Gamma spectrometric determination of the activities of natural radionuclides

γ-SPEKT/NATRAD

Authors:

U.-K. Schkade
A. Heckel
H. Wershofen
M.-O. Aust
F. Bruchertseifer
A. Dalheimer
S. Hofmann
G. Kanisch
C. Kowalik
F. Ober
K. Rupprecht

Drafting Committee
(Redaktionsausschuss der Messanleitungen des Bundes)

ISSN 1865-8725 Version June 2018 / verified November 2024

Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation
(Messanleitungen für die „Überwachung radioaktiver Stoffe in der Umwelt und externer Strahlung")

CONTENT

Gamma spectrometric determination of the activities of natural radionuclides

1 Introduction

Besides K-40 and cosmogenic radionuclides, the radionuclides of the three natural decay chains also belong to the natural radionuclides (see Figure 1). Within the scope of the Directive on Emission and Immission Monitoring regarding Mining (REI Bergbau) [1] the following nuclides

— uranium-238, radium-226 and lead-210 from the uranium-radium decay chain;

— uranium-235 and actinium-227 from the uranium-actinium decay chain, and

— thorium-232, radium-228 and thorium-228 from the thorium decay chain

are usually determined using gamma spectrometry. Some of these long-lived radionuclides can only be measured quantitatively by means of gamma spectrometry via the progeny nuclide after the radioactive equilibrium between the parent and the progeny radionuclides has been attained.

The fundamentals of gamma spectrometry are provided in the General Chapter γ-SPEKT/GRUNDL [2], more detailed information on background and interferences are given in the General Chapters γ-SPEKT/NULLEF [3] and γ-SPEKT/INTERF [4] of this Procedures' Manual.

2 Special requirements on the measurement system and its surroundings

2.1 Requirements related to the place of installation

Natural radionuclides are ubiquitous. They, therefore, occur in the construction materials used for flooring, walls and ceilings as well as in the air of laboratories and in the materials used to manufacture both the detectors and the shieldings.

In this context, particular attention is paid to the isotopes of the noble gas radon which are emanating from the above-mentioned materials into the laboratory air and contribute to the background spectrum. In particular when determining the activities of natural radionuclides, adequate measures must be taken to minimize the contents of radon isotopes and their progenies and to prevent, as far as possible, the contents to vary in order to be able to evaluate the pulse height spectrum correctly [3].

Note:

- High radon concentrations may occur in the basement of old buildings.
- Seasonal changes in the concentration of radon isotopes and their progenies must be taken into account, in particular when radon concentrations are low.

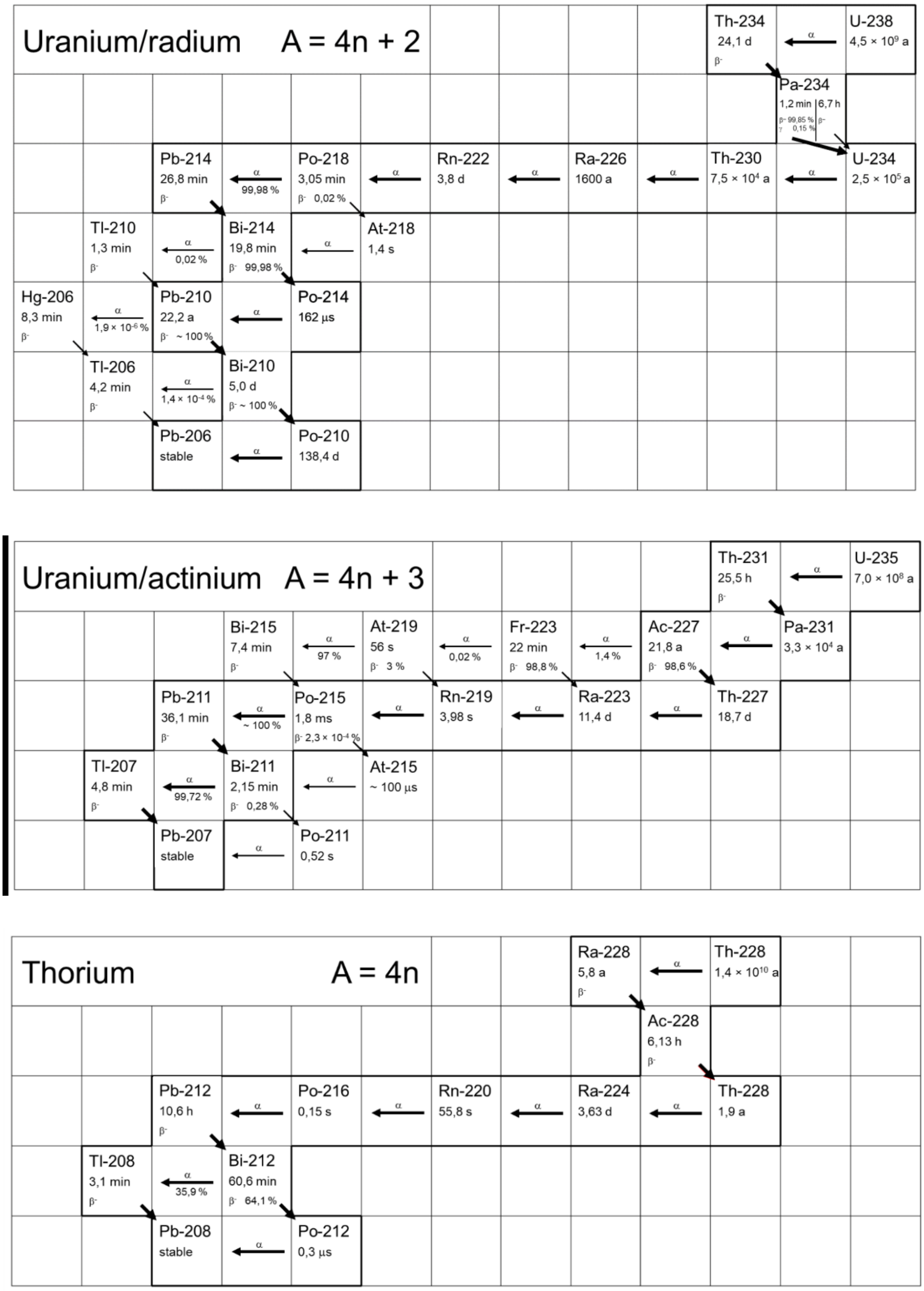

Fig. 1: The natural decay chains with decay mode and half-life as well as branching (nuclear data as of November 2024)

