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A revision factor to the Cutshall self-attenuation correction in ^{210}Pb gamma-spectrometry measurements

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HIGHLIGHTS

- The Cutshall method enables to determine self-attenuation correction experimentally.
- The method provides the results burdened with errors of up to 10%.
- Author proposes to introduce into the Cutshall correction a revision factor.
- Author establishes a relationship between revision factor and Cutshall correction.

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ABSTRACT

The Cutshall transmission method of determination of self-attenuation correction in ^{210}Pb measurements by gamma-spectrometry gives the results burdened with errors of up to 10%. The author proposes introducing into the Cutshall correction $C_{s,Cuts}$ an additional revision factor $CC_{s,Cuts}$ to eliminate errors. The proposed formula of the revision factor describes the $CC_{s,Cuts}$ value depending on the experimentally obtained $C_{s,Cuts}$ correction. Formula holds true in wide ranges of the measurement geometries and linear attenuation coefficients of both the standard and the sample.

1. Introduction

The correction for photon attenuation within the sample material studied itself is an important parameter applied in gamma-ray spectrometry of volumetric samples (Jodłowski, 2006). The self-attenuation correction C_s, for a given measurement geometry, is the ratio of the detector efficiency for the standard ε_c to the detector efficiency for the sample ε_s:

$$C_s(E) = \frac{\varepsilon_c}{\varepsilon_s} \tag{1}$$

For low energies of the gamma radiation, the C_s correction values are significant and additionally strongly depend on the chemical composition of the material studied.

The transmission method of C_s determination, proposed by Cutshall et al. (1983) is an often used laboratory method, in which a point radioactive source is located above the sample that rests directly on the detector. The $C_{s,Cuts}$ correction, called further the Cutshall correction (Cutshall et al., 1983, Jodłowski et al., 2014), for the sample (index s) with respect to the standard (index c) is:

$$C_{s,Cuts} = \frac{\ln (I_0/I_s) \;/\; (1 - I_s/I_0)}{\ln (I_0/I_c) \;/\; (1 - I_c/I_0)} \tag{2}$$

where I, I_0 – net count rate (after subtraction of the background and count rate originating from the sample itself) in the transmission measurement in the case when a sample or standard (I_s, I_c) or an empty sample container (I_0), respectively, is placed between the radioactive source and the detector.

Many authors question the Cutshall equation and point out that it generates systematic errors (Galloway, 1991; Miller, 1987; Sima and Arnold, 2002). Jodłowski et al. (2014) found that the Cutshall correction in ^{210}Pb measurements significantly differs from the correct C_s value. In the case of the water or an epoxy resin standard and the natural sample materials, this difference for the samples 4 cm thick may be even 9%.

The aim of this work is to establish a revision factor $CC_{s,Cuts}$ to be introduced into the Cutshall correction in ^{210}Pb measurements by gamma-spectrometry, defined as:

$$CC_{s,Cuts} = C_s/C_{s,Cuts} \;\Rightarrow\; C_s = CC_{s,Cuts} \cdot C_{s,Cuts} \tag{3}$$

From Eq. (3) it results that multiplying the Cutshall correction $C_{s,Cuts}$ by the revision factor $CC_{s,Cuts}$ gives the correct C_s value. The revision factor defined in this way is an inverse of the $C_{s,Cuts}/C_s$ ratio used by Jodlowski et al. (2014).

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The formula of the revision factor $CC_{s,Cuts}$ must have a possibly wide range of applicability, i.e., it can be used for samples with a wide range of their linear attenuation coefficients, for detectors of various efficiencies, and finally for samples of various diameters and heights.

2. Materials and method

The values of the $CC_{s,Cuts}$ revision factor for the 46.5 keV photons of ^{210}Pb were calculated using simulations with a Monte Carlo (MC) method. The Cutshall correction ($C_{s,Cuts}$) was obtained by simulating the count rates I_0 and I (I_c or I_s), their ratio I_0/I and then applying Eq. (2). The correct C_s values (based on the correction definition) were obtained by simulation of the detector efficiencies for the standard ε_c and the sample ε_s and then applying Eq. (1). Having known values of $C_{s,Cuts}$ and C_s, the revision factor $CC_{s,Cuts}$ has been calculated from Eq. (3).

