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Well GeHP detector calibration for environmental measurements using reference materials

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Abstract

A well-type detector installed in the Modane underground Laboratory (LSM) can combine both low background and high detection efficiency and it is well suited for the analysis of small amounts of environmental samples. Reference materials such as IAEA-447 (moss-soil), IAEA-RG-Th1 and IAEA-RG-U1 were used for the detector calibration, owing to a chemical composition close to those of the environmental samples. Nevertheless, the matrix effects and the true coincidence summing effects must be corrected from the full energy peak efficiency (FEPE). The FEPE was performed for a wide range of energy by a semi-empirical method using Monte Carlo simulation (MCNP6), intended for environmental measurements such as lake sediments dating. In the well geometry, the true coincidence summing effects could be very important and correction factors have been computed in three different ways.

Keywords: Well-type detector; Full energy peak efficiency; True coincidence summing; MCNP6; Efficiency correction

1. Introduction

2 The detector full energy peak efficiency (FEPE) calibration is always required to
3 reach accurate measurements and still represents a subject of considerable interest for

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4 the gamma spectrometry [1, 2, 4–10]. In this work, the measurements were carried
5 out with a well high-purity germanium (HPGe) detector, situated in the underground
6 Laboratory of Modane (LSM, located along the Frejus Tunnel Road in Savoy) where the
7 reachable sensitivity depends on the ultra-low background. The FEPE calibration of the
8 well detector [1, 2, 4, 7, 8, 10] is required for environmental measurements, mainly the
9 determination of fallout radionuclides in lake sediments such as ^{210}Pb (half-life 22.3 years)
10 and ^{137}Cs (half-life 30.05 years) for dating methods. To determine the FEPE function,
11 standard calibration sources, with the same size and composition as the samples, should
12 be used to have the same matrix effects (concerning mainly the auto-absorption due to
13 the density and the chemical composition) that will be corrected. Reference materials
14 such as IAEA-447 (moss-soil), RG-Th1 (thorium ore) and RG-U1 (uranium ore) were
15 used in the calibration process. Therefore, an important correction applied in close
16 measurements for this kind of detector, is related to the true coincidence summing effect
17 (TCS). TCS occurs when two (or more) emitted gamma or X-rays from a nucleus are
18 simultaneously detected within the resolving time of the gamma spectrometer system.
19 The magnitude of this effect depends on the detector efficiency (including the specific
20 source-detector geometry for a well detector) and the decay-scheme parameters. For
21 the concerned nuclei, TCS usually results in lower full-energy peak areas. In order to
22 compensate this loss of counts, a suitable correction must be performed. TCS correction
23 factors were computed for ^{214}Bi (half-life 20 min), using secular equilibrium between
24 ^{226}Ra (half-life 1600 years) and their progenies, especially ^{214}Bi and ^{214}Pb with their
25 free lines of TCS effect at 295.22 keV and 351.93 keV. A simple way to get the correction
26 factor is to compare their activities, for example with the Genie 2000 software [11], which
27 should be equal.

28 A comprehensive study of the efficiency calculation and calibration verification of
29 the well spectrometer was performed by a semi-empirical method using Monte-Carlo
30 simulation, where the key element for calibration is the accurate knowledge of the physical
31 and geometrical characteristics of the whole detector, such as length and diameter of the
32 Ge crystal, thickness of the dead layer and more generally features of other components
33 (endcap, crystal holder, insulators, ...). A detector model was created for the efficiency
34 calculation, using the MCNP6 code [12]. This allowed to achieve a better accuracy for the

35 activity measurements of samples with unusual shapes, where experimental calibration
36 with standard sources appears to be difficult.

37 **2. Materials and methods**

38 *2.1. Well HPGe detector*

39 The spectrometer used in this work is a Canberra High-Purity Germanium (HPGe)
40 well detector, model GCW4021 under a serial number b07035, with a relative efficiency
41 of 40%, an active volume of 238 cm³ and a nominal FWHM of 1.27 keV at 122 keV (⁵⁷Co)
42 and 2.03 keV at 1.33 MeV (⁶⁰Co). These features were supplied by the manufacturer. It
43 works coupled to a DSA-1000 Canberra multichannel analyser and provides a maximum
44 efficiency for small samples, because the sample is virtually surrounded by the active
45 detector material.