2.2 Requirements related to the gamma spectrometric measurement system

To determine very low activities of natural nuclides reliably, an ultra-low-level measurement system is usually used. Its components are made of materials whose own activity due to natural radionuclides is very low. Ideally, this measurement system should be placed in the centre of a room whose construction material exhibits activity contents of natural radionuclides as low as possible, the distance between the measurement system and the walls being as large as possible given the space of the room. The other requirements are described in [2: Section 2].

Some of the natural radionuclides can be only measured by use of gamma peaks in the low-energy region of the pulse height spectrum below 100 keV (see Figure 2). It is, therefore, an advantage if besides the current p-type germanium detectors an n-type detector can also be used.

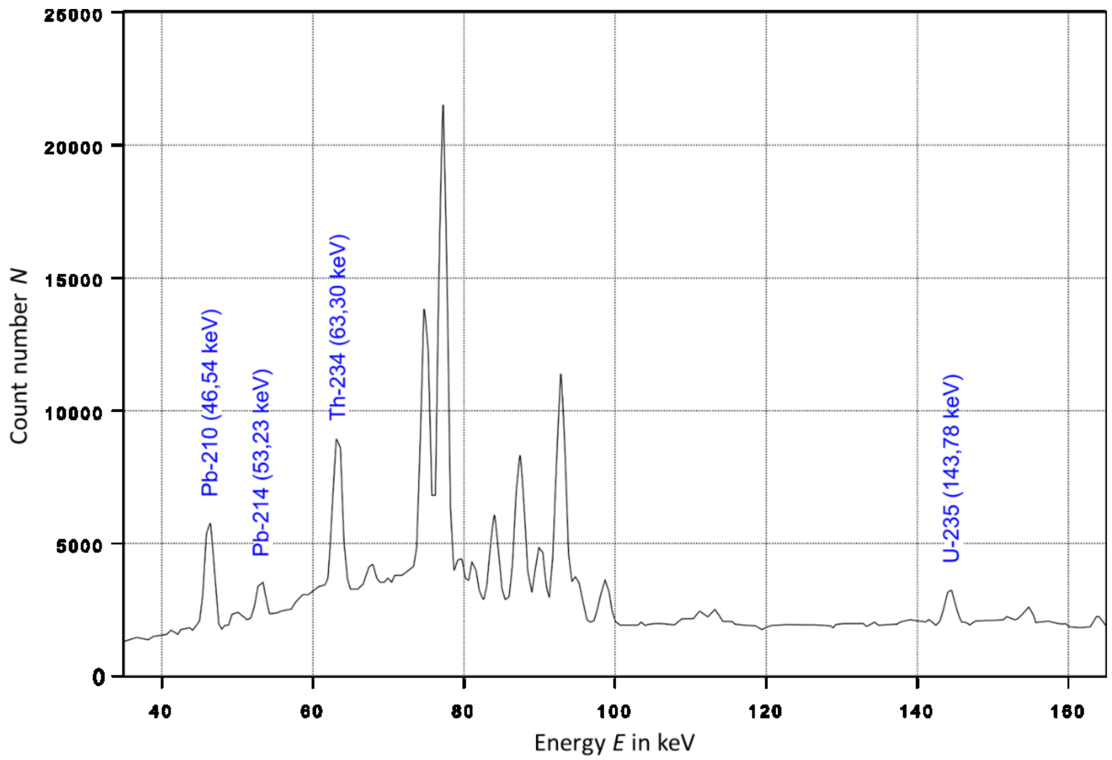

Fig. 2: Pulse height spectrum of a soil sample (energy region up to 160 keV) used to determine the activity concentration of Pb-210

3 Considerations on the radioactive equilibrium in decay chains

Radionuclides of the natural decay chains that do not emit gamma rays can only be determined indirectly via their gamma emitting progenies. For such measurements, it must be ensured that the radioactive equilibrium between the parent radionuclide and the progenies is reached.

In environmental samples, the radioactive equilibrium may be disturbed due to the different chemical and/or biochemical properties of the elements concerned. Examples are:

— different solubility of radium and thorium in water;
— different transfer behaviours of parent and progeny radionuclides in the *soil-vegetation-animal-milk chain*;
— disturbance of the radioactive equilibrium during the sampling (e.g. due to the use of filter materials);
— radon escaping from the sample.

The following measures are recommended:

— Storing the samples to be measured for a sufficiently long time prior to starting the measurement or keeping them for a check measurement that may be necessary. If the aim is to reach the equilibrium between a long-lived parent radionuclide and its short-lived progeny radionuclide, then the waiting time should amount to at least six half-lives of the progeny radionuclide.
— Transferring the sample material (in particular, when measuring short-lived progeny of Rn-222) into gas-tight measurement containers and waiting until the radioactive equilibrium to be reached. The dead volume between the sample filled in and the lid of the measurement cell should be as small as possible.

With respect to parent-progeny radionuclides, particular attention must be paid in order to replace the half-life of a short-lived progeny radionuclide by the half-life of the long-lived parent radionuclide, so that no physically unrealistic activities are calculated when correcting the decay to a reference point in time of an environmental sample which lies before the time of the measurement – usually, the sampling time. Then, both the radioactive decay of the respective radionuclide and growth from its parent radionuclide must be taken into account. Such examples are the radionuclide pairs: Ra-226/Pb-210, Ra-228/Th-228, U-238/Th-234.

