Detection of Photons and Electrons Using a Semiconductor Alpha Detector

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Abstract: The response of a silicon alpha detector to beta particles, electrons and photons was investigated using measurements and Monte Carlo simulations. This information is of relevance for in situ alpha spectrometry from different surfaces at ambient air pressure. According to the simulations, photon detection efficiencies were more than two orders of magnitude smaller than those of electrons. Photons generate signals mainly by Compton electrons. Counts originating from beta particles, electrons and photons were usually below 1 MeV in energy and no clear peaks could be identified from the measured spectra. Unequivocal identification of radionuclides emitting beta particles, electrons and photons is not possible when a mixture of different radionuclides is present in the source. However, radionuclide classification according to their emission energies appears to be possible. Surface contamination measurements will benefit from this capability.

Key words: Alpha spectrometry, alpha particle, beta particle, electron, photon.

1. Introduction

High-resolution alpha-particle spectrometry performed in a vacuum is usually applied for radiochemically processed sources. In that case, it is customary to utilize only part of the energy spectrum in the spectrum analysis. For example, if nuclides of transuranium elements are under investigation, the most important energy region is 4-6 MeV. Counts or peaks (if any) locating above this region may belong to radon progeny. Counts below this region may be due to the extended low-energy side tailing of the alpha peaks or they may be caused by the detector noise, photons or beta particles/electrons emitted by the source. In the latter cases, their registered energies are usually at the very beginning of the energy spectrum, i.e. below approximately 1 MeV (Fig. 1).

When alpha-particle spectrometry is applied at ambient air pressure, such as in continuous air monitoring or in surface contamination measurements, the registered alpha particle energies depend on the

SDD (Source-detector distance). For example, the kinetic energy of a 4 MeV alpha particle detected at an SDD of 2 cm in air is less than 1 MeV and its unambiguous identification may be questionable because of overlapping counts generated by alpha and beta particles and photons. Only if the nominal alpha-particle emission energies are high enough and the source material thickness is small enough the counts could be separated as shown in Fig. 1. Stressed overlapping appears in the case of thick sources (see for example Fig. 7 in reference [1]).

A prototype alpha spectrometer equipped with a semiconductor detector operating at ambient air pressure has recently been developed [2]. This instrument, which can use collimation to obtain good energy resolution, was designed to detect and identify alpha-particle-emitting radioactive substances from flat and smooth surfaces. The measurement range of the instrument is approximately from 50 keV to 10 MeV. In practice, because of the reasons mentioned above, unfolding of an alpha spectrum is possible when the registered alpha particle energies are considerably larger than 1 MeV. However, counts in the region below this value and originating from

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Fig. 1 Alpha-particle energy spectrum from radon progeny (^{212}Bi , ^{214}Po , ^{212}Po) collected on a membrane air filter and measured at ambient air pressure using a CAM2000AM (Canberra) alpha detector. A detector with a smaller area was used in other measurements presented in this paper (see later text). Counts originating from beta particles, electrons and photons are located at the beginning of the energy spectrum (here channels below 150, which refers to the energy of approximately 1 MeV), but there are also some counts from the alpha peak tails. In this case, the conversion gain was different from that for other measurements.

electrons/photons are of importance for *in situ* contamination measurements.

In the present paper we investigate the response of a semiconductor alpha detector to electrons, beta particles and photons using measurements and simulations. The same types of detectors were previously investigated for beta spectrometry [3]. In nondestructive alpha spectrometry the objective is to exploit, as far as possible, the entire energy spectrum for analysis. Here we examine the possibility of achieving nuclide identification from the low-energy part of the spectrum. Another goal is to identify the upper energy, where neither the electron counts nor photon counts interfere with those originating from alpha particles. This information may be essential in nondestructive alpha spectrometry to analyze the spectra with peaks of long low-energy tail.

2. Equipment, Sources and Data Acquisition

The measurements were performed indoors at ambient air pressure using a CAM450AM (Canberra) alpha detector. According to the manufacturer's data sheet, the thickness of the active area of the detector is 300 μm and this thickness is enough to fully absorb electrons up to 290 keV. The thickness of the dead

layer is approximately 1.5 μm equivalent silicon. Although this thickness is relevant for the detection of alpha particles, it has no essential influence on the detection of photons and electrons/betas at the energy region considered here. The number of the channels used in the measurements was 1024 (Amptek 8000A Pocket MCA) and the bias voltage was + 70 V. This voltage is recommended for alpha and beta detection in the detector specifications. The nominal energy resolution of alpha particles and betas are 34 keV and 17 keV, respectively. No values are given for the resolution of low-energy photons.

