

DETECTION EFFICIENCIES OF ^{226}Ra AND ^{232}Th IN DIFFERENT MODES OF COUNTING OF THE PRIPYAT-2M SPECTROMETER

by

Nevenka M. ANTOVIĆ¹ and Nikola SVRKOTA²

Received on March 30, 2009; accepted in revised form on July 9, 2009

Detection efficiencies of ^{226}Ra and ^{232}Th decay products, as well as corresponding minimum detectable activities in different modes of counting of the PRIPYAT-2M spectrometer (integral, when all pulses – coincident and non-coincident, are counted; non-coincident, when only non-coincident pulses are counted; coincident, when coincident pulses of multiplicity from 2 to 6 are counted), in energy ranges of 200 keV to 2000 keV and 300 keV to 3000 keV are presented here. It has been shown that the mode of double coincidences is the optimum one for measuring radium and thorium activity. In this mode of counting, the sensitivity of the spectrometer is the highest.

Key words: radium, thorium, multidetector spectrometer, detection efficiency, gamma-coincidences

INTRODUCTION

As is well known, ^{226}Ra originates from the radioactive series of ^{238}U . There are eight daughter radionuclides (^{222}Rn , ^{218}Po , ^{214}Pb , ^{214}Bi , ^{214}Po , ^{210}Pb , ^{210}Bi , ^{210}Po) which decay via 5 α - and 4 β^- -decays (excluding the ones with extremely low intensities), mostly accompanied by the emission of γ -rays. The last one (^{210}Po) decays to the stable isotope of lead – ^{206}Pb . The ^{232}Th radioactive series containing ten daughter radionuclides (^{228}Ra , ^{228}Ac , ^{228}Th , ^{224}Ra , ^{220}Rn , ^{216}Po , ^{212}Pb , ^{212}Bi , ^{208}Tl , ^{212}Po), undergoes a decay chain: 7 α , 5 β^- -decays, accompanied by an emission of γ -rays and ending with the stable isotope of lead – ^{208}Pb , (ref. 1).

Various radium and thorium measurements were mainly performed using standard alpha- or gamma-spectrometry, although other techniques have been used as

well. Coincidence methods enabled by some spectrometers and coincidence schemes are also used for radium and thorium measurements, (refs. 2-4).

Coincidence methods developed at the six-crystal 4π -spectrometer PRIPYAT-2M are based on coincidence counting of the 609 keV photons (from two-, three-, and four-step cascade transitions which follow the β^- -decay of ^{214}Bi (to ^{214}Po), in the decay chain of ^{226}Ra ; *i. e.*, 609 keV photon detection in the two-, three-, and four-fold coincidence modes of counting), as well as on coincidence counting of the 583 keV and 2615 keV photons from cascade transitions which follow the β^- -decay of ^{208}Tl (in the ^{232}Th decay chain). photopeak detection efficiencies, as well as minimum detectable activities in different modes of counting of the PRIPYAT-2M spectrometer – in two energy ranges (from 200 keV to 2000 keV, and from 300 keV to 3000 keV) are presented and discussed here. These energy ranges have been selected during the processing of the results.

^{226}Ra AND ^{232}Th MEASUREMENT BY THE PRIPYAT-2M SPECTROMETER

PRIPYAT-2M spectrometer

The PRIPYAT-2M spectrometer system, (ref. 5), with outer dimensions of 250 145 186 cm and a mass of 4200 kg, consists of 6 NaI(Tl) detectors (diameter: 15 cm, height: 10 cm), iron and lead passive

Nuclear Technology & Radiation Protection
Scientific paper
UDC: 539.166:543.42
DOI: 10.2298/NTRP0902109A

Authors' addresses:

¹ Faculty of Natural Sciences and Mathematics,
University of Montenegro
b.b., Džordža Vashiingtona Str., 20000 Podgorica, Montenegro

² Center for Ecotoxicological Research
2, Put Radomira Ivanovica Str.
20000 Podgorica, Montenegro

E-mail address of corresponding author:
nena@rc.pmf.ac.me (N. Antović)

shielding (up to 15 cm), an electro-motor, modular pulse-processing electronics in the CAMAC standard, PC, and PRIP software.

The spectrometer's sensitive volume allows the measurement of samples of any shape and volume (up to do 5 dm³) without preliminary preparations (for obtaining homogenized samples, for example). In addition, owing to its characteristics, the need for calibration measurements for different sample geometries can be avoided, (ref. 5).

The total solid angle of the spectrometer is $\sim 0.7 \cdot 4\pi$ sr with an energy resolution of 10.5% for the ¹³⁷Cs – 662 keV line. The resolution time for coincidences is 40 ns, and the multiplicity of coincidences – from 2 to 6. The dead time depends on source activity and in the case of background measurements it is usually less than 1%.

The PRIP software (with wide service possibilities – calibration, data acquisition, data processing, presentation and archiving, automatic control of all operations, *etc.*) enables several modes of counting:

- (1) integral mode [1-6], when all pulses coming from the detectors are counted (coincident and non-coincident);
- (2) non-coincidental mode [1-1], when only non-coincident pulses are counted (*i. e.*, photons detected without simultaneous (respecting the spectrometer's resolution time) detection of other photon(s) by other detector(s);
- (3) coincidence mode, when γ -spectra of coincident pulses [2-6] (with multiplicity from 2 to 6) are produced. This spectrum shows all coincident pulses (two-, three-, four-, five-, and six-fold ones) without their separation;
- (4) coincidence mode, when the γ -spectra of coincident pulses (separate two-, three-, four-, five-, and six-fold, *i. e.*, [2-2], [3-3], [4-4], [5-5], and [6-6], respectively), are produced simultaneously. In this mode of counting, a selection of the coincidence-fold range is possible.

In each mode of counting, the software gives six spectra from single detectors, as well as their sum spectrum and information about registered energy, photopeak count rate, photopeak width (in keV) *etc.* Moreover, it identifies radioisotopes (on the base of an existing library) and calculates their activity (and specific activity) in a sample.

Background count rates

Total background count rates obtained from the 1000 s real time spectra, in the energy range from 200 keV to 2000 keV (from channels 2 to 255), were: 31.5 cps in the integral ([1-6]), 25.5 cps in the non-coincident ([1-1]), 3.7 cps in the double coincidences ([2-2]), and 6.1 cps – in the [2-6] spectrum.

Total background count rates in the same energy range in other coincidence modes of counting ([3-3], [4-4], [5-5], and [6-6]) were: 1.5, 0.62, 0.34, and 0.09 cps, respectively. In the energy range from 300 keV to 3000 keV (from channels 2-255), these count rates were 26.4 cps - in the integral, 21.1 cps - in the non-coincident, 3.4 cps - in the double coincidences, 5.2 cps - in the [2-6] spectrum, and in the spectra of three-, four-, five-, and six-fold coincidences – 1.3, 0.57, 0.32, and 0.11 cps, respectively.

