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Coincidence summing corrections for the natural decay series in γ-ray spectrometry

M. García-Talavera[a],*, J.P. Laedermann[b], M. Décombaz[b], M.J. Daza[a], B. Quintana[a]

[a] *Grupo de Física Nuclear, Universidad de Salamanca, 37008 Salamanca, Spain*
[b] *Institut de Radiophysique Appliquée, Lausanne, Switzerland*

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Abstract

Using a Monte Carlo code and a Markov formalism to describe the decay schemes, coincidence-summing correction factors can be calculated with a suitable accuracy. For two different measuring geometries and an HPGe detector, calculated and experimental correction factors have been shown to closely agree for ^{152}Eu. The simulation method has subsequently been applied in assessing the need for coincidence-summing corrections for members of the uranium, thorium and actinium series measurable by γ-spectrometry. Correction factors were calculated for predominant γ emissions significantly affected by coincidence-summing effects and the correctness of our calculations tested for environmental samples. The test makes it evident that in order to obtain reliable and unbiased activity values for some natural radionuclides coincidence summing cannot be neglected in environmental measurements at small source–detector distances. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Coincidence-summing corrections; Gamma-ray spectrometry; Natural radionuclides.

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1. Introduction

Coincidence summing, for radionuclides which emit two or more photons within the resolving time of the spectrometer, requires correction of the full-energy peak areas of the emissions in the spectra. To derive the true activity value from these peaks, the apparent activity, i.e., uncorrected for summing effects, must be multiplied by a correction factor C. For point sources, the corrections can be calculated by analytical formulae. However, for extended sources the computation is more complex, since the contribution of each volume element to the efficiency depends on its position in the source. Several methods, each of a very different nature, have been proposed to deal with the problem, from purely experimental to Monte Carlo simulations (Quintana and Fernández, 1995; Décombaz et al., 1992; Korun and Martinic, 1993; Helmer and Gehrke, 1997).

The magnitude of coincidence-summing effects depends on the experimental setup, increasing with the efficiency. Therefore they are specially relevant for environmental samples because high-efficiency measuring setups are needed for their analysis due to their low-activity level. Furthermore, the calculation of corrections is essential in the measurements of the detector efficiency, which are carried out in the same conditions as the activity determinations, since they require a very high degree of accuracy. While large effort has focused on coincidence-summing effects for artificial radionuclides, usually in regard to the efficiency calibrations, the influence of this phenomenon for natural radionuclides has not been sufficiently studied. The reason is that coincidence-summing corrections are often assumed to be negligible, given that the counting uncertainties in

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*Corresponding author.
E-mail address: mgt@mozart.usal.es (M. García-Talavera).

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environmental measurements are usually high. This approach may be suitable for surveillance programs, where the main aim is to ensure that samples do not exceed the given level of activity. But for those applications based on differences of activity among radionuclides, such as sediment dating or studies on radionuclide migration, neglecting a systematic error may lead to erroneous conclusions. This is especially so for some radionuclides such as ^{214}Pb or ^{208}Tl, whose activities can be determined quite accurately in environmental samples, with relative uncertainties lower than 5%.

The objective of this paper is to assess the need of coincidence-summing corrections for those radionuclides from the uranium, thorium and actinium series whose γ emissions are measurable in the spectra. With that aim, coincidence-summing correction factors were calculated by a Monte Carlo (MC) method for two geometries currently employed for environmental samples and an HPGe detector. The simulation code Geant3 (Geant, 1987) was applied in conjunction with the program Sch2for (Laedermann and Décombaz, 2000), for the simulation of the decay schemes. For both geometries, previous studies have shown the code adequate in reproducing the full-energy peak efficiency values (García-Talavera et al., 2000). The reliability of the method in calculating summing corrections has been tested by comparing results computed for ^{152}Eu with those obtained by an empirical method developed by Quintana and Fernández (1995). Correction factors for the main emission of natural radionuclides were calculated by the simulation method and their efficacy was tested from γ-spectra analyses of several environmental samples. This verification procedure, based on the activity estimations derived from several γ emission of the same radionuclide or of radionuclides in secular equilibrium, shows the need for introducing coincidence-summing corrections for some natural radionuclides in environmental measurements.