The point sources (^{133}Ba , $^{137}\text{Cs}/^{137\text{m}}\text{Ba}$, ^{152}Eu , ^{22}Na and ^{60}Co , Amersham) used in the measurements were basically intended for the energy calibration of gamma-ray spectrometers (Table 1). They were encapsulated in a plastic plate of 2 mm in thickness, with a thinner area at the location of the active material, which means that electrons in particular will lose part of their energy in the plate. Alpha particles cannot penetrate the plate. ^{57}Co and ^{241}Am sources were placed between thin plastic foils in order to reduce absorption. The beta particle response of the detector was demonstrated using a $^{90}\text{Sr}/^{90}\text{Y}$ source with an active area diameter of 7 mm. The source was

Table 1 Source nuclide characteristics. Activities with standard uncertainty refer to the date of measurement. For $^{90}\text{Sr}/^{90}\text{Y}$ the activity is the sum of ^{90}Sr and ^{90}Y (the nuclides were in secular equilibrium, activity uncertainty unknown). Only those gamma-ray and electron emissions are presented that have the highest yields (percentage of photons/beta particles/electrons per disintegration) and energies larger than 50 keV. β_{max} refers to the maximum energy of the beta particles. For conversion electrons, there may be several adjacent energies, and in these cases only the energy range and sum of yields are presented. In the case of nuclides present in the air filter, only the data with highest yield are presented and the activities refer to the middle of the data acquisition. Because of limited space, the data presented here are rounded and simplified; full data can be found from http://www.nucleide.org/DDEP_WG/DDEPdata.htm.

Nuclide	Activity, Bq (unc.)	γ -rays, keV (yield)	β_{max} , keV (yield)	Electrons, keV (yield)
^{241}Am	37930 (3.0%)	60 (36%)	-	54-56 (8%)
^{57}Co	5780 (3.0%)	122 (86%) 136 (11%) 81 (33%)	-	115-136 (4%)
^{133}Ba	58700 (4.8%)	276 (7%) 303 (18%) 356 (62%) 383 (9%)	-	74-81 (10%) 320 (1%) 350-356 (1%)
$^{137}\text{Cs}/^{137\text{m}}\text{Ba}$	202100 (3.7%)	662 (85%) 122 (28%) 245 (8%) 344 (27%) 779 (13%) 964 (15%) 1086 (10%) 1112 (13%) 1408 (21%)	514 (94%) 1176 (6%) 175 (2%) 385 (2%) 696 (14%) 1063 (1%) 1475 (8%)	624-662 (9%) 75 (19%) 114-115 (11%) 120-122 (3%) 294 (1%)
^{152}Eu	83680 (5%)	1275 (100%) 511 (181%) 1173 (100%) 1332 (100%)	546 (90%) 318 (100%)	- -
^{22}Na	138 (3.7%)	-	546 (100%) 2280 (100%)	-
^{60}Co	3130 (4%)	-	-	-
$^{90}\text{Sr}/^{90}\text{Y}$	1356 (-)	-	-	-
Air filter				
^{214}Pb	5.7 (10%)	352 (36%)	667 (47%)	151-352 (27%)
^{214}Bi	10.5 (10%)	609 (45%)	3270 (20%)	296-1670 (1%)
^{212}Pb	3.0 (10%)	239 (44%)	331 (82%)	99-300 (44%)
^{212}Bi	3.5 (10%)	727 (7%)	2252 (55%)	-
^{208}Tl	2.9 (10%)	2615 (100%)	1801 (49%)	189-2601 (15%)

prepared on the surface of a metallic plate.

The data acquisition was performed in a laboratory in which the radon concentration in the air was of the order of $1 \text{ Bq}\cdot\text{m}^{-3}$ or less. The measurement geometry presented in Fig. 2a was arranged to minimize the scattering of photons and electrons from the surroundings. In addition to air, PMMA (Polymethyl methacrylate) and lead plates were alternatively used between the source and the detector. This was to investigate the effect of the absorbing material on different types of radiation. Beta particles/electrons may be effectively absorbed in PMMA whereas the effect is smaller for photons. They may be absorbed in

the lead plate. The background spectrum without the presence of the sources and above-mentioned absorbing material was also registered (Table 2).