In general, total background count rates were higher in the energy range of (200-2000) keV, than in that of (300-3000) keV. This confirms that the contribution of background radiation to the energy range from 200 to 300 keV is higher than to that of 2000 to 3000 keV. Moreover, total background count rates were significantly lower in the coincidence modes of counting of the PRIPYAT-2M spectrometer than in the integral and non-coincidental ones – in both selected energy ranges. On the other hand, these count rates decrease with an increase of the multiplicity of coincidences, as well. Considering the integral, non-coincidental [2-6], double, triple and four-fold coincidence mode of counting, the highest discrepancy between total background count rates in the 200 keV to 2000 keV and 300 keV to 3000 keV energy ranges appeared in the non-coincidental mode of counting, and the lowest one – in case of double and four-fold coincidences.

²²⁶Ra detection

The experiments performed by the PRIPYAT-2M spectrometer have shown that, if the radium in a probe is in radioactive equilibrium with its decay products, ²²⁶Ra activity (as well as its decay products' activity) can be determined by the 609 keV photopeak (the 609.312 keV photons which follow the β^- -decay of ²¹⁴Bi, with an intensity of 46.1%) – in the integral, non-coincidental, and in some of the spectra of coincidences (double, three- and four-fold ones), as well as in the [2-6] spectrum, *i. e.*, detecting simultaneously the 609 keV γ -ray and γ -rays in cascade with it. It is important to point out that the most intensive two-fold cascades are, (ref. 1):

1120.287 keV (15.1%) + 609.312 keV (46.1%),
1238.110 keV (5.79%) + 609.312 keV,
768.356 keV (4.94%) + 609.312 keV,
934.061 keV (3.03%) + 609.312 keV;

three-fold:

388.88 keV (0.37%) + 1120.287 keV + 609.312 keV,
386.77 keV (0.31%) + 768.356 keV + 609.312 keV,
1069.96 keV (0.275%) + 768.356 keV + 609.312 keV,
752.84 keV (0.13%) + 1120.287 keV + 609.312 keV;
and four-fold ones:

683.22 keV (0.081%) + 386.77 keV (0.31%) +
+ 768.356 keV + 609.312 keV,

847.16 keV (0.026%) + 469.76 (0.129%) + 768.356 keV + 609.312 keV,
 752.84 keV (0.13%) + 454.77 keV (0.30%) + 665.453 keV (1.46%) + 609.312 keV,
 501.96 keV (0.018%) + 348.92 keV (0.12%) + 806.174 keV (1.22%) + 609.312 keV.

The γ -transition intensities are presented in the brackets.

A ^{226}Ra probe of known activity (Pylon Electronics Inc. Canada, 2250 Bq, S/N 189) in a metallic cover (height: 6 cm, diameter: 4.4 cm), with ^{226}Ra in radioactive equilibrium with its decay products (no losses via ^{222}Rn emanation) was positioned in the center of the detection chamber of the PRIPYAT-2M spectrometer and measured for 1000 s real time. Three measurements were performed – in the integral, [2-6], and in modes [1-1], [2-2], [3-3], [4-4], [5-5], and [6-6], simultaneously. The energy ranges were selected during the processing of the results, as it was mentioned previously. Sum spectra in the 200 keV to 2000 keV energy range (from channels 2 to 255) in different modes of counting, after the subtraction of the corresponding background, are shown in fig. 1. Live measuring time in the integral mode of counting was 663.2

s, and in the non-coincidental and modes of coincidences – 666.3 s, while in the mode [2-6] it was 652.6 s. The same live measuring times were obtained in the case of the 300 keV to 3000 keV energy range (fig. 2).

Ratios of the total count rates in the probe and corresponding background spectra, in the energy region of 200 keV to 2000 keV, in the [1-6], [1-1], [2-6], [2-2], [3-3], [4-4], [5-5], and [6-6] mode of counting, were 56.74, 53.27, 68.91, 111.57, 25.49, 2.55, 0.44, and 1.02, respectively, and in the region of 300 keV to 3000 keV – 51.16, 48.89, 62.61, 98.56, 22.20, 2.12, 0.54, and 1.19, respectively.

As is seen, for the most part, ratios were higher in the 200 keV to 2000 keV range than those in that of 300 keV to 3000 keV. The best one was found for the double coincidences mode of counting ([2-2]), in both energy regions (although it was slightly higher in the 200 keV to 2000 keV range). The second best ratio was found for the [2-6], followed by the integral ([1-6]) mode of counting.

Figures 1 and 2, show that the 609 keV photopeak is most pronounced in the spectra of double and triple coincidences, as well as in the [2-6] spectra. In the four-fold coincidences spectra, for given measuring times, the said photopeak is not apparent

