Measurement of Efficiency Calibration and Coincidence Correction Factor for Well-type HPGe Detector

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Abstract

To calculate the detection efficiency curve and coincidence correction factors for a well-type HPGe detector, the detection efficiency of the HPGe was calibrated using commonly employed single-energy γ radionuclide standard sources, while cascade coincidence correction factors for common radionuclides such as 60Co, 88Y, 131I, 134Cs, 152Eu, and 133Ba were measured. The measurement results indicate that the efficiency values obtained using 139Ce from the commonly employed single-energy γ radionuclide standard sources can differ from the fitted values by up to 49%; the coincidence effect of the well-type HPGe significantly influences activity measurement results, with smaller sample heights yielding larger coincidence correction factors. When the sample height is 0.5 cm, the coincidence correction factor for the full-energy peak of the 563.23 keV γ-ray emitted by 134Cs reaches 8.00, while that for the 604.70 keV γ-ray full-energy peak is 3.01. When the activity of the sample exceeds approximately 1000 Bq, the contribution of random coincidence to the total coincidence correction factor gradually increases; when the activity of 131I increases from 1300 Bq to 6300 Bq, the coincidence correction factor for the 80.19 keV γ-ray full-energy peak increases by 10%. The measurement data can provide reference for the selection of efficiency calibration sources for well-type HPGe detectors and for the correction of radionuclide activity measurement results.

Full Text

Preamble

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Efficiency Calibration and Coincidence Correction Factor Measurements for Well-Type HPGe

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Abstract

Well-type high-purity germanium (HPGe) detectors are widely used for measuring small-volume samples due to their high detection efficiency. While summation corrections are essential in such measurements, relevant data for this detector type remain scarce. This study calculates detection efficiency curves and coincidence correction factors for well-type HPGe detectors by calibrating detection efficiency using common monoenergetic γ-ray standard sources and measuring cascade coincidence correction factors for radionuclides including ^{60}Co, ^{88}Y, ^{131}I, ^{134}Cs, ^{152}Eu, and ^{133}Ba. Results demonstrate that efficiency values obtained using ^{139}Ce from standard monoenergetic γ sources can deviate from fitted values by up to 49%. The coincidence effect significantly impacts activity measurements in well-type HPGe detectors, with smaller sample heights yielding larger correction factors. At a sample height of 0.5 cm, the coincidence correction factor reaches 8.00 for the 563.23 keV γ-ray full-energy peak of ^{134}Cs and 3.01 for the 604.70 keV peak. When sample activity exceeds approximately 1000 Bq, random coincidence contributions to the total correction factor increase progressively; for ^{131}I, increasing activity from 1300 Bq to 6300 Bq raises the correction factor for the 80.19 keV peak by 10%. These findings provide valuable guidance for selecting appropriate efficiency calibration sources and correcting nuclide activity measurements in well-type HPGe applications.

Keywords: Well-type HPGe, Coincidence Factor, ^{139}Ce, ^{134}Cs, ^{131}I

Introduction

HPGe detectors are routinely employed to measure radionuclide activities via γ-ray spectrometry. Well-type HPGe detectors, characterized by their well-shaped crystal geometry, offer large solid angles and high detection efficiencies, making them particularly suitable for small-sample measurements such as fallout and biological ash specimens weighing only a few grams. However, the enhanced detection efficiency simultaneously increases the probability of cascade coincidence effects, compromising measurement accuracy. Due to limited time resolution, γ-ray spectrometry systems cannot distinguish between two or more photons emitted in cascade, instead registering them as a single event. This cascade coincidence effect can either reduce or increase the count rate in the full-energy peak of interest [1,2], occurring not only between γ-rays but also between γ-rays and X-rays [3,4]. While calibrating HPGe detection efficiency using series of monoenergetic γ standard sources is a common approach for obtaining coincidence correction factors [5-7], the suitability of conventional monoenergetic sources for well-type and large-area HPGe detectors requires investigation. Numerous studies have addressed cascade coincidence corrections for top-mounted HPGe detectors (where samples are placed on the detector surface) [8-11], but few have reported measurement data for well-type HPGe. O. Sima et al. [12] calculated coincidence correction factors for ^{134}Cs and ^{60}Co in well-type HPGe using Monte Carlo methods, validated with ^{210}Pb, ^{57}Co, ^{51}Cr, ^{7}Be, ^{137}Cs, ^{54}Mn, ^{65}Zn, and ^{40}K standards. Wang Shilian et al. [13] computed correction factors for various nuclides in well-type HPGe based on decay schemes. However, these studies did not account for factors such as X-ray emission from standards, sample geometry characteristics, or random coincidence effects from high activities.