Radon progeny present in air filters pose an important challenge. Relevant (from the point of view of the present paper) short-lived radon progeny emitting high-energy beta particles are presented in Table 1. These beta particles produce high number of counts at the beginning of the measured energy spectrum (Fig. 1). The sample was collected on a membrane filter (Fluoropore, Millipore) with a diameter of 32 mm in a room where the radon concentration was of the order of $600 \text{ Bq}\cdot\text{m}^{-3}$ [1]. Data

Fig. 2 (a) Schematic representation of the measurement geometry. The sources (Table 1) were measured at ambient air pressure using a SDD of 12 mm (SDD = 13 mm for ^{57}Co , ^{241}Am and ^{90}Sr because of somewhat different source dimensions). During the measurements there was PMMA, lead or air (thickness 10 mm) between the source and the detector. The medium surrounding the sources was a non-scattering low-density material. (b) The detector model used in the simulations. See Table 3 for the material compositions.

Table 2 Data acquisition times (live time) in the measurements when there were air, PMMA plate or lead plate between the source and the detector. The background and air filter were only measured in the air medium.

Nuclide	Air (h)	PMMA plate (h)	Lead plate (h)
^{241}Am	1.00	1.00	1.00
^{57}Co	1.39	1.78	5.67
^{133}Ba	1.28	1.28	4.83
$^{137}\text{Cs}/^{137\text{m}}\text{Ba}$	0.082	0.083	1.0
^{152}Eu	1.27	1.28	1.97
^{22}Na	3.48	20.7	41.1
^{60}Co	1.72	15.3	16.7
$^{90}\text{Sr}/^{90}\text{Y}$	17.4	24.7	24.7
Air filter	5.0	-	-
Background	64.3	-	-

acquisition started 20 min after the end of sampling, and therefore no ^{218}Po was present in the filter.

3. Monte Carlo Simulations

Monte Carlo simulations were used to assess the response of the detector to photons and electrons. The detector materials and dimensions were obtained from the detector manufacturer, and the corresponding model used in the simulations is shown in Fig. 2b. The material compositions are presented in Table 3.

MCNPX version 2.6 [4] was used in the simulations. Photons and electrons were transported until they escaped the geometry, were absorbed or their energy fell below 1 keV or 5 keV respectively. When the particle energy fell below the cut-off energy, the particle history was terminated and the remaining kinetic energy was absorbed at the termination point. Photons or electrons were emitted from a mono-energetic isotropic point source located inside the polyethylene slab (at 0.5 mm depth) mimicking

the actual calibration source. Photon and electron energies from 60 to 2000 keV were simulated. The pulse height spectrum registered by the active volume of the detector was scored using the F8 tally of MCNPX. The simulated spectra were not folded with the internal detector resolution (i.e. full width at half maximum of the detector response).

The simulated spectra from monoenergetic electrons (Fig. 3) show that emitted electrons with an energy of up to approximately 200 keV cannot reach the active volume of the detector. A weak signal was, however, obtained from the bremsstrahlung photons generated in the plastic source. When the energy of emitted electrons exceeded 250 keV, a peak appeared in the spectrum corresponding to the maximum energy of the electrons entering the active volume. When the electron energy approached and exceeded 1000 keV, this full-energy peak diminished and finally totally disappeared, as only a very small fraction of the electrons leave their full energy in the detector. Even

Table 3 Composition of materials (Fig. 2b) used in the Monte Carlo simulations.

Material	Density (g/cm ³)	Constituent mass fraction											
		H	C	O	N	Ar	Cr	Mn	Fe	Cu	Zn	Sn	Pb
Air	0.00120		0.000124	0.232	0.755	0.0128							
Polyethylene	0.94	0.144	0.856										
Rubber	1.1	0.118	0.882										
Steel	7.87						0.14	0.01	0.85				
Red brass	8.5									0.85	0.05	0.05	0.05

Fig. 3 MCNPX computation of the probability distribution of counts (bin width 10 keV, air medium) per emitted monoenergetic electron (250, 400, 600 and 2000 keV) as a function of the detected energy.

Fig. 4 MCNPX computation of the probability distribution of counts (bin width 10 keV, air medium) per emitted monoenergetic photon (60, 150, 400, 600 and 2000 keV) as a function of the detected energy. The arrows show the position of photopeaks (if any). The locations of the Compton edges are denoted by the letter C.

around 250-300 keV in emitted electron energy, where the detector is in principle capable of fully absorbing the electron, backscattering from the active volume and scattering into the active volume of the detector from the surrounding materials produced a broad tail in the simulated pulse height spectrum. The total efficiency for electron detection in the simulated geometry was approximately constant (0.14) when the emission energy was above 400 keV. At the emission energy of 250 keV, the total detection efficiency was approximately 0.02.