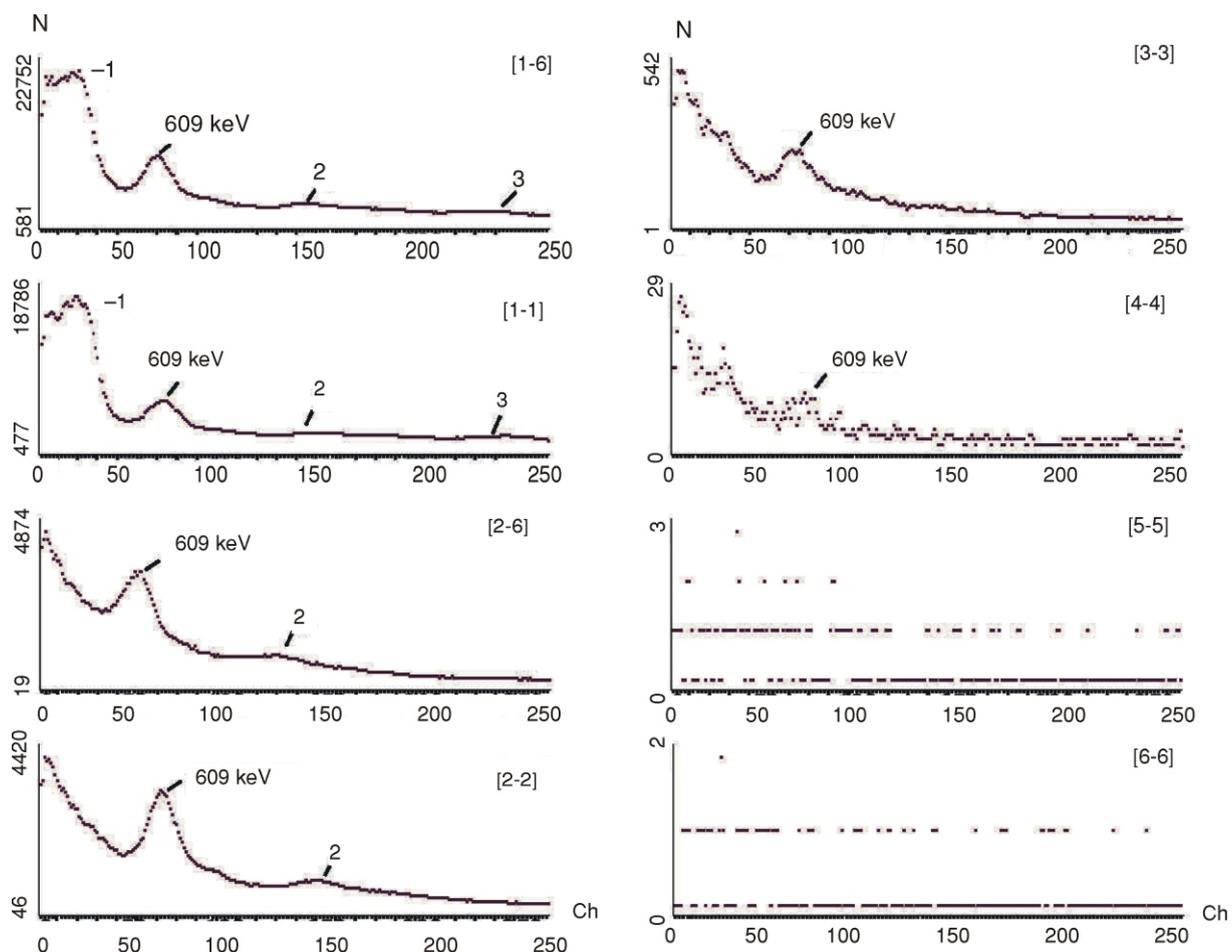


Figure 1. Sum spectra of the ^{226}Ra probe in different modes of counting of the PRIPYAT-2M spectrometer in the energy range from 200 keV to 2000 keV

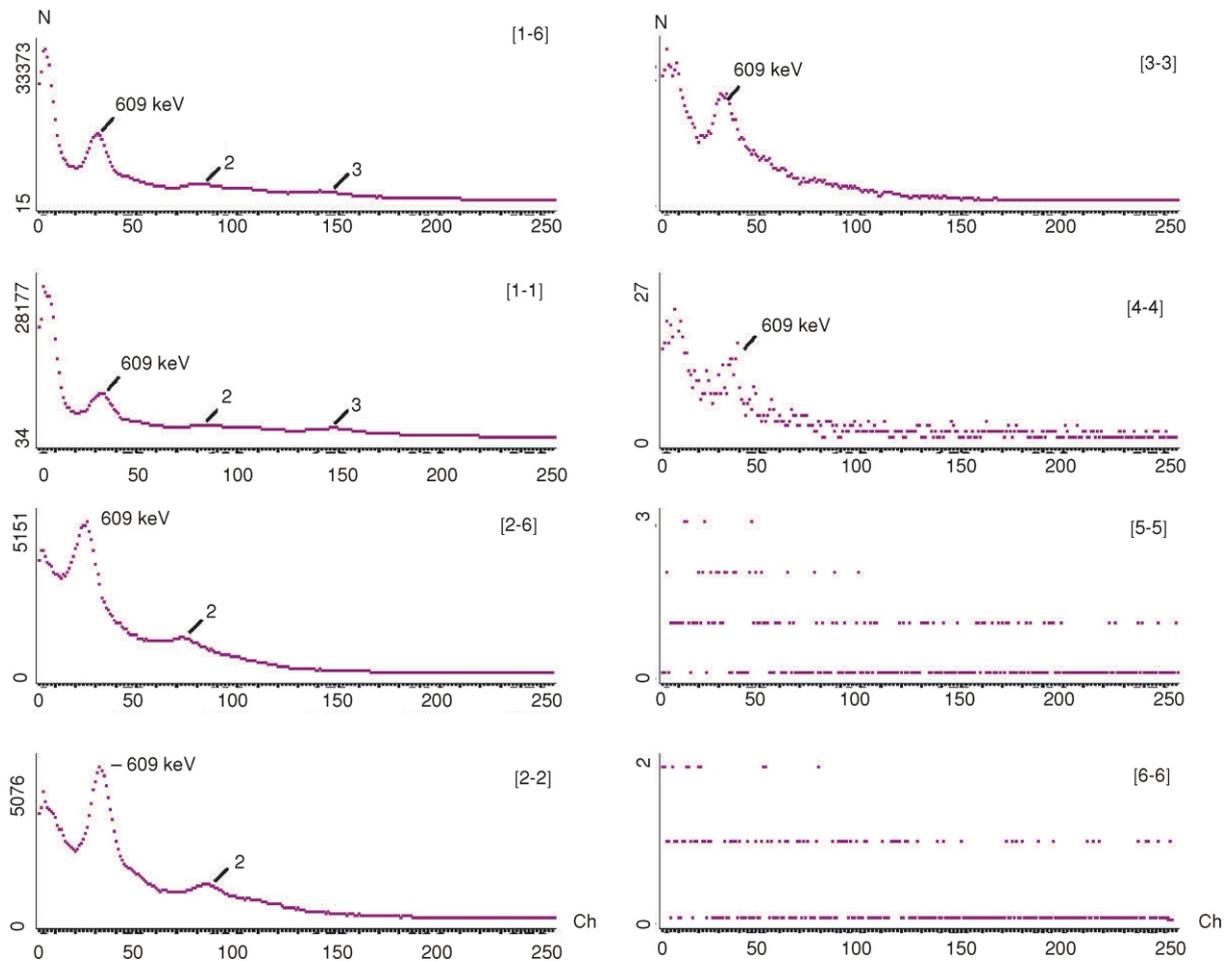


Figure 2. Sum spectra of the ^{226}Ra probe in different modes of counting of the PRIPYAT-2M spectrometer in the energy from 300 keV to 3000 keV

enough (for a precise analysis), while five- and six-fold coincidences with this photon were not registered.

The count rates in the range of the 609 keV photopeak in [1-6], [1-1], [2-6], [2-2], and [3-3] modes of counting, in the 200 keV to 2000 keV energy range, were 347.81, 218.77, 133.24, 125.46, and 9.13 cps, respectively (while the corresponding background count rates were 6.40, 5.17, 1.36, 0.83, and 0.25 cps, respectively) and in the 300 keV to 3000 keV energy range – 347.85, 211.53, 146.99, 127.14, and 9.13 cps, respectively (background count rates – 6.49, 5.01, 1.55, 0.86, and 0.25 cps, respectively).

For the most part, the region 1 represents an overlapping of peaks created by γ -rays with the energies of 351.932 keV (37.6%), 295.224 keV (19.3%), and 241.997 keV (7.43%), followed by the β -decay of ^{214}Pb (to ^{214}Bi), which is to say that they, thus, cannot be resolved due to the energy resolution of the PRIPYAT-2M spectrometer. The count rates in this energy range of the radium probe spectra were – 730.37 cps in the integral, and 581.18 cps in the non-coinci-

dent mode of counting, as background count rates were 11.38 cps and 8.75 cps, respectively.