46 The Canberra well detector is fabricated with a blind hole rather than a through
47 hole, leaving at least 15 mm of active detector thickness at the bottom of the well. The
48 counting geometry therefore approaches 4π sr.

49 The well insert in the end-cap is made of low background (LB) aluminium with a side-
50 wall thickness of 1.5 mm and a 1 mm thick bottom. The ion boron implanted contact on
51 the detector element is negligibly thin compared to 0.5 mm of aluminium, so this kind
52 of detector has intrinsically a good response at low energy, down to 20 keV [13]. The
53 detector is shielded with a foil of electrolytic copper (3 mm thick) and lead (12 cm of
54 low activity lead < 50 Bq kg⁻¹ and 3 cm of very low activity lead < 10 Bq kg⁻¹).

55 A completed description of the equivalent detector model is represented in Fig. 1,
56 where the dimensions are taken from the Canberra handbook.

57 Table 1 summarizes the values specified by Canberra for the geometric features of the
58 well detector shown in Fig. 1.

59 *2.2. Monte-Carlo simulations*

60 The characterisation of the detector usually combines experimental measurements
61 and Monte-Carlo simulations to calculate with accuracy the detector efficiency.

62 An initial model of the detector was performed by using the nominal dimensions and
63 features provided by the manufacturer and then was implemented in the Monte-Carlo

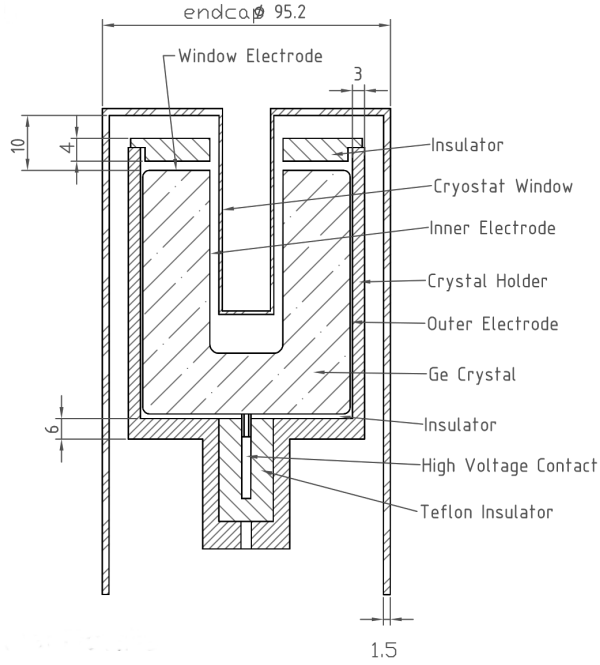


Figure 1: Well detector longitudinal section.

Parameters	Value (mm)
Outer electrode thickness	0.9
Inner electrode thickness	0.3×10^{-3}
Window electrode thickness	0.9
Cristal diameter	68
Cristal length	68
Core hole diameter	17
Endcap hole	diameter 11 mm and depth 40 mm
Core hole depth	35
Cryostat window material	LB aluminium 1 mm thick
Endcap material	LB aluminium 1.5 mm thick
Crystal holder	LB copper

Table 1: Well detector parameters.

64 code MCNP6. This detector model must be checked by comparing the efficiency curve
65 provided by MCNP6 with the experimental one obtained for source-detector geometry
66 and reference materials in a wide energy range. The detector model should be approved if
67 the calculated efficiencies are in a good agreement with the experimental values according
68 to a level of acceptable uncertainty. Note that MCNP6 intrinsically does not take into
69 account the TCS effect.

70 Fig. 2 shows the detector model obtained by MCNP6. The detector resolution was
71 taking into account through the GEB (Gaussian Energy Broadening) card.