2. Methods

2.1. Empirical method

The empirical method employed in this work is designed to be applied in efficiency calibration procedures, where both radionuclides with isolated γ emissions and radionuclides affected by coincidence summing are employed. It is based on a comparison between the measured areas from the same γ-ray emissions in two different geometries: the geometry employed for the activity measurements and a reference geometry which is not affected by coincidence summing. The main development in this work is the proposal of an analytical function for the ratio of efficiencies (C_G), which accounts for two effects: change of spatial distribution of radionuclides and self-attenuation in the volume of the source. From the value of C_G at the desired energy the values of the coincidence-summing correction factors can be derived. After correction, the experimental efficiency data are fitted to a spline function by a least squares analysis. The use of single line radionuclides together with radionuclides to which summation corrections are applied provides a way for checking the validity of the method. For the calculated coincidence-summing correction factors to be correct the behavior of both kind of radionuclides must agree, generating smooth efficiency calibration curve, as in those represented in Fig. 1.

2.2. Monte Carlo simulation

Regarding the simulation method, the code Geant has been used to reproduce the response of a n-type HPGe detector. Once a particle is initialized the program follows its history until its energy is dissipated taking into account the secondary particles created by the interaction processes. To simulate the decay schemes for the radionuclides of interest the program Sch2for has been used in conjunction with Geant. Sch2for provides a Markov chain approach to simulate complex decay schemes including β radiation, conversion electrons, γ-ray emissions and K- and L-shell X-rays. The decay is considered as a random walk from one state to another, the transitions being chosen according to the branching ratios associated with each state. Since resolving times associated with Ge coaxial detectors are long enough in

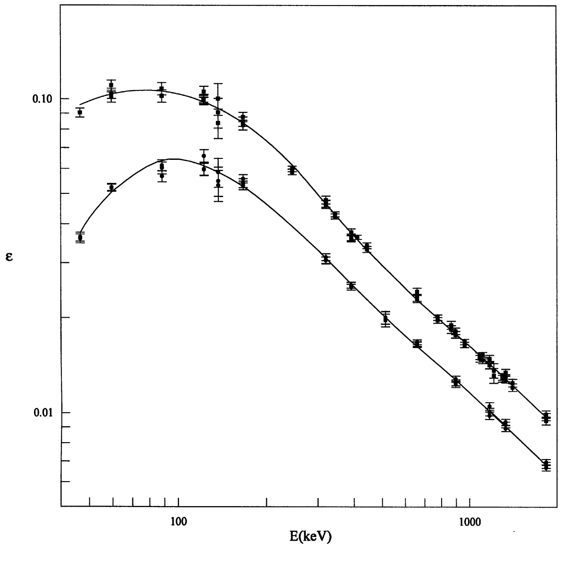

Fig. 1. Experimental efficiency curves for setups *MS* (circles) and *PS* (squares).

comparison with decay processes, we can assume that there is no appreciable time delay between the emission of all particles produced per nuclear decay. Therefore, they are stored in a particle stack, being tracked by Geant afterwards. The energy depositions of all these particles in the detector will be added by the program reproducing the coincidence-summing effects which also take place in experimental measurements. However, when metastable states are involved a different treatment is required, as described in detail in Laedermann and Décombaz (2000).

The data for the reproduction of the decay schemes have been taken from the Evaluated Nuclear Structure Data File (ENSDF). Data for K-shell fluorescence yield have been taken from Firestone (1996) and L-shell fluorescence yields from Singh et al. (1990).