Peaks marked as 2 and 3, with centroids at about 1200 keV and 1800 keV, respectively, mainly represent: peak 2, the registration of photons from the β -decay of ^{214}Bi (to ^{214}Po) with energies of 1120.287 keV (15.1%) and 1238.110 keV (5.79%) (peaks that cannot be resolved). The mentioned peaks are, possibly, also fed by a sum of the cascaded γ -rays from the same decay – for example, that of 609.312 keV (46.1%) and 665.453 keV (1.46%). In the 200 keV to 2000 keV energy range, count rates lower than the peaks in the probe spectra were 130.76 cps – in the integral, 77.87 cps – in the non-coincident, 34.93 cps – in the [2-6], and 40.41 cps – in the double coincidences mode of counting, while corresponding background count rates were 2.59, 2.35, 0.45, and 0.34 cps, respectively. In the 300 keV to 3000 keV energy region, the count rates in this region of the probe spectra were 141.21 cps (in the integral), 89.86 cps (in the non-coincident), 41.7 cps (in the [2-6]), and 42.43 cps (in the double coincidences mode of counting), and corresponding background count rates were

2.84, 2.02, 0.57, and 0.37 cps, respectively; peak 3: unresolved peaks of the 1764.494 keV (15.4%) and 1847.420 keV (2.11%) γ -rays. These photons follow the β^- -decay of ^{214}Bi , as well. The count rate under this peak in the probe spectrum, in the energy range of 200 keV to 2000 keV, in the integral and non-coincident modes of counting, was 76.18 cps and 68.24 cps, respectively; while in the corresponding background spectra it was 1.25 cps and 0.98 cps, respectively. In the energy region of 300 keV to 3000 keV, it was 96.58 cps and 84.06 cps, respectively (the probe spectra), and 1.76 cps and 1.24 cps, respectively (the background spectra).

For a better presentation of the above mentioned regions, a zoom of the spectra is shown in fig. 3: (a) 105-255 channel, in the region of 200 keV to 2000 keV, and (b) 55-255 channel, in the region of 300 keV to 3000 keV.

^{232}Th detection

If ^{232}Th in a probe is in radioactive equilibrium with its decay products, using the PRIPYAT-2M spectrometer and the energy region

of 300 keV to 3000 keV, its activity can be determined by the 911 keV photopeak (the 911.204 keV photons which follow the β^- -decay of ^{228}Ac , with an intensity of 25.8%) in the integral and non-coincident spectrum, as well as by the 583 keV and 2615 keV photopeak in the integral, non-coincident and coincidence spectrum (*i. e.*, detecting simultaneously the 583.191 keV (84.5%) and 2614.533 keV (99%) γ -rays (which follow the β^- -decay of ^{208}Tl) and γ -rays in cascade with them). The most intensive double coincidences are, (ref. 1):

583.191 keV (84.5%) + 2614.533 keV (99%),

860.564 keV (12.42%) + 2614.533 keV,

510.77 keV (22.6%) + 583.191 keV,

277.351 keV (6.31%) + 583.191 keV,

763.13 keV (1.81%) + 583.191 keV;

triple coincidences:

510.77 keV (22.6%) + 583.191 keV + 2614.533 keV,

277.351 keV (6.31%) + 583.191 keV + 2614.533 keV,

763.13 keV + 583.191 keV + 2614.533 keV,

982.7 keV (0.203%) + 583.191 keV + 2614.533 keV;

and four-fold coincidences:

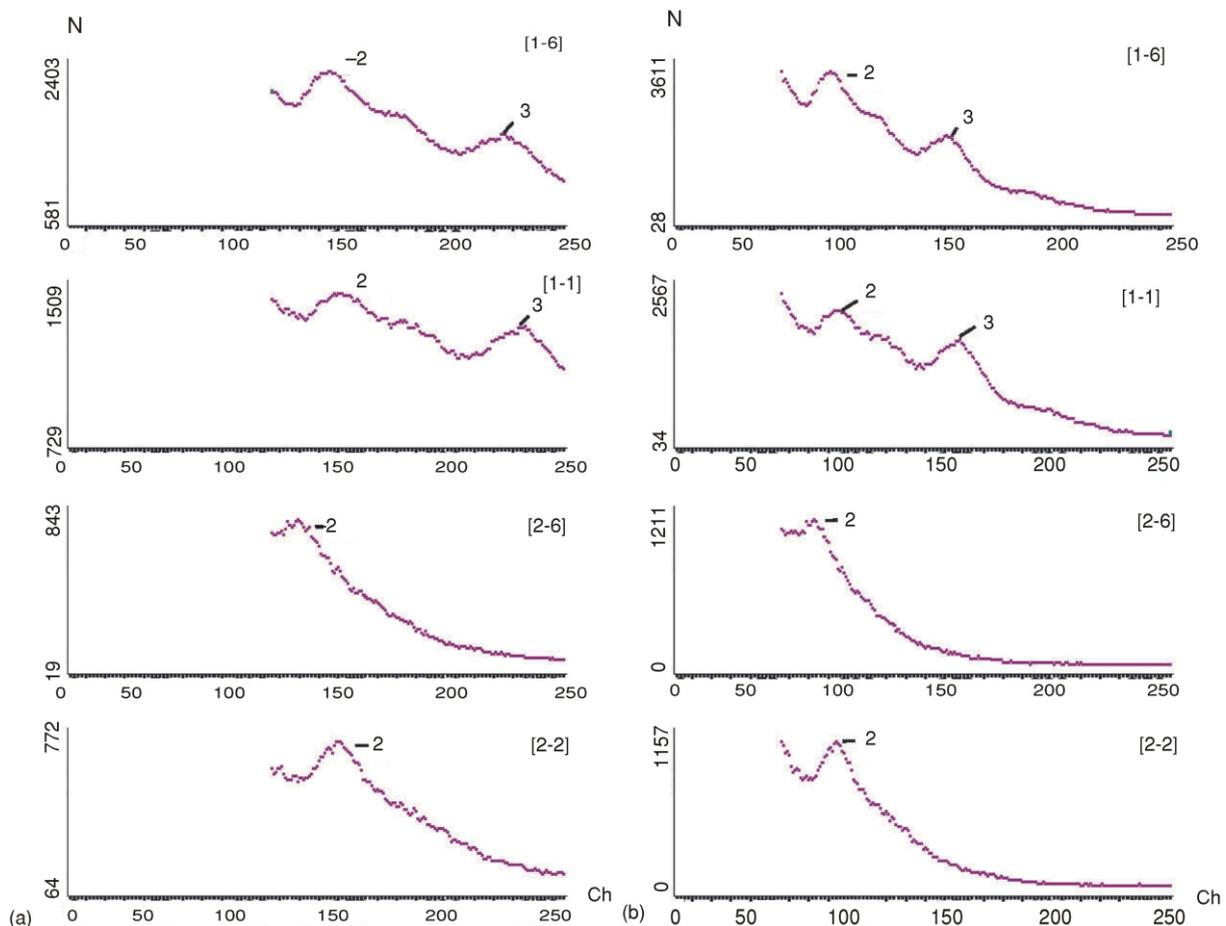


Figure 3. A zoom of the ^{226}Ra probe spectra: (a) 105-255 channel, in the region of 200 keV to 2000 keV; (b) 55-255 channel, in the region of 300 keV to 3000 keV

252.61 keV (0.69%) + 510.77 keV + 583.191 keV + 2614.533 keV,
 211.40 keV (0.178%) + 510.77 keV + 583.191 keV + 2614.533 keV,
 233.36 keV (0.30%) + 277.351 keV + 583.191 keV + 2614.533 keV.