Methods

1.1 Standard Source Method

This method employs a set of monoenergetic γ-ray standard sources to calibrate HPGe detection efficiency, yielding an efficiency curve (E) as a function of energy E without coincidence effects. Under identical matrix, geometry, and mass conditions as the monoenergetic standards, the detection efficiency $_0(E_0)$ at the energy of interest E_0 is determined using a standard source of the target nuclide. The coincidence correction factor F for the full-energy peak of γ-rays with energy E_0 is then calculated as:

$$F = {}_0(E_0) / (E_0)$$

The standard source method requires a calibrated standard source of the target nuclide with high activity accuracy.

1.2 Distance Method

Using monoenergetic γ standard sources and test samples with identical matrix, geometry, and mass, measurements are performed at two positions: a far position F (where coincidence summing is negligible) and a near position N (close to the detector). The efficiency curves F(E) and N(E) are obtained at these positions, along with count rates nF and nN for the target energy E_0. The coincidence correction factor F is given by:

$$F = (N(E_0)/ F(E_0)) \times (nF/nN)$$

While this method does not require prior knowledge of the target nuclide activity, it is unsuitable for samples measured inside well-type HPGe detectors.

Experimental Setup

2.1 Gamma Spectrometry Detectors

The well-type HPGe spectrometer used in this study was a Canberra GCW5021 model with a crystal measuring ø70 mm × 60 mm, energy resolution of 2.0

keV at 1332 keV (^{60}Co), well diameter of 10 mm, and well depth of 40 mm. Additionally, a BE5030 broad-energy HPGe detector with larger sensitive area (ø81 mm × 31 mm crystal, 1.9 keV resolution at 1332 keV) was employed.

2.2 Standard Sources

Monoenergetic γ standard sources were prepared from certified solutions produced by LEA, France, containing ^{241}Am, ^{109}Cd, ^{139}Ce, ^{57}Co, ^{51}Cr, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{54}Mn, and ^{65}Zn. The specific activity uncertainty was 5% (k=2) for ^{109}Cd and $ $3.5% (k=2) for other nuclides. A ^{40}K solution prepared from KCl had an uncertainty of ~4.0% (k=2). Standard sources of ^{133}Ba, ^{134}Cs, ^{152}Eu, and ^{226}Ra were produced by China Isotope & Radiation Corporation with specific activity uncertainties $ $2.9%, 3.5%, 3.2%, and 3.6% (k=2), respectively.

Results

3.1 Efficiency Calibration

Monoenergetic γ standard sources are commonly used for HPGe efficiency calibration as they emit single γ-ray energies without cascade coincidence effects. However, some nuclides emit X-rays in addition to γ-rays, potentially causing γ-X coincidences. ^{139}Ce, frequently used in standard source sets [1-7,11], emits 166 keV γ-rays accompanied by 33 keV and 38 keV X-rays [15]. Conventional P-type HPGe detectors have negligible response to photons below 40 keV [16-17], preventing cascade coincidence and making ^{139}Ce suitable for efficiency calibration. To investigate its applicability to well-type and broad-energy HPGe detectors with good low-energy response, efficiency calibration was performed using aqueous standard sources of various geometries for both GCW5021 (well-type) and BE5030 (broad-energy) detectors. Results are shown in [Figure 1: see original paper] and [Figure 2: see original paper].