3. Experimental

All experimental measurements in this work were performed using a Canberra n-type HPGe detector, with active volume 117 cm^3, relative photopeak efficiency at 1332 keV of 28.3% and resolutions at 122 and 1332 keV of 0.860 and 1.87 keV, respectively. The spectrometer is shielded by a 15 cm containment of low-background iron, lined with 2 mm of electrolytic copper. The detector preamplifier used in this study was a Canberra Model 2008, connected to an ORTEC Model 572 amplifier and a Canberra 8701 analog–digital converter. Spectra were stored through an AccuSpec/A interface card installed in a PC computer. The recorded spectra were analyzed with the program COSPAJ (Quintana and Fernández, 1998).

Water and sediment samples were contained in 0.25 l Marinelli beakers and Petri boxes of 6 cm diameter. In both cases, the source was placed directly on the top of the detector to increase the solid angle subtended by the detector. In total, three configurations were considered: Marinelli beakers filled with water or gross sands, designated as configurations *MW* and *MS*, respectively, and Petri boxes containing fine sands, labelled as *PS*. To obtain the efficiency calibration curves for the three configurations we followed the empirical method described in Section 2.1. The radionuclides employed for the calibration were ^{210}Pb, ^{152}Eu, ^{241}Am, ^{109}Cd, ^{51}Cr, ^{139}Ce, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{88}Y and ^{60}Co, the associated emissions from these covering the range 46–1836 keV. The subsequent efficiency curves have allowed us to compute the activities of the samples used in the test of the coincidence-summing corrections .

4. Comparison of the two methods for europium-152

One way of testing the accuracy of the correction factors calculated by the simulation method is to compare them with results obtained from the empirical method for several γ emissions from the decay of ^{152}Eu. This radionuclide can decay by β^- and electronic-capture modes, the coincidence-summing corrections for the γ rays following the electronic-capture decay being increased significantly by summing with the K-shell X-rays. In Table 1 results are presented for the three different setups. As can be seen from the Student *t*-test there is only one case out of 27 for which there are significant discrepancies, namely the 344 keV photon for the Marinelli beaker with water, this situation thereby infering that the problem may come from the experimental analysis.

5. Need for corrections for the radionuclides from the natural decay series

In Fig. 2 the uranium, thorium and actinium decay series are represented. Those radionuclides whose activities can be determined quantitatively in the environmental spectra are printed in boldface. The rest are not measurable, being either because their γ emissions are too weak as for ^{220}Rn, or because they are emitted at very low energies, as for ^{228}Ra. In addition, due to the complexity of the natural spectra, there are other nuclides whose activities cannot be measured even though they do not belong to any of the two mentioned categories. This is the case for instance for ^{223}Ra, whose most probable γ-ray emissions overlap with γ rays from other radionuclides. To deduce its activity, the contribution of the other radionuclides must be subtracted from the peaks. Thus said, for typical natural concentrations of ^{223}Ra, the resulting uncertainty, after subtraction, is too large to derive its activity with a suitable accuracy.

By examining the decay schemes we selected only those radionuclides for which coincidence-summing corrections could be necessary. As such, we chose ^{234}Th, ^{234m}Pa, ^{214}Pb and ^{214}Bi from the uranium decay series, ^{228}Ac, ^{212}Bi and ^{208}Tl from the thorium series and ^{235}U and ^{227}Th from the actinium family. The summing correction factors were calculated for their main γ emissions and whenever it was possible, the usefulness and accuracy of the calculations was tested with real spectra from environmental samples. In particular, solid samples were considered because their activity levels are usually much higher than those of the liquid samples. Using several emissions from the same radionuclide, or from radionuclides in secular equilibrium, different estimates of the activity can be obtained. The activity of the radionuclide can then be computed as a weighted average of all the estimations. The consistency of the set, with and without corrections can be compared, as can the differences between the resulting average values.

