Precise Efficiency Calibration of an HPGe Detector: Source Measurements and Monte Carlo Calculations with Sub-percent Precision

J. C. Hardy, R. G Neilson, J. M. Nelson, V. E. Iacob, M. Sanchez-Vega, and R. G. Helmer[1]
[1]*Idaho Accelerator Center, Idaho State University, Pocatello, Idaho, USA*

A key requirement of our program to test CKM unitarity via high precision measurements of superallowed β-decay [1] is to know the efficiency calibration of our 70% HPGe detector to a precision of about 0.1%. We have now reached this goal for the energy range we require for the measurement of ^{22}Mg decay [2]. To date, we have used high-statistics spectra from ten well-known radionuclides, including a ^{60}Co source whose absolute activity is known to 0.1% [3]. From these data we have extracted measured detector efficiencies for a total of 40 gamma-ray energies between 53 and 1836 keV. In addition, we have made detailed measurements relating to the physical dimensions of our HPGe detector and have input these results into the CYLTRAN Monte Carlo electron and photon transport code [4]. The un-renormalized output of this code agrees with the efficiency data – most of which is known to a precision between 0.1 and 0.5% – at the 70% confidence level. This concurrence now allows us to extract precise detector efficiencies via interpolation between measured values at any energy between 70 and 1500 keV.

In all, we have measured thirteen individual sources with activities between 2 and 47 kBq. Since our last progress report [5], we have added three key sources: ^{109}Cd, which was purchased from Isotope Products Laboratories in the form of an evaporated metallic salt on a thin, 9 mg/cm^2 Kapton backing; and ^{48}Cr and ^{120m}Sb, which were both produced with the cyclotron [6]. The activity of the commercial source was quoted to 3.1% at the 99% confidence level; the activities of the ones produced at the cyclotron were unknown. However, all three sources were chosen because they provided γ- or X-rays of precise relative intensities, which we used to specify efficiencies in previously ill-defined energy regions.

As before, the source measurements all took place in a laboratory well removed from the cyclotron or any other unnatural source of radioactivity. For each measurement the source was placed in open geometry in front of the detector, coaxial with the Ge crystal. The distance was carefully measured with a micrometer caliper from the source to a convenient reference point on the detector cap. This yielded a 0.2 mm uncertainty at 15 cm and 0.3 mm at 1 m.

Our analog-to-digital converter was an EG&G-Ortec TRUMP™-8k/2k card controlled by the MAESTRO™ software installed on a PC operating under Windows-95. All measurements were made under the same conditions as described previously [5] in a laboratory well removed from any accelerator-based radioactivity. No shielding was used, but the spectrum of room background was measured frequently and subtracted from the source spectra. Data analysis methods, too, were unchanged.

In last year's progress report [5], we described measurements aimed at determining two key dimensions of our ORTEC Gamma-X HPGe detector: the end-cap-to-crystal distance, D, and the length of the crystal, L (see Fig 1). The nominal values of both dimensions were kindly supplied to us by the manufacturer [7] but these values were of insufficient accuracy for our purposes since both depend in detail on the

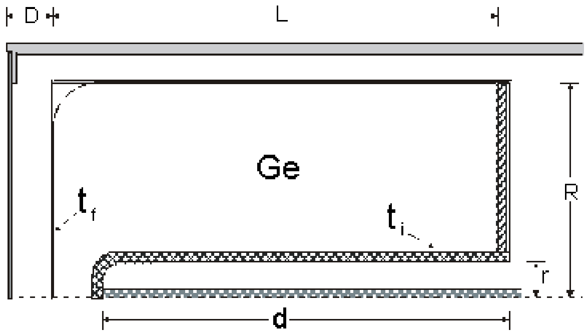

Figure 1: Sectional view of one-half of our detector, which has cylindrical symmetry about the marked center line. Dimensions are given in the text. The 0.5 mm beryllium window is shown in dark shading at the left of the figure; the o.5 mm container and the 1.6 mm outer can, both aluminum, appear in lighter shading at the top. A gold plated brass contact pin inserted into the hole in the Ge crystal is indicated by the checkerboard design, the lithium dead layer by cross-hatching and the 2-mm dead layer at the back of the crystal by diagonal lines.

manufacturing process. We have now augmented our previous measurements with X-ray pictures of the crystal within its aluminum container. These pictures were commercially made *in situ* with techniques normally used in the examination of pipelines. When the dimensions taken from the pictures were combined with results from our earlier measurements, we arrived at a final value for D of 7.2(1) mm. Our results for the length of the crystal led us to the inescapable conclusion that the physical length of the crystal was greater by about 2 mm than the length of its active volume. Defining L as the active length of the crystal, we obtain L=75.4(5) mm. (Measurements described in the next paragraph will demonstrate that essentially all of the 2-mm-thick dead volume lies at the back of the crystal.) Finally, the picture yielded a value for the crystal radius, R, of 34.6(3) mm.

