Precise efficiency calibration of an HPGe detector up to 3.5 MeV, with measurements and Monte Carlo calculations

N. Nica, J. C. Hardy, V. E. Iacob and R. G. Helmer[1]
[1]*Idaho National Engineering & Environmental Laboratory, Idaho Falls, Idaho*

In previous work [1], we determined the efficiency curve between 50 and 1400 keV for a coaxial, 280-cm^3 n-type Ge γ-ray detector, based on a combination of measured relative efficiencies for nine radionuclides, the measured absolute efficiency for the γ rays from ^{60}Co, and efficiencies calculated with CYLTRAN, a Monte Carlo photon and electron transport code. With the measured physical dimensions of the detector, only minor adjustments were required, well within tolerances, to obtain excellent agreement between the measured and calculated efficiency values [1]. From these results, we estimated the uncertainty in the final efficiency curve to be 0.15% relative and 0.2% absolute. Without changing the detector parameters in any way, we have now extended this work to 4.8 MeV by the continued use of both measured relative efficiencies and CYLTRAN-calculated efficiencies. This work is now complete and has been presented at the 14th International Conference on Radionuclide Metrology and its Applications in Dublin. A manuscript has been accepted for publication [2].

In this extension to 4.8 MeV, relative efficiencies for the full-energy (FE) peaks were measured for the strong γ rays from three additional sources: ^{24}Na, ^{56}Co, and ^{66}Ga. We produced 15-hour ^{24}Na by thermal neutron capture on Na_2CO_3 at the Texas A&M reactor, the source material being deposited on, and covered by 0.08-mm plastic foil. For 9.5-hour ^{66}Ga, we used a ^{66}Zn beam from the Texas A&M K500 Cyclotron to initiate the reaction $^{1}H(^{66}Zn, n)^{66}Ga$, the recoiling ^{66}Ga nuclei being separated from other reaction products in the MARS recoil spectrometer, and then implanted into 0.08-mm plastic foil. The 77-day ^{56}Co source was purchased from Isotopes Products Laboratory. The efficiency measurements were made, and the spectra analyzed, as described in [1]. Since the γ rays from these nuclides are generally in cascade and the source-detector distance was 15.1 cm, corrections for coincidence summing were made: for most γ rays these corrections were less than 1% and were never larger than ~2%.

The relative FE efficiencies deduced from these measurements depend on the relative γ-ray emission probabilities used for these nuclides. On the one hand, the value for the two strong ^{24}Na γ rays is well known [3]. On the other, those for the more complex decays of ^{56}Co and ^{66}Ga have only recently become reasonably well determined; we used the values from reference [4]. We considered only those γ rays with emission probabilities known to 1% or better and, among those, we only retained the ones that were cleanly observed – uncontaminated by escape peaks, for example – with measured areas in our spectra determined to 1% or better. This left us with a total of 26 FE peaks between 834 and 4806 keV from the three sources.

Measured efficiencies for these peaks were compared with Monte Carlo calculations performed with the same CYLTRAN code and identical dimensions to those used in our earlier work between 50 and 1400 keV. The results appear in Fig. 1. In this comparison, there are only three free parameters – a single scaling factor for each nuclide. We determined these scaling factors by minimizing the weighted differences between the measured values and the Monte Carlo efficiency values: that is, by means of a

