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Experimentally determined vs. Monte Carlo simulated peak-to-valley ratios for a well-characterised n-type HPGe detector

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HIGHLIGHTS

- The MC description of the detector was important when calculating the PTV ratio.
- The MC calculated PTV differed significantly compared to measured PTV ratio.
- More detailed simulations gave less agreement to measured values.

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ABSTRACT

Measurements and simulations to investigate the contributing factors to the peak-to-valley (PTV) ratio have been both experimentally determined as well as Monte Carlo simulated for a well-characterised HPGe n-type detector together with a Cs-137 gamma source encapsulated in thin polystyrene. Measurements were carried out in a low-background gamma counting facility at Lund University. The results of the PTV ratio have been compared to distinguish what components or variables in the setup that significantly influence the ratio. In addition to manufacture specifications, the detector components have been examined using planar X-ray, source scanning and computer tomography in order to determine and verify component dimensions when necessary. In spite of these efforts a discrepancy of approximately 25% for thin absorbers in the PTV ratio between measurements and calculations is observed. However, this discrepancy becomes less significant for larger absorbing layers of copper (> 1 mm). This indicates that it would be difficult to achieve a field calibration for in-situ gamma spectrometry using the PTV ratio that could position a Cs-137 source in soil depth shallower than corresponding 1 mm layer of copper. The results also showed that when building a detector in simulations part by part, the inner dead layer, and the contact pin are of great importance for the accuracy of the PTV ratio simulations.

1. Introduction

Radioactive fallout as a result of a detonation of nuclear weapons or an accident at a nuclear power plant has serious effects on society, especially in the production of food. It is important to know whether the activity has penetrated the soil and started to migrate downwards, or if it is to a large extent still found on the ground vegetation. This information provides authorities with the basis for decision-making and dose predictions. Beck et al. (1972) introduced an in situ method of determining surface deposition using high-resolution gamma spectrometry based on the assumption that the radioactivity is distributed evenly or exponentially throughout the topsoil.

The peak-to-valley (PTV) method was first proposed by Zombori et al. (1992). The peak region of interest (ROI) corresponds to the ^{137}Cs full energy peak and the valley ROI corresponds to ^{137}Cs photons scattered in the soil, air and the materials surrounding the detector. The valley ROI should be selected in the energy region between the full energy peak and the Compton escape edge. Zombori et al. (1992) calculated the ratio between the net peak area and these valley counts as a way of estimating the penetration depth of the ^{137}Cs in radioactive fallout (Zombori, 2012, 2013). Several others have used this method and evaluated the feasibility in different situations (Feng et al., 2009; Gering et al., 1998; Hjerpe and Samuelsson, 2002; Kastlander and Bargholtz, 2005; Panza, 2012; Lemercier, 2007; Tyler, 2004). The contribution in the valley ROI is dependent of detector characteristics, and to further develop the PTV method, a better understanding of contributing factors is necessary.

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The aim of this study was to investigate how the PTV ratio is affected by detector characteristics (material, geometry, etc.) by comparing measurements carried out under optimised laboratory conditions with Monte Carlo calculations.

2. Theoretical outline

The PTV ratio is defined in Eq. (1), where E_γ is the energy of the peak, and ROI_{peak} is the number of net counts in the full energy peak. ROI_{Valley} is the number of counts in a selected ROI in the spectrum between the full energy peak and the primary Compton escape edge Δ (where Δ is defined in Eq. (2).) and n is the lower energy limit and a *is* the width of the chosen valley ROI. FWHM in Eq. (1) is the full width at half-maximum obtained in the spectrum, specific for the settings of the electronics and intensity of the photon radiation field. k is a detector-specific variable, determined by investigating the photo peak in the spectrum and in the current study with the specific settings of the electronics, k was set to 1.54.

$$\mathrm{PTV} = \frac{\mathrm{ROI}_{\mathrm{Peak}}[E_\gamma - k\bullet\mathrm{FWHM},\ E_\gamma + k\bullet\mathrm{FWHM}]}{\mathrm{ROI}_{\mathrm{Valley}}[n,\ (n+a)]\mathrm{keV}} \quad (1)$$

$$\Delta = E_\gamma\left(1 - 2\frac{E_\gamma}{(m_0c^2 + 2E_\gamma)}\right) \quad (2)$$

The PTV ratio will be dependent on the depth of the radionuclide of interest. If the radionuclide is distributed in the ground material after a fallout it is expected to be concentrated to the uppermost layer. Therefore the distribution of the radionuclide is frequently approximated by a single exponential distribution, which can be described with the expression:

$$A_{\mathrm{m}}(\zeta) = A_{\mathrm{m}}(0)e^{-(\zeta/\beta)} \quad (3)$$

where the depth (ζ) is described as the mass of material per unit area down to depth z, β is the relaxation mass per unit area, and $A_{\mathrm{m}}(0)$ is the activity per unit mass at the surface. The mass depth, ζ can be expressed as follows:

$$\zeta = \int_0^z \rho(z')dz' \quad (4)$$

where $\rho(z)$ is the material density as a function of depth (Beck et al., 1972; Zombori et al., 1992).