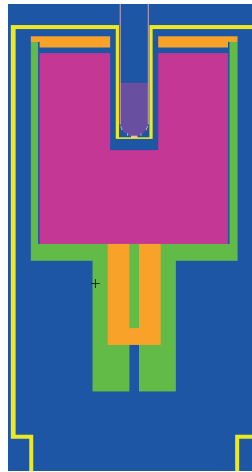


Figure 2: 2-D representation of the well detector MCNP 3-D model.

72 2.3. IAEA447 Standard

73 The experimental efficiency calibration was carried out in the 46.54–2614.51 keV
74 energy range using the IAEA-447 standard (moss-soil). The milled material was sieved
75 to obtain a maximum particle size distribution of 150 μm . The material density was
76 measured in 5 test portions and found to be $1.03 \pm 0.05 \text{ g cm}^{-3}$ [14].

77 The certified values used to evaluate the activities of radionuclides were established
78 on the basis of results reported by the IAEA Terrestrial Environment Laboratory in
79 Seibersdorf, Austria [14].

80 Radionuclides from this sample and their activities estimated at the date of our
81 experiment are represented in Table 2.

Radionuclides	Certified Values (Bq kg ⁻¹)	Uncertainty (Bq kg ⁻¹)
¹³⁷ Cs	383.46	10.00
²¹⁰ Pb	378.65	0.02 × 10 ³
²¹⁰ Po	378.65	10.00
²¹² Pb	8.28	1.50
²²⁶ Ra	25,05	2.00
²²⁸ Ac	15,49	2.00
²³⁴ U	21.80	0.80
²³⁸ U	22.20	0.80
²³⁸ Pu	0.15	0.02
^{239–240} Pu	5.30	0.20
⁴⁰ K	550	0.02 × 10 ³
⁹⁰ Sr	4.50	0.30
²³² Th	37.30	20
²⁴¹ Am	2.20	0.20
²⁴¹ Pu	6.45	1.00

Table 2: Estimated values of activities by Darwin software from IAEA-447 certified ones.

82 *2.4. IAEA-RGU-1 and IAEA-RGTh-1 Standards*

83 Both IAEA-RGU-1 and IAEA-RGTh-1 reference materials were prepared, on be-
84 half of the International Atomic Energy Agency by the Canada Centre for Mineral and
85 Energy Technology, by dilution of respectively a uranium ore BL-5 (7.09% U) and a
86 thorium ore OKA-2 (2.89% Th, 219 µg U/g) with floated silica powder of similar grain
87 size distribution. BL-5 has been certified for uranium, ²²⁶Ra and ²¹⁰Pb, confirming that
88 it is in radioactive equilibrium. The agreement between radiometric and chemical mea-
89 surements of thorium and uranium in OKA-2 shows that both series are in radioactive
90 equilibrium [15].

91 The activities of radionuclides from IAEA-RG-Th1 and IAEA-RG-U1 are shown in
92 Table 3.

IAEA-RG-Th1		IAEA-RG-U1	
Radionuclide	Activity (Bq kg ⁻¹)	Radionuclide	Activity (Bq kg ⁻¹)
²³² Th	3250	²³² Th	< 4
²³⁵ U	3.6	²³⁵ U	238
²³⁸ U	78	²³⁸ U	4940
⁴⁰ K	6.3	⁴⁰ K	< 0.68

Table 3: IAEA-RG-Th1 (thorium ore) and IAEA-RG-U1 (uranium ore) certified values of activities.

93 2.5. Experimental

94 All measurements in this work were performed at the LSM. The laboratory is shielded
95 from cosmic radiation by 1700 m of rocks, equivalent to 4400 m of water, and an air
96 flushing without radon (generated from the radon trapping facility at the LSM) is done
97 into the measurement cell, inside the lead shielding . Thus the background rate between
98 20 keV and 2 MeV is of 23 counts h⁻¹. Three reference materials cited above were used
99 in containers with the following features:

- 100 • IAEA-447 in a PE tube of 28 mm of height and 1.341 g of weight;
- 101 • IAEA-RG-Th1 in a PE tube of 28 mm and 1.4 g;
- 102 • IAEA-RG-U1 in a PE tube of 28 mm and 1.849 g.