The MCNP4C code was used in the Monte Carlo computations (Briesmeister, 2000). The calculation time selected had to keep the type A uncertainty of the calculation results lower than 0.1%. The input data for the computations included the geometry of the measurement as well as the chemical composition and the density of a standard or a sample, it means two crucial parameters of the linear attenuation coefficient.

The basic simulations applied to the determination of the $CC_{s,Cuts}$ ($C_{s,Cuts}$) formula were carried out for the following spectrometric setup and samples. The spectrometric setup (Jodłowski and Kalita, 2010) includes a semiconductor detector HPGe (Canberra GX4020) with the relative efficiency 42% and a carbon epoxy window 0.6 mm thick. The detector crystal is a cylinder with the diameter 6.1 cm and the height 6.0 cm; the distance between the detector crystal and the sample is 0.81 cm. In the transmission method a ^{210}Pb the point source is positioned axially, directly on the sample cap; the distance between the active part of the source and the crystal depends on a sample height (h) and ranges from 2.1 cm (for $h=1$ cm) to 5.1 cm (for $h=4$ cm). Cylindrical samples in polystyrene containers are positioned axially, directly on the detector. The sample diameter d is 60 mm and heights h are $h=1$ cm, 2 cm, 3 cm, and 4 cm. The detailed description of the setup and samples studied is given in our previous article (Jodłowski et al., 2014).

When characterizing the materials of both the standard and the sample used in the simulations, the linear attenuation coefficient μ_I was considered while the chemical composition and the density of the sample were omitted, the latter is contrary to the sample description in our previous article. The simulations were done for 10 various standards and 10 various samples with the μ_I values in the range 0.01–1.0 cm^{-1} with a step of 0.1 cm^{-1}. To obtain such μ_I values, a material with the matrix of quartz sand and respective densities was used.

However all the calculations carried out to establish the applicability range of the $CC_{s,Cuts}$ ($C_{s,Cuts}$) formula, were conducted for a cylindrical sample with various d and h values, the standard with $\mu_I=0.2$ cm^{-1} and the sample with $\mu_I=0.6$ cm^{-1}; such assumptions correspond to the real environmental measurements (Jodłowski et al., 2014). The applicability range established in such a way is valid for the $C_{s,Cuts}$ values (for any μ_I value; cf. Section 4) in the range 0.70–1.40, 0.60–1.60 and 0.55–1.75 for sample heights 2 cm, 3 cm, and 4 cm respectively.

The calculations of the dependence between $CC_{s,Cuts}$ values and the detector relative efficiency were conducted for detectors with the crystal diameters 4.8, 6.1, 6.9 and 7.6 cm (the crystal diameter equals the crystal height, relative efficiency about 20%, 42%, 60% and 80% respectively – cf. formula in an ORTEC technical note). MCNP models of detector are based on MCNP model of GX4020 detector (developed with manufacturer provided dimensions: front dead layer 0.4 μm, detector inner hole 1 cm in diameter and 4.95 cm in height); the end-cup diameters are 7.6 cm, 7.6 cm, 8.9 cm and 9.5 cm for detector with efficiencies 20%, 42%, 60% and 80% respectively. The next simulations, in which dependence between $CC_{s,Cuts}$ and the sample diameter was tested, were conducted for the samples with their diameters changing from 1 to 10 cm.

3. Results

The first stage involved the basic calculation, for GX4020 detector, of the $C_{s,Cuts}$, C_s, and then the $CC_{s,Cuts}$, for various μ_I values of both the standard and the sample, and for $d=6$ cm and various sample heights. The results shown in the Fig. 1 indicate that:

- $CC_{s,Cuts}$ values for sample height 1 cm are very close to 1.00 (range 0.992–1.008); this means that the $C_{s,Cuts}$ value revision is not necessary;
- the relation between the $CC_{s,Cuts}$ and $C_{s,Cuts}$:

– does not depend significantly on the material (μ_I value) of the standard and sample used in $CC_{s,Cuts}$ calculation (see Fig. 1);
– is monotonic and after fitting can be represented by power function.

After fitting a power function to the data simulated generalized $CC_{s,Cuts}$ ($C_{s,Cuts}$, h) formula were determined:

$$CC_{s,Cuts} = C_{s,Cuts}^{\,0.1104-0.08129*h+0.003685*h^2} \quad (4)$$

where h is expressed in cm. The differences between the values of the fitting function and the computed values of $CC_{s,Cuts}$ do not exceed 0.6%.