The full energy peak from monoenergetic photons is visible in the simulated pulse height spectra when the energy of the emitted photon was below 400 keV (Fig. 4). Above that energy, the signal was generated solely by the Compton electrons and fully absorbed photons that were scattered from the surrounding structures, and thus entered the active volume with lower energy than the emitted photons. The peak efficiency in the simulated geometry was 1.2×10^{-3} (3%) for 60 keV and 2.3×10^{-5} (9%) for 200 keV photons, where numbers in the parentheses refer to the corresponding standard uncertainties related to the statistical uncertainty in the Monte Carlo simulation.

4. Measured Spectra

The spectra measured from the sources

characterized in Table 1, and using the measurement geometry visualized in Fig. 2a, are presented in Fig. 5 (see text later for the energy calibration). The number of counts per channel was corrected according to the data acquisition time (Table 2). This normalization was also taken into account in the background spectrum. The purpose was to qualitatively compare the measured spectra produced by each source when different materials were present between the detector and the source. No other corrections, such as different source activities and small changes in the source-detector distance (see text of Fig. 2), were accounted for.

High-energy beta particles emitted by $^{90}\text{Sr}/^{90}\text{Y}$ generated the most prominent signal. However, the betas were effectively removed by using PMMA and lead plates (bottom right spectrum in Fig. 5). This means that the counts above the background of other spectra in Fig. 5, and measured using PMMA and lead media, were definitely generated by photons.

In the case of ^{241}Am and ^{57}Co , the low-energy peaks below channel 50 are due to the 60, 122 and 136 keV gamma rays (see Table 1). The influence of the PMMA plate on the count rate of the low-energy peaks is small compared to the effect of lead. The lead plate effectively removes low-energy quanta. For ^{57}Co the count rates are close to that of the background above

Fig. 5 The spectra measured from sources (^{241}Am , ^{57}Co , ^{133}Ba , ^{137}Cs , ^{60}Co , ^{152}Eu , ^{22}Na and ^{90}Sr) presented in Table 1. Horizontal axes refer to channels and vertical axes count rate per channel (s^{-1}). The background spectrum is shown for comparison (red curve; except in the case of ^{90}Sr , the spectra measured with PMMA and lead media were practically equal to the background). Other spectra are organized as follows: the topmost spectra (black) refer to the measurements performed in the air medium, whereas the spectra below correspond to the PMMA (dotted blue curve) and lead (green) media, respectively.

channel 50, whereas for ^{241}Am the count rates between channels 30-100 were slightly higher than the

background. This was because of the high-energy photons of ^{241}Am not presented in Table 1.

In the case of the ^{133}Ba point source, there are two distinguishable bumps in the energy spectrum. The bump in channels below 150 arises from gamma rays and electrons. The contribution of electrons is supported by the fact that the PMMA absorber removes a notable number of counts above channel 70. The lower-energy bump (channels below 70) is due to the Compton electrons generated by the gamma rays in the detector or materials surrounding it.

A prominent feature of the spectra measured from ^{137}Cs is the bump in channels below 150, which corresponds to the Compton electrons generated by 662 keV gamma rays. However, the effect of beta particles is notable, which is evidenced by the fact that the count rate is an order of magnitude smaller when the PMMA plate was used as an absorber. The difference between the cases of PMMA and lead absorbers (approximately at channel 150) is due to the secondary radiation produced in the Pb absorber.

Since the average energy of ^{60}Co beta particles is 96 keV, most of the betas were absorbed in the source or in the medium material. The count rate deviates from the background up to channel 350 (this corresponds to the registered energy of 800-900 keV) because of high-energy photons. The high-energy counts originated from Compton electrons generated in the

detector, in the absorbing materials or in the structure materials surrounding the sensitive layer of the detector.

The overall shape of the ^{152}Eu spectra is similar to that of ^{60}Co . Although the decay of ^{152}Eu leads to the emission of high-energy photons and beta particles, there are also several low-energy gamma rays and electrons. Thus, the differences between air and the PMMA/lead medium are larger than for ^{60}Co . On the basis of the emission data, no clear differences were anticipated between ^{22}Na , ^{60}Co and ^{152}Eu sources. Although the activity of the ^{22}Na source was low, this assumption was found to be valid. In the case of ^{22}Na , the small “bump” below channel 100 was mainly due to the low-energy beta particles.

