ANALYSIS OF INTERFERENCES FROM FULL ENERGY PEAKS IN GAMMA SPECTROMETRY OF NORM AND TENORM SAMPLES

by

Miloš Z. ŽIVANOVIĆ [1*], ***Jelena D. NIKOLIĆ*** [1],
Andrei I. APOSTOL [2], ***and Marios J. ANAGNOSTAKIS*** [3]

[1]Radiation and Environment Protection Department, Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[2]Radiation Control Laboratory, Republican Center of Applied Soil Science, Chisinau, Moldova
[3]Nuclear Engineering Department, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece

Scientific paper
DOI: 10.2298/NTRP1204380Ž

A considerable number of primordial radioisotopes are present in almost all the samples extracted from the Earth's crust, such as oil, rock, soil or other materials. Their concentrations are often determined by gamma spectrometry. Although the relative concentrations of isotopes often fluctuate within a narrow range, it is not always the case. Some natural materials (such as naturally occurring radioactive material) show unusual activity ratio between ^{238}U and ^{232}Th, while technologically processed materials (technologically enhanced naturally occurring radioactive material) might also introduce significant disequilibrium in radioactive chains. Knowing that primordial radioisotopes emit in total more than a thousand gamma and characteristic X-ray photons and that many of them interfere with each other, a question arises whether for some activity ratios commonly used photopeaks become useless for quantitative analysis, due to interferences with other photopeaks. A computer program was developed in order to calculate full energy photon interferences for any chosen photopeak. The calculations are based on the inputs in the form of isotope activities and detector calibration equations and its characteristics are presented in this paper.

Key words: gamma spectrometry, interference, NORM, TENORM, radioactivity

INTRODUCTION

NORM and TENORM are abbreviations for naturally occurring radioactive material and technologically enhanced naturally occurring radioactive material, respectively. While the natural radioactivity is present everywhere, in some cases human activities create greater chances for the exposure of general population to particular natural radioactive material. TENORM is a NORM material in which the natural concentrations of radioactive materials are modified by some technological process (oil extraction, combustion, water treatment in water plants, *etc*.) [1].

Gamma spectroscopy is often used to examine radioactive content of natural materials, in every day practices as well as in science. Materials extracted from the Earth's crust are more or less isolated from the atmosphere, so the content of artificial (and cosmogenic) radionuclides is usually very low, meaning that they can be classified as NORM materials. Primordial radionuclides ^{238}U, ^{232}Th, and ^{235}U with progenies, as well as ^{40}K are always present in some quantities and all contribute to the gamma radiation levels.

There are three principal problems in assigning the physical meaning to detector signals generated by photons in gamma spectroscopy. First, not all the photons will deposit all of their energy in the detector [2]. This problem was addressed in a number of papers and thus will not be further analyzed in this paper. Second, even if the first problem were somehow avoided, a finite resolution of the detector remains a problem: the photons that are within a certain energy window cannot be distinguished. In the case of samples containing several radionuclides with many gamma photons, the spectrum can become very complex and many photons can fall within a detector full width at half maximum (FWHM) at certain energy. Quantitative analysis of such photopeaks can be a troublesome job and includes using of deconvolution software, estimating interferences based on other photopeaks of the same radionuclide or quantitative analysis by other methods [2]. Another approach might be radioche- mical sepa-

* Corresponding author; e-mail: milosz@vinca.rs

ration of radionuclides [3]. Finally, several photons may interact with the sensitive volume of the detector during the time interval shorter than the resolving time of the detector, and then the effect of summing will occur. This problem was also analyzed in literature [4] and is usually insignificant for low count rates typical for environmental samples, so it would not be discussed further.