Additional information is given in the in the General Chapter γ-SPEKT/ GRUNDL of this Procedures' Manual [2].

4 Considering selected natural radionuclides

In the following, the natural radionuclides required to be measured in accordance with the REI Bergbau directive will be discussed thoroughly [1]. For certain cases, the requirement of correction for self-absorption losses and true coincidence summing will be addressed.

The tables below list the photon energies (E_γ) and emission intensities (p_γ) of the radionuclides considered as well as that of their interfering nuclides. In the case of the decay chains at equilibrium, the emission intensities stated here each refer to one decay of the parent radionuclide and already take possible branching into account. An example is the determination of Th-228 content via the progeny Tl-208 in Section 4.8. The Tl-208 emission intensities listed there already consider that the Tl-208 activity only represents 35,93 % of its parent nuclide Th-228 due to a branching of the decay chain at Bi-212 (see Figure 1).

Note:
Nuclear data of the regarded radionuclides refer to the sources mentioned in the General Chapter KERNDATEN of this Procedures' Manual [5].

4.1 Uranium-238

With its half-life of $4{,}468 \cdot 10^9$ years, uranium-238 (U-238) is the parent radionuclide in the uranium-radium decay chain. Using gamma spectrometry, U-238 can only be determined via its progenies Th-234 and Pa-234m.

In most cases, the 63,3 keV peak of Th-234 is used for this purpose. At such a low energy, the matrix differences between the calibration and counting source significantly influence the results due to specific self-absorption effects and must be considered correspondingly [2]. In addition, the peak at 63,3 keV is subject to an interference caused by the peak of Th-232 at 63,8 keV with an emission intensity of 0,259 %.

Note:
To determine the U-238 content, the doublet peak of Th-234 at the energies of 92,4 keV and 92,8 keV with the combined emission intensity of 4,33 % (2,18 % + 2,15 %), should not be used.

Due their higher energies, the peaks of Pa-234m at 1001,0 keV and 766,4 keV are better suited to evaluate the pulse height spectrum. Their low emission intensities, however, lead to poor detection limits (see Figure 3).

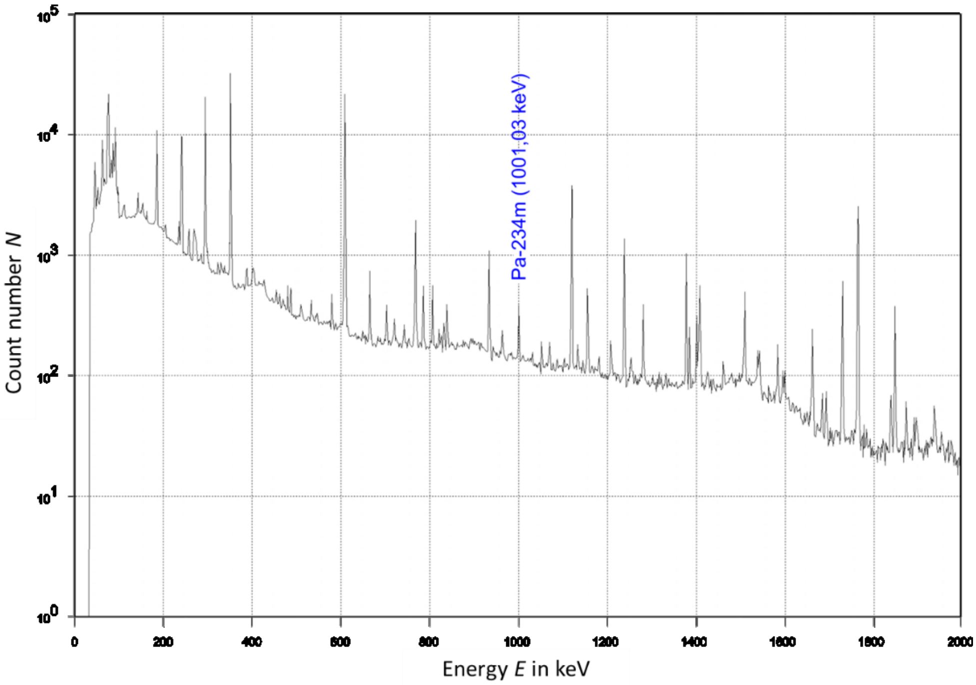

Fig. 3: Evaluating the Pa-234m peak in the pulse height spectrum of a soil sample used to determin of the specific activity of U-238

The peaks suitable for the evaluation are compiled in Table 1.

Tab. 1: Nuclear data of the radionuclides to be determined and their interfering nuclides when determining the U-238 content by means of gamma spectrometry

Radionuclide to be determined	E_γ in keV	p_γ in %	Interfering radionuclide	E_γ in keV	p_γ in %
Th-234	63,30	3,75	Th-232	63,81	0,259
	92,38	2,18	Th-234 (Kα1 + Kα2)	93,35	5,6
	92,80	2,15			
Pa-234m	766,36	0,323			
	1001,03	0,847			

In the case of samples of natural origin, the nearly constant natural U-238/U-235 activity ratio of 21,7 may be referred to for plausibility reasons (see Section 4.4).

4.2 Radium-226

With a half-life of 1600 years, radium-226 (Ra-226) is a long-lived radionuclide in the uranium-radium decay chain. To determine this radionuclide, two approaches are possible:

— evaluation of the 186,2 keV peak of Ra-226 in the pulse height spectrum, or
— evaluation of the gamma peaks of the short-lived progeny radionuclides of Rn-222, Pb-214 and Bi-214, in the pulse height spectrum after reaching the radioactive equilibrium between Ra-226, Rn-222, Pb-214 and Bi-214 (see Figure 4).