Basic calculations of the revision factor $CC_{s,Cuts}$ and establishing its formula were conducted for the specific measurement configuration described in Section 2. The geometric considerations and the literature data indicate that the C_s and $CC_{s,Cuts}$ should depend, but only to an insignificant degree, on the detector size or the diameter of a sample. It means that the applicability of the $CC_{s,Cuts}$ formula established by the author can be considerably extended so as to make it available to laboratories working with different detectors and measurement geometries.

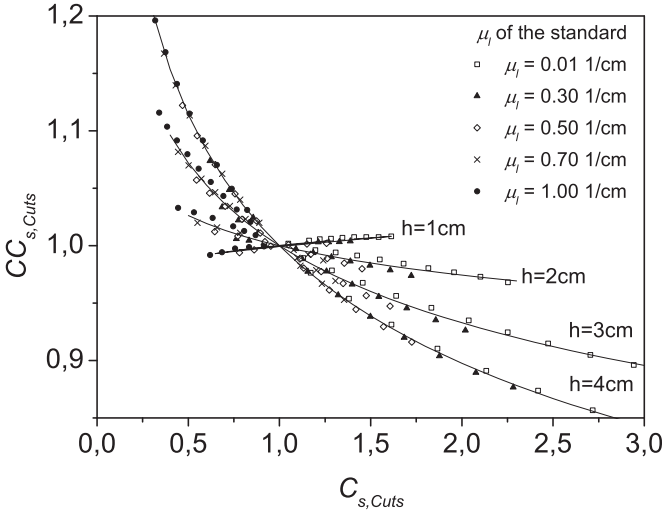

Fig. 1. Relationship revision factor $CC_{s,Cuts}$ versus Cutshall correction $C_{s,Cuts}$ for sample diameter $d=6$ cm, different sample heights h and for various linear attenuation coefficient μ_I of the standard and of the sample. Several data are omitted for clarity.

