

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

J.C. Hardy, V.E. Jacob, M. Sanchez-Vega, R.T. Effinger, P. Lipnik, V.E. Mayes,
D.K. Willis and R.G. Helmer^a

^a*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%. To approach this goal, we have used high-statistics spectra from seven well known radionuclides, including a ^{60}Co source whose absolute activity is known to 0.1% [2], to extract our measured detector efficiencies, and then combine the results – for 31 gamma-ray energies in all, between 53 and 1836 keV – with un-renormalized Monte Carlo calculations based on our detector's actual properties.

So far, we have measured ten individual sources with activities between 2 and 47 kBq. Four sources, ^{60}Co , ^{88}Y , ^{133}Ba and ^{137}Cs , were purchased from Nycomed Amersham (now AEA Technology); in each case, the radioactive isotope was absorbed on a 1mm diameter ion-exchange bead inside a rectangular plastic capsule with 1-mm-thick walls. Three other sources, $^{108\text{m}}\text{Ag}$, ^{133}Ba and ^{134}Cs , came from Isotope Products Laboratories in the form of evaporated metallic salts on a thin, 9 mg/cm² Kapton backing. We prepared one source, $^{180\text{m}}\text{Hf}$, ourselves [3]. Finally, we used two ^{60}Co sources supplied by Physikalisch-Technische Bundesanstalt (PTB) [3]. The commercial sources all had activities quoted to 3%, with the exception of $^{108\text{m}}\text{Ag}$ which was an uncalibrated impurity in a $^{110\text{m}}\text{Ag}$ source. The activities of the PTB ^{60}Co sources were quoted as 46600 (30)

and 10565.0 (65) Bq, their uncertainties being below 0.1%!

For each measurement, a source was placed in front of the detector, coaxial with the Ge crystal. The distance was carefully measured from the source to a convenient reference point on the detector cap. For the PTB ^{60}Co sources, where precision in the distance was crucial, it was measured with a micrometer caliper, yielding 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 TRUMPTM-8k/2k card controlled by the MAESTROTM software installed on a PC operating under Windows-95. The TRUMPTM card uses the Gedcke-Hale method [4] to determine a live time that corrects for dead-time losses and random summing. When the counts in the photopeak are divided by that live time, the resulting rate is a close approximation to the true counting rate. We carefully tested these corrected results by first measuring a ^{60}Co source alone, and then re-measuring it in the presence of a ^{133}Ba source, which was placed at various source-detector distances in order to increase the dead-time and the probability of chance coincidences. Thus we could increase the overall counting rate while keeping the ^{60}Co rate constant. We found a very small residual rate-dependent effect: a fractional drop in the observed ^{60}Co counting rate of 2.5×10^{-4} per 1% increase in the dead time. Since our measurements had 2-3% dead time, this residual

correction was always less than 0.1% and only needed to be applied to the PTB ^{60}Co -source measurements.

Each source was measured for a long enough period that the statistical uncertainties on the photopeak areas were significantly smaller than the uncertainties in the corresponding gamma-ray relative intensities as recommended by the IAEA [5]. Measurements were made 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. This introduced very little additional uncertainty, particularly to the 15-cm measurements.

Gamma-ray peaks were analyzed with GF2, a least-squares peak-fitting program in the RADware series. A Gaussian peak with a smoothed step function, and a linear (or, rarely, quadratic) background in the peak region were sufficient to achieve reasonable agreement with the data in all cases. The effects of coincidence summing were incorporated for all cases in which they were a factor. This involved a careful analysis of the decay schemes of ^{133}Ba and ^{134}Cs , for example, to obtain the appropriate coincidence probabilities (with gammas and x-rays) and to account for gamma-gamma angular correlations. For each source, the corrected peak areas, adjusted for attenuation due to the appropriate source container, were then compared to the known relative gamma-ray intensities, thus yielding a set of relative detector efficiencies, often to 0.5% or better. Because we had two differently configured ^{133}Ba sources, we were also able to confirm that we were properly accounting for any attenuation in the different source containers. The relative efficiencies obtained in this way could then be

converted to absolute efficiencies in cases where the source intensity was known, but only the PTB ^{60}Co source had sufficient precision in its quoted activity to make this a valuable contribution.

Photopeak efficiency calculations were performed by the Monte Carlo electron and photon transport code CYLTRAN from the Integrated Tiger Series, ITS, set of codes[6]. This code, which calculates in three dimensions for a cylindrically symmetric source-detector geometry, has a growing record of success in the context of precise (0.1%) relative efficiencies above 400 keV [7,8] although it has never before been tested at lower energies or for absolute efficiencies at this level of precision. Before doing so, however, it was essential that we be able to specify the accurate configuration of our detector.

Our detector is an EG&G ORTEC Gamma-X HPGe, of coaxial type with an active volume of 280 cm^3 . Some information on its internal dimensions came with the detector when it was delivered in 1997, and more specific details of its configuration were kindly provided later by the manufacturer [9] from their records. Even so, not all detector properties were known with sufficient confidence: for example the cap-to-crystal distance, D , is assembly dependent and can be expected to differ by up to several millimeters from its nominal value. Furthermore, the back of the crystal (and front corners) are hand polished, leaving its length, L , (and the corner shapes) in some doubt. Finally, the dead layer depths are only estimates.