If the Ra-226 peak at 186,2 keV is evaluated, its overlapping with the U-235 peak at 185,7 keV must be considered. In natural sample materials, the activity content of U-235 amounts to approx. $^{1}/_{22}$ of the 1 of Ra-226. In comparison, the emission intensity of the U-235 peak at 185,7 keV is by a factor of 16 higher than the emission intensity of the Ra-226 line at 186,2 keV.

Assuming that the sample is at radioactive equilibrium, this overlapping is not problematic. This means that the contents of U-238 and Ra-226 are the same and therefore, the content of U-235 is also known. Environmental samples, however, are not always in radioactive equilibrium, while industrial residues and products containing naturally occurring radioactive material (NORM) are never in equilibrium. Therefore, the correction due to the overlapping of the Ra-226 peak at 186,2 keV with the interfering U-235 peak at 185,7 keV is only possible if the U-235 activity is determined based on other gamma peaks or if it is derived from the U-238 activity.

Note:
The U-238 content of a sample can also be obtained by means of other methods such as alpha spectrometry, X-ray fluorescence measurement or mass spectrometry.

Gas-tight measurement containers are required to determine the activities of the short-lived progeny radionuclides of Rn-222, since otherwise, the pulse counts acquired for Pb-214 and Bi-214 in the pulse height spectrum are too low due to Rn-222 emanating from the measurement container. The period of time between the filling of the sample into the gas-tight measurement container and the beginning of the measurement should amount to at least 23 days, this period being determined by the half-life of Rn-222 which amounts to 3,82 days. A summation correction is necessary when evaluating the pulse height spectrum [2, 6].

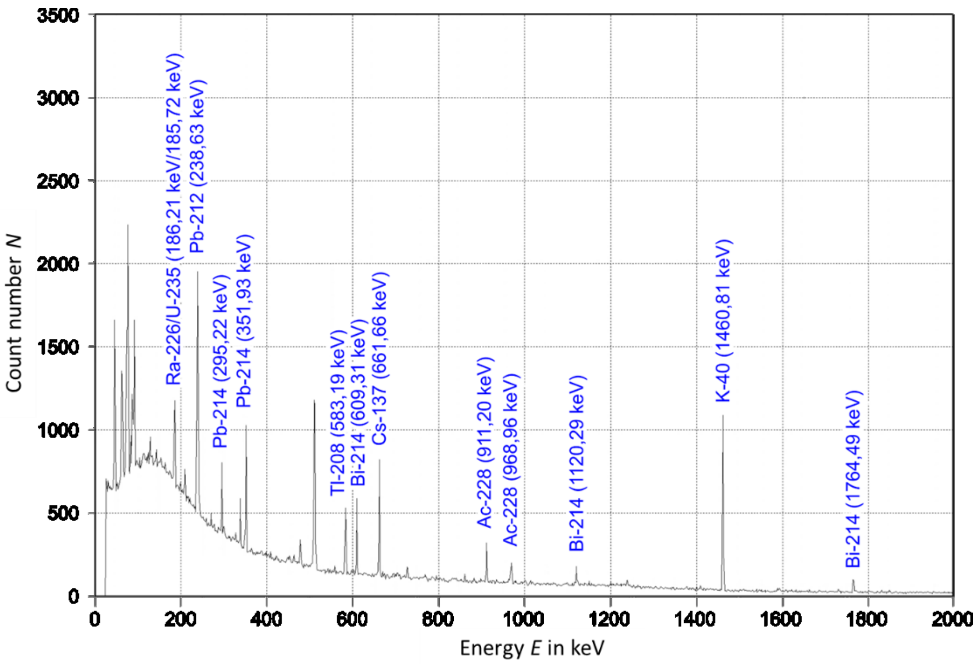

Fig. 4: Evaluating the Pb-214 and the Bi-214 peaks in the pulse height spectrum of a soil sample used to determine the specific activity of Ra-226

A few peaks suitable for the evaluation are compiled in Table 2.

Tab. 2: Nuclear data of the radionuclides to be determined and their interfering nuclides when determining the Ra-226 content by means of gamma spectrometry

Radionuclide to be determined	E_γ in keV	p_γ in %	Interfering radionuclide	E_γ in keV	p_γ in %
Ra-226	186,21	3,56	U-235	185,72	57,0
Pb-214	295,22	18,41			
	351,93	35,6	Bi--211	351,03	13,00
Bi-214	609,31	45,49			
	1120,29	14,91			
	1764,49	15,31			

4.3 Lead-210

Lead-210 (Pb-210) is a radionuclide in the uranium-radium decay chain; its half-life is 22,23 years. The Pb-210 content is determined directly via the gamma peak at the relatively low energy of 46,5 keV (see Table 3). At this energy, the differences in the material composition of the calibration and counting source play a key role due to self-absorption; adequate correction factors must be applied [2].

Tab. 3: Nuclear data of the radionuclide to be evaluated for the gammaspectrometric determination of the Pb-210 content

Radionuclide to be determined	E_γ in keV	p_γ in %	Interfering radionuclide	E_γ in keV	p_γ in %
Pb-210	46,54	4,25			

4.4 Uranium-235

Uranium-235 (U-235) is the parent radionuclide of the uranium-actinium decay chain; its half-life is $7{,}04 \cdot 10^8$ years. The U-235 content can be determined directly by means of the gamma peaks listed in Table 4 at 143,8 keV, 163,4 keV, 185,7 keV and 205,3 keV. The following aspects must be taken into account when evaluating these gamma peaks in the pulse height spectrum:

— To evaluate the gamma peak at 185,7 keV, which has the highest emission intensity, the activity of Ra-226 must be known (see Section 4.2).

— The Ra-223 gamma peak at 144,2 keV interfers with the gamma peak at 143,8 keV (see Figure 2).