Quantitative gamma analysis of NORM and TENORM materials is often performed without radiochemical separation. Even in the case of high resolution germanium detectors (which have much better resolution compared with NaI(Tl) detectors), photopeaks that are used in quantitative analysis can interfere with other photopeaks. This means that several photopeaks are so close that they cannot be resolved by the detector system, and an overall photopeak is detected instead. The contribution to the overall photopeak by all the photons except for the photon being analyzed is considered to be interference. In this paper, the interferences were calculated for most of the commonly used photopeaks and for several realistic cases of natural radioactivity content. In some cases present in the environment, the isotope activities deviate significantly from the "normal" cases and interferences might mask important photopeaks to such extent to render them completely useless for quantitative analysis. Knowing these cases is particularly important for the laboratories that perform routine gamma spectroscopic analysis.

Samples with roughly equal activity of ^{238}U and ^{232}Th are commonplace [5]. If radioactive equilibrium is assumed as well as natural uranium isotopic composition, it is possible to calculate emission and detection rates for all the emitted photons, along with the interferences that they cause to the photons important in quantitative analysis. In this case, all the important photons are either nearly free of interferences, or the extent of those interferences is well known. However, environmental samples such as zircon ore with ^{238}U to ^{232}Th activity ratio of 10:1, or phosphate rock samples with ^{238}U to ^{232}Th activity ratio of 1:3 are not rare, and even higher imbalances can be found. Radioactive chains might also be significantly disturbed, especially in TENORM materials. In these cases, some low yield photons that can be normally neglected during gamma spectroscopic analysis make significant contribution to the spectrum, and in some cases they might even completely mask photons that are normally free from interferences.

An extensive literature research resulted in a set of important photons commonly used in quantitative gamma spectroscopic analysis. A further research resulted in some extreme cases of significant disruption of radioactive equilibrium and/or extreme values for the ^{238}U to ^{232}Th ratio. In the last step, a computer program was developed and used to analyze all the collected data.

MATERIALS AND METHODS

A computer program INCA (interference calculator) currently under development was used for the calculations. The program uses a custom photons database that includes the photons of all isotopes listed in tab. 1. For simplicity, only photons with emission probability higher than 0.1% were included in the database. Important gamma photons in the context of this paper are photons commonly used in quantitative analysis of NORM and TENORM materials. In order to determine such photons, an extensive literature research was made [6-13]. All the selected photons are listed in tab. 1, and the papers in which they were used are indicated with x. The values for photon energies and yields, for branching ratios and other data are obtained from BIPM monograph [14]. The program inputs are the detector energy and efficiency calibration data and the specific activities of all radionuclides existing in a sample. The interferences can be estimated for real samples before the gamma spectrometry measurement is started if the calculations are performed with expected or typical values of activities for the type of material (phosphate, zircon ore, *etc*.) that is being measured. The program combines the input data with the data from the photon database to calculate the number of detected photons for each gamma line and isotope for specific sample. Then, a set of photons selected by the user is checked for full energy peak interferences. The user is free to choose the energy window within which he wishes to investigate for possible interferences. This window can be the detector FWHM or FWTM calculated from detector calibration curves or an arbitrary energy window defined by the user.

A hypothetical "typical" case was created in order to have a standard or reference sample, suitable for comparison with TENORM material spectra. For this purpose, UNSCEAR report for year 2000 was used [5]. According to this report, the values around 500 Bq/kg, 40 Bq/kg, and 40 Bq/kg can be considered as very likely activities of ^{40}K, ^{238}U, and ^{232}Th in soil around the world, respectively. For this typical sample, radioactive equilibrium was further assumed. The case of the "typical sample" is important for the illustration of how the interferences might significantly differ if radioactive equilibrium is disturbed or the ^{238}U to ^{232}Th ratio takes extreme values.

The other cases were chosen in such fashion that the gamma emitting isotopes relative activities are as different from the reference case as possible.