Standard source samples were prepared in containers commonly used in environmental monitoring: ø50 mm × 2 mm, ø50 mm × 20 mm, ø70 mm × 65 mm, ø75 mm × 10 mm, and ø10 mm × 47 mm. These were placed on both detector surfaces, with the ø10 mm × 47 mm geometry used exclusively for well-type measurements. For the well-type HPGe, deviations between the 166 keV efficiency point from ^{139}Ce and fitted efficiency curves were $ $2% for all geometries except the ø10 mm × 47 mm well geometry, which showed a 38% deviation. For the broad-energy HPGe, deviations were $ $2% for ø70 mm × 65 mm and ø75 mm × 10 mm geometries, but reached 12% for ø50 mm × 2 mm and 6% for ø50 mm × 20 mm.

To verify efficiency consistency near 166 keV, a ø10 mm × 47 mm ^{226}Ra standard source was prepared, utilizing its 186 keV γ-ray. Measurements showed $ $1% deviation from the fitted efficiency curve. [Figure 2: see original paper] presents γ-ray spectra of ^{139}Ce standard sources measured by both detectors. When efficiency deviations are large, coincidence peaks of 166 keV γ-rays with 33 keV and 38 keV X-rays are prominent; when deviations are small, these peaks are negligible.

Detection efficiency is the primary factor influencing coincidence effects. The GCW5021 and BE5030 detectors have larger solid angles and crystal volumes than conventional P-type HPGe, increasing γ-ray and X-ray detection efficiency. Their encapsulation materials and electrode configurations further enhance low-energy photon detection, raising the probability of γ-X coincidences. Therefore, when using ^{139}Ce-containing standard sources for HPGe calibration, potential coincidence effects must be verified for the specific detector and sample geometry. Higher detection efficiency for photons below 40 keV leads to more pronounced coincidence effects and greater impact on calibration accuracy. Many studies [4,6] have overlooked ^{139}Ce coincidence effects, potentially compromising efficiency calibration results.

3.2 Sample Height Effects on Efficiency

To investigate the relationship between detection efficiency and sample height in well-type HPGe, aqueous standard sources with 10 mm diameter and heights H = 0.5, 1, 2, 3, 4, and 5 mm were prepared. Additionally, simulated soil standard sources (SiO_2:Al_2O_3 mass ratio 5:2, density 1.4 g/cm^3) were measured. Results are shown in [Figure 3: see original paper].

For aqueous solutions, maximum detection efficiency occurred at H = 2 cm; efficiency decreased for both smaller and larger heights. For simulated soil, maximum efficiency occurred at H = 1 cm. Aqueous samples consistently showed higher efficiency than soil samples at the same height due to lower self-absorption. Deviations at 166 keV from fitted curves were 49%, 48%, 46%, 41%, 40%, and 38% for H = 0.5, 1, 2, 3, 4, and 5 cm aqueous samples, respectively. Corresponding deviations for soil samples were 44%, 41%, 38%, 35%, and 30%. Smaller heights produce larger deviations, with aqueous samples showing greater deviations than soil samples at identical heights. Thus, larger detector solid angles and higher detection efficiencies for ^{139}Ce γ- and X-rays increase coincidence probability and its impact on results.

HPGe detection efficiency for γ- and X-rays depends primarily on solid angle and sample self-absorption. For well-type HPGe, positioning more sample material within the well center increases interaction probability while reducing Compton-scattered photon escape, thereby enhancing efficiency. However, increased sample density and mass raise self-absorption probability, reducing efficiency. The overall efficiency represents a combined effect of detector solid angle and sample properties.

3.3 Coincidence Correction Factors

Coincidence correction factors for full-energy peaks of ^{60}Co, ^{88}Y, ^{134}Cs, ^{152}Eu, and ^{133}Ba in well-type HPGe were measured using the standard source method. For ^{131}I, a combination of distance and standard source methods was employed.

Measurements were performed for both well-positioned (ø10 mm × 47 mm) and surface-positioned (ø50 mm × 20 mm) samples, with results summarized in .

