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W. D. Kulp, J. L. Wood, K. S. Krane, J. Loats, P. D. Schmelzenbach, C. J. Stapels, E. B. Norman

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An investigation of ^{154}Eu as a high-precision multi-γ-ray intensity calibration standard for detector arrays.

W. D. Kulp*, J. L. Wood*, K. S. Krane†, J. Loats†, P. D. Schmelzenbach†, C. J. Stapels† and E. B. Norman**

*School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0430
†Department of Physics, Oregon State University, Corvallis, OR 97331-6507
**Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Abstract. The decay of ^{154}Eu has been studied using γ-ray singles and $\gamma-\gamma$ coincidence spectroscopy with an array of Compton-suppressed Ge detectors. Particular attention to coincidence summing in the analysis, with consideration of detailed decay cascades and angular correlation effects, suggests that previous studies have overlooked necessary corrections. It is concluded that ^{154}Eu provides 26 γ-rays that can be used for relative efficiency calibrations from 120 to 1600 keV at the 0.7% precision level and that this precision could be improved in the future.

INTRODUCTION

Precision calibration methods applicable to single-detector systems are not suitable for arrays of detectors. Such methods require, e.g., detailed characterization of a detector through simulations and calibration using multiple single-γ-ray standards. The large number of detectors in an array and the possibility of disturbances to the array (changes in electronics, detector interchanges, etc.) make detector-by-detector calibration impractical, if not impossible. A method of calibration with multi-γ-ray standards is therefore desirable.

The decay of ^{154}Eu to ^{154}Gd is an excellent candidate for a precision multi-γ-ray standard. Adopted intensities [1] of the 12 strongest lines are reported with errors $\leq$ 0.70%. An additional number of γ-ray lines fairly evenly spaced over the energy range 123-1597 keV (cf. Fig. 1) could be developed for calibration. Sources of ^{154}Eu may be produced in high isotopic purity using reactor-induced neutron capture with "burn-out" of ^{152}Eu through neutron capture to stable ^{153}Eu. As a β^--decaying isotope, ^{154}Eu is free of the X-ray summing that plagues EC decaying isotopes.

EXPERIMENT

Gamma-ray spectroscopy of the decay of a $\sim$5 μCi ^{154}Eu source was carried out using the 8π spectrometer at Lawrence Berkeley National Laboratory. The 8π spectrometer was configured as an array of 20 Ge(HP) detectors in a regular icosahedron geometry with a source-to-detector distance of 22.0 cm. Bismuth germanate scintillators around each Ge detector provided Compton suppression.

Gamma-ray singles and $\gamma-\gamma$ coincidence events were recorded event-by-event on magnetic tape. The data sets contained 1.00×10^8 $\gamma-\gamma$ coincidence events and 2.38×10^8 singles events. The γ-ray singles spectrum from the experiment is presented in Fig. 1. Additional experimental details, including information on detector volumes, data analysis, source contaminants, and background lines has been published previously [2].

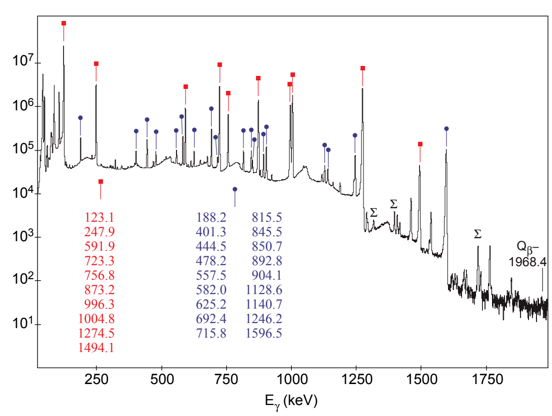

FIGURE 1. The γ-ray singles spectrum of ^{154}Eu $\rightarrow$ ^{154}Gd. Square markers indicate the ten lines used for calibration. Circular markers indicate additional peaks with intensity $>$ 0.5. Peaks used for summing normalization are identified by Σ.

Standard sources were used to characterize the array. The peak:total curve was deduced using lines from the decays of ^{22}Na, ^{60}Co, ^{137}Cs, and ^{154}Eu. A quartic polynomial fitted to log(efficiency) versus log(energy) for 10 strong lines (cf. Fig. 1) in the ^{154}Eu decay scheme was used to determine γ-ray intensities [I_γ (1274.5) $\equiv$ 100.0]. No summing effects were considered and the adopted intensities in Nuclear Data Sheets [1] were used.

To evaluate the errors in the relative efficiency curve, intensities of γ rays with reported intensities >0.5 (cf. Fig. 1) were calculated using the polynomial fit. Calculated intensities were compared with the adopted [1] intensities without applying summing corrections, as shown in Fig. 2. The quantity $\delta I_\gamma = (I_\gamma^{\rm calc} - I_\gamma^{\rm NDS})/I_\gamma^{\rm calc}$ was used as a figure of merit. The deduced error in the efficiency curve was $\pm$0.7%.

