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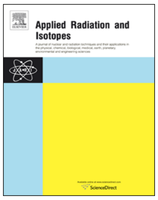

Determination of the shielding factors for gamma-ray spectrometers

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HIGHLIGHTS

- A model is described to assess shielding factors for gamma-ray spectrometers.
- The background due to the detector, shield and ambient radiation must be known.
- The sample attenuation, its dimensions and distance from the crystal are considered.
- Shielding factors for gamma-rays from the ^{232}Th and ^{226}Ra decay chains are assessed.
- For a water sample with a mass of 0.25 kg, shielding factors above 0.88 are obtained.

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ABSTRACT

A method for determining the shielding factors for gamma-ray spectrometers is described. The shielding factors are expressed by decomposing the peaked background of the spectrometer into contributions of the detector, spectrometer shield and ambient radiation to the spectrometer background. The dimensions of the sample and its mass-attenuation coefficient are taken into account using a simple model. For six spectrometers, with contributions to the background quantified, the shielding factors were determined for the background based on the thorium decay series and the radon daughters. For a water sample with a diameter of 9 cm and a thickness of 4 cm and the nuclides of the thorium decay series that are in the spectrometer shields, the values of the shielding factors lie in the interval 0.95–1.00. For a spectrometer exhibiting the diffusion of radon into the shielding material, the values of the shielding factors for the same sample for gamma-rays from the radon daughters lie in the interval 0.88–1.00.

1. Introduction

Shielding factors describe the influence of a sample on the spectrometer peaked background. The standard ISO 11919 (ISO, 2010) defines the shielding factor as the ratio of the background peak count rate in the presence of the sample, i.e., the background count rate attenuated in the sample matrix, and the background peak count rate in the absence of the sample. Since in the spectral analysis the background count rates must be subtracted from the peak count rates in the sample measurement, for each peak in the background spectrum its specific shielding factor must be determined, depending on the source of the background and the peak energy.

In gamma-ray spectrometry, three sources contribute to the background: the detector, the shield of the spectrometer and the ambient radiation penetrating the shield. The sample matrix attenuates the background radiation with the exception of the contribution of the detector contamination; therefore, the attenuation factors depend on the counting geometry and the sample material. In this contribution we show how to determine the attenuation factors as functions of the detector and sample parameters.

2. Materials and methods

The attenuation factors were assessed for six spectrometers with vertically positioned gamma-ray detectors. The properties of the spectrometers, located in a basement, are presented in Table 1. The cavities of the spectrometer shields are flushed with radon-free nitrogen to minimize the background of the radon daughters. The backgrounds of the spectrometers due to the members of the thorium and uranium decay chains were characterized (Bučar et al., 2012; Korun et al., 2012; Maver Modec et al., 2012); therefore, the location of the sources of the background and their contributions to the count rates in the background peaks were known.

The location of radionuclei that emit gamma-rays in a broad energy range can be inferred from the energy dependence of their apparent activity (Bučar et al., 2012; Korun et al., 2012; Maver Modec et al., 2012). The apparent activity of the nuclide i at an

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Table 1
Characteristics of the detectors according to the manufacturer's data and the thickness of the spectrometer shields. *r*, *H* and *h* denote the radius of the detector crystal, its thickness and the distance from the detector cap, respectively.

Spectrometer	*r* (cm)	*H* (cm)	*h* (cm)	Material of the shield	Total shield thickness/(cm)
D1	2.8	4.8	0.5	Iron	15
D2	3.03	5.88	0.5	Lead	16
D3	2.55	5.7	0.5	Lead	12
D4	3.2	4.8	0.5	Paraffin: 10 cm Lead: 12 cm	22
D5	2.94	6.92	0.5	Mercury: 1 cm Lead: 10 cm	11
D6	3.16	6.91	0.4	Mercury: 1.2 cm Lead: 10 cm	11.2

energy *E* is calculated as

$$A_i(E) = \frac{\dot{N}(E)}{I_{\gamma i}(E)\varepsilon(E)} \tag{1}$$

where $\dot{N}(E)$ denotes the count rate in the peak of energy *E*, $I_{\gamma i}(E)$ is the emission probability of a gamma-ray with energy *E* in the decay of a radionucleus *i* and $\varepsilon(E)$ is the probability for registration of the emitted gamma-ray in the full-energy peak. Since the location of the decaying nucleus is not known, neither is the efficiency, but if for $\varepsilon(E)$ the efficiency of a non-attenuating source is used, the energy dependence, which originates in the detector properties, is taken into account to a large extent and the energy dependence of $A_i(E)$ reflects only the energy dependence due to the attenuation of gamma-rays between the emission point and the detector. It then follows that the contamination of the detector cap and its interior results in an apparent activity, which does not depend on energy. It is easy to see that the contamination of the shielding material induces an energy dependence, which exhibits a slow increase at low energies (Bučar et al., 2012), whereas the penetration of the gamma-rays through the shielding material with a high atomic number increases sharply the apparent activity at the highest energies (Maver Modec et al., 2012).