The spectra measured in the air medium are compared in Fig. 6, in which normalization to the source activities is taken into account. Small changes in the SDD, and the source diameter in the case of ^{90}Sr , were also taken into account via the geometrical detection efficiency, ε_g (see Fig. 2, SDD of 12 mm was assumed as a nominal case). For example, $\varepsilon_g = 0.146$ for a point source at SDD = 12 mm, whereas $\varepsilon_g = 0.179$ at SDD = 10 mm. These numbers were computed using the AASI program [5].

In the air medium, the registered energies from electrons may sometimes be above 1 MeV, which must

Fig. 6 Comparison between the spectra produced by different sources when there is air between the source and the detector (SDD = 10 mm). In addition to the data acquisition times, the counts are normalized here according to the source activities.

Fig. 7 Low-energy part of the energy spectrum obtained from radon progeny compared to the measured data of $^{90}\text{Sr}/^{90}\text{Y}$ from Fig. 5. For both spectra, the number of counts per channel was normalized according to the maximum number of counts per channel. The detector and conversion gain, and thus the channel numbers, were different from those presented in Fig. 1, although the sample was the same.

be taken into account when unfolding the alpha particle energy spectra. The linear energy calibration assumed in Fig. 6 was performed using the 60 keV peak of ^{241}Am and the right side of the bump of ^{137}Cs (662 keV), corresponding to the Compton edge at 480 keV. Thus, the calibration is only indicative, especially at higher energies.

In general, performing the energy calibration for different types of radiation in (air) medium is extremely challenging. This is because the alpha particle energy loss in the medium is different compared to that of the beta particles and photons. Basically, a separate scale for the energy axis should be used for each type of the quanta, but usually this is not practical. This is why channels instead of energy are here used for the horizontal axis of Figs. 1, 5 and 7.

The spectrum measured from the air filter showed two different components (Fig. 7): High number of counts below channel 50 and a slowly decreasing tail with higher energy. Counts below channel 50 were mainly generated by beta particles/electrons from ^{214}Pb and ^{212}Pb , but there is certainly a contribution of other nuclides mentioned in Table 1 (under the heading Air filter). The high-energy tail was caused by ^{214}Bi , ^{212}Bi and ^{208}Tl and the slope was approximately the same as for $^{90}\text{Sr}/^{90}\text{Y}$. There were no major differences in the detector response between

uranium-series and thorium-series radon progeny. This was verified by saving the spectra at different decay times and by resetting the counts. Long-lived ^{210}Pb has no essential role because of the low emission energies.

In practical situations, unequivocal identification of radionuclides emitting photons, electrons and beta particles seems to be impossible on the basis of the results presented above. Nevertheless, the nuclides might be classified according to the detected energies. For example, radionuclides used in the present investigation can be divided into two or three categories: Low-energy emitters such as ^{241}Am and ^{57}Co generate counts mainly below channel 50 (approximately 150 keV). Medium-energy emitters such as ^{133}Ba and ^{137}Cs generate counts below the channel of approximately 200 (500 keV), whereas high-energy emitters may produce counts even above the energy of 1 MeV. However, this classification may be inappropriate when counts generated by high-energy emitters mask those generated by low-energy emitters.

The question arises as to how sensitively the different radionuclides mentioned in Table 1 could be detected in the air medium when the average value of the background is well known and the same as in the present study. Only point sources (including $^{90}\text{Sr}/^{90}\text{Y}$),

Table 4 Minimum detectable activities in the air medium for point source nuclides presented in Table 1 assuming data acquisition time of 1 min. The activities are for channels 0-50 (number of background counts per minute 13.7), 51-200 (7.5 min⁻¹) and 201-600 (0.25 min⁻¹). In the background measurement the average count rate per minute above channel 600 was 5.7×10^{-3} .