Table 1
Comparison of the coincidence summing corrections factors for ^{152}Eu calculated by the two presented methods for geometries *MW*, *MS* and *PS*. Values of the Student *t*-test results indicate which values differ statistically

	E (keV)	C_{cal}	C_{exp}	t
MW	121	1.24(1)	1.20(2)	1.79
	244	1.30(1)	1.31(2)	0.44
	344	1.03(1)	1.10(1)	4.90
	779	1.10(2)	1.12(2)	0.70
	867	1.37(2)	1.35(2)	0.55
	964	1.22(2)	1.21(1)	0.45
	1112	1.16(2)	1.14(2)	0.71
MS	121	1.19(1)	1.12(17)	0.4
	244	1.21(1)	1.23(16)	0.1
	344	1.04(1)	1.06(3)	0.1
	779	1.09(1)	1.07(1)	1.4
	867	1.21(3)	1.27(2)	1.5
	964	1.10(2)	1.09(2)	0.04
	1112	1.05(1)	1.05(1)	0.0
PS	121	1.28(1)	1.21(3)	2.2
	244	1.37(1)	1.36(2)	0.4
	344	1.05(1)	1.07(1)	1.4
	779	1.11(2)	1.10(2)	0.3
	867	1.46(3)	1.46(3)	0.0
	964	1.28(2)	1.23(2)	1.7
	1112	1.20(2)	1.18(2)	0.7

5.1. Main features of the selected decay schemes

5.1.1. Uranium decay series

Among the decay series most widely studied is the uranium decay chain, mainly for natural analogues and dating of ancient sediments. These type of studies are based on the activity disequilibria found between the long-lived radionuclides of the series.

The precursor of the chain, ^{238}U, does not yield any significant γ lines, and estimate of its activity has to be done by means of its progeny ^{234}Th and $^{234\mathrm{m}}$Pa, both of which reach secular equilibrium with ^{238}U within a period of 120 days in a closed system. Among the emissions of ^{234}Th, the 63.3 keV photon is the most suitable for activity determination, although it does include weak contributions from ^{232}Th and ^{231}Th. This γ ray is in cascade with the emission of 29.5 keV which is nearly completely internally converted. The rest of the emissions of the decay scheme do not contribute significantly to the coincidence effects with the photon of interest.

Regarding $^{234\mathrm{m}}$Pa, the strongest line from this appears to be at 1001.0 keV, the advantage being that self-absorption effects are not so critical as for the ^{234}Th γ-ray. The emission of 43.5 keV, with a high probability of internal conversion, may lead to summing-out of the 1001.0 full-energy peak while summing-in effects and coincidence with photons from upper levels can be neglected.

The radionuclides of this series with the most intense emissions in the spectra are ^{214}Pb and ^{214}Bi. Due to their short half-lives, these two radionuclides soon reach equilibrium, and in a closed system they achieve secular equilibrium with ^{226}Ra within 1 month. For ^{214}Pb the principal γ line is 351.9 keV, and this is not expected to need significant correction. Other intense γ rays affected by summing effects, as for instance the 242.0 keV photon, are also to be found in the experimental spectra, but they will not be considered in this work since they are overlapped by emissions from other nuclides. For ^{214}Bi, 609.3 and 1120.3 keV are the most probable γ emissions. Both of these may suffer significant summing-out, since they are always emitted in cascade with other photons.

5.1.2. Thorium decay series

From the point of view of environmental studies the most interesting radionuclides in the thorium chain are ^{232}Th, ^{228}Ra and ^{228}Th. These cannot be determined by γ-ray spectrometry, unless it is assumed that they are in equilibrium with their progeny. In nature this is not always the case for ^{232}Th (Chu and Wang, 1997) while the determination of ^{228}Ra can be done from ^{228}Ac, and of ^{228}Th from its progeny ^{212}Pb, ^{212}Bi and ^{208}Tl.

The most intense γ rays of actinium, 911.2 and 969.0 keV, come from a level significantly populated from other levels, the implication being that coincidence effects due to cascades with other photons may be significant. In addition, the photon of 911.2 keV is followed by the emission of 57.0 keV which is almost all internally converted.