We next addressed the issue of the thickness of the Ge dead layer at the front of the crystal, t_f. To determine it, we used the ^{109}Cd source, which has a single γ-ray at 88.034 keV and K X-rays from 21.99 to 25.60 keV. The relative intensity of the K_α X-rays to the γ-ray is known [8] to a precision of ~1% and that for the K_β X-rays to ~2%. We compared the measured ratio of efficiencies to that calculated by the Monte Carlo code with different assumed dead layers. Best agreement was obtained with a dead layer of t_f = 2.5(6) μm. Since the effect of this small dead layer on efficiency is very strongly energy dependent, the precision with which it is determined from the 26-keV data is more than enough to establish its effect to better than 0.1% precision above 70 keV.

Table 1: Properties of our HPGe detector, as specified by the manufacturer and as determined by our measurements.

Dimension	Nominal	Determined
Crystal radius, R	34.95 mm	34.5(1) mm
Active length, L	77.7 mm	75.4(5) mm
Cap-crystal dist., D	5.6 mm	7.2(1) mm
Hole radius, r	5.8 mm	
Hole depth, d	69.7 mm	
Int. dead layer, t_i	~1 mm	1.34(15) mm
Front dead layer, t_f	0.3 μm	2.5(6) μm

At this stage we used the Monte Carlo code to determine how strongly the calculated efficiency depended on each detector parameter. Of the dimensions already specified, only the crystal radius, R, produced significant variations in the calculated efficiency for changes within its uncertainty (0.3-mm). In addition, of course, the thickness of the internal (Li) dead layer, t_i, was a critical parameter as yet undetermined. The former tended to shift efficiencies at all energies together, while the latter affected high-energy efficiencies more than low-energy ones. As before [5], we used the PTB ^{60}Co source measurements as the measure of our absolute experimental efficiencies at 1173 and 1332 keV with 0.25% associated uncertainties. We then adjusted R and t_i to bring the calculated efficiencies into agreement with the measured ^{60}Co values while also reproducing the slope of the measured efficiencies as a function of energy. The final results were R = 34.5(1) mm and t_i = 1.34(15) mm. The measured dimensions for the detector parameters are compared with the nominal values in Table 1. In all cases, the differences are consistent either with the original tolerances or with possible changes introduced in the manufacturing process.

We then fitted the measured relative efficiencies obtained from each source to the Monte Carlo calculations by adjusting a single normalization factor to minimize chi-squared for that source. In no case did the normalization factor differ from unity by more than 3%, the uncertainty on the absolute activity quoted by the supplier. The results, shown in Figure 2, have an overall normalized chi-squared of 0.85. Obviously, the agreement is excellent.

With results from the sources already studied, we consider that we can now quote efficiencies to 0.1% for energies above 200 keV and to 0.15% below that energy, using the Monte Carlo calculations to interpolate to any desired energy.

References

[1] J. C. Hardy *et al., Progress in Research*, Cyclotron Institute, Texas A&M University (2001-2002), p. I-21.

[2] M. Sanchez-Vega *et al., Progress in Research*, Cyclotron Institute, Texas A&M University (2001-2002), p. I-24.

[3] E. Schoenfeld, H. Janssen, R. Klein, J. C. Hardy, V. Iacob, M. Sanchez-Vega, H. C. Griffin, and M. A. Ludington, Applied Radiation and Isotopes **56**, 215 (2002).

[4] J. A. Halbleib and T. A. Mehlhorn, Nucl. Sci. Eng. **92** (1986) 338-339.

[5] J. C. Hardy *et al., Progress in Research*, Cyclotron Institute, Texas A&M University (2000-2001), p. V-24.

[6] R. G. Neilson, *Progress in Research*, Cyclotron Institute, Texas A&M University (2001-2002), p. V-12.

[7] B. Kennedy, private communication.

[8] IAEA Coordinated Research Program, *X-ray and gamma-ray standards for detector calibration*, IAEA-TECDOC-619 (1991).

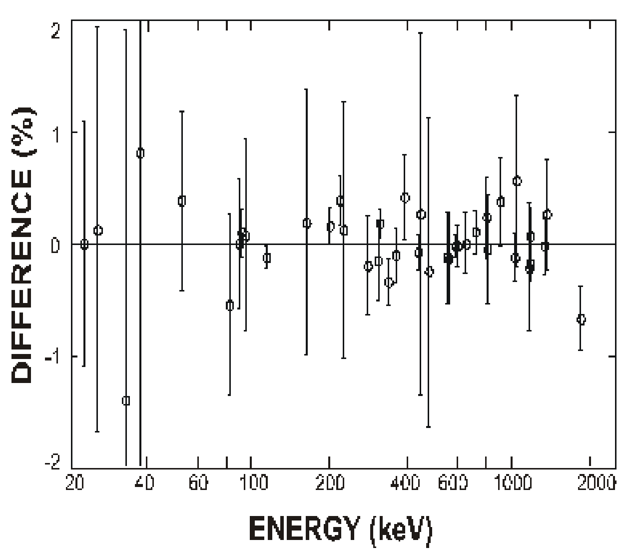

Figure 2: Percentage differences between the experimental detector efficiencies and those calculated with the Monte Carlo code CYLTRAN (experiment minus calculation, divided by calculation).