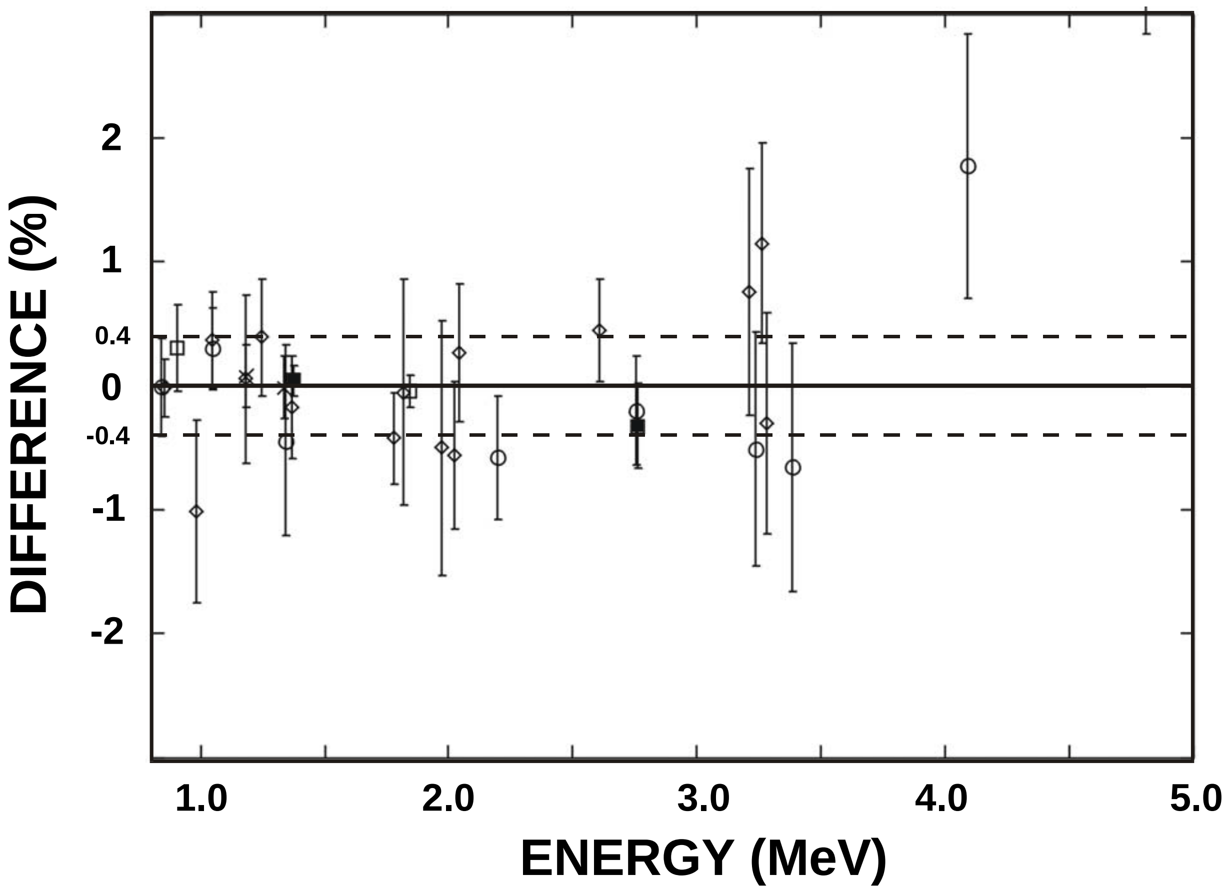

Figure 1. Differences between the measured efficiencies (points with uncertainties) and the corresponding Monte Carlo calculated values (line at 0). The differences are calculated as experiment minus calculation, divided by calculation, and are expressed as a percent. The points can be identified with individual sources as follows: ^{24}Na, solid squares; ^{56}Co, open diamonds; ^{60}Co, x's; ^{66}Ga, open circles; and ^{88}Y, open squares.

least-squares fit. Each of these nuclides has one or more γ rays below 1400 keV where the FE efficiency curve has already been determined precisely [1]. Therefore, the efficiencies at the higher energies presented here are completely consistent with those at the lower energies reported in reference [1]. Note that the figure also includes the results of two measurements from our previous work [1], those of ^{60}Co and ^{88}Y. The former provides an *absolute* efficiency determination that anchors the overall efficiency curve, while the latter yields a useful efficiency ratio that overlaps the energy region of interest in the present work.

As indicated in Fig. 1, the agreement between measured and calculated efficiencies below 3500 keV is excellent. Over this energy region, the normalized chi-squared for the 24 points from ^{24}Na, ^{56}Co and ^{66}Ga (with 21 degrees of freedom) is 0.70. We suggest that the uncertainty in the deduced efficiencies is 0.4% between 1400 and 3500 keV. Above 3500 keV there are two ^{66}Ga γ rays with emission probabilities claimed to better than 1%, both of which deviate significantly from the Monte Carlo calculations. Whether these represent real discrepancies between experimental and theoretical efficiencies or a systematic error in the accepted emission probabilities can only be decided by further experiments. For now, we forego any estimation of the uncertainty in our calibration curve above 3500 keV.

