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Derivation of an efficiency-calibration simulation for a well-type HPGe detector using the Monte Carlo approach and analytical techniques

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HIGHLIGHTS

- Dependence of full-energy peak efficiency by Monte Carlo simulations was studied.
- Semi empirical model was presented (150–2000 keV) for well type detector.
- Deviations between calculated and experimental efficiencies were less than ±10%.
- Therefore, the simulation model appeared to be acceptable for 150–2000 keV.

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ABSTRACT

Simulation is a simple method that allows for facile estimation of a detector response function when the specifications of the investigated sample and the sample-detector geometry are known. In this study, the dependence of the full-energy peak efficiency on the sample and detector specifications was studied via analytical techniques and the Monte Carlo approach in the energy range of 150–2000 keV for a well-type measuring geometry, and a semi-empirical model was developed. The modeling of the detector efficiency is described in detail. The compute results were compared with experimental data, and comparison of the calculated efficiencies with the measured values indicated that the deviations between the calculated and experimental efficiencies were mostly less than ±10%. Therefore, the simulation model appear to be suitable for routine environmental radionuclide analysis when uncertainties of up to 10% are acceptable for energies between 150 and 2000 keV.

1. Introduction

Gamma-ray spectrometry with germanium detectors is one of the most widely used procedures to determine the radionuclide concentration in any type of sample by allowing a precise quantitative determination. The primary advantage of gamma-ray spectrometry is that the quantitative characterization of gamma-ray emitters can be achieved without application of tedious and skill-intensive sample preparation. To determine the activity concentration of a radionuclide Eq. (1) is used for gamma spectrometric measurements.

$$A = \frac{N}{\varepsilon \times f_\gamma \times t} \quad (1)$$

where N is the number of net counts recorded in the full-energy peak at energy E, t is the effective measuring time, f_γ is the photon-emission probability, and ε is the full-energy peak efficiency (FEPE) at the considered energy E.

The parameters N, t and f_γ can be easily obtained, but the FEPE is the main concern in gamma spectrometric measurements. In practice, the FEPE represents the ratio of the number of photon counts that reach the detector to the number of photons emitted by the source. The ability to accurately obtain the FEPE is of great importance in the correct and reliable determination of the activity of each radionuclide and the quality of the results is strongly dependent on the accuracy of the efficiency calibration of the detector.

Detector efficiency (FEPE) is a complex function of the energy, spectrometer characteristics, source-to-detector geometry, sample geometry and characteristics. In the case of a well detector, the FEPE depends on factors that can be classified into two groups: The first is the intrinsic characteristics of the detector, such as the active crystal volume, detector geometry and surrounding materials. The

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second is the measurement geometry, such as the detector-sample positioning, sample geometry, and physical and chemical characteristics of the sample under study, such as geometrical dimensions, particle size, density, and chemical composition.

The FEPE can be obtained experimentally by measuring large number of primary standard sources at numerous energies that have very similar geometrical dimensions, source configurations and chemical–physical specifications to those of the sample of interest. However, such primary standard sources, if available at all, are costly and would need to be periodically replaced, especially for radionuclides with short half-lives. Thus, in practice, it is not always possible to use ideally matched sets of samples and standards. In addition, calibrated gamma-ray sources can be prepared for all the geometrical arrangements used in gamma-ray spectrometry (IAEA, 1989), but this method incurs high financial cost and requires considerable, time and material for the preparation of the sources. To properly determine the FEPE, the relevant correction factors (photon attenuations in all types of pathway materials, coincidence-summing, dead time, etc.) must also be considered for each sample matrix and geometry. When calibration standards with same geometry as the samples as well as, similar sample properties and activity concentrations are available, the comparison method is the preferred method. This method is based on comparison of the sample peak area at the energy of interest to the area of the standard source peak at the same energy. Using the comparison method, it is possible to ensure the determination of a correct and precise FEPE value.

Because of the problems encountered in experimental methods, the determination of the FEPE has been a long-standing problem, and there is no single, universal method of efficiency calculation. Several authors (Abbas et al., 2006; Arnolda and Sima, 2004; Garcia-Talavera et al., 2000; Helmer et al., 2003; Karamanis et al., 2002; Laborie et al., 2000; Lepy, 2007; Pommé, 2004; San Miguel et al., 2004; Schoenfeld et al., 2002; Vidmar et al., 2001a, 2001b) have proposed and applied various non-experimental methods of FEPE determination and have provided useful solutions for overcoming these problems.