The first case was taken from [15]. Phosphogypsum produced in a sulphuric acid process is doubly interesting: ^{232}Th activity is much lower than ^{238}U activity, and ^{226}Ra is concentrated 4 times compared to ^{238}U. Since only the activities for ^{238}U, ^{226}Ra, ^{232}Th, and ^{210}Pb were given, it was assumed that the other radioisotopes are in equilibrium

Table 1. List of photons commonly used in gamma spectroscopic analysis of natural radionuclides

Reference		[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Isotope	Energy [keV]								
^{40}K	1460.822	x	x	x			x	x	x
^{234}Th	63.3				x	x	x		
^{234}Th	92.8					x			
^{234m}Pa	1001.026					x	x		
^{234}U	53.2					x			
^{230}Th	67.67					x			
^{226}Ra	186.211				x	x			
^{214}Pb	295.224		x			x	x	x	
^{214}Pb	351.932		x			x	x	x	x
^{214}Bi	609.312		x			x	x	x	x
^{214}Bi	1120.287	x					x	x	
^{214}Bi	1764.494	x	x	x			x		
^{210}Pb	46.539				x	x			
^{228}Ac	338.32		x			x	x	x	
^{228}Ac	911.196		x			x	x	x	x
^{228}Ac	968.96					x			
^{224}Ra	240.986					x			
^{212}Pb	238.632		x			x		x	x
^{208}Tl	583.187		x			x		x	
^{208}Tl	2614.511	x	x	x					
^{235}U	143.767				x		x		
^{235}U	163.356						x		
^{235}U	185.72				x				

with their parents, and that the uranium isotopic composition is natural.

In second case, a sample with naturally depleted uranium (DU) was considered. ^{235}U isotopic fraction as low as 0.44% was found in samples from Oklo mine [16]. The reason for the disturbance of isotopic composition is the natural nuclear reactor that was active in Oklo at least 2 billion years ago. Radioactive equilibrium has been achieved again since. This is a hypothetical sample. It was assumed that it is completely analogous to the reference case, with the exception of uranium composition. ^{238}U and ^{232}Th activities were set to 40 Bq/kg, ^{40}K activity to 500 Bq/kg and the other isotopes activities were calculated having in mind altered uranium isotopic composition.

Activities for the third case were obtained from [17]. Phosphate rock activities were interesting because ^{232}Th activity was three times higher than ^{238}U activity. Radioactive equilibrium was also disturbed to some extent. ^{235}U chain activities were calculated assuming natural isotopic composition.

The last case was Zircon ore. Zircon is an interesting example of NORM material. ^{238}U activities are typically higher up to an order of magnitude than ^{232}Th activities, and ^{40}K activities are usually lower than either ^{238}U or ^{232}Th activities [11, 18]. The case that was studied was of a zircon ore originating from the USA. ^{238}U chain activities were around 8 times higher than ^{232}Th chain activities, with some equilibrium disturbances. ^{235}U chain activities were calculated assuming natural isotopic composition.

For all the samples, several assumptions were made: all the radionuclides are in radioactive equilibrium with their respective parents, unless another activity is specified. ^{238}U and ^{235}U activities are calculated according to natural isotopic composition, except for the Oklo mine case. In all the cases, concentrations of all the isotopes were calculated according to these ad hoc rules, but the ^{40}K concentration is set to 0 if the data is not available.

Since all the calculations require a known detector efficiency and FWHM, depending on energy, or otherwise set energy window, an actual detector calibration equations were used. Because of the very rich spectrum, the detector that was chosen is an extended range germanium detector, with 105% relative efficiency and FWHM of 1.03 keV at 122 keV and FWHM of 2.04 keV at 1332 keV. For calibration purposes, IAEA spiked soil sample was used. Admittedly, three of the samples that were studied have somewhat different matrix and density then the soil sample used for calibration, so the detector efficiency will be different. However, using of the same calibration equation is justified by the fact that the interferences that are calculated depend on the ratio of the count rates of the interfering photopeaks and do not depend on the absolute value of efficiency. Density effects on efficiency will have the same influence on all the interfering photons, because the efficiency will drop linearly with density [19]. Matrix effects will not be significant, especially considering that the photons that interfere with each other have similar energies. Any uncertainties introduced this way will be small compared to the

other sources of uncertainties, above all, values for activities of the samples.