For many of the γ rays, our measured spectra also yielded single-escape (SE) and double-escape

(DE) peak relative efficiencies. We compared them with Monte Carlo calculations as well and, in doing so, we have found it most useful to express them as ratios of escape-peak areas to that of the corresponding FE peak. These ratios are independent of the γ-ray emission probabilities and of any coincidence summing corrections. However, when the measured SE/FE and DE/FE ratios were first compared with the Monte Carlo calculations, they were found to be consistently lower than the calculated ratios by up to 7%. We then learned from an author of the CYLTRAN code [5] that the program takes no account of positron annihilation-in-flight (AIF). Clearly, since the pair-produced positrons that do annihilate in flight produce photons with energies that are significantly different from 511 keV, the SE and DE peak areas calculated by the code need to be reduced by the known probabilities for AIF [6]. For each particular γ ray of energy E_γ, we reduced the SE and DE efficiency values from the Monte Carlo calculation by the AIF probability determined for a positron with energy ½ (E_γ - 1022 keV). As shown in Fig. 2, this produced excellent agreement with the measured escape ratios.

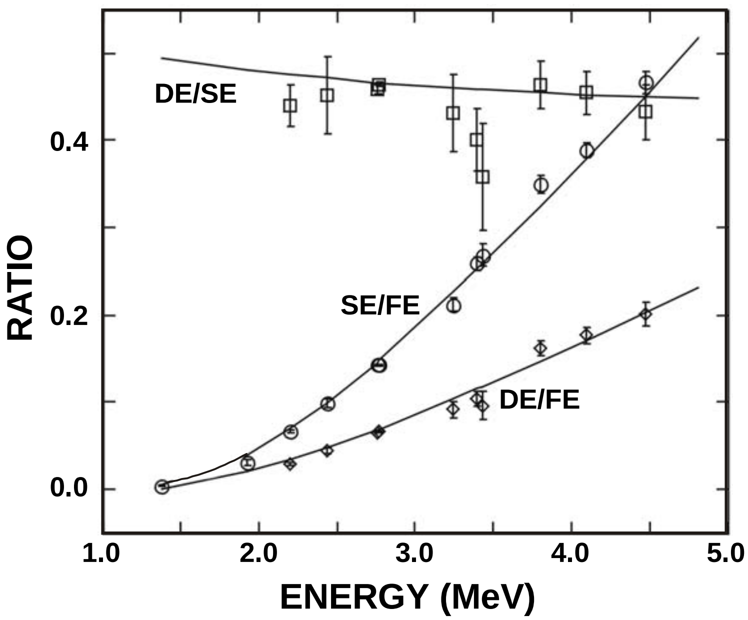

Figure 2. Measured escape ratios (points with uncertainties) compared with CYLTRAN Monte Carlo calculations (curves) that have been corrected for positron annihilation in flight.

With completion of this work, we have demonstrated that we can determine absolute γ-ray intensities to about 0.2% from 50 to 1400 keV and to about 0.4% from there to 3500 keV. This meets our requirements in measuring precise β-branching ratios for superallowed decays.

References

[1] J. C. Hardy *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2002-2003) p. I-22; R. G. Helmer, J. C. Hardy, V. E. Iacob, M. Sanchez-Vega, R. G. Neilson and J. Nelson, Nucl. Instrum. Methods Phys. Res. A, in press.

[2] R. G. Helmer, N. Nica, J. C. Hardy and V. E. Iacob, Int. J. Appl. Radiat. Isot., to be published.

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

[4] C. M. Baglin, E. Browne, E. B. Norman, G. L. Molnár, T. Belgya, Zs. Révay, F. Szelecsényi, Nucl. Instrum. Methods Phys. Res. A **481**, 365 (2002).

[5] R. P. Kensek, private communication (2003).

[6] E. Browne, R. B. Firestone, *Table of Radioactive Isotopes*, John Wiley & Sons (New York, 1986), p. D-6.