Regarding ^{212}Bi, its most suitable emission is 727.3 keV, with corrections possibly being necessary in order to take account of the coincidence with γ rays from higher energy levels. For ^{208}Tl, which is found in equilibrium with the latter radionuclide, the main emission line appears at 583.3 keV. Its associated coincidence-summing correction is expected to be especially significant, particularly since it is always followed by an emission of 2614.5 keV. Moreover, it is often in cascade with other emissions since the beta branching ratio of the level is only about half of its depopulating intensity.

5.1.3. Actinium decay series

The measurement of radionuclides from the actinium series by γ-ray spectrometry is seldom possible in environmental samples. However, for some areas with enhanced natural radioactive levels ^{235}U and ^{227}Th can be determined.

The most probable γ line of ^{235}U occurs at 185.7 keV, being recorded in spectra in the same peak as the 186.1 keV photon of ^{226}Ra. However, for samples where

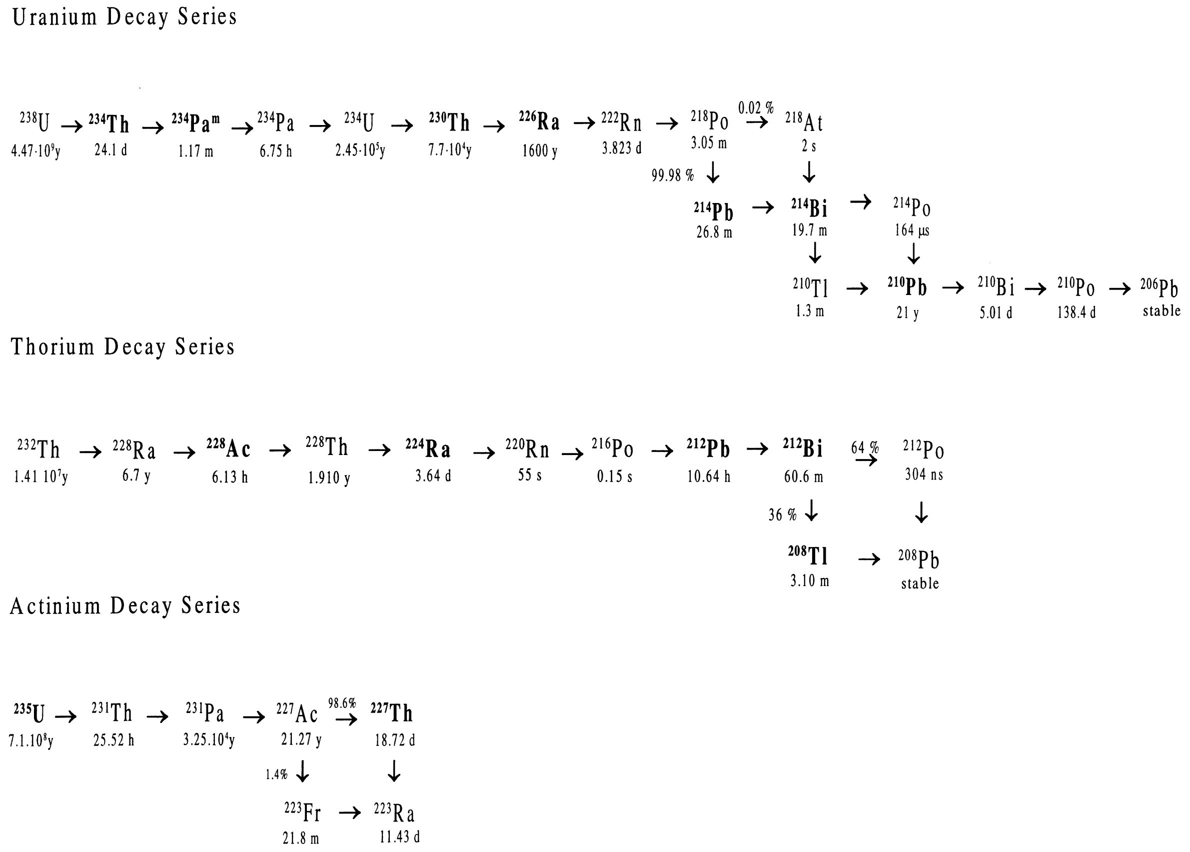

Fig. 2. Uranium, thorium and actinium decay series. Radionuclides measurable by γ spectrometry are printed in bold. Actinium decay series nuclides are only represented up to ^{223}Ra, since we are not concerned about the rest of the chain.

the secular equilibrium between ^{226}Ra and ^{214}Pb is not attained, ^{235}U activity has to be determined from the peaks of 163.3 and 205.3 keV, although both peaks also include very weak contributions of other radionuclides. These two emissions could suffer significant summing-in effects due to the cascades 19.6–143.7 keV and 19.6–185.7 keV, respectively. Summing-out effects also take place for all the mentioned γ rays.

For ^{227}Th the only photopeak suitable for activity determination is that at 236.0 keV. All the other peaks include contributions from other radionuclides. The 236.0 keV photon is always followed by one or more emissions leading to the ground level, and this could make necessary the introduction of corrections.

5.2. Results

5.2.1. Uranium decay series

Present calculations show that the emission at 63.3 keV of ^{234}Th does not require corrections for any of the studied geometries. This is probably due to the fact that we are dealing with extended sources. As such, the summing-out effect that would be mainly produced mainly by L-shell X-rays is not significant because they would be mostly absorbed within the source. The same holds for the 1001.0 keV photon of ^{234m}Pa.