RESULTS AND DISCUSSION

The activities of all the radioisotopes of all the samples were calculated where these activities were not previously available, and are presented in tab. 2. Isotopes were grouped to indicate sub-chains within the main radioactive chains. Sub-chains were identified according to the time needed for radioactive equilibrium to be achieved between two subsequent radionuclides.

The interferences were calculated using INCA program for 23 peaks for 4 samples and the reference sample. The energy window used is calculated from the calibration formula for an extended range germanium detector. The example of calculated values for FWTM is 3.05 keV at 100 keV and 4.65 keV at 1 MeV. Two tables are given, one for the energy window equal to 1 FWHM and another for the energy window equal

Table 2. Overview of the activities of all the isotopes in the studied cases

Isotope	Activity [Bqkg^{-1}]				
	Reference sample	Phosphogypsum	Natural DU	Phosphate rock	Zircon ore
^{238}U	40	200	40	140	1320
^{234}Th	40	200	40	140	1320
^{234m}Pa	40	200	40	140	1320
^{234}Pa	0.06	0.3	0.06	0.21	1.98
^{234}U	40	200	40	140	1320
^{230}Th	40	200	40	140	1320
^{226}Ra	40	850	40	140	1500
^{222}Rn	40	850	40	140	1500
^{218}Po	40	850	40	140	1500
^{214}Pb	39.99	849.81	39.99	139.97	1499.67
^{218}At	0.01	0.19	0.01	0.03	0.33
^{214}Bi	40	850	40	140	1500
^{214}Po	39.99	849.82	39.99	139.97	1499.69
^{210}Tl	0.01	0.18	0.01	0.03	0.32
^{210}Pb	40	200	40	120	1500
^{210}Bi	40	200	40	120	1500
^{210}Po	40	200	40	120	1500
^{232}Th	40	17	40	470	190
^{228}Ra	40	17	40	550	190
^{228}Ac	40	17	40	550	190
^{228}Th	40	17	40	550	190
^{224}Ra	40	17	40	550	190
^{220}Rn	40	17	40	550	190
^{216}Po	40	17	40	550	190
^{212}Pb	40	17	40	550	190
^{212}Bi	40	17	40	550	190
^{212}Po	25.63	10.89	25.63	352.39	121.73
^{208}Tl	14.37	6.11	14.37	197.62	68.27
^{235}U	1.8	9	1.10	6.28	59.19
^{231}Th	1.8	9	1.10	6.28	59.19
^{231}Pa	1.8	9	1.10	6.28	59.19
^{227}Ac	1.8	9	1.10	6.28	59.19
^{227}Th	1.78	8.88	1.08	6.19	58.38
^{223}Fr	0.02	0.12	0.02	0.09	0.82
^{223}Ra	1.8	9	1.10	6.28	59.19
^{219}Rn	1.8	9	1.10	6.28	59.19
^{215}Po	1.8	9	1.10	6.28	59.19
^{211}Pb	1.8	9	1.10	6.28	59.19
^{211}Bi	1.8	9	1.10	6.28	59.19
^{211}Po	0.005	0.02	0.003	0.02	0.16
^{207}Tl	1.80	8.98	1.09	6.26	59.03
^{40}K	500	0	500	0	0

to 1 FWTM (tabs. 3 and 4). Detection rates are also calculated based on the actual detector calibration and the known activities. The interferences thus calculated are approximate and the calculations are valid given that the following assumptions are true:

– only the isotopes listed in tab. 2 are present in the sample,
– contribution of gamma photons and characteristic X-rays with yield lower than 0.1 per 100 disintegrations is negligible, and
– bremsstrahlung, Compton continuum, X-ray escape peaks, single and double escape peaks and electron escape peaks are deducted from the spectrum or are negligible to begin with.

