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Cascade summing effects in close geometry gamma-ray spectrometry

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Abstract

Low-level gamma-ray spectrometry, particularly in underground laboratories, is used to measure radioactivity in diverse close geometries, often placing samples directly on the detector which favours strong cascade summing effects. Monte-Carlo modelling of the efficiency is extended to cascade summing effects from complete decay sequences including positron emitting radionuclides. The effect of geometrical uncertainties on the overall uncertainty is presented. The results reinforce the need for radiography of the detector and inclusion of the detector shielding in the model.

Keywords: Low-level; Gamma-ray spectrometry; ^{106}Ru; ^{26}Al; Cascade summing; True summing; EGS4; Monte-Carlo simulations

1. Introduction

Gamma-ray spectrometry measurements in underground laboratories provide the capability of quantifying very small levels of radioactivity in diverse samples. The samples are of diverse form—in terms of geometry, materials and radionuclides encountered. The greatest sensitivity is achieved by having the largest available sample close to the detector. This results in a different geometry for each sample. The only practical method for efficiency calibration of these diverse samples is Monte-Carlo (MC) modelling.

Efficiency calibration of gamma-ray spectrometers by MC modelling has a long history (Miller et al., 1957) and is increasingly widely used for gamma-ray detectors' calibration and cascade summing correction calculations (Nakamura and Suzuki, 1983; Garcia-Torano et al., 2005). The MC method is based on the simulation of radiation transport. Each photon is tracked along its path from its origin inside the source to the detector. All photon interactions are included and secondary photons and any secondary particles created are also tracked. By tracking radiation showers, the energy deposited in the active volume of the detector is computed for a large number of emitted photons providing an estimate of the response function and thus the full energy peak efficiency as a particular result.

Many radionuclides emit cascades of radiations that allow simultaneous detection of energy from several radiations—coincidence summing. The extension of the modelling of single photons to whole decay cascades is straight-forward. Instead of considering photon emission sites, we now consider decay sites from which a sequence of radiations is emitted. There is greater complexity in a decay cascade than in the emission of one or even a sequence of photons because there are branching processes possible at each step of the cascade.

The cascade is divided into a series of stages. The first stage involves the emission of an alpha-particle, electron or is an internal or isomeric transition. The subsequent stages are handled as gamma-decays from excited states to states of lower excitation or the ground state. Alpha-particles and negatrons are normally ignored in the model. Each stage of the cascade is modelled as arising from the same decay site but the directions of emission are modelled as uncorrelated. Neglecting directional correlations between cascade stages is a simplification adopted in this work. Positrons are modelled using the average particle energy for the transition. The model additionally allows for internal conversion processes and K X-rays that result from them.

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2. Problems in Monte-Carlo modelling of coincidence summing corrections

2.1. What the detector supplier can and cannot tell you

The general approach involves the characterisation of the geometry and materials of the detector, the sample and their surroundings so that the efficiency can be computed. The detector is characterised using (i) the detector supplier's information about the detector, (ii) radiography of the detector and (iii) experimentally determined parameters.

The detector supplier can provide detailed specification of the materials that have gone into the detector manufacture and the processes by which the detector was produced. The manufacturer can provide dimensions of the objects inside the cryostat at the time of assembly at room temperature. However, the manufacturer is generally not able to specify the final position at which the crystal is located when it is cooled to liquid nitrogen temperatures because the mechanical support for the crystal changes due to stress and contractions upon cooling. The other parameters which need to be experimentally determined are the deadlayers on the detector crystal.

Once the detector has been characterised, the source similarly needs to be characterised and its position relative to the detector determined. These data allow the modelling of the full energy peak detection efficiency for the diverse range of samples encountered in this work. It is useful to use Monte-Carlo model even if reference sample is available because there are often small differences between geometry and matrix for different samples.

2.2. Radiography

Radiography is an important tool in the creation of an appropriate Monte-Carlo model. In Fig. 1, a radiograph of a coaxial HPGe-detector with 60% relative efficiency (Ge-3) is shown. The radiograph provides information that is not obtainable by other means, e.g. the distance from the crystal face to the detector endcap face, which is a critical dimension for solid angle. The detector has rounded front corners which complicate the modelling and the detector is tilted 1° in x-direction and 2° in the y-direction.