Conversely, coincidence summing is important for the main γ rays of ^{214}Bi. The values of the corrections can be seen in Table 2 for two different setups. For the validation of these results three different sediment samples have been chosen for each measuring configuration. Since ^{214}Bi is in equilibrium with ^{214}Pb in the samples, the same activity value should be derived from the ^{214}Bi emissions at 609.3 and 1120.3 keV and the ^{214}Pb emission at 351.9 keV. The fact that the latter photon does not require summing correction while the magnitude of the correction factors for ^{214}Bi clearly exceeds that of the measurement uncertainties allows us to check the validity of our results. From Tables 3 and 4 it can be seen that the spread shown in the uncorrected activity estimations largely decreases when these are corrected for summing effects. This indicates that the calculated coincidence-summing correction factors are valid. The importance of taking summing effects into account is reflected in the average activities obtained from the uncorrected and from the corrected values as well as in the associated uncertainties. Of further note is that the average values of both differ significantly, the average of the corrected values being much more precise.

5.2.2. Thorium decay series

Table 5 reports the values of the correction factors for the most probable gamma emissions of ^{228}Ac, ^{212}Bi and ^{208}Tl. The corrections are particularly high for the 583.3 keV photon. The validation procedure is similar to that followed for ^{214}Pb (see Tables 6 and 7). We have estimated the activity of ^{228}Ra, from the values derived from the γ emissions of ^{228}Ac at 911.2 and 969.0 keV, and the activity of ^{228}Th from the photons of 727.3 and 583.3 keV emitted by ^{212}Bi and ^{208}Tl, respectively. Given the measurement uncertainties, coincidence summing corrections must be accounted for in all cases, other than that of the 727.3 keV photon in the Marinelli beaker geometry, in order to obtain accurate activity values.

To support the importance of taking into account coincidence-summing effects in the thorium decay series we have evaluated in more detail the results for the *PS* setup. The reason we selected this configuration is that summing corrections are higher for the *MS* setup, the effect of introducing the corrections then being more noticeable. According to the results in Table 8, if coincidence summing were not taken into account we would be lead to the conclusion that the activities of ^{228}Ra and ^{228}Th do not differ significantly. However once the correction factors are introduced, the resulting ^{228}Th activity exceeds that of ^{228}Ra in every case, as can be expected for riverine sediments because of the ability of radium to diffuse out sediments into the overlying water (Scott, 1992).