In the energy range from 200 keV to 2000 keV, the possibility for thorium detection is reduced at the 583 keV photopeak and the 911 keV one, (ref. 6).

A thorium probe (height: 10 mm, diameter: 15 mm, mass: 1.41 g, activity: 1000 Bq; Institute of Physics, Belarusian Academy of Sciences, Minsk), with ^{232}Th and its decay products in radioactive equilibrium, no losses via thoron (^{220}Rn) emanation, positioned in the center of the detection chamber of the PRIPYAT-2M spectrometer, was measured for 1000 s in the integral (live time: 794.5 s), non-coincident and coincident modes of counting (live time: 794.6 s), as well as in the [2-6] modes of counting (live time: 835 s). Sum spectra in the energy region from 200 keV to 2000 keV (from channels 2 to 255), after the subtraction of the corresponding background, are shown in fig. 4, while the

spectra in the energy range from 300 keV to 3000 keV are shown in fig. 5 (these energy regions were selected during the processing of the results, as with radium measurement).

Ratios of the total count rates in the probe and background spectra, in the 200 keV to 2000 keV energy range, in the [1-6], [1-1], [2-6], [2-2], [3-3], [4-4], [5-5], and [6-6] modes of counting, were 28.82, 26.82, 38.26, 57.48, 18.54, 2.44, 0.56, and 1.12, respectively; and in the 300 keV to 3000 keV energy range: 24.66, 21.21, 37.77, 56.45, 18.86, 2.26, 0.73, and 1.26, respectively. The best ratio was found for the double coincidences mode of counting ([2-2]), in both energy ranges (yet, slightly higher in that of 200 keV to 2000 keV (b)).

A zoom of the thorium probe spectra is shown in fig. 6, from channels 162 to 255, in the range from 200 keV to 2000 keV (a), and from channel 95 to 255, in the range from 300 keV to 3000 keV (b).

As can be seen in figs. 4 and 5, five- and six-fold coincidences with the 583 keV γ -ray are not registered. On the other hand, this photopeak is most pronounced

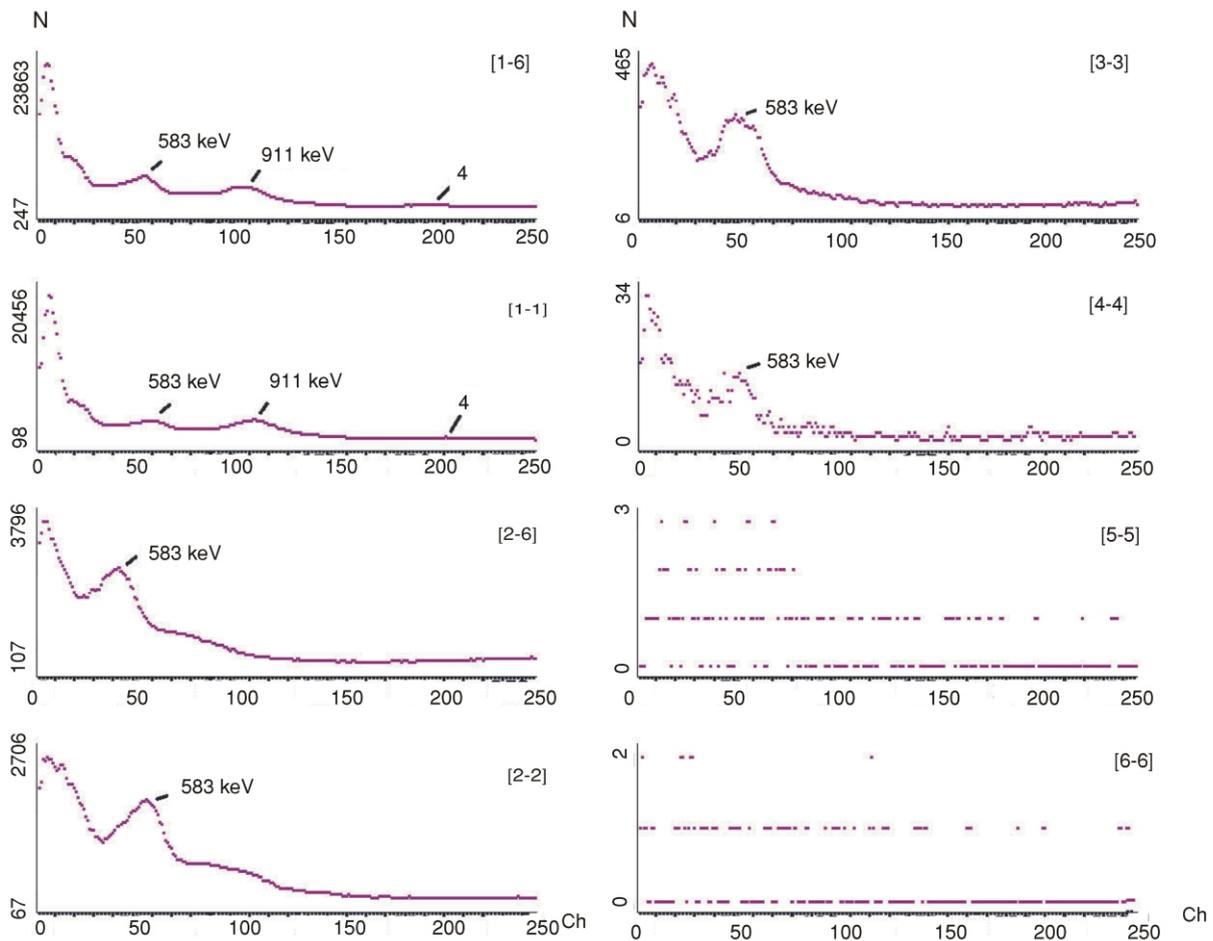


Figure 4. Sum spectra of the ^{232}Th probe in different modes of counting of the PRIPYAT-2M spectrometer in the energy range from 200 keV to 2000 keV