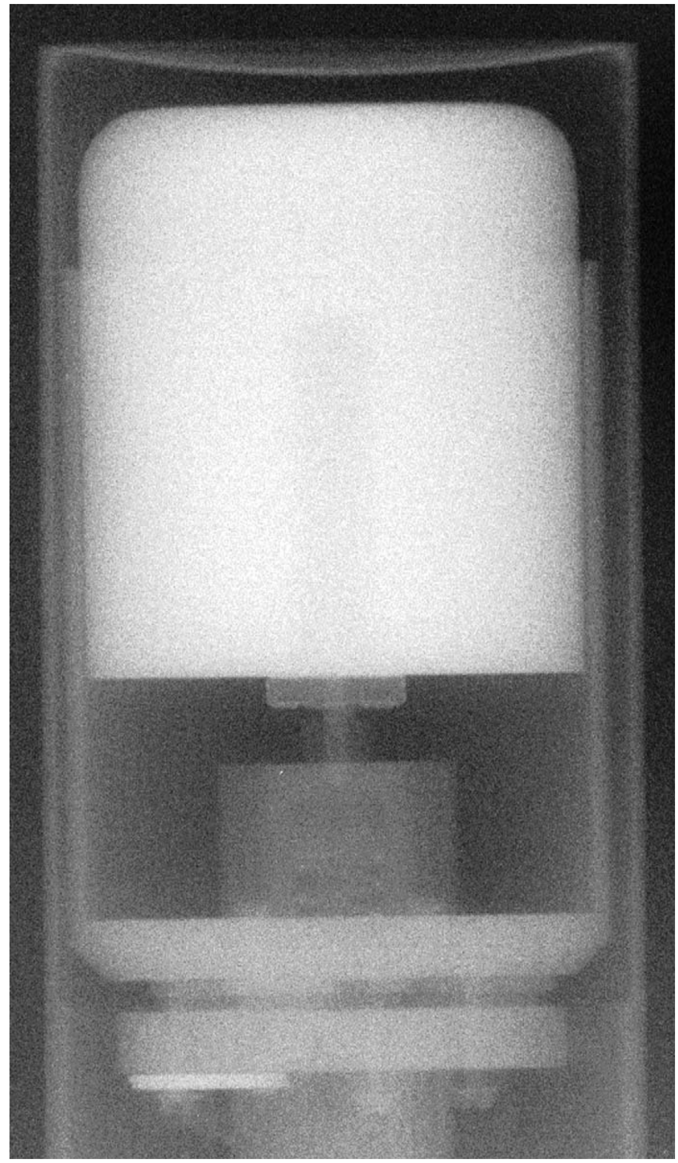

Fig. 1. Radiograph of "Ge-3", which is a coaxial p-type HPGe detector with a crystal radius of 3.291 cm and length of 7.54 cm. The re-entrant is not clear in this figure but can be seen by changing brightness, etc. Normally the values for the re-entrant given by the manufacturer are sufficiently accurate.

2.3. Positron emitters

In the underground laboratory HADES (Hult et al., 2003), measurements involving positron-emitters have been important amongst radionuclides with significant coincidence summing and present two major issues. Firstly, the positron can travel a non-negligible distance before annihilation. This is primarily an issue for very thin samples or samples with the activity in one surface, e.g. activation targets from JET (Gasparro et al., 2006). In this case the sample may be covered by a layer to cause the positrons to annihilate locally. Secondly, the two annihilation quanta go in opposite directions doubling the efficiency for losing energy in the detector and causing coincidence loses.

2.4. Shielding

In practice, the full energy peak efficiency for a single photon emitter is only very weakly dependent on the detector surroundings as scattered radiations have little chance of contributing to the full energy peak. For coincidence summing, scattered and secondary radiations that reach the detector are just as effective for generating summing losses as unscattered photons and may be much more abundant. This means that the surrounding spaces of