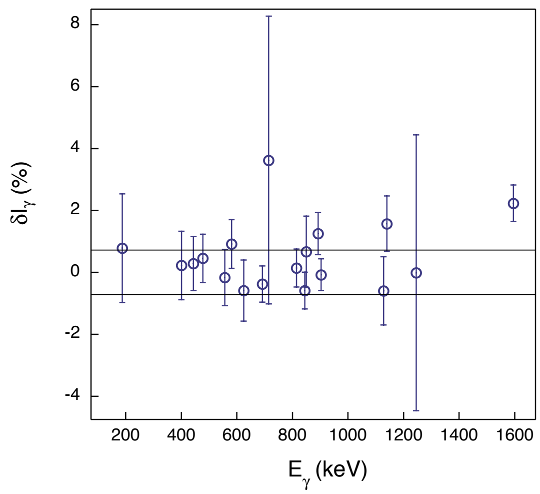

FIGURE 2. Plot of the deviations of intensities of γ-ray lines, deduced from the efficiency calibration used, from the adopted[1] values. The horizontal lines delineate $\pm$0.7%.

SUMMING CORRECTIONS

Comparison with coincidence intensities indicated that summing corrections were required. Summing gains were systematically calculated for all possible cascading γ-ray pairs, both for direct and indirect cascades, using:

$$n_{12} = N I_\gamma(1)\varepsilon_\gamma(1)B_\gamma(2)\varepsilon_\gamma(2)C_{12}^{\Sigma}, \qquad (1)$$

where n_{12} is the number of sum peak events produced by γ_1 (feeding) and γ_1 (de-exciting) transitions, N is a normalization constant, the ε_γ are relative photopeak efficiency values, $I_\gamma(1)$ is the intensity of the feeding γ ray, $B_\gamma(2)$ is the branching fraction of the de-exciting γ ray, and $C_{12}^{\Sigma} = C_{12}(0^\circ)$, i.e., the angular correlation factor at 0°.

TABLE 1. Angular correlation correction factors averaged over the entire array (C_{12}) and at 0° (C_{12}^{Σ}) for a selection of γ-ray cascades. A dash indicates a pure $E2$ while (δ) indicates a mixed $E2/M1$ transition.

$J_1 - J_2 - J_3$	C_{12}	C_{12}^{Σ}	
2(E1)2-0	1.0130	0.7537	
3(E1)2-0	1.0037	0.9297	
3(E1)4-2	1.0073	0.8618	
3(δ)2-0	1.0151	0.7136	$\delta = -100$
	1.0186	0.6470	$\delta = -10$
	1.0105	0.7997	$\delta = +10$
	1.0143	0.7290	$\delta = +100$
3(δ)4-2	1.0078	0.8518	$\delta = -100$
	1.0039	0.9258	$\delta = -10$
	1.0126	0.7616	$\delta = +10$
	1.0087	0.8352	$\delta = +100$
Indirect coincidence sums			
2(E1)2(δ)2-0		0.9490	$\delta = -10$
2(E1)3(δ)2-0		0.9565	$\delta = -10$

The geometric symmetry of the 8π spectrometer minimizes angular correlation effects when averaged over the entire array, as shown by relatively small corrections (C_{12}) in Table 1. However, coincidence summing occurs at a single angle (0°). The varied values for C_{12}^{Σ} presented in Table 1 illustrate the need to consider angular correlations, particularly for summing calculations.

The normalization constant, N, was calculated from the peaks (cf. Fig. 1) at 1397.4 (Σ 1274 + 123) and 1719.4 keV (Σ 1597 + 123, Σ 904+815, Σ 723+996). Assuming that the 1397.4 and 1719.4 keV peaks contain no events due to M2 decays to the ground state, these are direct cascades with spin-parity and multipolarity sequences $2(E1)2^+(E2)0^+$ ($C_{12}^{\Sigma} = 0.7537$). The only source of X-ray summing was due to internal conversion of the 123 keV transition, which required a constant correction factor of 1.26 (determined from the ratio of Σ1274+K_α events to Σ1274+123 events).

In addition to a parallel cascade summing contribution to a "cross-over" transition (e.g., the $\Sigma 881 + 248$ contribution to the 1129 keV γ ray, cf. Fig. 3), two other classes of correction are incurred: the first is the summing of a direct cascade and the second is the summing of an indirect cascade, in each case producing events sufficiently close to a transition in the scheme that the sum peak is not resolved. Each type of summing is illustrated in Fig. 3. The $\Sigma 1005 + 123$ sum is a direct cascade which is not in parallel with the affected γ-ray transition. The $\Sigma 723 + 123$ cascade is an indirect cascade sum which contributes to the peak at 846 keV.