	Channels 0-50 (Bq)	Channels 51-200 (Bq)	Channels 201-600 (Bq)
²⁴¹ Am	3600	93000	14000000
⁵⁷ Co	940	81000	350000
¹³³ Ba	280	1200	1800000
¹³⁷ Cs/ ^{137m} Ba	56	24	13000
¹⁵² Eu	66	36	670
²² Na	65	54	1800
⁶⁰ Co	140	72	840
⁹⁰ Sr/ ⁹⁰ Y	4.2	3.1	31

one at a time, are considered in the following calculation. The data acquisition time is assumed to be 1 min and the measurement geometry is same as presented in Fig. 2. Following Currie [6], the detection limit, L_d , can be determined as $L_d = 2.71 + 4.65 b^{1/2}$, where b is the number of background counts in the region of interest. Minimum detectable activities can be calculated by dividing the detection limit by the number of background-corrected counts per minute of the nuclide in question (Table 4). Even though the above-mentioned radionuclide classification appears to be somewhat arbitrary, it has obvious advantages. Indicative results may be obtained from the very beginning (< 1 MeV) of the full energy spectrum (from 0 up to 10 MeV), although no detailed nuclide-specific information can be accessed.

Counts notably above the energy of 1 MeV are also possible. They may be considered as random events originating from radon and its alpha-particle-emitting progeny present in ambient air or possible cosmic ray interactions in the detector. If the measurements are performed in an environment where the concentrations of radon progeny are high, there is a risk of radon progeny accumulation on the detector surfaces. This may impair spectrum analysis by causing spurious peaks in the spectrum, as evidenced in reference [1].

5. Discussion

From the point of view of the present paper, the

primary application of interest is to detect contamination of alpha-particle-emitting radionuclides from smooth surfaces at ambient air pressure and to identify alpha emitters. For this purpose, knowledge of the detector response to photons, electrons and beta particles is of importance because they may produce notable amount of counts especially in the low-energy part of the alpha spectrum. Without this information, reliable in situ spectrometric measurements and analysis of the alpha spectra cannot be ensured.

It can be assumed that the detector's intrinsic efficiency for alpha particles is 1, i.e. all alpha particles entering the detector will be registered, although a small fraction of them may be backscattered from the dead layer. For electrons, the role of backscattering is larger. It is possible that the detector can fully absorb electrons and beta particles, even if their energy is larger than 290 keV, but most probably only a fraction of their kinetic energy is absorbed.

Monte Carlo simulations were performed for monoenergetic photons and electrons. This is because appropriate radionuclide sources were inaccessible for the measurements. Results of the simulations supported those obtained from the measurements.

In the measured spectra, there are no clear peaks generated by photons. Nevertheless, signals from photons can be registered, even though the detector efficiency for high-energy photons is low. The signals

are mainly generated by Compton electrons. These secondary particles deposit (part of) their kinetic energy in the detector. The signals may also originate from background photons, such as radon progeny present in air. The counts from bremsstrahlung or scattered quanta coming from the materials surrounding the active volume of the detector are also possible.

Based on the simulations and measurements presented above, it is evident that unfolding of the (alpha particle) energy spectrum below approximately 1 MeV is extremely challenging. In practice, unequivocal identification of beta-particle/electron/photon-emitting radionuclides is not possible when a mixture of different radionuclides emitting a range of different quanta is anticipated to be present in the source. Nevertheless, radionuclide classification on the basis of their emission energies seems to be possible, although in the case of multiple radionuclides the counts generated by high-energy emitters may mask those generated by low-energy emitters. It can be concluded that knowing the detector response to photons/beta particles also benefits alpha spectrometric measurements.

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<https://www.stuk.fi/web/en/services/aasi-program-for-simulating-energy-spectra-in-alpha-spectrometry>.

References

- [1] Pöllänen, R., Peräjärvi, K., Siiskonen, T. and Turunen, J. 2013. "In-situ Alpha Spectrometry from Air Filters at Ambient Air Pressure." *Radiation Measurements* 53-54: 65-70.
- [2] Pöllänen, R., Turunen, J., Karhunen, T., Peräjärvi, K., Siiskonen, T. and Wirta, M. et al. 2015. "Novel Equipment for in-situ Alpha Spectrometry with Good Energy Resolution." *Health Physics* 109 (6): 601-5.
- [3] Courti, A., Goutelard, F., Burger, P. and Blotin, E. 2000. "Development of a β -Spectrometer Using PIPS Technology." *Applied Radiation and Isotopes* 53: 101-8.
- [4] MCNPXTM User's Manual. 2008. Edited by Pelowitz, D. B. LA-CP-07-1473.
- [5] Siiskonen, T. and Pöllänen, R., 2005. "Advanced Simulation Code for Alpha Spectrometry." *Nuclear Instruments and Methods A* 550: 425-34.
- [6] Currie, L. A. 1968. "Limits for Qualitative Detection and Quantitative Determination, Application to Radiochemistry." *Analytical Chemistry* 40: 586-93.