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Coincidence Corrected Efficiency Calibration of Compton-Suppressed HPGe Detectors

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I. Introduction

The use of highly efficient detector geometries is often limited by the summing of gamma rays which are emitted in coincidence. Multiple coincident gamma rays from the same nuclide may interact in the detector, removing counts from the full-energy peaks and creating a sum peak. When a Compton anti-coincidence detector is used to suppress the background continuum, this problem is compounded by coincidences between the two detectors.

Despite these limitations, Compton-suppressed spectrometers can be very valuable in detecting small activity concentrations. In particular, one common problem requires the detection of a low activity in the presence of higher-energy gamma rays. For example, the Compton scattering from prominent fission products such as ^{137}Cs will increase the background continuum for lower-energy gamma rays. Similarly, neutron activation analysis often creates interfering nuclides such as ^{24}Na which limit the sensitivity to detect other nuclides.

Currently available commercial software struggles to compensate for coincidence summing in well detectors [1] and are unable to account for a Compton-suppressed system. Furthermore, most approaches rely on a detailed Monte Carlo simulation of the detectors, which is often unavailable. Previous methods [2] have shown success for highly efficient geometries without Compton suppression, but do not take into account suppression shields and often require specially-prepared calibration sources.

Here we present a reliable method to calibrate the full-energy efficiency and the coincidence correction factors using a commonly-available mixed source gamma standard. This is accomplished by measuring the peak areas from both summing and non-summing decay schemes and simultaneously fitting both the full-energy efficiency, as well as the total efficiency, as functions of energy. By using known decay schemes, these functions can then be used to provide correction factors for other nuclides not included in the calibration standard.

II. Experimental

The detector system consists of a p-type high-purity germanium (HPGe) well detector and a sodium iodide (NaI) annulus as the Compton suppressor. The NaI annulus is read out by four photomultiplier tubes with a common preamplifier. The resulting pulses are sent to a fast single channel analyzer (SCA) to create a veto signal. The lower-level threshold on the SCA corresponds to an energy of about 50 keV. The HPGe detector is read out by a Canberra Lynx system, which simultaneously acquires two spectra—one with the veto enabled, and one without. This functionality allows for the analysis of peaks in the event that the unsuppressed spectra provides a lower minimum detectable activity; however, this functionality is not required for the calibration approach outlined here.

A calibration spectrum was taken using a mixed-gamma source spanning the energy range from ^{241}Am (59.5 keV) to ^{88}Y (1836.1 keV). The calibration source was prepared in the 5 mL test tube, the same geometry used in the samples to be tested. The resulting spectra (both with and without the veto enabled) are shown in figure 1. While the exact mixture of nuclides is not critical, it is important to include those which exhibit known coincidence summing. In this case, the standard includes ^{57}Co, ^{139}Ce, ^{60}Co, and ^{88}Y, all of which exhibit summing in this detector system. In addition, the source contains many nuclides that exhibit no observable summing, including ^{241}Am, ^{109}Cd, ^{113}Sn, ^{137}Cs, ^{54}Mn, and ^{65}Zn.

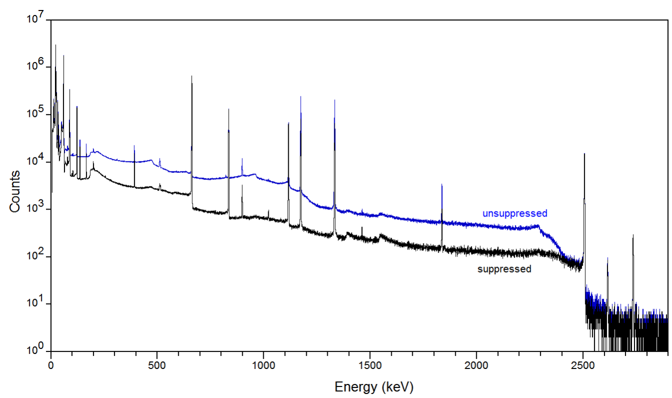

Fig. 1. Suppressed (black) and unsuppressed (blue) HPGe spectra taken with the mixed-gamma calibration source. Note the suppression of counts in the ^{60}Co peaks, but not in the ^{137}Cs peak.

III. Analysis

In order to account for the effects of coincidence summing, two efficiency curves are required. The first is the typical full-energy efficiency, which here is fit with a fourth-order polynomial in log-log space. The second is the effective total efficiency [3], which is modified to include the efficiency of both the HPGe and NaI detectors. This is accomplished by using the known decay scheme to infer the energy of the coincidence gamma.

For instance, examining the decay scheme for ^{60}Co, shown in figure 2, reveals that there are only two gamma rays of real importance (1173.2 and 1332.5 keV) which are nearly always emitted in coincidence. From this, equations for the number of counts in each peak in the presence of summing can be derived [1], one for each gamma ray and one for their sum:

$$n_1 = Ap_1\epsilon(E_1) - Ap_1\epsilon(E_1)\epsilon_T(E_2) \quad (1)$$

$$n_2 = Ap_2\epsilon(E_2) - Ap_1\epsilon(E_2)\epsilon_T(E_1) \quad (2)$$

$$n_3 = Ap_3\epsilon(E_3) + Ap_1\epsilon(E_1)\epsilon(E_2)l^2 \quad (3)$$

where n_i is the number of counts observed at energy E_i, A is the number of decays in the source, p_i is the branching ratio for that line, $\epsilon(E)$ is the full-energy efficiency, $\epsilon_T(E)$ is the total efficiency for any interaction to occur in either detector, and l is the so-called "linear-to-square" term [3] to account for the fact that the source is not a point source. Here, n_1 corresponds to the first gamma ray emitted in the cascade (1173.2 keV), n_2 is the second (1332.5), and n_3 is the sum (2505.7).