Table 2
Coincidence summing corrections factors calculated for the main emissions of ^{214}Pb and ^{214}Bi. The subscript to C indicates the measuring geometry

E (keV)	Radionuclide	C_{MS}	C_{PS}
351.9	^{214}Pb	1.01(1)	1.00(1)
609.3	^{214}Bi	1.12(2)	1.13(1)
1120.3	^{214}Bi	1.14(2)	1.16(1)

Table 5
Coincidence summing corrections factors for the main emissions of ^{228}Ac, ^{212}Bi and ^{208}Tl

E (keV)	Radionuclide	C_{MS}	C_{PS}
911.2	^{228}Ac	1.050(20)	1.090(10)
969.0	^{228}Ac	1.070(20)	1.050(10)
727.3	^{212}Bi	1.010(20)	1.025(16)
583.3	^{208}Tl	1.170(20)	1.175(13)

Table 3
Experimental validation for geometry *PS* for three sediment samples, S1, S2 and S3. The activity value of ^{214}Pb has been calculated from the emissions given in the table. Columns labeled by A represent the activity values derived when coincidence summing corrections are not accounted for. In columns A_{corr} the activity values have been corrected by multiplying the corresponding C, the values of which are given in Table 2

	S1		S2		S3	
	A	A_{corr}	A	A_{corr}	A	A_{corr}
351.9 keV	112.9(12)	112.9(12)	119.8(12)	119.8(12)	56.9(8)	56.9(8)
609.3 keV	99.6(11)	112.1(17)	106.5(13)	119.2(19)	49.2(8)	55.4(10)
1120.3 keV	96.0(27)	111.4(33)	98.4(30)	114.2(37)	49.0(20)	56.8(24)
A_{average}	104.9(48)	112.5(9)	112.5(53)	119.2(10)	52.7(27)	56.3(6)

Table 4
As for Table 3, but for geometry *MS* and samples S4, S5 and S6

	S4		S5		S6	
	A	A_{corr}	A	A_{corr}	A	A_{corr}
351.9 keV	25.55(19)	25.55(19)	43.69(20)	43.69(20)	28.48(20)	28.48(20)
609.3 keV	22.80(17)	25.54(49)	38.75(20)	43.40(80)	25.59(17)	28.32(53)
1120.3 keV	22.66(19)	25.83(50)	38.30(30)	43.70(80)	26.05(52)	29.70(79)
A_{average}	23.60(92)	25.58(17)	40.7(18)	43.67(19)	26.6(11)	28.53(20)

Table 6
Experimental validation of the correction factors given in Table 5 for geometry *PS* using samples S1, S2 and S3

	S1		S2		S3	
	A	A_{corr}	A	A_{corr}	A	A_{corr}
911.2 keV	74.9(16)	81.7(19)	68.6(16)	74.8(19)	45.10(12)	49.2(14)
969.0 keV	76.2(21)	80.0(23)	72.1(23)	75.7(25)	46.3(12)	48.6(13)
A_{average}	75.4(13)	81.0(14)	69.7(16)	75.1(15)	45.7(8)	48.9(9)
727.3 keV	81.0(38)	83.0(41)	78.1(46)	80.1(49)	52.4(31)	53.7(34)
583.3 keV	73.7(13)	86.6(18)	70.5(16)	82.8(21)	43.7(15)	51.1(20)
A_{average}	74.5(22)	86.0(16)	71.3(23)	82.4(19)	43.3(34)	51.8(11)

