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Development of a stochastic detection efficiency calibration procedure for studying collimation effects on a broad energy germanium detector

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ABSTRACT

ISPRA, the Italian nuclear safety regulatory body, has started a measurement campaign for validating the performances of in situ gamma-ray spectrometry based on BEGe detectors and ISOCS software. The goal of the validation program is to verify if the mathematical algorithms used by Canberra to account for collimation effects of HpGe detectors continue to work well also for BEGe detectors. This has required the development of a calibration methodology, based on MCNPX code, which, by avoiding any mathematical algorithm utilization, is purely stochastic.Experimental results obtained by such a new procedure, were generally found to be 5% of the reference values. While, in the case of gamma-ray energies greater than 400 keV and small angles collimation, results given by ISOCS software produced larger deviations, around 20%. This work presents a detailed description of the simulation procedure and of the first experimental results.

1. Introduction

In many operative situations that require immediate radiometric characterization, in situ gamma-ray spectrometry represents an ideal technique for providing, directly on site, radionuclide concentrations and other related quantities, such as activities per unit area and exposure rates. The potentialities of such a technique have been strongly enhanced by the introduction of BEGe detectors, which allow an extended assay energy range from 3 keV to 3 MeV in the same measurement, by combining the spectral advantages of low energy and coaxial detectors. Furthermore, software tools based on mathematical models aimed at simulating a wide variety of sample shapes eliminate the need of radionuclide standards for detector's efficiency calibration. Summing up, it is expected that a portable system composed of a broad energy germanium detector, a detector holder, a nuclear electronics workstation, and a laptop PC implementing spectrum analysis and calibration software, should be able to face almost every in situ situation, mostly in decommissioning operations of nuclear installations. For this work, a portable gamma-ray spectrometry system provided with a BE3825 Canberra detector [1] and with ISOCS™ software [2] was considered.

As described by Venkataraman et al. [3,4] the ISOCS calibration method is based on a detailed Monte Carlo model of a specific germanium detector created using the nominal dimensions provided by the production facility. The detector model is validated by comparing Monte Carlo detection efficiencies to measured efficiencies for several source geometries and at a range of energies. These two efficiency data sets are then meshed together into a single characterization file, which contains a series of equations defining the detector response which are then implemented in the ISOCS software.

When operating with portable systems in in situ conditions, the typical scenario is characterized by the contemporaneous presence of many spatially distributed radioactive sources; a direct consequence of such a situation is the need to reduce the detector's field of view by proper collimation. Obviously, the consequent detection efficiency modifications introduced by changing detector collimation should be taken into account by the ISOCS software. Introducing corrections for collimation effects on detection efficiency may be a not easy solution task. For instance, Venkataraman and Bronson [5] point out that in earlier version of ISOCS (up to Version 1.2b) the uncertainty in the efficiency calibration for collimated geometries was larger than that for non-collimated geometries. This defect was then corrected, and for more recent ISOCS versions Canberra has designed and tested for accuracy improvements, and minimal computational speed degradation, a series of collimator algorithms to be used with germanium detectors. Venkataraman and Bronson [5] reports that accuracies of both collimated and uncollimated

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detector efficiencies are about 4–5% (1σ) at photon energies >150 keV, and 8–10% at energies <150 keV. Anyway, the ISOCS (Version 4.0) validation manual [6], reports that, in some cases, when small aperture collimators are involved, deviations as much as 22% from reference values may appear.

A nuclear safety regulatory body may judge such a magnitude uncertainties unacceptable. Such an assessment can be understood just on the basis of the peculiar advantages of in situ gamma-ray spectrometry respect to laboratory gamma-ray spectrometry, that can be summarized by the words of Benke and Kearfott [7]: "The possibility to characterize larger volume of materials, of requiring less time to determine accurate radionuclide concentrations, and of minimizing worker doses and the risk of radioactive contamination". Further, making errors around 20% can be harmful not only for wrong estimations of workers' doses and radioactive contaminations, but also when discriminating between radioactive wastes and clearable materials.

Starting from these assumptions, ISPRA, the Italian High Institute for Environmental Protection and Research, has initiated a task to validate the performances of recently acquired ISOCS system with a BEGe detector; in particular, the target is to verify if collimator algorithms of ISOCS Version 4.0 software, originally developed for HpGe detectors, remain still valid for BEGe detectors within the whole energy range that this kind of detectors can assay. Such a validation task is based on experimental measurements of reference sources carried out by the ISOCS hardware, ISOCS software, and by an original stochastic calibration procedure based on MCNPX™ [8].

The MCNPX calibration procedure developed for this work includes stochastic models for both detector and collimator, hence it represents a novel contribution respect to ISOCS characterization software, because it does not use algorithms for taking into account the additional attenuation due to the collimator. Making use of such a pure stochastic calibration procedure allows to obtain measured results that, without and with collimation, are generally within 5% from reference values.