To experimentally determine the influence of various components on the PTV ratio, the most basic geometry was studied, which comprises: i) a point source in air, ii) a detector with well-known dimensions, and iii) a low, almost constant background. The optimum choice of the valley region is a ROI with little or no influence from natural radionuclides. When the natural background has been subtracted, the counts in the valley region would purely be Compton-scattered photons originating from any material between the source and the sensitive part of the detector. Monte Carlo computer codes allow the modelling of a specific environment and evaluation of the detector response for a specific situation. The influence of different parts of the real detector can be investigated by changing the geometry in the Monte Carlo simulation, to determine which parts of the detector that must be described accurately in order to calculate a more precise PTV ratio.

3. Experimental materials and methods

3.1. Reference source and HPGe detector characteristics

An ORTEC GMX series n-doped, beryllium-windowed HPGe detector (SN: 42-N21758A), with an efficiency of 18% relative to a 76.2 mm by 76.2 mm sodium iodide detector at 1332 keV, was used in the experiments. The mono-energetic gamma photon emitter ^{137}Cs was chosen as the source for PTV ratio measurements. The 39.7 kBq ^{137}Cs source (US Dept. of Commerce, National Bureau of Standards, SRM 4200B-109) was a plated source between two very thin polystyrene films minimising scatter and attenuation. ^{137}Cs has a single gamma decay with an energy of 661.7 keV (N_γ=0.85), and two 32 keV X-rays ($N_{\gamma tot}$=6.8%, (Chu et al., 1999). The detector was connected to an ORTEC Dspec^{plus} multichannel analyser (MCA), which was in turn connected to a laptop running the ORTEC Maestro v. 6.09 software. According to the manufacturer's specifications, the detector crystal has a length of 78.3 mm and an outer cylindrical diameter of 45.1 mm. The bulletised crystal is mounted in an endcap with a beryllium window with a nominal thickness of 0.5 mm. The detector is equipped with a transistor-reset pre-amplifier well suited to handle high-count rates and the rise-time in the settings of the preamplifier was set to 4 μs (Twomey et al., 1991). Investigations of the detector made prior to the present study showed no significant effects on the PTV ratio caused by incomplete charge collection or pile-up up to 35% dead time, other than equivalent loss of counts in both the full energy peak and the valley. Nevertheless, the dead time was kept below 2% in this study.

3.2. The LBC facility and evaluation of the gamma radiation background

All measurements were carried out at the low background counting (LBC) facility at Skåne University Hospital located in Lund in Sweden. The characteristics of the LBC facility are described in detail elsewhere (Naversten et al., 1969). Prior to the PTV ratio measurements, the gamma radiation background in the LBC facility was evaluated. Measurements were divided into 3-h periods, to evalutate the concentration of radon decay daughters in the indoor air supplied by the indoor venting system during varying weather conditions.

3.3. Rotational symmetry of the HPGe detector

The rotational symmetry and integrity of the HPGe detector were evaluated by measurements before starting the PTV ratio measurements. It was found by radiographic imaging that the crystal was not centred in the mount cup (Fig. 10), creating a slight deviation from the assumed symmetric geometry (see Fig. 3). These measurements were performed with a 0.73 MBq ^{125}I point source in the form of a seed developed for brachytherapy. A lead collimator with a 75 mm long hole of 1.5 mm diameter was used to collimate the 35 keV photons (N_γ=6.68%, Chu et al., 1999), to obtain an estimate of the detector crystal surface sensitivity. The distance between the endcap and the source was 80 mm. The live acquisition time was set to 600 s and the detector was connected to its mother cryostat during these measurements. The detector was maintained at liquid nitrogen temperature during these measurements and during all PTV ratio measurements to avoid undesired temperature cycling effects. Three measurements were carried out along the sides of the detector endcap, separated by 120° and 3 mm steps along the z-axis (Fig. 1). An additional scan was also made across the beryllium window. A xyz-coordinate board was used to align the ^{125}I source to minimise the effects of position uncertainties, i.e. source displacement to less than 0.1 mm.

3.4. Determination of PTV for different Cu sheets

The set-up was made as close to ‘free in air’ as possible using a 3 cm thick, 60 cm wide and 120 cm long Styrofoam™ board supported by a thin aluminium table frame. The source-to-endcap