— The two other gamma peaks have emission intensities that are so low that they are usually not considered to evaluate samples with low U-235 content.

Tab. 4: Nuclear data of the radionuclide considered and its interfering nuclides when determining the U-235 content by means of gamma spectrometry

Radionuclide to be determined	E_γ in keV	p_γ in %	Interfering radionuclide	E_γ in keV	p_γ in %
U-235	143,77	10,94	Ra-223	144,27	3,36
	163,36	5,08			
	185,72	57,0	Ra-226	186,21	3,56
	205,32	5,02			

4.5 Actinium-227

Actinium-227 (Ac-227) is a radionuclide in the uranium-actinium decay chain; its half-life is 21,77 years. Ac-227 can only be determined by gamma spectrometry using its short-lived progenies Th-227, Ra-223 and Rn-219. Preferably, the Th-227 peak at 236,0 keV in the pulse height spectrum is evaluated (see Section 5 and Table 5). The other potentially evaluable peaks either have lower emission intensities or the gamma peaks of other radionuclides interfere with them.

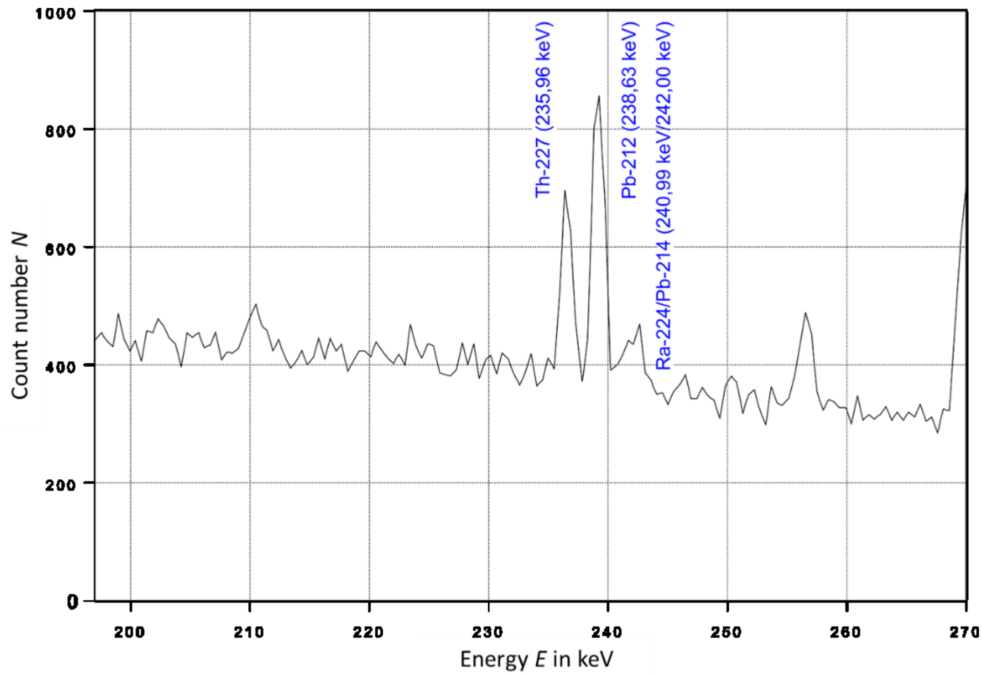

Fig. 5: Evaluation of the 236,0 keV peak of Th-227 in the pulse height spectrum of a sponge sample (Greenland) used to determine the specific activity of Ac-227

Tab. 5: Nuclear data of the radionuclide to be evaluated when determining the Ac-227 content by means of gamma spectrometry

Radionuclide to be determined	E_γ	p_γ	Interfering radionuclide	E_γ	p_γ
	in keV	in %		in keV	in %
Th-227	235,96	12,6			

4.6 Thorium-232

With a half-life of $1{,}40 \cdot 10^{10}$ years, thorium-232 (Th-232) is the parent radionuclide of the thorium decay chain. At 63,8 keV, Th-232 has a gamma peak with a very low emission intensity of 0,259 %. A gamma peak of Th-234 at 63,3 keV with a higher emission intensity of 3,75 % interferes with this gamma peak (see Table 1), so that Th-232 cannot be determined directly by means of gamma spectrometry in environmental samples.

Determining Th-232 via its progenies Ac-228, Pb-212 and Tl-208 is only possible if these radionuclides are at radioactive equilibrium with each other and with their parent radionuclide Th-232. Environmental samples, however, are not always in radioactive equilibrium, while industrial residues and products containing naturally occurring radioactive material (NORM) are never in equilibrium. This is caused by the radionuclide Ra-228, which is located between Th-232 and Ac-228 in the decay chain, and can modify the radioactive equilibrium due to its chemical properties and mobility.

4.7 Radium-228

Radium-228 (Ra-228) is a radionuclide of the thorium decay chain; its half-life is 5,75 years. The Ra-228 content is determined by evaluating the gamma peaks of its progeny Ac-228, which is at radioactive equilibrium with Ra-228 after approx. 30 hours due to its short half-life of 6,15 hours. Here, a coincidence summation correction must always be performed [2]. In Table 6, gamma peaks are listed which are suitable for the evaluation.

If the activities of Ra-224, Pb-212 and Tl-208 (whose gamma peaks are listed in Table 7) do not significantly deviate from the activity of Ac-228, then these radionuclides may also be used to determine the activity of Ra-228.