Table 3. Interferences given as the percentage of the photopeak calculated for energy window equal to 1 FWHM of the simulated XtRa germanium detector

Isotope	Interferences in the photopeak [%]					
	Energy [keV]	Reference sample	Phosphogypsum	Natural DU	Phospate rock	Zircon ore
^{40}K	1460.822	0.68	n. a.	0.68	n. a.	n. a.
^{234}Th	63.3	6.73	0.88	6.65	19.05	1.28
^{234}Th	92.8	76.79	63.37	76.06	89.89	62.71
^{234m}Pa	1001.026	0	0	0	0	0
^{226}Ra	186.211	42.01	14.56	30.63	41.93	38.85
^{214}Pb	295.224	0.22	0.12	0.18	0.22	0.20
^{214}Pb	351.932	1.63	0.39	1.00	1.63	1.44
^{214}Bi	609.312	0	0	0	0	0
^{214}Bi	1120.287	0.0025	0.0006	0.0025	0.0025	0.0022
^{214}Bi	1764.494	0	0	0	0	0
^{210}Pb	46.539	0.20	0.20	0.12	0.23	0.18
^{228}Ac	338.32	1.11	11.69	0.68	0.28	7.23
^{228}Ac	911.196	0.00	0.12	0.00	0.00	0.02
^{228}Ac	968.96	0.00	0.00	0.00	0.00	0.00
^{224}Ra	240.986	63.76	98.88	63.76	30.93	93.28
^{212}Pb	238.632	0	0	0	0	0
^{208}Tl	583.187	0.39	0.40	0.39	0.39	0.40
^{208}Tl	2614.511	0	0	0	0	0
^{235}U	143.767	23.53	23.53	23.57	23.54	23.54
^{235}U	163.356	2.98	2.98	2.98	2.98	2.98
^{235}U	185.72	58.04	85.45	69.43	58.12	61.19

Table 4. Interferences given as the percentage of the photopeak calculated for energy window equal to 1 FWTM of the simulated XtRa germanium detector

Isotope	Interferences in the photopeak [%]					
	Energy [keV]	Reference sample	Phosphogypsum	Natural DU	Phosphate rock	Zircon ore
^{40}K	1460.822	0.68	n. a.	0.68	n. a.	n. a.
^{234}Th	63.3	6.73	0.88	6.65	19.05	1.28
^{234}Th	92.8	86.10	82.71	85.74	94.66	74.42
^{234m}Pa	1001.026	0	0	0	0	0
^{226}Ra	186.211	42.01	14.56	30.63	41.93	38.85
^{214}Pb	295.224	0.22	0.12	0.18	0.22	0.20
^{214}Pb	351.932	1.97	0.73	1.34	1.96	1.77
^{214}Bi	609.312	0.0012	0.0003	0.0012	0.0012	0.0011
^{214}Bi	1120.287	0.0025	0.0006	0.0025	0.0025	0.0022
^{214}Bi	1764.494	0	0	0	0	0
^{210}Pb	46.539	0.41	0.41	0.25	0.48	0.36
^{228}Ac	338.32	4.52	14.96	4.09	3.70	10.56
^{228}Ac	911.196	0.00	0.12	0.00	0.00	0.02
^{228}Ac	968.96	23.94	23.97	23.94	23.94	23.96
^{224}Ra	240.986	92.54	99.00	92.54	91.73	96.08
^{212}Pb	238.632	9.65	19.73	9.24	8.86	15.49
^{208}Tl	583.187	1.58	37.89	1.58	0.70	9.06
^{208}Tl	2614.511	0	0	0	0	0
^{235}U	143.767	40.46	26.83	47.37	62.76	27.90
^{235}U	163.356	2.98	2.98	2.98	2.98	2.98
^{235}U	185.72	58.16	85.47	69.49	58.24	61.30

A conservative approach during gamma-ray spectrometry is that two lines can be resolved if their separation is higher than ~1 FWHM. It is clear from tab. 3 that many photons have a significant and variable interference from other photons within the energy window of 1 FWHM. For the energy window of 1 FWTM, interferences are higher, as expected.