We performed two measurements aimed at determining dimensions D and L . The first involved measurement of the 122-keV gamma ray from ^{57}Co at two distances from the detector cap – 4 cm and 20 cm. The ratio of peak areas

at the two distances was then compared with the calculated Monte Carlo result for various values of D . The result, 7.6 (1) mm, is larger than the nominal value by 2.0 mm. In the second measurement, a 1-mm collimated beam of ^{60}Co gamma rays was directed at the side of the detector, perpendicular to its axis. The detector was then moved on a linear bearing along its axis, and a series of spectra recorded at various well measured positions as the gamma-ray beam scanned the length of the crystal. This scan,

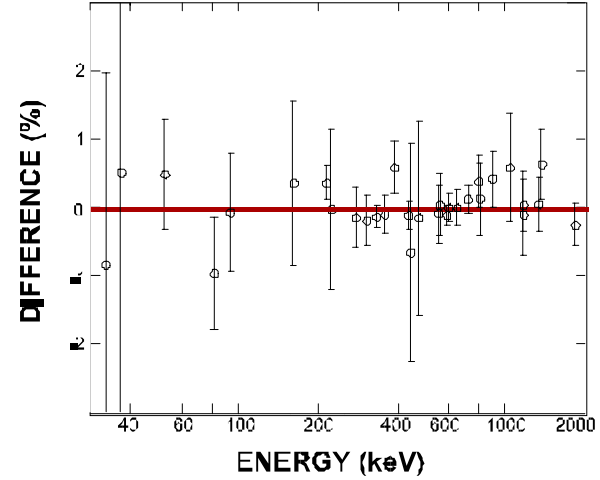
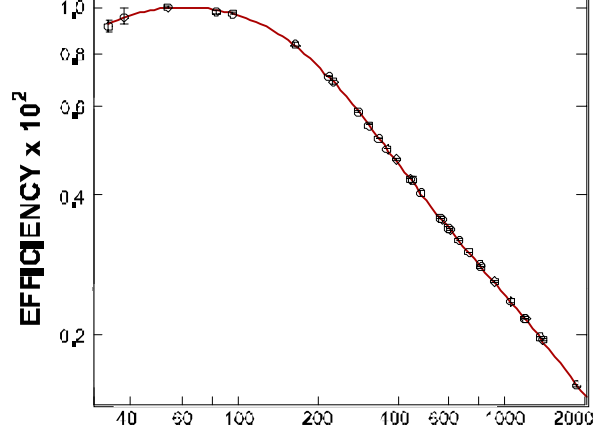


Figure 1: Experimental detector efficiencies at 15 cm Compared with Monte Carlo calculations. Absolute efficiencies are shown at the top, and percent differences (experiment minus calculation, divided by calculation) appear at the bottom.

which was also repeated with the lower energy gamma rays from ^{133}Ba , confirmed the value of D already determined and established that the length, L , of the sensitive volume of the detector was 74.4 (5) mm, 3.3 mm shorter than the nominal value. This result is consistent with material being lost in the hand polishing of the rear surface of the detector.

The two remaining parameters of importance, the thicknesses of the contact dead-layers, cannot be directly measured. However, the thickness of the internal (Li) dead layer only affects the detector efficiency for gamma rays above a few hundred keV, while that of the front dead layer affects only gamma rays below a few hundred keV. Both were used as adjustable parameters, independently fitted to the two energy regions, as explained in the following.

Because of their statistical definition, source measurements at the 15-cm source-detector distance were used as our primary data set. At that distance, the PTB ^{60}Co sources yielded absolute experimental efficiencies at 1173 and 1332 keV with 0.25% associated uncertainties.

With nominal dead-layer thicknesses

used in

the Monte Carlo calculation, the calculated efficiencies came out 3.5% higher than the experimental values. A modest increase in the assumed thickness of the internal dead layer, t_i , from 1.0 to 1.76 mm brought the two into exact agreement. Next, we used the ^{137}Cs source, which emits x-rays at 32 and 36 keV and a gamma ray at 662 keV, to compare the low-to-high-energy efficiency ratio between experiment and calculation. At the nominal front-dead-layer value, $t_f = 0.3$. m, the calculated ratio was about 10% higher than experiment; good agreement required the dead-layer to be 26 . m thick, a considerable increase over the nominal value. This is not implausible, however, since charge collection is known to be imperfect near the front surface of the crystal, an effect that we have actually observed in the detector's behavior for x-rays below about 10 keV. We believe that the relatively large value (relative to nominal) we require for the front dead layer is actually taking account of these deficiencies in charge

collection as well. In any case, with these two parameter corrections made, no further adjustments were made to the input for the Monte Carlo calculations.

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 the figure, have an overall normalized chi-squared of 0.62. Obviously, the agreement is excellent.

With results from the sources already studied, we consider that we can now quote efficiencies to 0.2% for energies above 200 keV and to 0.4% below that energy, using the Monte Carlo calculations to interpolate to any desired energy. We plan to study other sources, *viz.* ^{48}Cr and ^{120}Sb , with which we expect to be able to reduce the uncertainty at lower energies even further.

References

- [1] J. C. Hardy *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2000-2001) p. I-24.
- [2] 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*, to be published.
- [3] M. Sanchez-Vega *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2000-2001) p. V-22.
- [4] R. Jenkins, R. W. Gould and D. Gedcke, *Quantitative X-Ray Spectrometry* (Marcel Dekker Inc., 1981) pp 266-267.

- [5] IAEA Co-ordinated Research Program, *X-ray and gamma-ray standards for detector calibration*, IAEA-TECDOC-619 (1991).
- [6] J. A. Halbleib and T. A. Mehlhorn, *Nucl. Sci. Eng.* **92**, 338 (1986).
- [7] R. G. Helmer, *et al.*, *Nucl. Instr. and Meth.* **A351**, 406 (1994).
- [8] M. A. Ludington and R. G. Helmer, *Nucl. Instr. And Meth.* **A446** (2000) 506-521.
- [9] B. Kennedy, Private communication.