103 The reference material samples are well sealed to ensure its air-tightness, so secular
104 equilibrium between ²²⁶Ra and ²¹⁰Pb can be reach after 20 days with 95%. In envi-
105 ronmental samples measurement, the activity levels are low, so if statistically significant
106 results require long count periods, they are recovery until several days in this work.

107 3. Results and discussion

108 3.1. FEP efficiency

109 For the analysis of the IAEA-447 standard, a correction factor is generally required
110 for the spectral interfering γ -rays to determine the net areas of the analytical peaks,
111 because some of those interferences often might contribute to the analytical peaks of

112 interest [16]. The nuclide identification was performed using our library containing radio-
 113 isotopes presented in the IAEA-447 sample where ^{238}U , ^{232}Th progenies and ^{40}K were
 114 identified. About ^{234}Th gamma emission at 92.38 keV, there is a single peak in the
 115 spectral region 92-93 keV resulted from two energies (92.56 keV and 92.78 keV), where
 116 the total emission probability was taken into account (the net total peak area of this
 117 unresolvable multiplet is accounted for without deconvolution).

Table 4 lists the main correction factors for some radionuclides peaks [16].

Radionuclide	Nuclides in the peak	Energy (keV)	Proportion in the peak (%)
^{234}Th	^{234}Th	63.28	98.2
	^{232}Th	63.81	1.8
^{226}Ra	^{226}Ra	186.21	57.1
	^{235}U	185.72	42.8
^{212}Pb	^{212}Pb	238.63	62.4
	^{214}Pb	242.00	31.7
	^{224}Ra	240.99	5.9
^{40}K	^{40}K	1460.82	94.8
	^{228}Ac	1459.14	5.2

Table 4: Interference factors of such radionuclides in IAEA-447 [16].

118

119 Table 5 compares the experimental and simulated efficiencies for the IAEA-447 stan-
 120 dard for the most intense peak of radionuclides. To calculate the efficiency, we have used
 121 the following equation:

$$\varepsilon = \frac{N_{net}}{A(Bq) \times I_{\gamma} \times t(s)} \quad (1)$$

122 where A is the initial activity carried out with the Darwin software [17] taking into ac-
 123 count the radioactive affiliations, N_{net} is the number of counts under the net peak area,
 124 I_{γ} is the probability of gamma emission and t the acquisition time.

125

126 A number of analytical functions describing the dependence of the FEPE as a function
 127 of the energy have been proposed by several authors [18, 19]. The efficiency function used

Radionuclide	Energy (keV)	Intensity (%)	ε_{exp}	ε_{sim}	Ratio ($\varepsilon_{\text{exp}}/\varepsilon_{\text{sim}}$)
^{210}Pb	46.54	4.25	0.422 ± 0.006	0.457 ± 0.001	0.92 ± 0.01
^{241}Am	59.54	35.90	0.482 ± 0.060	0.536 ± 0.044	0.90 ± 0.23
^{234}Th	63.28	4.80	0.492 ± 0.040	0.539 ± 0.068	0.91 ± 0.22
	92.37	2.81	0.531 ± 0.02	0.561 ± 0.067	0.95 ± 0.16
^{226}Ra	186.21	3.55	0.450 ± 0.02	0.474 ± 0.038	0.95 ± 0.12
^{212}Pb	238.63	43.60	0.375 ± 0.005	0.384 ± 0.069	0.98 ± 0.19
^{214}Pb	295.22	18.5	0.294 ± 0.010	0.311 ± 0.025	0.95 ± 0.11
	351.93	35.6	0.253 ± 0.008	0.263 ± 0.021	0.96 ± 0.11
^{208}Tl	583.19	85.00	0.144 ± 0.007	0.149 ± 0.025	0.97 ± 0.22
^{214}Bi	609.31	45.49	0.077 ± 0.007	0.142 ± 0.011	0.54 ± 0.17
	1120.29	14.90	0.039 ± 0.010	0.071 ± 0.005	0.55 ± 0.32
^{137}Cs	661.66	84.99	0.125 ± 0.001	0.130 ± 0.004	0.96 ± 0.04
^{228}Ac	911.20	25.80	0.095 ± 0.004	0.093 ± 0.012	1.02 ± 0.17
^{40}K	1460.82	10.60	0.053 ± 0.001	0.052 ± 0.002	1.02 ± 0.18
^{208}Tl	2614.51	99.75	0.026 ± 0.001	0.027 ± 0.004	0.96 ± 0.05

Table 5: Experimental and calculated efficiencies for the IAEA-447 standard.