The photons in these tables can be divided in three groups: photons with significant and variable interferences, photons with significant but constant interferences and photons with negligible interferences. The first group is the most interesting for the topic of this paper.

As can be seen from the tables, a large interference is present in case of ^{224}Ra in all the samples. Also, a considerable interference can be found at the 186 keV photopeak that belongs to ^{226}Ra and ^{235}U, which was expected. Three photons are especially interesting: ^{208}Tl photon at 583 keV and ^{212}Pb photon at 239 keV have significant interferences when the window is set to 1 FWTM, and the extent of interferences is very much dependent on the case that is examined. However, if the window is set to 1 FWHM, no interferences are recorded. ^{228}Ac photon at 338 keV has significant interferences at both energy window settings, and they are affected by the case that is studied. All these lines are often used for quantitative analysis.

The reason for such behaviour of these photopeaks can be found by analysing other photons with similar energies, which is another option available in the INCA program. Within 1 FWTM of the ^{212}Pb photon at 239 keV, there are the contributions of two other photons. One is emitted by ^{227}Th, and the other by ^{224}Ra. ^{224}Ra and ^{212}Pb are in the same radioactive chain, and the radioisotopes between them have short half-lives (3.6 days at most). Since most of the laboratories wait up to 30 days to perform the measurements, it is very likely that ^{212}Pb and ^{224}Ra activities are equal within the experimental error margin. Th-227, on the other hand, belongs to ^{235}U chain. As the ^{235}U activity is connected to ^{238}U activity in most of the samples, so is the ^{227}Th activity. This photon proves to be the reason for the difference in interferences to ^{212}Pb photon between the cases.

If the same process is repeated with ^{208}Tl photopeak at 583 keV, it can be seen that in its vicinity there are 3 photopeaks. Again, one photon is emitted by an isotope in the same radioactive chain, ^{228}Ac, and its contribution to the photopeak should not vary by much. Another photon is emitted by ^{234}Pa, and due to its low yield and low ^{234}Pa activity due to the branching ratio, it is insignificant. The third photon is emitted by ^{214}Pb, which belongs to ^{238}U radioactive chain. Its contribution to the overall photopeak ranged from under 1% to over 30%.

Finally, ^{228}Ac photopeak at 338 keV also has 3 photopeaks in its vicinity. One of them also belongs to ^{228}Ac, and hence does not represent any problems. The other is a low yield photon of ^{231}Pa, and can be neglected in all the cases. The third photon belongs to ^{223}Ra and is shifted less than 0.1 keV from the ^{228}Ac photon. These two peaks are irresolvable by conventional gamma spectrometers. It also proves that this photon's contribution to the overall photopeak can vary by the factor 10 at least. In the different cases studied, it was less than 1% and more than 10%.

Similar discussion can be repeated for all the listed photons, or any other photon that is available to the INCA program through the database.

It is also interesting to identify the photons such as ^{228}Ac photon at 969 keV, which has almost constant interferences for all the cases studied. Other photons have no interferences within used energy windows. It is impractical and even impossible to predict and analyse all the possible scenarios, but it was shown conclusively that performing quantitative gamma analysis of NORM and TENORM materials might be erroneous without estimating the contribution of the photons with similar energies.

CONCLUSIONS

In this paper, it was shown that some photons commonly used for NORM and TENORM quantitative analysis can get interferences so large that they become useless for the analysis, only by varying isotopes concentrations. This is true even if a germanium detector with FWHM of 1.03 keV at 122 keV and FWHM of 2.04 keV at 1332 keV was used. The influence of interferences becomes much more significant if a NaI(Tl) detector is used, due to its inferior resolution.