Tab. 6: Nuclear data of the radionuclide to be evaluated and of the interfering nuclide when determining the Ra-228 content by means of gamma spectrometry

Radionuclide to be determined	E_γ in keV	p_γ in %	Interfering radionuclide	E_γ in keV	p_γ in %
Ac-228	209,25	3,97			
	338,32	11,40	Ra-223	338,28	2,85
	911,20	26,20			
	968,96	15,90			

4.8 Thorium-228

Thorium-228 (Th-228) is a radionuclide of the thorium decay chain; its half-life is 1,91 years. At radioactive equilibrium, Th-228 content may be determined by evaluating the gamma peaks of its short-lived progenies Ra-224, Pb-212 and Tl-208. Regarding radioactive equilibrium, it is important to differentiate between solid and liquid samples:

— In liquid samples, radioactive equilibrium is certainly reached after a period of 23 days.

— In solid samples, radioactive equilibrium is prevalent at the time of sampling.

When evaluating the gamma peak of Ra-224 at 241,0 keV, the interfering gamma peak of Pb-214 at an energy of 242,0 keV must be taken into account (see Figure 5).

If the content of Th-228 is determined via the gamma peaks of the radionuclides Pb-212 and Tl-208, Rn-220 must remain in the sample matrix which is usually given due to its low half-life of 55,8 seconds. Preferably, the gamma peak of Pb-212 at 238,6 keV is used for the evaluation where coincidence summation corrections must always be applied [2].

Tab. 7: Nuclear data of the radionuclides to be evaluated and the interfering nuclides when determining the Th-228 content by means of gamma spectrometry

Radionuclide to be determined	E_γ in keV	p_γ in %	**Interfering radionuclide**	E_γ in keV	p_γ in %
Ra-224	240,99	4,12	Pb-214	242,00	7,27
Pb-212	238,63	43,60			
	300,09	3,18	Th-227	300,50	0,014
			Pa-231	300,06	2,41
Tl-208	277,37	2,37	Ac-228	278,80	0,235
	583,19	30,54	Ac-228	583,39	0,120
	860,53	4,46			
	2614,51	35,84			

4.9 Potassium-40

Potassium-40 (K-40) is present in the isotopic mixture of natural potassium (K-39, K-40, K-41) at the rate of 0,0117 weight by weight. It decays with a half-life of $1{,}25 \cdot 10^9$ years to Ca-40 (β^- decay) and Ar-40 (electron capture), respectively. K-40 is determined via its 1460,8 keV gamma peak (see Figure 4).

The interference due to Ac-228 shown in Table 8 must be taken into account for example when determining activity content in sewage sludge and/or in various NORM substances in which – contrary to environmental samples – elevated activity contents of Ra-228 occur as compared to K-40.

Tab. 8: Nuclear data of the radionuclide to be evaluated and of the interfering nuclide when determining the K-40 content by means of gamma spectrometry

Radionuclide to be determined	E_γ in keV	p_γ in %	**Interfering radionuclide**	E_γ in keV	p_γ in %
K-40	1460,82	10,55	Ac-228	1459,13	0,87

Annex A
Nuclear data of selected radionuclides

Sources of nuclear decay data are compiled in the General Chapter KERNDATEN of this Procedures' Manual [5]. Table A1 compiles the gamma photon energies in the energy region above 25 keV and the associated emission intensities corrected for branching for selected natural radionuclides. The listed emission intensities of X-ray peaks are not corrected for branching, which is indicated by an asterisk (*) following the emission intensity.

Note:
The emission intensities of the characteristic X-ray photons apply to the corresponding nuclear transformations. It must be pointed out that characteristic X-rays may also occur in the form of fluorescence radiation. When determining the activity of natural radionuclides in environmental samples, the contribution of fluorescence radiation to the net count rates is, however, negligible in most instances.

In addition, the column "Other" contains artificial radionuclides, which are generally used in calibration standards, and activation products, which may be generated in the measurement system by neutrons originating in cosmic radiation [3: Section 2, 5].

Tab. A1: Photon energies and emission intensities of selected radionuclides

Peak	Th-232 and progeny radionuclides		Ra-226 and progeny radionuclides		U-238/U-235 and progeny radionuclides		Ac-227 and progeny radionuclides		Other	
E_γ in keV	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ or origin
25,64					Th-231	0,139				
39,86	Bi-212	0,00107								
46,54			Pb-210	0,0425						
50,13							Th-227	0,082		
53,16									Ba-133	0,0214
53,20					U-234	0,00125				
53,23			Pb-214	0,0106						
53,47									Ge-73m	(n, γ)
57,75	Ac-228	0,0047								
59,54									Am-241	0,359
63,30					Th-234	0,0375				
63,81	Th-232	0,00259								
66,75									Ge-73m	(n, γ)
67,67					Th-230	0,00377				
72,80	Pb-Kα2	0,0077*								
72,87							Tl-Kα1	0,01225*		
74,82	Bi-Kα2	0,107*	Bi-Kα2	0,0626*						
74,97	Pb-Kα1	0,0361*								

Peak	Th-232 and progeny radionuclides		Ra-226 and progeny radionuclides		U-238/U-235 and progeny radionuclides		Ac-227 and progeny radionuclides		Other	
E_γ in keV	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ or origin
76,86			Po-Kα2	0,00426*						
77,11	Bi-Kα1	0,177*								
79,29			Po-Kα1	0,00710*						
79,61									Ba-133	0,0263
79,72							Th-227	0,0189		
81,00									Ba-133	0,333
81,07	Rn-Kα2	0,0013	Rn-Kα2	0,00192*			Rn-Kα2	0,150*		
83,78	Rn-Kα1	0,00215	Rn-Kα1	0,00317*			Rn-Kα1	0,249*		
84,21					Th-231	0,0670				
84,37	Th-228	0,0119								
84,94	Pb-Kα1	0,0117*								
85,43							Ra-Kα2	0,0017*		
87,34	Bi-Kα1	0,0612*								
88,03									Cd-109	0,0366
88,47							Ra-Kα1	0,0028*		
89,81			Po-Kα1	0,00245*						
89,95	Th-Kα2	0,025*								
92,38					Th-234	0,0218				
92,80					Th-234	0,0215				
93,35	Th-Kα1	0,041*								
93,93							Th-227	0,0137		
94,86			Rn-Kα1	0,198*			Rn-Kα1	0,0870*		
96,73									Se-75	0,0335
97,90							Rn-Kα2	0,0280*		
99,51	Ac-228	0,0126								
102,27					Th-231	0,00441				
105,31									Eu-155	0,211
105,60	Th-Kα1	0,00155*								
109,19					U-235	0,0166				
109,70									F-19	(n,n', γ)
112,81					Th-234	0,00215				
115,18	Pb-212	0,00624								
121,12									Se-75	0,169
122,06									Co-57	0,855
122,32							Ra-223	0,0124		
129,07	Ac-228	0,0250								
136,00									Se-75	0,577
136,47									Co-57	0,107
139,20									Ge-75m	(n, γ)
143,77					U-235	0,109				
144,27							Ra-223	0,0336		
145,44									Ce-141	0,483
145,84	Ac-228	0,00169								
153,97	Ac-228	0,00754								