The data reveal substantial differences between well- and surface-positioned samples, with correction factors differing by up to 5.5 times. Well-positioned samples exhibit significantly higher coincidence probabilities due to greater detection efficiency. The 245 keV γ-ray of ^{152}Eu shows the largest correction factor (6.69), with considerable variation among different γ-ray energies of the same nuclide, reflecting inherent nuclear decay processes. When measuring atmospheric fallout ^{131}I with well-type HPGe, the 364 keV peak requires no correction (F = 0.99), while the 80 keV and 284 keV peaks demand correction. For ^{134}Cs in fallout samples measured in-well, the 605 keV peak area must be multiplied by 1.94, compared to only 1.09 for surface measurements.

To examine the relationship between correction factor and sample height in the well, ^{134}Cs aqueous standard sources (10 cm diameter, H = 0.5, 1, 2, 3, 4, and 5 cm) were prepared. Results are shown in [Figure 4: see original paper].

Smaller sample heights yield larger correction factors. At H = 0.5 cm, factors reach 8.00 for the 563.23 keV peak and 3.01 for the 604.70 keV peak, decreasing to 3.38 and 1.94 at H = 5 cm, respectively. According to the ^{134}Cs decay scheme, the 563.23 keV γ-ray has the highest cascade emission probability, resulting in larger correction factors. Reduced sample height increases detector solid angle and the probability of simultaneous interaction of cascade photons with the crystal, thereby increasing correction factors.

3.4 Random Coincidence Effects

Random coincidence occurs when photons from different nuclei arrive simultaneously within the HPGe time resolution, registering as a single event and altering full-energy peak counts. Measured correction factors include contributions from both cascade and random coincidence; the former is activity-independent, while the latter depends on sample activity. Random coincidence is typically neglected in environmental sample measurements [17] but becomes significant for high-activity samples measured with high-efficiency, large-solid-angle well-type HPGe. To investigate the activity dependence, correction factors were measured for ^{131}I, ^{134}Cs, and ^{133}Ba standard sources (ø10 mm × 47 mm) at various activities, as shown in [Figure 5: see original paper]. [Figure 6: see original paper] illustrates several random coincidence peaks in the ^{133}Ba spectrum.

For ^{131}I and ^{133}Ba, correction factors increase with activity above ~1000 Bq, remaining constant below this threshold. In contrast, ^{134}Cs shows constant factors below 1000 Bq. Increasing ^{131}I activity from 1300 Bq to 6300 Bq raises the 80.19 keV peak correction factor by 10%, while ^{133}Ba activity increase from 1600 Bq to 27000 Bq enhances the 276.40 keV factor by 20%. Below 1000 Bq, cascade coincidence dominates and random coincidence is negligible; above this level, random coincidence contributions grow progressively due to system time resolution limitations. Under current spectrometry technology, random coincidence must be considered when measuring high-activity samples with well-type HPGe.

Conclusions

(1) When calibrating HPGe efficiency with monoenergetic γ-ray sources, coincidence between ^{139}Ce γ-rays and X-rays can be ignored for detectors with negligible response below 40 keV. However, for well-type and broad-energy HPGe detectors with good low-energy response, the impact of ^{139}Ce standard sources must be verified. Larger detector solid angles and higher detection efficiencies for ^{139}Ce emissions increase coincidence probability and its effect on calibration results.

(2) Few monoenergetic γ-emitting nuclides exist between 150–300 keV, most with short half-lives. ^{139}Ce, with its relatively long 137-day half-life, is commonly used for HPGe efficiency calibration in this energy region where efficiency varies significantly and data points are sparse. Coincidence-induced deviations may be difficult to detect during curve fitting.

(3) For well-type HPGe measurements, smaller sample height does not guarantee higher efficiency. The optimal height for maximum efficiency must be determined experimentally and varies with sample matrix.

(4) When measuring radionuclide activities with large-solid-angle HPGe detectors, coincidence effects significantly impact results and must be corrected based on decay processes and sample geometry. For high-activity samples, random coincidence effects may also require consideration.

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