The apparent activity of the background from the nuclide *i* is the sum of three contributions,

$$A_i(E) = A_{iD}(E) + A_{iS}(E) + A_{iA}(E) \tag{2}$$

where $A_{iD}(E)$, $A_{iS}(E)$ and $A_{iA}(E)$ denote the contributions of the detector, shield and ambient, respectively. The apparent activity due to the contamination of the detector is not affected by the sample. The effect of the sample on the other two contributions to the background can be assessed as follows.

2.1. Contribution of the shield contamination

Since the shielding material surrounds the sensitive volume of the detector from all directions, it can be assumed that the gamma-rays impinge on the detector isotropically. Then, for a cylindrical sample with radius *R*, which is smaller than the radius of the crystal *r*, that is placed coaxially with the symmetry axis of the detector, it can be supposed that the efficacy of the shielding of the crystal front surface is proportional to R^2/r^2 and that no shielding of the crystal mantle takes place. Samples with a radius exceeding the radius of the crystal shield the front surface of the crystal completely and partially also shield its mantle. The efficacy of the shielding at a point on the crystal mantle at a distance *x* from the sample is proportional to the solid angle $\Omega(x)$ that the part of the sample extending over the detector crystal subtends from *x* (Fig. 1). Here, for assessing $\Omega(x)$, the area of one half of the disc extending over the horizon is used. The disc with the radius $R-r$ is centered at *r* from the symmetry axis and $\Omega(x)$ is approximated by the solid angle subtended by the one half of the disc from the distance *x* (Debertin and Helmer, 1988):

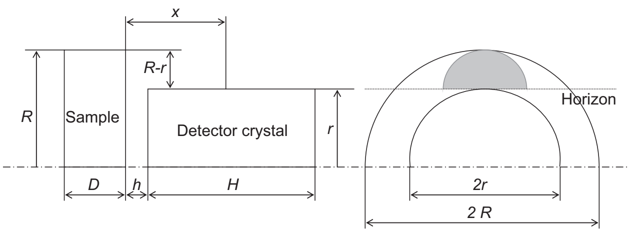

Fig. 1. Schematic presentation of the geometry of the sample and detector crystal. See text for the description of the distances indicated.

$$\Omega(x) = \pi\left(1 - \frac{1}{\sqrt{1+(R-r)^2/x^2}}\right) \tag{3}$$

This approximation underestimates the solid angle where it is small, i.e., at small values of $R-r$ and at large values of *x*, since here a segment with the height $R-r$ of a disc centered on the detector axis is approximated with the one half of the disc.

Then, in the case of a sample with $R > r$, the shielding factor for the contamination of the shield can be expressed as the ratio

$$\begin{aligned} f_S(E) &= \frac{f_\mu \pi r^2 + 2\pi r \int_h^{H+h} \{f_\mu \Omega(x)/2\pi + [1-\Omega(x)/2\pi]\}dx + \pi r^2}{2\pi r^2 + 2\pi r H} \\ &= \frac{f_\mu (1+S)/2 + 1/2 + H/r - S/2}{1+H/r}, \end{aligned} \tag{4}$$

where *H* and *h* denote the thickness of the crystal and its distance from the cap, respectively, while *S* denotes

$$S = \frac{H}{r} - \sqrt{\frac{(H+h)^2}{r^2} + \frac{(R-r)^2}{r^2}} + \sqrt{\frac{h^2}{r^2} + \frac{(R-r)^2}{r^2}} \tag{5}$$

and f_μ denotes the fraction of radiation penetrating the sample

$$f_\mu = e^{-1.5\mu(E)\rho D} \tag{6}$$

Here, $\mu(E)$, ρ and *D* denote the mass-attenuation coefficient in the sample material, the density and the sample thickness, respectively. The factor 1.5 in Eq. (6) was used to take into account the fact that that photons penetrate the sample on longer paths than the sample thickness.

Samples with a radius that is smaller than the radius of the crystal do not shield the mantle of the crystal; therefore, here the shielding factor can be calculated as

$$f_S(E) = \frac{(f_\mu - 1)\pi R^2 + 2\pi r^2 + 2\pi r H}{2\pi r^2 + 2\pi r H} \tag{7}$$

2.2. Contribution of the ambient radiation

To calculate the total shielding factor comprising the contribution of the contamination of the shielding material and the penetration through the shield, a supposition on the anisotropy of the radiation from the environment and penetrating the shield must be made. Here, isotropy cannot be assumed, since more radiation may be emitted from the floor than from the walls and the ceiling. To estimate the degree of anisotropy, measurements were made with a cylindrical copper block resembling an attenuating sample, placed on the front surface of the detector. In these measurements the apparent activity can be expressed as

$$A_i'(E) = A_{iD}(E) + f'_S(E) A_{iS}(E) + A'_{iA}(E) \tag{8}$$

where $f_{S'}(E)$ and $A_{iA'}(E)$ denote the fraction of the radiation penetrating the copper block resembling the sample and the