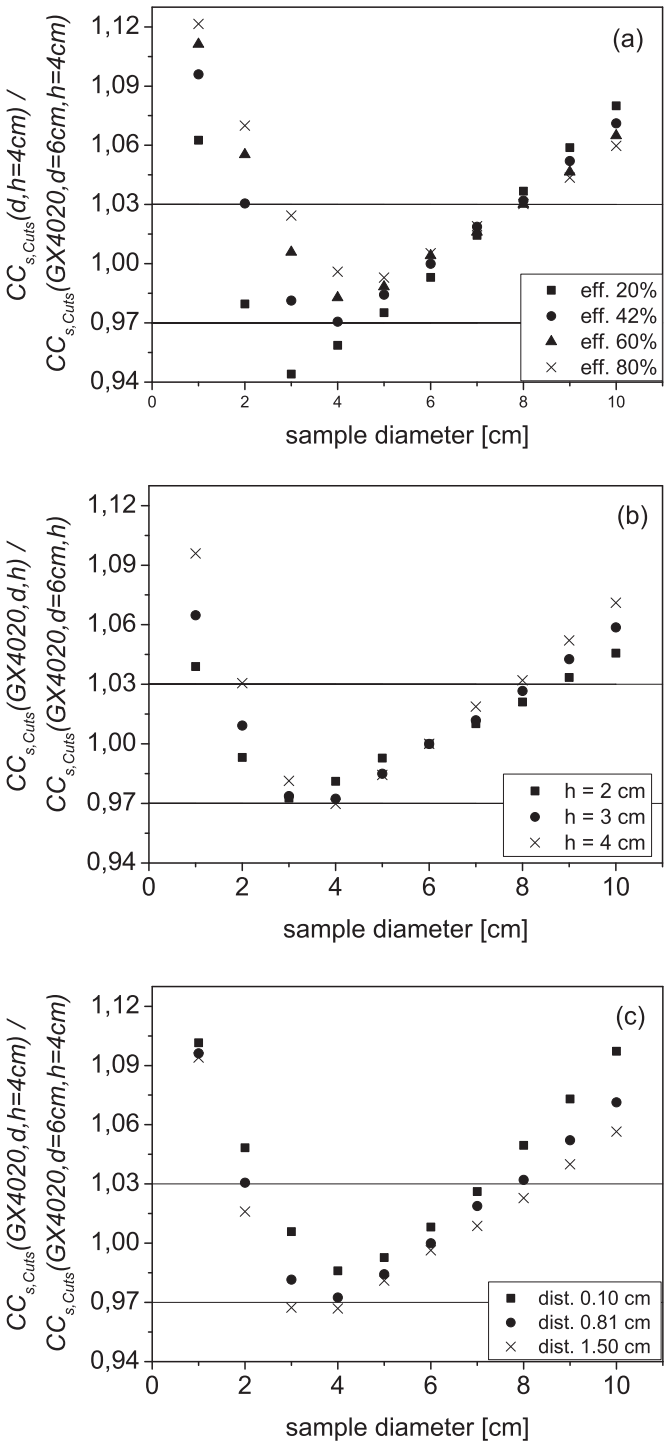

Fig. 2. Results of calculations carried out to establish the applicability range of the $CC_{s,Cuts}$ ($C_{s,Cuts}$) formula. Explanations: (a) relationship $CC_{s,Cuts}$ (d,h=4 cm)/$CC_{s,Cuts}$ (*GX4020*,d=6 cm,h=4 cm) versus sample diameter for various detector efficiencies; $CC_{s,Cuts}$ (*GX4020*,d=6 cm,h=4 cm) – result of the basic calculation for detector GX4020, sample diameter d=6 cm and sample height h=4 cm; (b) relationship $CC_{s,Cuts}$ (*GX4020*,d,h)/$CC_{s,Cuts}$ (*GX4020*,d=6 cm,h) versus sample diameter for various sample heights; (c) relationship $CC_{s,Cuts}$ (*GX4020*,d,h=4 cm)/$CC_{s,Cuts}$ (*GX4020*, d=6 cm,h=4 cm) versus sample diameter for various detector crystal – sample distances.

The next stage involved the analysis of the dependence of the $CC_{s,Cuts}$ value on the size (relative efficiency) of detector and sample diameter. The calculations indicate that $CC_{s,Cuts}$ values for the samples with their diameters 3–8 cm and heights up to 4 cm, and for various detectors efficiencies (between 20% and 80%) do not generally differ more than 3% from the values obtained in basic calculations (cf. Fig. 2a and b).

Furthermore, at the example of a GX4020 detector and d=6 cm and h=4 cm sizes dependence between the $CC_{s,Cuts}$ value and the following parameters was established:

- distance between detector crystal and sample: $CC_{s,Cuts}$ values for the crystal – sample distances 0.1 and 1.5 cm and for distance used in basic calculations (0.81 cm) do not generally differ (for d changing from 3 to 8 cm and h=4 cm) more than 3% (cf. Fig. 2c).
- the thickness and the material of the detector window: spread of the results around the average below 0.5% for the windows made of carbon epoxy 0.6 mm thick, Al 1.0 mm thick, beryllium 0.5 mm thick,
- the thickness and the material of the sample container: difference below 0.5% for the containers made of aluminum 1.0 mm thick and polystyrene 1.0 mm thick,
- the thickness of the dead layer on the upper surface of the detector crystal: spread of the results around the average below 0.5% for the dead layers from 4 μm to 300 μm thick.

4. Conclusions

Using MC simulations the formula of the revision factor $CC_{s,Cuts}$ to the Cutshall self-attenuation correction $C_{s,Cuts}$ in ^{210}Pb measurements using gamma spectrometry has been established. The formula is applicable not only to the spectrometric setup considered in basic calculations. It can also be used to the cylindrical samples with the height 1–4 cm and the diameters 3–8 cm, positioned directly on the detector, and can be applied to detectors with efficiencies 20–80%. This applicability range is valid for $C_{s,Cuts}$ values in the range 0.70–1.40, 0.60–1.60 and 0.55–1.75 for sample heights 2 cm, 3 cm, and 4 cm respectively. An uncertainty of $C_{s,Cuts}$ value is generally below 3% (cf. Fig. 2). For a sample height of 1 cm the $C_{s,Cuts}$ value revision is not necessary.

The value of the revision factor $CC_{s,Cuts}$ for a given measurement geometry is a function of the $C_{s,Cuts}$ value that is measured in the transmission experiment, and, as such, can be determined simultaneously with the $C_{s,Cuts}$ value in the same measurement. The correct value (i.e. within assumed uncertainty) of the self-attenuation correction C_s is obtained multiplying the correction $C_{s,Cuts}$ measured in the transmission experiment by the revision factor $CC_{s,Cuts}$.

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