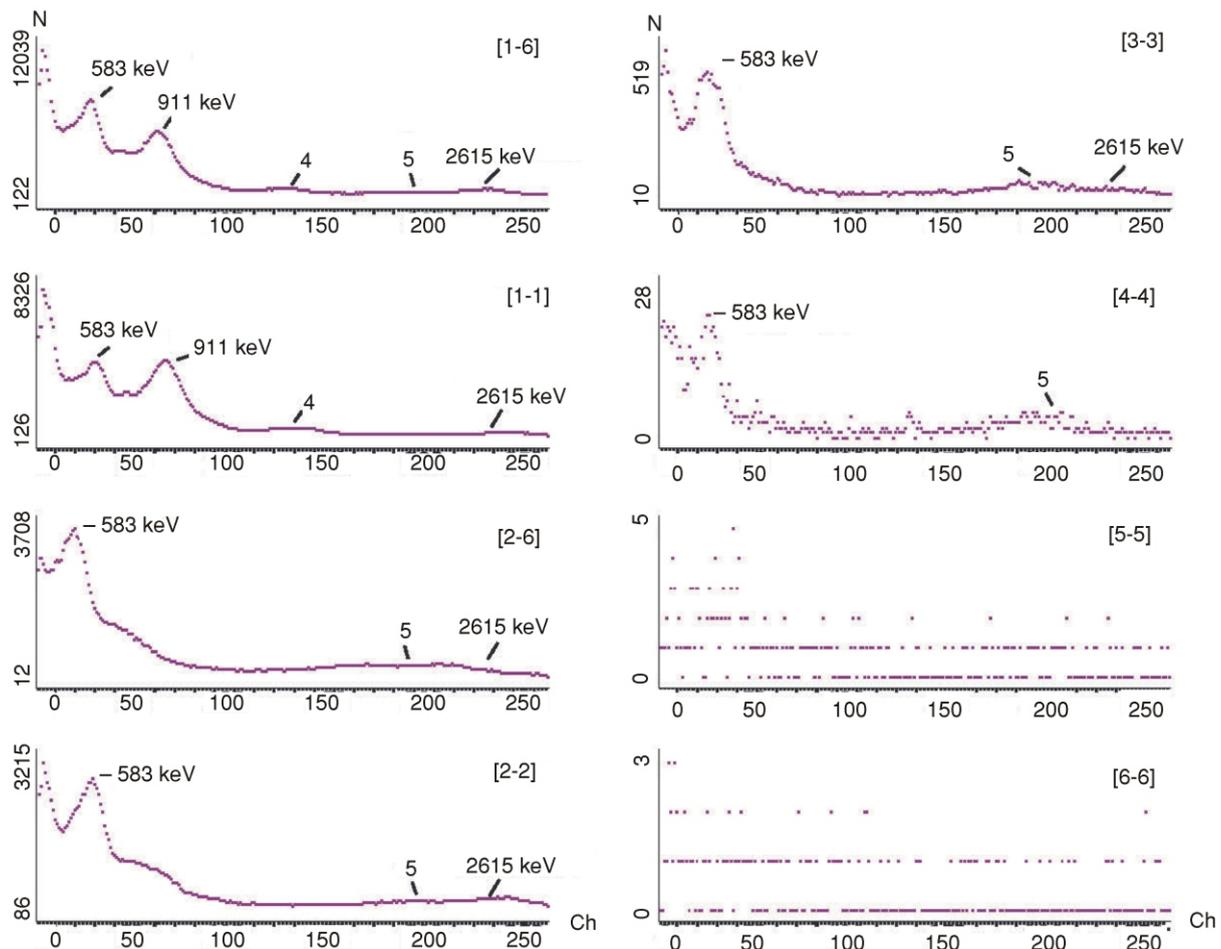


Figure 5. Sum spectra of the ^{232}Th probe in different modes of counting of the PRIPYAT-2M spectrometer in the energy range from 300 keV to 3000 keV

in the integral, as well as in the double (and in the [2-6]), triple and four-fold coincidences modes of counting. Our analysis has shown that a precise and certain use of this photopeak in the four-fold coincidences mode of counting requires a somewhat longer measuring time. In the non-coincident mode of counting it is less pronounced than the 911 keV one.

The count rates in the region of the 583 keV photopeak in the [1-6], [1-1], [2-6], [2-2], and [3-3] modes of counting, in the 200 keV to 2000 keV energy range were 182.36, 94.77, 84.16, 74.98, and 11.28 cps, respectively (the corresponding background count rates were 7.36, 4.89, 1.68, 1.07, and 0.48 cps, respectively), and in the 300 keV to 3000 keV energy range – 186.94, 97.48, 90.39, 75.45, and 10.65 cps, respectively (the background count rates – 7.77, 5.19, 1.83, 1.10, and 0.45 cps, respectively).

In the region of the 911 keV photopeak, the count rates in the probe spectra in the [1-6] and [1-1] modes of counting, in the 200 keV to 2000 keV range

were 139.84 cps and 117.44 cps, while the background ones were 3.68 cps and 2.99 cps, respectively. In the 300 keV to 3000 keV range of the probe spectra they were 139.69 cps and 115.95 cps, and in the background spectra – 3.75 cps and 2.97 cps, respectively.

The 2615 keV photopeak (if the energy region from 300 keV to 3000 keV is selected) in the triple coincidences mode of counting appears only slightly (in this measuring time), while four-fold coincidences with this γ -ray are not registered. The count rates under this photopeak in the probe [1-6], [1-1], [2-6], and [2-2] spectrum were 34.09, 17.07, 16.98, and 14.38 cps, respectively. In the same range, in the corresponding background spectra, they were 0.74, 0.49, 0.29, and 0.15 cps, respectively.

Peak 4, pronounced in the integral and non-coincident spectra, with a centroide at about 1600 keV, mainly represents the 1588.19 keV γ -ray (^{228}Th , 3.22%) peak, overlapped with the 1630.627 keV (^{228}Th , 1.51%) one. Ratios of count rates under this peak in the