Five different cases were studied, all of which represent realistic examples of what any laboratory can come across. It was shown that not only in cases when the equilibrium in radioactive chains is disturbed, but also when the ratio between ^{232}Th and ^{238}U changes, unexpected interferences may occur. ^{232}Th and ^{238}U activity ratio can vary in NORM materials by more than one order of magnitude, which could cause some important photons to be completely masked.

While the analyzed cases illustrate the change in interferences, they are far from the most extreme. Another important addition to this work may be identification of summation and escape peaks that might interfere with photopeaks commonly used in quantitative analysis. Also, NORM and especially TENORM samples can be contaminated by artificial or cosmogenic radionuclides. If the study was extended to the photopeaks of these radionuclides, additional valuable data might have been acquired.

ACKNOWLEDGEMENT

The research was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under the Project III43009 -

New Technologies for Monitoring and Protection of Environment from Harmful Chemical Substances and radiation impact. Part of the work was carried out during the "Postgraduate Educational Course in Radiation Protection and the Safety of Radiation Sources" (held in Athens, Greece, from 10 October 2011 to 30 March 2012), supported by IAEA Technical Cooperation Project "RER/9/101 Building Competence Through Education and Training in Support of Radiation Protection Infrastructures".

AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by M. Z. Živanović and M. J. Anagnostakis. Computer code INCA was written by M. Z. Živanović. Literature research was carried out by M. Z. Živanović and J. D. Nikolić. Calculations were performed by M. Z. Živanović and A. I. Apostol. Figures were prepared by M. Z. Živanović and J. D. Nikolić. All authors discussed the results and participated in the writing of the manuscript. Research was co-ordinated by M. J. Anagnostakis.

