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Summing coincidence correction for γ-ray measurements using the HPGe detector with a low background shielding system

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A R T I C L E   I N F O

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A B S T R A C T

A Monte Carlo method based on the GEANT4 toolkit has been developed to correct the full-energy peak (FEP) efficiencies of a high purity germanium (HPGe) detector equipped with a low background shielding system, and moreover evaluated using summing peaks in a numerical way. It is found that the FEP efficiencies of ^{60}Co, ^{133}Ba and ^{152}Eu can be improved up to 18% by taking the calculated true summing coincidence factors (TSCFs) correction into account. Counts of summing coincidence γ peaks in the spectrum of ^{152}Eu can be well reproduced using the corrected efficiency curve within an accuracy of 3%.

1. Introduction

The γ-ray spectroscopy using high-purity germanium (HPGe) detectors is widely applied in radiation measurements due to its excellent energy resolution. Moreover, low-background detection systems are developed to suppress the interference from environmental radiations and cosmic rays during accurate measurements of extreme low-activity samples [1]. Detection efficiency determination in such cases is thus crucial for a reliable measurement of low-activity samples. Usually standard sources such as ^{133}Ba and ^{152}Eu are used for the purpose of efficiency calibration [2]. However, one difficulty here is that the cascade gamma-rays in these sources will lead to true summing coincidences due to the short distance between the source and the detector and the narrow space available from the shielding system [3].

When two or more γ rays emitted from the radionuclide are detected within the time resolution of a detector, the true summing coincidence takes place, i.e., these two or more γ rays would be summed and mistaken as one. In recent years, Monte Carlo simulations have been used to correct the summing coincidences [4–6]. High-precision modeling of HPGe detector systems is requested to calculate true summing coincidence factors (TSCFs) and full-energy peak (FEP) efficiencies in the energy range of interest [7–10]. Alternatively, a numerical model was also developed to provide TSCFs for radionuclides [11]. Even spectra of complex decay scheme such as ^{152}Eu can be predicted nicely [12]. Both methods have their restrictions in practice: the first method has to rely on the model optimization with references of FEP efficiencies, which are basically determined from a number of monoenergetic sources, while the numerical approach is hard to extend to cases with complex geometries such as volumetric sources and materials surrounding the detector.

In the present work, we attempt to reduce the dependence of the simulation on monoenergetic sources and meanwhile maintain the accuracy of the calibration process. This method could be applied to activation experiments relevant to nuclear astrophysics with extremely low cross sections [13–15]. Two monoenergetic point-sources ^{241}Am and ^{137}Cs, and three standard point-sources ^{60}Co, ^{133}Ba and ^{152}Eu are used to construct the simulation model of the HPGe detector equipped with the shielding system. The toolkit GEANT4 [16–18] is adapted to simulate the effect of shielding materials around the detector, in which the scattered or induced photons can take part in summing coincidences. Moreover, to inspect the FEP efficiency we developed a numerical approach to calculate the counts of the summing peaks of cascade γ rays.

This paper is organized as follows. After an introduction to our experimental setup in Section 2, we expatiate in Section 3 on the construction process of the simulation model, the calculation of TSCFs and the result of the FEP efficiency calibration. Then the pile-up effect and the numerical examination method with summing peaks are discussed in Section 4. Finally, the conclusion is summarized in Section 5.

2. Experiments

Measurements were taken using a HPGe detector equipped with a low background shielding system. The detector is an ORTEC GEM

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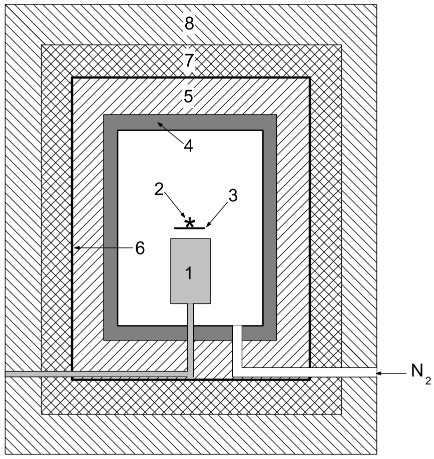

Fig. 1. Schematic of the low-background setup. 1 is the HPGe detector, 2 the source, 3 the acrylonitrile butadiene styrene (ABS) plastic holder, 4 the copper liner, 5 the inner lead ring, 6 the cadmium absorber, 7 the plastic scintillator, and 8 the outer chamber.

Table 1
Dimensions of the HPGe detector and low-background shielding system.

	Component	Dimension (mm)
HPGe	Crystal diameter	85
	Crystal length	79.8
	Lithium diffused depth	~0.7
	Hole diameter	9
	Hole depth	66.2
	Carbon fiber window thickness	0.9
	Detector surface to crystal surface	7
Shields	Outer chamber thickness	115
	Plastic scintillator thickness	100
	Cadmium absorber thickness	1
	Inner lead ring thickness	75
	Copper liner thickness	25
	Copper liner diameter	180
	Copper liner length	500

series P-type coaxial HPGe detector with a 0.9 mm thick carbon-fiber window [19]. Its relative efficiency[1] is 105% for the 1.332 MeV γ-ray (active volume around 400 cm^3) and the energy resolution is 1.84 keV at 1.332 MeV. The key dimensions of the HPGe detector and the shielding system provided by the manufactory are summarized in Table 1.