Peak	Th-232 and progeny radionuclides		Ra-226 and progeny radionuclides		U-238/U-235 and progeny radionuclides		Ac-227 and progeny radionuclides		Other	
E_γ in keV	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ or origin
154,21							Ra-223	0,0584		
159,50									Ge-77m	(n, γ)
160,61									Ba-133	0,00638
163,36					U-235	0,0508				
174,88									Ge-71m	(n, γ)
185,72					U-235	0,570				
186,01			Ra-226	0,0356					Cu-66	(n, γ)
186,20									Ge-70m	(n, γ)
191,35	Ac-228	0,00133								
197,90									Ge-71m	(n, γ)
198,61									Se-75	0,0146
202,12					U-235	0,0108				
205,32					U-235	0,0502				
209,25	Ac-228	0,0397								
210,65							Th-227	0,0111		
215,51									Ge-77	(n, γ)
223,24									Ba-133	0,00450
235,96							Th-227	0,126		
238,63	Pb-212	0,436								
240,99	Ra-224	0,0412								
242,00			Pb-214	0,0727						
256,23							Th-227	0,070		
258,87			Pb-214	0,00532						
264,66									Se-75	0,588
269,46							Ra-223	0,142		
270,25	Ac-228	0,0355								
271,23							Rn-219	0,111		
274,80			Pb-214	0,00362						
276,40									Ba-133	0,0713
277,37	Tl-208	0,0237								
278,24									Cu-64	(n, γ)
278,80	Ac-228	0,00235								
279,20									Hg-203	0,815
279,54									Se-75	0,249
283,69					Pa-231	0,0165				
286,12							Th-227	0,0154		
288,18	Bi-212	0,0032								
295,22			Pb-214	0,184						
300,05							Th-227	0,000140		
300,06					Pa-231	0,0241				
300,09	Pb-212	0,0318								
302,67					Pa-231	0,023				
302,85									Ba-133	0,183
303,92									Se-75	0,0131

Peak	Th-232 and progeny radionuclides		Ra-226 and progeny radionuclides		U-238/U-235 and progeny radionuclides		Ac-227 and progeny radionuclides		Other	
E_γ in keV	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ or origin
304,52							Th-227	0,012		
320,08									Cr-51	0,0989
321,65	Ac-228	0,00232								
323,87							Ra-223	0,0406		
328,04	Bi-212	0,00121								
328,00	Ac-228	0,0304								
329,85							Th-227	0,027		
330,04					Pa-231	0,0136				
332,37	Ac-228	0,0037								
334,38							Th-227	0,0105		
338,28							Ra-223	0,0285		
338,32	Ac-228	0,1140								
340,97	Ac-228	0,00405								
351,03							Bi-211	0,130		
351,93			Pb-214	0,356						
356,01									Ba-133	0,621
383,85									Ba-133	0,089
386,77			Bi-214	0,00296						
388,88			Bi-214	0,00394						
400,66									Se-75	0,114
401,81							Rn-219	0,0675		
404,83							Pb-211	0,0383		
409,46	Ac-228	0,0202								
427,15							Pb-211	0,0181		
445,03							Ra-223	0,0128		
452,98	Bi-212	0,00340								
454,77			Bi-214	0,00288						
463,00	Ac-228	0,0445								
475,37									Cs-134	0,0148
477,60									Be-7	0,104
480,43			Pb-214	0,00337						
487,09			Pb-214	0,00433						
503,82	Ac-228	0,00171								
508,96	Ac-228	0,00510								
510,74	Tl-208	0,0808								
558,46									Cd-114	(n, γ)
562,50	Ac-228	0,00890								
563,25									Cs-134	0,0834
569,33									Cs-134	0,154
570,88	Ac-228	0,00190								
580,13			Pb-214	0,00369						
583,19	Tl-208	0,305								
583,39	Ac-228	0,00120								
595,85									Ge-74	(n,n', γ)