128 in this work has the form of logarithmic positive power transferred series, which has been
129 proposed in [20, 21]:

$$\ln \varepsilon = a_0 + a_1 \ln E + a_2 \ln^2 E + a_3 \ln^3 E + a_4 \ln^4 E \quad (2)$$

130 Fig. 3 shows the experimental and simulated efficiencies as a function of the energy,
131 where both were fitted using a fourth order polynomial from Eq. 2, because it is the
132 adequate order which groups the best statistical parameters, such as trust and residues
133 factor which must be the smallest in the sense of least squares method.

134 From Table 5, we can see that the simulated values are always greater than experimen-
135 tal values, excepted for ^{228}Ac at 911.2 keV and for the primordial isotope of potassium
136 ^{40}K at 1460.82 keV, due to the presence of this isotope everywhere and chiefly from
137 the human radioactivity. A good agreement is found to be within 10% between almost

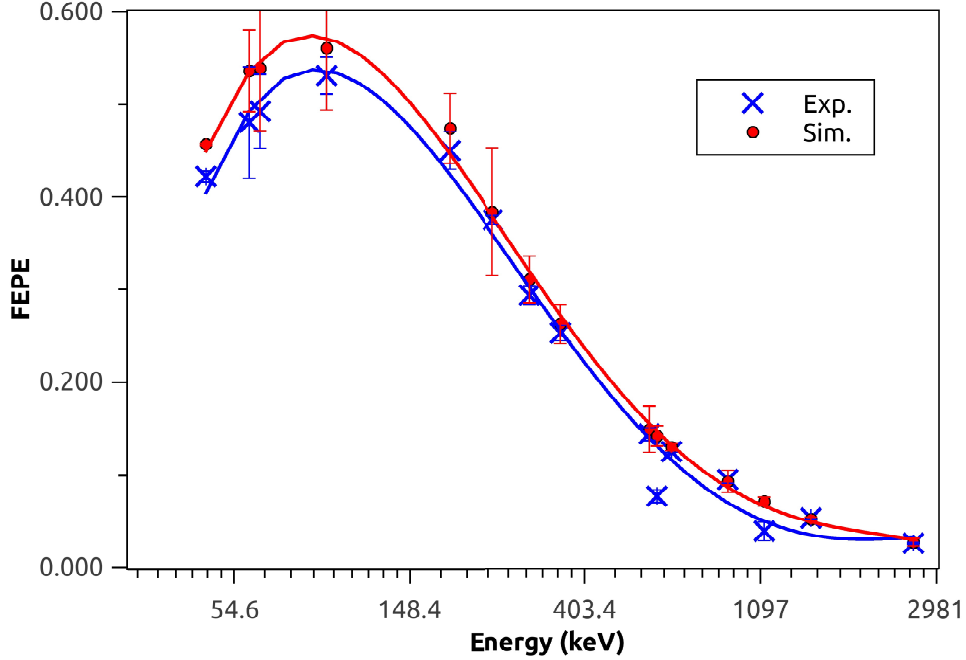


Figure 3: Comparison between experimental and calculated values of the FEP efficiency for the IAEA-447 standard.

138 all experimental and simulated values as shown in Table 5 and Fig. 3: experimental
 139 and simulated efficiencies are very close, starting from 92.37 keV line for ^{234}Th with the
 140 ratio (0.95 ± 0.16) . In the low energy range where the self-attenuation phenomenon is
 141 not insignificant, a correction in this case should be applied. For some lines with a low
 142 number of counts, the uncertainties are important, due to the behaviour of the analysis
 143 software towards weak peaks. The most important differences are for ^{214}Bi at the two
 144 main lines 609.31 keV and 1120.29 keV, where only 54-55% of counts were detected. In
 145 this case, the TCS effect decreases the count number by summing those energies with
 146 other in succession.