REFERENCES

[1] ***, IAEA, Radioactive Waste Management Glossary, IAEA, Vienna, 2003
[2] Godon, R. G., Practical Gamma-Ray Spectrometry – 2nd ed., John Wiley & Sons, New York, Ltd. ISBN: 978-0-470-86196-7, 2008
[3] Finston, H. L., Miskel, J., Radiochemical Separation Techniques, *Annual Review of Nuclear Science, 5* (1955), pp. 269-296
[4] Nadjdjerdj, L., Jordanov, D., Davidović, M., A New Matrix Method for Calculating Coincidence Summing Effects for Gamma Spectroscopy, *Nuclear Instruments and Methods in Physics Research, A 66*2 (2012), 1, pp. 21-25
[5] ***, UNSCEAR 2000 Report on Sources and Effects of Ionizing Radiation to the General Assembly, Vol. I: Sources, Annex B: Exposures from Natural Radiation Sources, Annex B: Exposures from Natural Radiation Sources, United Nations, New York, 2000
[6] Odumo, O. B., *et al*., Radiological Survey and Assessment of Associated Activity Concentration of the Naturally Occurring Radioactive Materials (NORM) in the Migori Artisanal Gold Mining Belt of Southern Nyanza, Kenya, *Applied Radiation and Isotopes, 69* (2011), 6, pp. 912-916
[7] El Afifi, E. M., *et al*., Evaluation of U, Th, K, and Emanated Radon in some NORM and TENORM Samples, *Radiation Measurements, 41* (2006), 5, pp. 627-633
[8] Alatise, O. O., Babalola, I. A., Olowofela, J. A., Distribution of Some Natural Gamma-Emitting Radionuclides in the Soils of the Coastal Areas of Nigeria, *Journal of Environmental Radioactivity, 99* (2008), 11, pp. 1746-1749
[9] Luca, A., *et al*., Activity Measurements of Technically Enhanced Naturally Occurring Radionuclides (TENORM) in Phosphogypsum, *Applied Radiation and Isotopes, 67* (2009), 5, pp. 961-963
[10] Murray, A. S., *et al*., Analysis for Naturally Occurring Radionuclides at Environmental Concentrations by Gamma Spectrometry, *Journal of Radioanalytical and Nuclear Chemistry, 115* (1987), 2, pp. 263-288
[11] Janković, M., Todorović, D., Concentrations of Natural Radionuclides in Imported Zirconium Minerals, *Nucl Technol Radiat, 26* (2011), 2, pp. 110-114
[12] Abo-Elmagd, M., *et al*., Radiological Hazards of TENORM in the Wasted Petroleum Pipes, *Journal of Environmental Radioactivity, 101* (2010), 1, pp. 51-54
[13] Hamby, D. M., Tynybekov, A. K., Uranium, Thorium and Potassium in Soils along the Shore of Lake Issyk-Kyol in the Kyrghiz Republic, *Environmental Monitoring and Assessment, 73* (2002), 2, pp. 101-108
[14] ***, Monograph BIPM-5, Table of Radionuclides Vol. 1-6; Bureau International des Poids et Mesures, Sevres (2004-2011)
[15] Anagnostakis, M. J., Industrial Processes Producing TENORM, National Technical University of Athens, Presented at: IAEA Technical Visit on: "Measurement of Natural Radionuclides in Environmental Samples, NORM and TENORM by Gamma Spectrometry: Experimental Difficulties and Methodologies, Monaco December 4-9, 2011
[16] Karam, A., The Natural Reactor at Oklo: a Comparison with Modern Nuclear Reactors, www.physics.isu.edu/radinf/Files/Okloreactor.pdf
[17] Van der Westhuizen, A. J., Public Exposure from Mines Operating on an Igneous ore Body, (Naturally Occurring Radioactive Material (NORM V), *Proceeding*s, International Symposium, Seville, Spain, March 19-22, 2007), IAEA, Vienna
[18] Doring, J., *et al*., Exposure and Radiation Protection for Work Areas with Enhanced Natural Radioactivity, (Naturally Occurring Radioactive Material (NORM V) – *Proceedings*, International Symposium, Seville, Spain, March 19-22, 2007), IAEA, Vienna
[19] Boshkova, T., Minev, L.,Corrections for Self-Attenuation in Gamma-Ray Spectrometry of Bulk Samples, *Appl. Radiat. Isotopes, 54* (2001), 5, pp. 777-783

Received on May 25, 2012
Accepted on October 27, 2012

**Милош З. ЖИВАНОВИЋ, Јелена Д. НИКОЛИЋ,
Андреи И. АПОСТОЛ, Мариос Ј. АНАГНОСТАКИС**

АНАЛИЗА ИНТЕРФЕРЕНЦИЈА ФОТОПИКОВА У ГАМА СПЕКТРОМЕТРИЈИ NORM И TENORM УЗОРАКА

Значајан број примордијалних радионуклида налази се у скоро свим узорцима пореклом из Земљине коре, било да се ради о нафти, камену, земљишту или неком другом материјалу. Њихове концентрације се често одређују гама спектрометријски. Иако се релативне концентрације радионуклида углавном крећу у релативно уском опсегу, то није увек случај. Неки природни материјали (NORM) садрже ^{238}U и ^{232}Th са неуобичајеним односом активности, а технолошки измењени материјали (TENORM) могу такође имати радиоактивне низове у значајној неравнотежи. Ако се зна да примордијални радионуклиди емитују више од 1000 гама фотона и карактеристичних X-зрака и да многи од њих међусобно интерферирају, поставља се питање да ли за неке односе концентрација често коришћени фотони постају неупотребљиви за квантитативну анализу. У циљу налажења таквих случајева развијен је рачунарски програм који може да рачуна интерференције које потичу од фотона који су предали целу енергију детектору, за било који одабрани фотон. Израчунавања се заснивају на унетим активностима изотопа и калибрационим једначинама детектора.

Кључне речи: гама спектрометрија, интерференција, NORM, TENORM, радиоактивност