Peak	Th-232 and progeny radionuclides		Ra-226 and progeny radionuclides		U-238/U-235 and progeny radionuclides		Ac-227 and progeny radionuclides		Other	
E_γ in keV	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ or origin
600,70									Ge-74	(n,n', γ)
604,72									Cs-134	0,976
608,35									Ge-74	(n,n', γ)
609,31			Bi-214	0,455						
651,26									Cd-114	(n, γ)
661,66									Cs-137	0,850
665,45			Bi-214	0,0153						
669,60									Cu-63	(n,n', γ)
693,40									Ge-72	(n,n', γ)
703,11			Bi-214	0,00479						
719,86			Bi-214	0,00393						
726,88	Ac-228	0,00680								
727,33	Bi-212	0,0665								
755,31	Ac-228	0,0103								
763,45	Tl-208	0,0647								
765,80									Nb-95	0,998
766,36					Pa-234m	0,00323				
768,36			Bi-214	0,0489						
772,29	Ac-228	0,0152								
782,14	Ac-228	0,00500								
785,37	Bi-212	0,0111								
785,96			Pb-214	0,0106						
794,94	Ac-228	0,0431								
795,86									Cs-134	0,855
801,95									Cs-134	0,0869
803,00									Pb-206	(n,n', γ)
805,89									Cd-114	(n, γ)
806,17			Bi-214	0,0126						
830,48	Ac-228	0,00610								
831,98							Pb-211	0,0350		
834,85									Mn-54	0,9998
835,70	Ac-228	0,0170								
839,04			Pb-214	0,00587						
840,37	Ac-228	0,00970								
860,53	Tl-208	0,0446								
867,90									Ge-74	(n, γ)
893,41	Bi-212	0,0038								
904,20	Ac-228	0,0078								
911,20	Ac-228	0,262								
934,06			Bi-214	0,0310						
962,00									Cu-63	(n,n', γ)
964,79	Ac-228	0,0499								
968,96	Ac-228	0,159								
1001,03					Pa-234m	0,00847				

Peak	Th-232 and progeny radionuclides		Ra-226 and progeny radionuclides		U-238/U-235 and progeny radionuclides		Ac-227 and progeny radionuclides		Other	
E_γ in keV	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ	Nuclide	p_γ or origin
1038,61									Cs-134	0,00991
1051,96			Bi-214	0,00324						
1063,60									Pb-207	(n,n', γ)
1078,63	Bi-212	0,00550								
1115,54									Cu-65	(n,n', γ)
1120,29			Bi-214	0,149						
1127,80									Ge-(75)	(n, γ)
1155,19			Bi-214	0,0164						
1167,97									Cs-134	0,0179
1173,23									Co-60	0,9985
1207,68			Bi-214	0,00454						
1238,11			Bi-214	0,0583						
1247,10	Ac-228	0,00524								
1280,96			Bi-214	0,0144						
1327,00									Cu-63	(n,n', γ)
1332,49									Co-60	0,9998
1365,19									Cs-134	0,0302
1377,67			Bi-214	0,0397						
1385,31			Bi-214	0,00795						
1401,50			Bi-214	0,0133						
1407,98			Bi-214	0,0239						
1412,00									Cu-63	(n,n', γ)
1459,13	Ac-228	0,00870								
1460,82									K-40	0,106
1495,90	Ac-228	0,00920								
1501,59	Ac-228	0,00513								
1509,23			Bi-214	0,0213						
1512,70	Bi-212	0,00290								
1538,50			Bi-214	0,00401						
1543,32			Bi-214	0,0302						
1580,53	Ac-228	0,00620								
1583,22			Bi-214	0,00707						
1588,20	Ac-228	0,0306								
1599,31			Bi-214	0,00322						
1620,74	Bi-212	0,0151								
1630,62	Ac-228	0,0152								
1638,27	Ac-228	0,0046								
1661,28			Bi-214	0,0105						
1729,60			Bi-214	0,0284						
1764,49			Bi-214	0,1531						
1838,36			Bi-214	0,0034						
1847,42			Bi-214	0,0203						
2118,55			Bi-214	0,0116						
2204,21			Bi-214	0,0491						

Peak E_γ in keV	Th-232 and progeny radionuclides Nuclide	p_γ	Ra-226 and progeny radionuclides Nuclide	p_γ	U-238/U-235 and progeny radionuclides Nuclide	p_γ	Ac-227 and progeny radionuclides Nuclide	p_γ	Other Nuclide	p_γ or origin
2293,40			Bi-214	0,0031						
2447,86			Bi-214	0,0155						
2614,51	Tl-208	0,358								

References

[1] *Richtlinie zur Emissions- und Immissionsüberwachung bei bergbaulichen Tätigkeiten (REI-Bergbau)* from 10.11.2020. Available at: https://www.bfs.de/SharedDocs/Downloads/BfS/DE/fachinfo/ion-altlasten/rei-bergbau.pdf?__blob=publicationFile&v=3. [Last access 21.08.2024].

[2] Arnold, D., Debertin, K., Heckel, A., Kanisch, G., Wershofen, H., Wilhem, C.: *Fundamentals of gamma spectrometry*. γ-SPEKT/GRUNDL, Version March 2018. In: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (ed.): Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation. ISSN 1865-8725. Available at: https://www.bmuv.de/WS1517-1. [Last access 27.10.2023].

[3] Arnold, D., Heckel, A., Wershofen, H.: *Background contributions in gamma spectrometry*. γ-SPEKT/NULLEF, Version June 2019. In: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (ed.): Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation. ISSN 1865-8725. Available at: https://www.bmuv.de/WS1517-1. [Last access 21.08.2024].

[4] Kanisch, G., Mundschenk, H., Schkade, U.-K., Wershofen, H.: *Interferences in gamma spectrometry*. γ-SPEKT/INTERF, Version March 2019. In: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (ed.): Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation. ISSN 1865-8725. Available at: https://www.bmuv.de/WS1517-1. [Last access 21.08.2024].

[5] Heckel, A., Wershofen, H.: *Nuclear Data*. KERNDATEN, Version November 2024. In: Federal Ministry for Environment, Nature Conservation, Nuclear Safety and Consumer Protection, (ed.): Procedures' Manual for moitoring of radioactive substances in the environment and of external radiation. ISSN 1865-8725. Available at: https://www.bmuv.de/WS1517-1. [Last access 22.08.2024].

[6] Arnold, D., Kanisch, G., Wershofen, H.: *Summation peaks and escape peaks of selected radionuclides in gamma spectrometry*. γ-SPEKT/SUMESC, Version November 2018. In: Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (ed.): Procedures' Manual for monitoring of radioactive

substances in the environment and of external radiation. ISSN 1865-8725. Available at: https://www.bmuv.de/WS1517-1. [Last access 21.08.2024].