The summing paths shown in Fig. 3 illustrate that non-parallel cascades may produce greater summing effects than the parallel cascades. The summing gains from these paths may be inspected in Table 2. The parallel con-

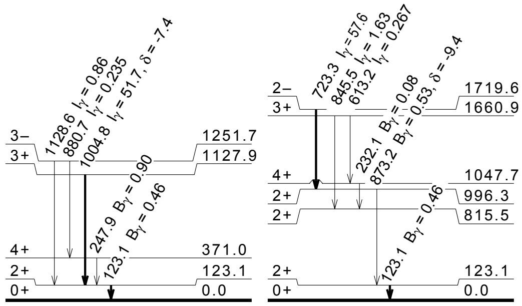

FIGURE 3. An illustration of direct and indirect summing effects considered in the decay of ^{154}Eu $\rightarrow$ ^{154}Gd. The data are taken from [1, 2].

tributions in each case are less than 0.1%, while the non-parallel contributions exceed 2%.

A comparison of coincidence intensities to sum-corrected singles intensities was used to evaluate the method of sum correction. As shown in Fig. 4, summing-corrected singles intensities generally agreed better with coincidence data (cf. the 716 and 1129 keV γ rays). However, some coincidence intensities were particularly sensitive to angular correlations due to the selected γ ray cascade (e.g., the 846 keV γ ray).

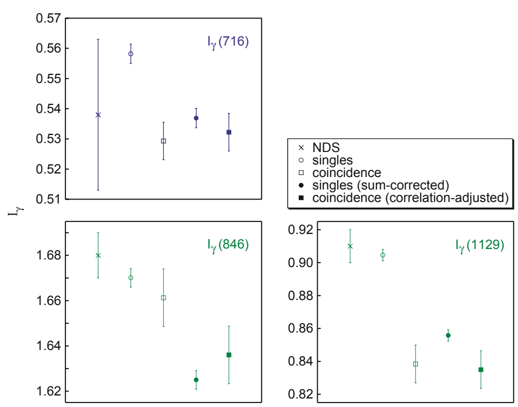

FIGURE 4. Comparison of calculated γ-ray intensities. Error bars for measured quantities reflect only the statistical (fit) uncertainties.

RESULTS

A plot of the deviations of the sum-corrected intensities from the adopted values shows that an additional 16 γ rays (secondary lines) are potentially useful for calibration. While there is a systematic shift of $+0.65\%$ (from calibration without inclusion of summing losses), the spread of values (excepting the 846 and 1129 keV lines) indicates a precision of $\pm 0.65\%$ has been reached.

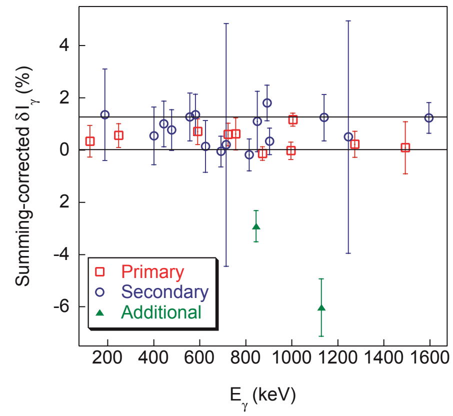

FIGURE 5. Deviations of the summing-corrected intensities of the γ-ray lines, deduced from the efficiency calibration used, from the adopted[1] values. The horizontal lines delineate $(+0.65 \pm 0.65)\%$.

The difference between summing-corrected singles and the adopted [1] intensities for the 846 and 1129 keV γ rays suggests that summing corrections have not been made for these lines. The good agreement between summing-corrected singles and angular-correlation-corrected coincidence intensities for these two peaks suggests that corrections can be made using the methods outlined here. New measurements to reduce the uncertainties of the 716 and 1246 keV lines would further improve the value of this calibration source.

Detailed summing correction improves agreement between singles and coincidence measurements, but requires corrections for complicated decay branching, corrections for angular correlations, and knowledge of weak decay branches. With these corrections, ^{154}Eu shows promise as a precision multi-γ-ray calibration source. Further development requires new measurements, particularly of δ and B_γ values.

ACKNOWLEDGMENTS

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TABLE 2. Angular correlation correction factors for coincident summing (selected spin sequences).

Σ	$I_\gamma(1)$	$\varepsilon_\gamma(1)$	$B_\gamma(2)$	$\varepsilon_\gamma(2)$	C	n_{12}	% gain
1005+123	51.7	204415	0.455	803089	0.6470	9112	5.34
881+248	0.235	225061	0.900	665425	0.8618	100	0.06
723+123	57.6	262393	0.526 0.455	803089	0.9490	10054	2.59
613+232	0.267	301219	0.079	697159	0.9258	15	0.004

Due West, SC 29639, and J. Loats is at the Department of Physics & Engineering, Fort Lewis College, 1000 Rim Dr., Durango, CO 81301.

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