147 3.2. True Coincidence Summing correction

148 The true coincidence summing effect was observed for radio-isotopes which have a
 149 complex decay scheme, such as ^{214}Bi which can be used in the ^{226}Ra activity evaluation,
 150 required in the ^{210}Pb dating method of lake sediments. For ^{214}Bi , we have considered

151 height major lines (with the most important intensities) from its numerous γ radiations.
 152 We assumed that ^{226}Ra is in secular equilibrium with its progenies, which implies that
 153 they have the same activity, and we have compared the ^{214}Bi activity with that of ^{214}Pb ,
 154 which is free from TCS at 351.9 keV and slightly affected with 1.9% at 295.38 keV [8].

155 Table 6 shows the TCS correction factors calculated for the major lines of ^{214}Bi in
 156 three different ways:

- 157 • Activity correction: it was given by the ratio between the raw activity of every line
 158 of ^{214}Bi and the activity of ^{214}Pb , used as a reference and equal to 23.85 ± 0.02
 159 Bq kg^{-1} ;
- 160 • TCS factor (Genie 2000): it was determined from the FEPE experimental fitting
 161 curve given by Genie 2000;
- 162 • Ratio $\varepsilon_{\text{exp}}/\varepsilon_{\text{sim}}$: that is the ratio between the experimental efficiency and the
 163 efficiency calculated from the MCNP6 simulations.

Energy (keV)	Intensity (%)	Activity (Bq.kg ⁻¹)	Correction factors		
			Activity Correction	TCS factor (Genie 2000)	Ratio ($\varepsilon_{\text{exp}}/\varepsilon_{\text{sim}}$)
609.31	45.49	12.72 ± 0.02	0.53	0.58	0.54
1120.29	14.91	8.91 ± 0.06	0.37	0.57	0.55
1238.1	5.83	13.05 ± 0.11	0.55	0.56	0.55
1377.7	3.97	32.07 ± 0.18	1.34	1.40	1.27
1729.5	2.84	75.07 ± 0.27	3.14	3.07	2.78
1764.5	15.31	40.70 ± 0.09	1.70	1.75	1.61
1847.42	2.11	69.94 ± 0.29	2.93	2.15	1.76
2204.1	4.91	53.99 ± 0.23	2.26	2.38	2.20

Table 6: TCS correction factors for the ^{214}Bi major lines.

164 We can observe an important under estimation at 609.31 keV and 1120.29 keV, be-
 165 cause these lines are the most involved in the TCS with the other photons emitted by
 166 ^{214}Bi , leading to an important loss of counts for these peaks. The difference between the

167 correction factor obtained at 1120.29 keV and the TCS factor and the ratio $\varepsilon_{\text{exp}}/\varepsilon_{\text{sim}}$
 168 is due to the weak count rate in this line. The correction factors determined in three
 169 different ways are in good agreement and are close to those obtained in the literature
 170 for the most of values [8, 22]. For both lines at 1764.5 keV and 2204.1 keV, there are
 171 significant differences compared with the values from the literature.