It has become common practice to use analytical and mathematical modeling methods, mostly commercial simulation programs, as an alternative to experimental efficiency-calibration methods. In addition, various modeling methods that require an abundance of mathematics and computer-programming knowledge can offer improvements with respect to commercial efficiency-calculation programs. Simulation is the numerical modeling of a real system using its inputs and outputs and the transferral of this model to computer media for investigation in multiple situations. Properly planned simulations yield information concerning system performance much more quickly, accurately and inexpensively than do experimental methods. Thus, interactions between system variables and systems can be investigated and numerical results can be obtained without the necessity of preparing a variety of real systems.

A survey of FEPE studies has indicated that the use of computer codes based on Monte Carlo simulation is an effective approach that complements the use of experimental efficiency-calibration procedures in gamma-ray measurements (Bochud et al., 2006; Ewa et al., 2001; Hemler, 2003; Hemler et al., 2004; Hernandez ve Daoushy, 2003; Laborie et al., 2000; Nedjadi et al., 2007; Garcia-Talavera et al., 2000; Vargas et al., , 2002, 2003). Monte Carlo methods are a practical tool that allows, an experiment to be reproduced numerically using statistical techniques and the efficiency values for various measurement conditions to be calculated within a short time. Nevertheless, the accuracy of such simulation techniques must be evaluated before incorporating them into the laboratory routine. Several comparisons of the responses of high-resolution gamma-ray spectrometers with the results of commercial Monte Carlo programs have been published. Most authors have reported agreement with the experimentally obtained efficiency values within 10% (Abbas, 2006 – agreement greater than 96%; Bochud et al., 2006 – agreement greater than 94%; Ewa et al., 2001 – agreement greater than 88%; Hemler, 2003 – agreement 99.8%; Helmer et al., 2003 – agreement 99.9%; Hemler et al., 2004 – agreement 99.6%; Laborie et al., 2000 – agreement greater than 85%; Garcia-Talavera et al., 2000 – agreement greater than 96.7%; Vargas et al., 2002 – agreement greater than 98%; Vargas et al., 2003 – agreement greater than 95%).

In the present work, we developed a simulation program using analytical modeling techniques and Monte Carlo principles to calculate the FEPE of a well-type HPGe detector. The proposed method combines mathematical modeling methods and certain simulation techniques.

In the simulation, the photo-electric-effect type of gamma-ray interaction was considered, and a custom simulation program for HPGe detectors was prepared instead of using commercial Monte Carlo code. The self-absorption and absorption efficiencies of the detector were calculated using Monte Carlo logic and principles. In addition, analytical models were developed for various geometric arrangements because the analyzed radioisotopes could be positioned randomly throughout the sample. Thus, many position vectors were investigated by the program for a given radioisotope, and the results were used by the efficiency-calculation program. In the developed program, the training parameters could be modified for different situations because all code was written by us using the MATLAB programming language. Our program is a novel program for the efficiency calibration of gamma detectors since there is no other study presented in the literature in which MATLAB is used as the programming language for the same purpose.

The results were compared with experimental data and literature values. The accuracy of the method is discussed at the end of this paper.

2. Experimental

2.1. Experimental set-up

Accurate data for the detector parameters and source-to-detector arrangement are important to ensure the compatibility of experimental results with simulated results. In our studies, an ORTEC HPGe well-type detector with a crystal volume of 110 cm^3 was used for experimental measurement of the FEPE and modeling studies. The detector had nominal FWHM resolutions of 0.90 keV at 122.07 keV and 1.92 keV at 1332.5 keV, and the resolution of ^{60}Co at 1.33 MeV was 3.78 keV. The detector was connected to conventional electronic components with an amplifier gain of 21.25 and a shaping time of 6 μs. The detector had a crystal height and diameter of 50 mm and 75 mm, respectively. The well depth was 54 mm, and the diameter was 33 mm. The detector was shielded with electrolytic copper of 0.5 cm and lead of 10 cm. A technical drawing of the source-detector geometrical arrangement and the physical characteristics of the detector is provided in Fig. 1.

2.2. Experimental photopeak efficiency

The photoelectric-effect interaction of gamma rays was considered for the experimental efficiency calculations, which were performed by investigating the photopeaks of the spectra. Experimental data points for the FEPE of the detector were obtained using a mixed tube standard source placed in the detector well that was emitting photons with various energies in the region between 150 and 2000 keV. The standard was obtained from Isotope Product