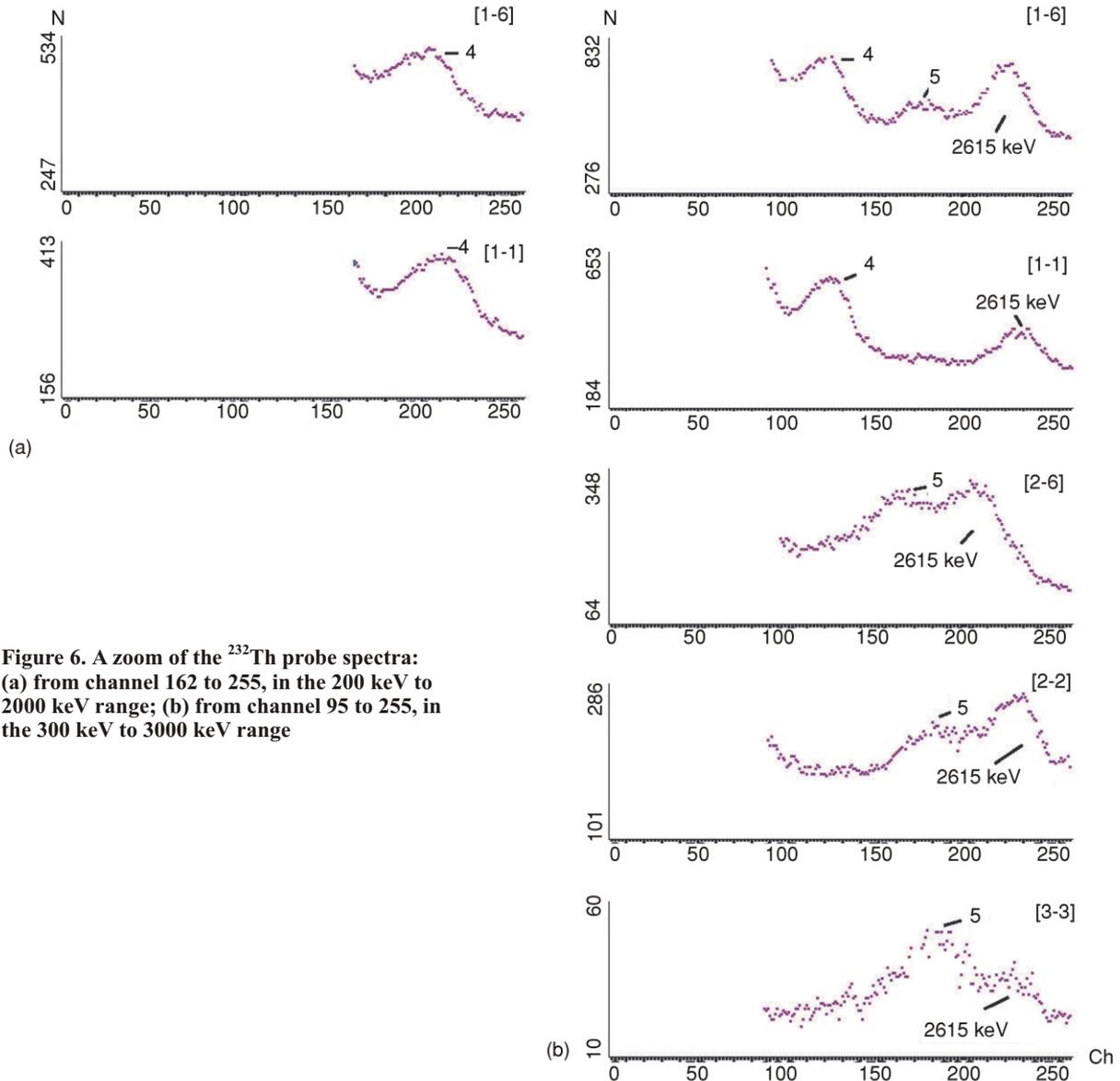


Figure 6. A zoom of the ^{232}Th probe spectra:
(a) from channel 162 to 255, in the 200 keV to 2000 keV range;
(b) from channel 95 to 255, in the 300 keV to 3000 keV range

probe spectra and in the same range of the corresponding background spectra in the 200 keV to 2000 keV energy range, were 15.14 (in the integral) and 15.19 (in the non-coincident mode of counting), while in the 300 keV to 3000 keV energy range – 15.54 (in the integral) and 14.97 (in the non-coincident mode of counting).

Region 5, with a peak centroide at about 2200 keV, appears in the integral, [2-6], double and triple coincidence modes of counting (where it is more pronounced than the 2615 keV photopeak). Most probably, the counts in this region originate from the Compton scattering of the 2615 keV photons and sum peaks of cascaded γ -rays (particularly the ^{228}Th and ^{208}Pb ones). Ratios of the count rates in this region of the thorium probe spectra and in the corresponding background spectra were: 21.67 (in the integral), 51.82 (in the double coincidences), and 41.38 (in the triple coincidences mode of counting).

Photopeak detection efficiency and minimum detectable activity

Photopeak (583 keV, 609 keV, 911 keV, and 2615 keV) detection efficiencies given in tab. 1 are calculated on the basis of experimental data and the characteristics of the ^{226}Ra and ^{232}Th decay chain.

The minimum detectable radium and thorium activity, estimated according to the formula already used in cases of coincidence measurement by a spectrometer of the PRIPYAT type was, (ref. 7)

$$A_{\min} = \frac{m\sqrt{N_b}}{\varepsilon\sqrt{t}} \quad (1)$$

where ε is the photopeak detection efficiency, N_b – the background count rate in the photopeak region, t – the data acquisition time, and $m = 2$ – the number of root

Table 1. Photo peak detection efficiency and minimum detectable activity

Photopeak [keV]	Energy region [keV]	Mode of counting	N_b [s^{-1}]	ϵ	A_{min} [Bq]
583	200-2000	[1-6]	7.36	0.216	0.89
		[1-1]	4.89	0.112	1.40
		[2-6]	1.68	0.099	0.91
		[2-2]	1.08	0.088	0.84
		[3-3]	0.48	0.013	3.78
	300-3000	[1-6]	7.77	0.221	0.89
		[1-1]	5.19	0.115	1.40
		[2-6]	1.83	0.107	0.87
		[2-2]	1.10	0.089	0.83
		[3-3]	0.45	0.012	3.96
609	200-2000	[1-6]	6.40	0.335	0.59
		[1-1]	5.17	0.210	0.84
		[2-6]	1.36	0.128	0.71
		[2-2]	0.83	0.120	0.58
		[3-3]	0.25	0.008	4.84
	300-3000	[1-6]	6.49	0.335	0.59
		[1-1]	5.01	0.204	0.85
		[2-6]	1.55	0.092	1.06
		[2-2]	0.86	0.122	0.58
		[3-3]	0.36	0.009	5.16
911	200-2000	[1-6]	3.68	0.542	0.25
		[1-1]	2.99	0.455	0.27
	300-3000	[1-6]	3.75	0.541	0.25
		[1-1]	2.97	0.449	0.27
2615	300-3000	[1-6]	0.92	0.034	2.01
		[1-1]	0.49	0.017	2.92
		[2-6]	0.30	0.017	2.23
		[2-2]	0.13	0.014	1.96

mean square (rms) deviations due to statistical background fluctuations, in the two energy ranges and different modes of counting, also given in tab. 1.

DISCUSSION

The results of ^{226}Ra measurements indicate that in the region from 200 keV to 2000 keV, ^{226}Ra is detectable by the 609 keV photopeak in several modes of counting of the PRIPYAT-2M spectrometer, but the optimal one comes from the mode of double coincidences ([2-2]). In comparison to the integral mode, in this mode of counting photopeak detection efficiency decreases for about 2.7 times, but this is compensated by a decrease in the background count rate (of about 7.7 times). The factors obtained from a comparison with the non-coincident mode of counting are 1.7 and 6.2, respectively. Additionally, though the background count rate in the [2-2] mode is about 3.3 times higher than that of triple coincidences, photopeak detection efficiency is higher around 15 times. In the [2-6] mode of counting, the background count rate is around 1.6 times higher than in the mode of separate double coin-

cidences, as the 609 keV photopeak detection efficiencies in these modes differ only slightly.