Table 7
As for Table 6, but for geometry *MS* and samples S4, S5 and S6

	S4		S5		S6	
	A	A_{corr}	A	A_{corr}	A	A_{corr}
911.2 keV	22.30(27)	23.42(53)	21.36(26)	22.43(50)	18.02(25)	18.92(44)
969.0 keV	22.51(36)	24.08(60)	20.76(34)	22.21(55)	17.59(92)	18.82(104)
A_{average}	22.37(22)	23.71(39)	21.14(29)	22.33(39)	17.99(24)	18.90(40)
727.3 keV	23.54(61)	23.54(61)	21.96(57)	21.96(57)	20.82(61)	20.82(61)
583.3 keV	21.07(21)	24.65(49)	18.51(19)	21.66(37)	16.73(26)	19.60(47)
A_{average}	21.33(76)	24.21(51)	18.80(100)	21.80(30)	17.40(150)	20.05(59)

5.2.3. Actinium decay series

The calculated coincidence-summing correction factors for all the above-mentioned emissions of ^{235}U and ^{227}Th are given in Table 9. Since the 19.6 keV photon intervenes in the summation effects for the γ emissions of 163.3 and 205.3 keV their corresponding correction factors will have marked sensitivity to the geometry of the source. For the configuration *MS* summing corrections can be neglected. However, for *PS* they are considerable since self-absorption in this geometry is lower. Unfortunately, for this radionuclide we cannot perform the experimental test provided for other radionuclides. The reason is that the relative uncertainties in the activity values derived from the 163.3 and 205.3 keV photopeaks are up to about 30% for all the samples. With errors of this order one cannot come to any conclusions about the correctness of the calculated coincidence summing corrections factors.

Regarding ^{227}Th, the only estimation of its activity can be made from the 236.0 keV, as has been already stated. Therefore, we are once again unable to check the accuracy of the proposed correction factor in this case.

6. Conclusions

We have proposed a method to calculate coincidence-summing corrections in γ-ray spectrometry consisting of the application of the Monte Carlo code Geant3 in conjunction with Sch2for. The results of the method for an HPGe detector and three setups have been shown to agree, within the statistical uncertainties, with the values obtained by an empirical method for ^{152}Eu. The accuracy of the code in reproducing coincidence-summing correction factors is of profit in analyzing the need for corrections for the radionuclides belonging to the three natural decay series. For our detector and two measuring geometries, correction factors were provided for the main emissions of those natural radionuclides significantly affected by coincidence-summing effects. Furthermore, the following general statements can be made concerning our results:

Table 8
Results of the comparison between the activities of ^{228}Ra and ^{228}Th for three riverine sediment samples. The Student *t*-test values are presented. The test was performed on the average activities with no summation corrections considered (t_{wc}) and subsequent to correction (t_{corr})

	t_{wc}	t_{corr}
S1	0.3	2.3
S2	0.5	3.0
S3	0.7	2.0

For the uranium decay series, with the exception of ^{214}Bi, there is no need to introduce coincidence-summing correction factors. In case that no corrections are made it is more correct to derive the activity of ^{214}Pb

Table 9
Coincidence summing corrections factors for the main emissions of ^{235}U and ^{227}Th

E (keV)	Radionuclide	C_{MS}	C_{PS}
163.3	^{235}U	1.000(10)	0.938(7)
185.7	^{235}U	1.000(10)	1.060(20)
205.3	^{235}U	0.963(9)	0.700(6)
236.0	^{227}Th	1.020(10)	1.104(8)

using only its γ emission of 351.9 keV instead of computing an average value including also the emissions of ^{214}Bi.

Regarding the thorium decay series, the introduction of corrections for ^{228}Ac and ^{208}Tl is essential if accurate results are required, as confirmed by the example case of disequilibrium between ^{228}Th and ^{228}Ra in sediment samples.

For ^{235}U and ^{227}Th the value of the corrections is very sensitive to the measuring geometries. Special attention should be paid to the 205.3 keV peak, this particular emission being the one, most affected by the coincidence-summing effects.

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