A schematic view of the whole detector system is shown in Fig. 1. The shielding system consists of following components: (a) an outer support chamber made of lead and steel, it is designed to eliminate most of the low energy background; (b) plastic scintillator detectors as the veto detector for cosmic rays; (c) a cadmium absorber for thermal neutrons; (d) an inner lead ring, which can significantly reduce the influences from samples inside to the plastic scintillators, and its radioactive contamination was 300 Bq/kg measured in 2009; (e) an oxygen-free copper liner surrounding the detector, it can inhibit most of the bremsstrahlung radiations from ^{210}Pb and ^{210}Bi in lead shields and also the γ-induced X-rays. As indicated in Fig. 1, the detector chamber is filled with nitrogen to remove radioactivity from the radon in air.

The veto detector is composed of three parts: the bottom, the well type surrounding the inner lead shield, and the plug for the entrance of samples. 22 HAMAMATSU CR135 photomultiplier tubes (PMT) are used to view the scintillator signals. The anti-coincidence circuit is set up using the single-channel analyzer (SCA) function of a time-to-amplitude converter (TAC) module. The width of the anti-coincidence signal is 30 μs and its counting rate is around 325 s^{-1} during our measurements.

[1] Relative efficiency is respect to the efficiency of a point ^{60}Co source at 25 cm from the face of a standard 3 inch × 3 inch right circular cylinder NaI(Tl) detector.

Table 2
Characteristics of the standard sources used and time of measurements.

No.	Nuclide	Activity (kBq)	Measured time (s)	
			Live	Dead
1	^{241}Am ^{137}Cs ^{60}Co	5.96 (10) 1.07 (2) 1.45 (2)	1000	25
2	^{133}Ba	29.4 (6)	300	76
3	^{152}Eu	19.0 (4)	600	107

The whole detector system provides an overall background counting rate of only ~0.1 Hz within the energy region of 50–3000 keV. This number should be compared with 600–6000 Hz of sources used for efficiency calibrations, thus the background effect was safely neglected in our simulations.

Signals of the HPGe detector were recorded using a multi-channel analyzer (MCA), the ORTEC DSPEC^{PLUS} module [20], which contains an automatic pulse pile-up rejector. ORTEC software MAESTRO version 7 [21] was used to record data. A mixed standard point-source composed of ^{60}Co, ^{137}Cs and ^{241}Am and two point-sources ^{133}Ba and ^{152}Eu were used in measurements. Table 2 lists the activities of different sources and measurement times. All these standard sources were placed on an acrylonitrile butadiene styrene (ABS) plastic holder with a thickness of 2.5 mm, and were 22.1 mm away from the front surface of the detector. The measured γ-ray spectra of three different sources are shown in Fig. 2 with black lines, from which the counts of FEPs were deduced with the analysis software Radware [22].

3. FEP efficiency and correction of TSCF

3.1. FEP efficiency

The FEP efficiency of the HPGe detector, ε, can be calculated by the following equation:

$$\varepsilon = \frac{N}{tAB_\gamma} F_{tsc}, \tag{1}$$

where N is the net counts of FEPs, t the live time of measurements, A the source activity, B_γ the branching ratio of a specific gamma ray and F_{tsc} the true summing coincidence factor.

Generally, if the distance between the source and the detector surface is long enough with respect to the size of the detector surface, and if there are no other objects surrounding the detector, which lead to γ-scattering or γ-induced photons, the parameter F_{tsc} can be safely treated as 1 in Eq. (1). Under the assumption above, the FEP efficiencies were extracted from the measurement spectra, as shown in Fig. 3(a).

A Polynomial function in the log–log scale is usually used to describe the relationship between the FEP efficiency and the γ energy. However, in order to show the attenuation effect in absorbers (e.g., the dead layer and the carbon window) before entering the detector sensitive area, we used the EFFIT program in the Radware package to describe the efficiency curve at the low-energy and high-energy regions separately. The fitting function is:

$$\varepsilon_\gamma = exp\{[(a + bx + cx^2)^{-g} + (d + ey + fy^2)^{-g}]^{-1/g}\}, \tag{2}$$

in which $x = \log(E_\gamma/E_1)$ and $y = \log(E_\gamma/E_2)$, $E_1 = 100$ keV, $E_2 = 1000$ keV and E_γ is in keV. The seven parameters, a to g, were determined by a fit to the data. The values are also listed in Fig. 3.

A fluctuation of data points around the fitting experimental FEP curve can be seen in Fig. 3(a). This can be traced back to the fact that the distance of the source to the detector is only 22.1 mm in our measurements, and the shielding materials are very close to the detector, which can result in true summing coincidences. Therefore, the correction of the true summing coincidence factor is necessary for the FEP efficiency calibration.