The same conclusion follows from the analysis of the radium spectra in the range from 300 keV to 3000 keV. The 609 keV photopeak detection efficiency in the mode of double coincidences decreases 2.7 and 1.7 (and the background count rate – 7.5 and 5.8) times, in comparison to the integral and non-coincident mode of counting, respectively. It is 1.3 times higher than that of the [2-6] mode of counting (the background count rate being 1.8 times lower), and more than 13 times higher than that in the triple coincidence modes of counting (the background count rate being 2.4 times higher).

In relation to the ^{232}Th measurement, – in the energy range from 200 keV to 2000 keV, the ^{232}Th detection by the 583 keV photopeak is optimal in the [2-2] mode of counting where, in comparison to the integral mode, photopeak detection efficiency decreases about 2.5 times, while the background count rate decreases about 6.8 times. A comparison with the non-coincident and [2-6] mode of counting showed a decrease in photopeak detection efficiency (and the background count rate) in the double coincidences mode for 1.2 and 4.5 (*i. e.*, 1.1 and 1.5) times, respectively. An increase in the background count rate in the double coincidences mode of counting in comparison to that of triple coincidences (2.2 times) is compensated by an increase in photopeak detection efficiency (6.7 times).

In the range from 300 keV to 3000 keV, a detection of the 583 keV photopeak in the mode of separate double coincidences is the optimum one, as well. The photopeak detection efficiency, in comparison to the integral, non-coincident and [2-6] mode of counting, decreases by a factor of 2.5, 1.3, and 1.2, respectively (at the same time, the corresponding background count rate decreases for about 7, 4.7, and 1.6 times, respectively). In particular, in comparison to the triple coincidences mode of counting, photopeak detection efficiency is 7.4 (as the background count rate is 2.4) times higher, which causes minimum detectable activity in the triple coincidences mode of counting to increase according to eq. (1);

– ^{232}Th can be detected by the 911 keV photopeak in the integral and non-coincident mode of counting in both energy ranges. The indubitable advantage for determining the ^{232}Th activity using this photopeak is in the weak dependence of results on ^{220}Rn emanation from the sample.

In the range from 300 keV to 3000 keV, ^{232}Th detection is also possible by the 2615 keV photopeak. As in the previous cases, the [2-2] mode of counting is the optimum one. In comparison to the integral, non-coincident and mode [2-6], photopeak detection efficiency in that mode of counting decreases for about 2.4, 1.2, and 1.2 times, respectively, while corresponding back-

ground count rates decrease 6.1, 3.3, and 2 times, respectively.

The advantage of using this method for thorium detection (although the photopeak detection efficiency is lower) lies in the fact that intensive γ -rays due to the decay of other natural radionuclides which could affect thorium measurements do not appear in this energy range. In particular, when a sample contains radium and thorium, and the 583 keV and 609 keV photopeak cannot be resolved (due to the PRIPYAT-2M energy resolution), the 2615 keV photopeak should be used for thorium activity measurement (besides the 911 keV one).

CONCLUSIONS

The coincidence methods for ^{226}Ra and ^{232}Th decay products' measurements developed at the six-crystal γ -ray PRIPYAT-2M spectrometer (which allows measuring of samples of any shape without their preliminary preparation and calibration measurements for different sample geometries), have relatively high photopeak detection efficiencies and a good sensitivity. Decreases in background count rates which were higher than decreases in photopeak detection efficiencies, in comparison to other modes of counting, showed the best signal-to-noise ratio in the spectra of double coincidences. Therefore, this mode of counting is the optimum one for the ^{226}Ra and ^{232}Th measurements, regardless of the selected energy range.

However, the energy region from 300 keV to 3000 keV should be used for thorium measurements, as well as for measurements of samples containing both radium and thorium, when peaks created by photons with energies of 583 keV and 609 keV cannot be resolved due to the energy resolution of the PRIPYAT-2M spectrometer.

ACKNOWLEDGEMENTS

A part of the research was supported by the Ministry of Education and Science of Montenegro (under the Contract 05-1/3-3354). The authors also wish to thank S. K. Andrukhovich (Stepanov Institute of Physics, Minsk) for his help in the modification of the spectrometer's PRIPYAT-2M electronics and software.

REFERENCES

- [1] ***, LBNL Isotopes Project – LUNDS Universitet, Nuclide Data Search, Version 2.1, 2004
- [2] Sanderson, C. G., Determination of ^{226}Ra and ^{228}Th in Food, Soil, and Biological Ash by Multidimensional Coincident Gamma-Ray Spectrometry, *Health Physics*, 16 (1969), 6, pp. 747-753
- [3] Overton, T. R., Burch, P. R. J., A Coincident Gamma-Ray Spectrometer and Its Application to Measurement of Low Level Radioactivity, *Physics in Medicine and Biology*, 11 (1966), 1, pp. 47-61
- [4] Hashimoto, T., Sakai, Y., Selective Determination of Extremely Low-Levels of the Thorium Series in Environmental Samples by a New Delayed Coincidence Method, *Journal of Radioanalytical and Nuclear Chemistry*, 138 (1990), 2, pp. 195-206
- [5] Andrukhovich, S. K., Berestov, A. V., Gutko, V. I., Khil'manovich, A. M., High-Sensitive Multidetector Gamma Spectrometers PRIPYAT, Preprint of the Institute of Physics, Belarus Academy of Science, Minsk (1995) (in Russian)
- [6] Antović, N., Svrkota, N., Vukotić, P., Thorium Measurements by the Six-Crystal Spectrometer PRIPYAT-2M, *Radiation Measurements*, 43 (2008), 9-10, pp. 1558-1562
- [7] Andrukhovich, S. K., Antovich, N. M., Berestov, A. V., Rudak, E. A., Khil'manovich, A. M., A Method for Determining the Concentration of Radon Decay Products Using a Coincidence γ -Spectrometer, *Instruments and Experimental Techniques*, 42 (1999), 1, pp. 123-126

Невенка М. АНТОВИЋ, Никола СВРКОТА

ЕФИКАСНОСТ ДЕТЕКЦИЈЕ ^{226}Ra И ^{232}Th У РАЗЛИЧИТИМ РЕЖИМИМА РАДА СПЕКТРОМЕТРА ПРИПЈАТ-2М

Представљене су ефикасности детекције продуката распада ^{226}Ra и ^{232}Th , као и одговарајуће минималне детектибилне активности у различитим режимима рада спектрометра ПРИПЈАТ-2М: у интегралном режиму, када се региструју сви импулси (коинцидентни и некоинцидентни); некоинцидентном, када се региструју само некоинцидентни импулси; коинцидентном, када се региструју коинцидентни импулси вишеструкости од 2 до 6 – у енергетским опсезима од 200 keV до 2000 keV и од 300 keV до 3000 keV. Показано је да је режим двоструких коинциденција оптималан за мерење активности ^{226}Ra и ^{232}Th . Осетљивост спектрометра највећа је у овом режиму рада.

Кључне речи: радијум, торијум, вишедецикаторски спектрометар, ефикасности детекције, $\bar{\gamma}$ ма-коинциденције