172 Fig. 4 shows the values of efficiency after correction from TCS for ^{214}Bi at 609.31
 keV and 1120.29 keV.

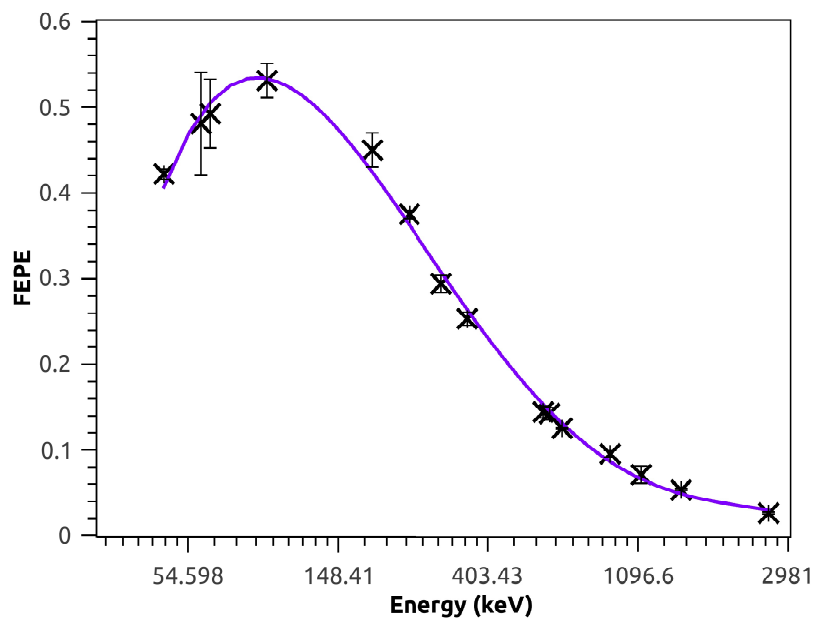


Figure 4: Experimental values of the FEPE for the IAEA-447 corrected from TCS.

173

174 3.3. Density effect on TCS

175 We have compared the results of efficiencies obtained by IAEA-447, IAEA-RG-U1
 176 and IAEA-RG-Th1 analysis with the common main lines of progenies from ^{238}U and
 177 ^{232}Th . The results are listed in Table 7, where efficiency ratios between two standards
 178 are shown in the last column with their uncertainties for the same energy lines for the
 179 three reference materials.

180

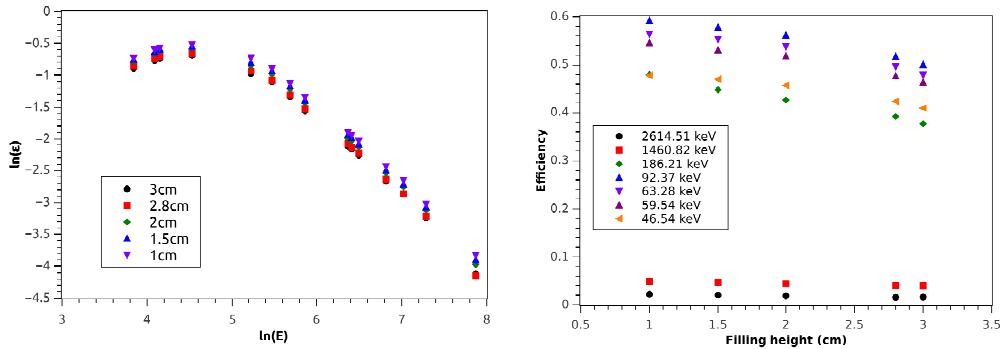
Radionuclide	Energy (keV)	$\epsilon_{\text{IAEA-447}}$	$\epsilon_{\text{RG-U1}}$	$\epsilon_{\text{RG-Th1}}$	Ratio between efficiencies
^{210}Pb	46.54	0.422 ± 0.006	0.403 ± 0.006	—	0.95 ± 0.01
^{234}Th	63.28	0.492 ± 0.040	0.485 ± 0.007	—	0.99 ± 0.10
	92.37	0.531 ± 0.020	0.518 ± 0.008	—	0.98 ± 0.05
^{226}Ra	186.21	0.450 ± 0.020	0.425 ± 0.006	—	0.94 ± 0.06
^{212}Pb	238.63	0.375 ± 0.005	—	0.369 ± 0.020	0.98 ± 0.07
^{214}Pb	295.22	0.294 ± 0.010	0.290 ± 0.004	0.98 ± 0.05	
	351.93	0.253 ± 0.008	0.241 ± 0.003	—	0.95 ± 0.04
^{208}Tl	583.19	0.144 ± 0.007	—	0.103 ± 0.006	0.72 ± 0.10
^{214}Bi	609.31	0.077 ± 0.007	0.062 ± 0.001	—	0.80 ± 0.10
	1120.29	0.039 ± 0.01	0.03 ± 0.001	—	0.77 ± 0.27
^{228}Ac	911.2	0.095 ± 0.004	—	0.082 ± 0.005	0.86 ± 0.10
^{208}Tl	2614.51	0.026 ± 0.001	—	0.014 ± 0.001	0.54 ± 0.10

Table 7: Comparison between IAEA-447, IAEA-RG-U1 and IAEA-RG-Th1 results.

