray. A more accurate correction can be obtained using the 2-source method described by Blaauw.

Table 2 *Comparison of Calculated and Known Activity Using True Coincidence Correction*

Nuclide	Measured Activity	Known Activity	Difference (%)
^{241}Am	5539.3	5571.4	-0.6
^{109}Cd	52351.0	50639	3.4
^{57}Co	1328.0	1343.2	-1.1
^{139}Ce	1918.2	1749.7	9.6
^{203}Hg	3998.5	4224.5	-5.3
^{113}Sn	2632.6	2715.6	-3.1
^{134}Cs	6095.2	6183.2	-1.4
^{137}Cs	1459.0	1476.4	-1.2
^{54}Mn	3509.6	3521.8	-0.3
^{65}Zn	9057.2	9245.1	-2.0
^{88}Y	6826.7	6563	4.0

Table 3 *Minimum Detectable Activity (mBq) for Various Counting Times and Nuclides*

Time (hours)	^{60}Co mBq	^{133}Ba mBq	^{137}Cs mBq	^{210}Pb mBq	^{214}Bi mBq	^{235}U mBq	^{241}Am mBq
43	1.06	0.81	0.89	7.34	2.04	0.55	0.72
111	0.68	0.51	0.56	4.61	1.26	0.34	0.45
200	0.49	0.38	0.42	3.45	0.94	0.25	0.33
333	0.37	0.29	0.32	2.66	0.72	0.20	0.26
406	0.34	0.27	0.29	2.42	0.66	0.18	0.23
560	0.29	0.23	0.25	2.06	0.56	0.15	0.20
611	0.28	0.22	0.24	1.97	0.53	0.15	0.19
833	0.24	0.19	0.20	1.69	0.46	0.12	0.16
944	0.22	0.18	0.19	1.58	0.43	0.12	0.15

Using the TCC calibration and the background spectrum, the MDAs were calculated using the KTA Rule formula. The KTA Rule formula was chosen because it is relatively simple, uses a fixed width (based on the FWHM) for the peak region, and is similar to the methods used in many areas of the world. The nuclides considered were ^{210}Pb, ^{241}Am, ^{214}Bi, ^{137}Cs, ^{235}U, and ^{60}Co. Table 3 and Fig. 7 show the MDA values for these nuclides as a function of counting time. Note that the MDA depends on the nuclide yield for the gamma rays used to calculate MDA (typically the most intense), the efficiency and background count rate at that energy, and the counting time. The major contribution to the low measured values is the high efficiency of the well detector, especially for low energies.

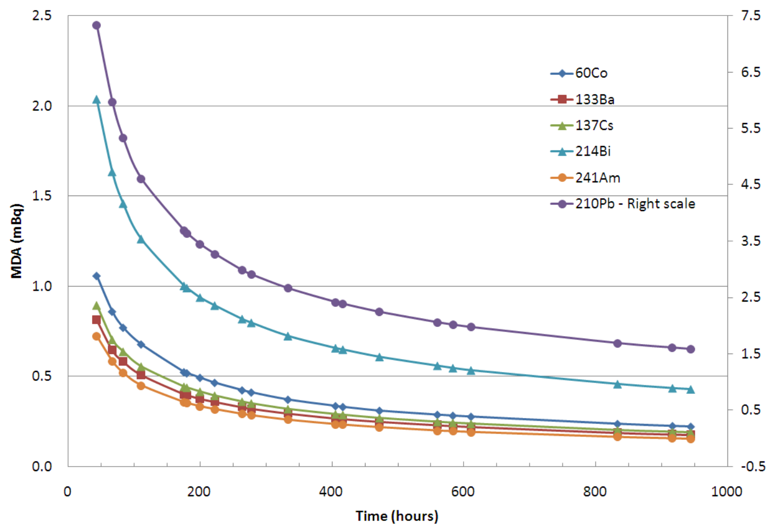

Figure 7 ***MDA vs Time for Several Nuclides***

4 CONCLUSIONS

The HPGe well detector with copper endcap and cup, and carbon fiber well tube is a highly efficient detector for low energies and has acceptable efficiency for energies above 400 keV. The carbon fiber well tube transmission improves the efficiency over the traditional aluminum thin wall tube by a factor of 95 at 10 keV. The transmissions are about equal above 60 keV. This converts to an improvement in the MDA for ^{210}Pb of about 2.5% and about 5.8% for ^{125}I with the carbon fiber. The reduction in the attenuation of low-energy X- and gamma-rays does increase both the random and coincidence summing. Calibration and data collection for the low-energy gamma rays must be done at low countrate to reduce the random summing. However, TCS depends on the nuclide decay scheme and not on count rate. Thus, the TCC calibration method is necessary for most situations because of the high low energy efficiency. To accumulate useable spectra, the use of absorbers during efficiency calibration for energies above 200 keV to limit the dead time and pileup is recommended. A separate efficiency calibration for low energies requires calibrated sources with low energy gamma rays and low activities. The two calibrations are then combined.

One important reason for using well detectors is to reduce the MDA to the required low value for environmental and forensic studies. The close geometry does increase the efficiency, but it also increases the impact of TCS on the results. The GammaVision TCC method for calibration and activity calculation allow the use of these detectors for low-count, small sample studies to produce the lowest MDAs possible.

References

1 IEEE 325-2010 (Draft), "IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors", IEEE, 3 Park Avenue, New York, NY 10016-5997, USA

2 Blaauw, Menno, "Calibration of the well-type germanium gamma-ray detector employing two gamma-ray spectra," Nuclear Instruments and Methods in Physics Research A 419 (1998) 146-153

3 Keyser, Ronald M., Haywood, Susan E., and Upp, Daniel L., "Performance of the True Coincidence Correction in Gamma Vision," Proceedings of the ANS Annual meeting, June 2001