2. Monte Carlo simulation of the detector

Monte Carlo simulation of gamma-ray radiation detectors is a powerful tool for determining detection efficiency in many measurement configurations, even if, as focused by many authors, it requires a thorough knowledge of structural characteristics of the detectors. As pointed out by Décombaz and Laedermann [9] such a requirement may be simply accomplished for NaI detectors, for which only dimensions and materials of the crystal and housing must be accurately known. On the other hand, for germanium detectors the determination of geometrical parameters can be extremely complicated as a larger number of dimensions are involved. For instance, Vargas et al. [10], dealing with a coaxial n-type HpGe detector, describe seven main parameters: diameter and height of the crystal, diameter and height of the internal core, thickness of the beryllium window, distance between the crystal top and the Be window, and the thickness of the dead layer of Ge. Bochud et al. [11] consider that notwithstanding manufacturers usually document geometrical dimensions, the associated uncertainties, that may play a fundamental role in the quality of the simulation, are not very well known. Rodenas et al. [12] emphasize how the dead layer thickness [13] plays a non-negligible role in accurate Monte Carlo simulations. Due to the impossibility of performing physical measurements of the extension of the dead layer, in Monte Carlo detector simulations this value is tuned from experimental measurements; an accurate description of such a sensitivity analysis is given by Luis et al. [14]. Having described accurately the detector's internal structure and the experimental set-up, it is possible to obtain calculated detection efficiencies that generate measured activity values from net peak areas of gamma-ray spectra [11,12].

For this work a Broad Energy Germanium detector has been utilized and for this kind of detectors simulation is even more complicated due to the presence of two dead layers: the top dead layer and the lateral one. It is a planar p-type High Purity Germanium detector, [13], with the Li-drifted n^+ contact covering the whole outer surface, and a small p^+ contact on the back side. The top n^+ contact is very thin to reduce absorption of low energy gamma rays. Accurate descriptions of this kind of detector are given by Luis et al. [14], Mueller et al. [15], Budjas et al. [16], and Barrientos et al. [17]. In particular, we used the BE3825 Canberra model, characterized by 28% relative efficiency, and values of full width at half maximum (FWHM) of about 0.72% at 122 keV and 1.978% at 1333 keV [1].

Structural characteristics of the detector were derived from manufacturer's data sheets and from Gonzalez et al. [18]. As dead layer values are concerned, the usual operation of preliminary tuning vs. experimental data was carried out, which allowed to obtain practically the same results reported in [18]. Figs. 1 and 2 give an idea of the degree of detail of the simulation. Obtained by means of MCNPX Visual Editor [19], Fig. 3 gives a three-dimensional view and highlights the germanium crystal as well as the carbon epoxy window, the copper crystal holder, and the aluminum end cap assembly.

Simulation of the detector was carried out using MCNPX version 2.7.0 [8], by trying to account for those composing sections that influence the detection efficiency.

2.1. Simulation technique

With the aim to obtain a simulated gamma-ray spectrum, the output of the simulation was given in terms of the Pulse Height Tally F8 [8], i.e. the tally reproducing the energy distribution of pulses created inside the detector by radiation. Tally F8 has many options. The standard F8 tally is a pulse-height tally and the energy bins are no longer the energies of scoring events, but rather the energy balance of all events in a history. When flagged with an asterisk, *F8 becomes an energy deposition tally.

To improve simulation of the gamma-ray spectrum, the Gaussian Energy Broadening (GEB) option was adopted. GEB is a special feature, activated by entering the FT card [8] in the input file, which reproduces the Gaussian fluctuation that a single

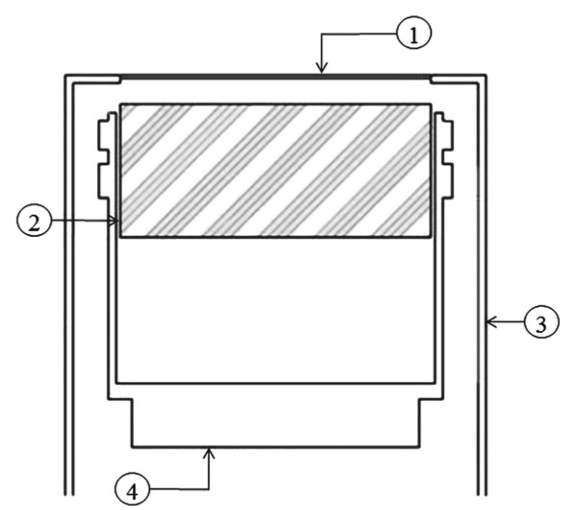

Fig. 1. Schematic view of the detector assembly, Carbon epoxy window (1), gap between crystal and crystal holder filled with thick plastic insulator all around the crystal (2), aluminum end-cap (3), and copper crystal holder (4).