181 FEPE values of radionuclides presented in the IAEA-447 reference material are always
182 greater than those obtained by IAEA-RG-Th1 and IAEA-RG-U1, because the TCS effect
183 increases with activity where IAEA-RG radionuclides have greater activities than those
184 of IAEA-447. The results show a slight discrepancy between common lines of IAEA
185 reference materials less than 10% in the range of low energies. This is due to the density
186 difference between IAEA samples, where heavy elements such as thorium and uranium
187 are presented in IAEA-RG, leading to a higher density than IAEA-447. This density
188 impact is presented for all energies. The difference between efficiencies is low for the
189 intermediate energy range. For higher energies, mainly those of ^{214}Bi , ^{208}Tl , and ^{228}Ac ,
190 differences are greater and vary between 14% for 911.2 keV of ^{228}Ac and reach 46% for
191 ^{208}Tl at 2614.51 keV. For such environmental matrices which contain high Z elements
192 (e.g. thorium, uranium, lead, . . .) in significant quantities, the threshold at which matrix
193 effects take place is moved to higher energies [23].

194 *3.4. Influence of sample height on the FEP efficiency*

195 We have further used MCNP6 to compute the FEPE for the IAEA-447 standard as
 196 a function of the sample height. The sample heights are 1, 1.5, 2, 2.8 and 3 cm and the
 197 results obtained are shown in Fig 5.a. The impact of the sample height on the efficiency
 198 is shown in Fig 5.b for the lowest energies (corresponding to ^{210}Pb , ^{241}Am and ^{234}Th)
 and for the highest energies (corresponding to ^{40}K and ^{208}Tl at 2614.51 keV).



(a) Simulated values of FEP efficiency for several IAEA-447 standard heights. (b) The impact of the IAEA-447 standard heights on FEP efficiency.

Figure 5: Simulated values of FEP efficiency as function of the IAEA-447 standard heights.

199

200 The results show that the impact of the sample filling height is very important in
 201 the low energy range compared to the high energy range. The efficiency decreases with
 202 increasing in the sample filling height. Therefore for our future measurements, we will
 203 take into account the height of the sample, through a specific FEPE depending on the
 204 filling height.

205 **4. Conclusion**

206 The FEPE calibration of an HPGe well-type detector detector was performed in this
 207 work motivated by applications in environmental measurements, especially to determine
 208 the activities of radioactive fallout in the lake sediments such as ^{210}Pb , ^{241}Am and ^{137}Cs ,
 209 used in dating methods. We have used the IAEA-447 (moss-soil) reference material as
 210 a standard to approach at best the matrix effects due to the chemical composition of
 211 the samples. A well detector model was implemented in MCNP6 with the features

212 provided by the manufacturer. The simulated values are greater than the experimental
213 ones for most of the energy lines. The results show mostly a good agreement with
214 respect to the experimental values and discrepancies are within 10%. This allows us
215 to determine the efficiency calibration curve without an experimental work, and can be
216 considered as an efficiency transfer model, that can be used in other investigations such
217 as self-attenuation in samples. We have also calculated the true coincidence summing
218 correction factors for the lines emitted in the complex decay chains of ^{214}Bi with three
219 manners, which have showed a good agreement with the literature values. In order to
220 show matrix effects such as the density influence, we have compared the results from the
221 FEPE obtained by three reference materials IAEA-447, IAEA-RG-Th1 and IAEA-RG-
222 U1. The impact of the sample filling height was investigated. It was remarkable for low
223 energies, where the efficiency decreases with increasing in filling heights. A reduction
224 of the filling height would diminish the matrix effects [5]. Finally, the efficiency curve
225 can be used in activities evaluation for the environmental measurements, but to improve
226 accuracy, other corrections must be done such as self-attenuation, density and sample
227 height filling effects.

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