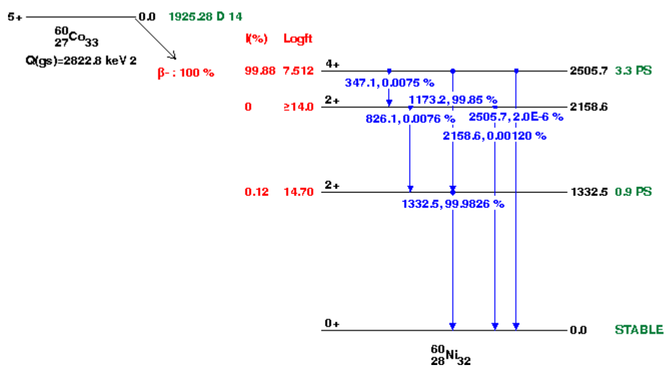

Fig. 2. Decay scheme of ^{60}Co, showing the two primary gamma rays which are emitted in coincidence, as well as other, minor emissions [4].

For some nuclides, such as ^{139}Ce, coincidences are instead seen between gamma rays and X-rays, and for others, such as ^{57}Co, the two gamma rays are not always emitted in coincidence due to internal conversion. In addition, every line need not be visible in the spectrum. For instance, the X-rays from ^{139}Ce are at 33 keV and cannot be resolved from other X-rays at that energy. However, equation 1 allows the total efficiency at the X-ray energy E_2 to be measured from only the gamma ray counts n_1.

The counts n_i in each peak are measured, and the two efficiency functions $\epsilon(E)$ and $\epsilon_T(E)$ are simultaneously fit to fourth-order polynomials in log-log space. The resulting fits are shown in figure 3. This figure shows that the efficiency can be corrected to create a consistent calibration curve, while also creating a total efficiency curve to extend the corrections to other nuclides. Unlike previous work, which did not include the Compton suppression, care must be taken not to allow the total efficiency to go above unity. This is accomplished by applying a smoothing filter of the form:

$$y = (x - \sqrt{x^2 + 0.1})/2 \quad (4)$$

which restricts the function to negative values in log space.

Finally, the two efficiency curves can be used to derive correction factors for other nuclides which exhibit summing.

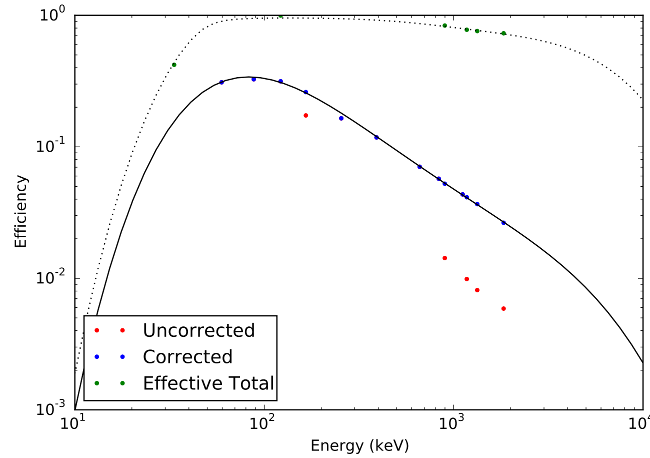

Fig. 3. Full-energy efficiency (solid line) and effective total efficiency (dotted line) curves, along with the uncorrected (red) and corrected (blue) efficiency measurements. The effective total points (green) are obtained from eq. 1–2.

A ^{226}Ra source was measured, and its daughter ^{214}Pb was analyzed using its known decay scheme and the derived coincidence correction factors. Table I shows the results of the peak analysis for two peaks in coincidence, as well as a third peak with no summing. The correction gives consistent results for all three peak activities to within error. Note that even the uncorrected activities require a valid full-energy efficiency calibration which is provided by this approach.

TABLE I
UNCORRECTED AND CORRECTED ACTIVITIES OF LEAD-214 PEAKS

Energy (keV)	Uncorr. Act. (nCi)	Correction Factor	Corr. Act. (nCi)
242.0	0.56±0.01	0.87	0.64±0.02
295.2	0.63±0.02	1.04	0.61±0.02
351.9	0.61±0.01	1.00	0.61±0.01

IV. CONCLUSION

We have demonstrated a straightforward approach to obtaining an efficiency calibration for a Compton-suppressed HPGe detector which exhibits prominent summing both within the HPGe crystal as well as between the HPGe and NaI detectors. A commonly available mixed gamma source was used to simultaneously calibrate both the full-energy efficiency and the total effective efficiency using this source. This allows for a more accurate measurement of the full-energy efficiency in suppressed spectrometers, and it enables correction factors to be evaluated for other gamma rays which exhibit summing. The approach was validated by an additional source which exhibits both summing and non-summing gamma rays.

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