THE COMPARISON OF DETECTION PARAMETERS OF SELECTED PHOTOMULTIPLIERS DEPENDING ON THE SHAPE OF THE SCINTILLATOR

by

Jiri JANDA* and Sabina HOHNOVA

NBC Defence Institute, University of Defence, Vyskov, Czech Republic

Scientific paper
http://doi.org/10.2298/NTRP1801061J

The manuscript clarifies the issues concerning the effective miniaturization of readout of the plastic scintillators while maintaining their high detection efficiency and sensitivity. Values obtained from the measurements of the chosen gamma emitters (^{60}Co, ^{137}Cs, ^{241}Am), at various distances, were used to compare the detection efficiencies. The organic plastic scintillators, with the ternary system of different shapes and volumes, were chosen for the measurement. The detection parameters for the examined 1" PMT, with variable photocathode geometry, were experimentally found and compared to the normally used 2" PMT, with the circular type of photocathode. The primary aim of this work was to verify whether, in the case of mobile applications, such as UAV, it is possible to replace the currently bulky and quite heavy electronics with a miniature version and simultaneously preserve their detection parameters.

Key words: detection efficiency, photomultiplier, scintillation detector, plastic detector

INTRODUCTION

Scintillation detectors, together with semiconductor detectors, belong to the most used detectors for spectrometry of ionizing radiation, especially for low-resolution gamma spectrometry. In addition, the detection of radioactive contamination is mostly performed using gas, semiconductor, or just scintillation detectors. The wide variety of scintillation detectors is due to different properties of the scintillation materials and read-out electronics (*e. g.* photomultiplier (PMT), avalanche photodiode (AVPD), and silicon photomultiplier (SiPM)). These properties determine their application usage, such as their use in nuclear physics for detection of different types of radiation [1-5]. Further use is in radiochemistry [5-7], radiology [8-10], metallurgy [11-13] and in the industry for discharging static charge, thickness gauge, level meter, *etc*. The high sensitive scintillation detectors are commonly used for uranium and thorium ore prospecting [14-16].

Another area, where scintillation detectors are widely used, are security and safeguard applications [17-19]. Among the special cases of security applications are detection systems for long-range mapping of radiation field using a robot or UAV. One of the many examples is the detection system Androne (project MOSTAR funded by Ministry of Interior of Czech Republic) designed for dose rate measurement. It can be mounted on a robot, or drone; in this case on Orpheus platform (Brno University of Technology, CZ) and Kingfisher (Robodrone Industries Inc.). This solution can dramatically enhance the ability to measure at locations that may be highly contaminated, or where a helicopter can not be deployed. Another possible use lies in searching for lost or hidden sources or illegal transportation. The system consists of 9 cm 9 cm cylindrical plastic scintillation detector (Nuvia, CZ) with readout electronics, high voltage (HV) module, multichanel analyzer (MCA), global positioning system (GPS), control and data transfer module (fig. 1) [20].

Figure 1. Mobile detection system ANDRONE

* Corresponding author; e-mail: jiri.janda@unob.cz

All the above-mentioned applications have one thing in common – the best detection characteristics of scintillators and the dimension and weight of the system. The aim of the work is to compare the detection efficiencies of 2" standard PMT with a circular photocathode, with 1" PMT with different types of photocathodes, in connection with plastic scintillators with different detection volumes. As far as we know, this comparison has never been done before.

EXPERIMENTAL

Device and equipment

The following sizes and shapes of plastic detectors (Nuvia, CZ) were chosen: 9 cm 9 cm cylindrical and board types with dimensions of 15 cm 10 cm 5 cm, 80 cm 10 cm 5 cm and 100 cm 50 cm 5 cm. The composition of all the detectors was done as – polystyrene matrix with p-terphenyl (PPO) as a primary fluor and 1,4-bis(5-phenyl oxazole-2-yl)benzene (POPOP) as a wavelength shifter.

The 2" PMT with circular photocathode type 9266KB50 (ET Enterprises, GB) was used as an etalon for all plastic scintillators. The digiBase (Ortec, USA) was used as read-out electronics. The spectra evaluations were performed using GammaVision v. 6.07 (Ortec, USA). The 3 3" NaI:Tl detector (Harshaw, USA), as a representative of the inorganic scintillator, was used for comparison the measurements. The read-out electronics, as well as software, were the same. In order to use 1" PMT, the new active divider and preamplifier were developed (Nuvia, CZ, fig. 2).

The comparison measurements were performed for 1" PMT with different photocathodes: circular photocathode (9107B), 2 photocathode (9900B), and hemispherical photocathode (9114B). The gain of all PMT was the same (10^6). The active areas of used PMT are stated in tab. 1. The MCA NuNa was used as readout electronics and the spectra evaluations were performed using NuSOFT GAMWIN (both Nuvia, CZ).

The settings (tab. 2) differed depending on the type of the detector used. All the detectors were calibrated at

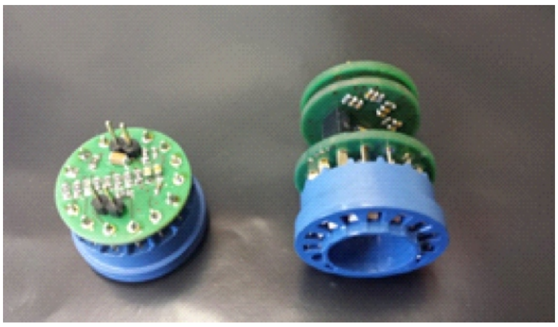

Figure 2. Active divider (left) and active divider in connection with a preamplifier (right)

Table 1. Active areas of the used photomultipliers

PMT	Designation	Area [cm^2]	against 9266KB50 PMT
9266KB50	2" circular	20.83	–
9107B	1" circular	6.25	3.3x smaller
9900B	1" 2	23.96	1.2x bigger
9114B	1" hemispherical	10.13	2.1x smaller

Table 2. Used settings of the selected PMT in connection with different plastic scintillators

Dimensions of the detector [cm]	Parameters	2" circular	1" circular	1" 2	1" hem
9 9 "cylinder"	HV [V]	970	818	818	803
	Coarse gain	1	2	8	1
	Fine gain	0.5	1.5	1.5	1.5
15 10 5 "block"	HV [V]	920	880	810	806
	Coarse gain	1	2	8	1
	Fine gain	1.2	1.5	1.5	1.5
80 10 5 "bar"	HV [V]	1095	950	855	880
	Coarse gain	1	8	16	2
	Fine gain	1.2	1.5	1.5	1.5
100 50 5 "board"	HV [V]	1100	950	855	880
	Coarse gain	3	8	16	2
	Fine gain	1.2	1.5	1.5	1.5

the Compton edge of the ^{137}Cs radionuclide so that the resulting spectrum ranged from 0-2000 keV.

DOW Corning grease was used as an optical coupling. The radionuclide sources ^{60}Co (3.44 MBq), ^{137}Cs (7.73 MBq), and ^{241}Am (50.44 MBq) with the activity related to the date of June 10, 2017, were used for comparative measurements.

Method of the measurement

The detector was fastened to the stand at height of 1 m. In addition, the center was marked for all the detectors. The measurements were carried out according to the same procedure for all the radionuclides. The source was placed at a different distance which varied from 0.5 m up to 5 m directly opposite to the marked center of the detector. The distance varied for detectors with volumes less than 1000 cm^3 and for detectors with volumes greater than 1000 cm^3. For a pair of smaller detectors, these distances were 0.5-3 m, for the two larger detectors this distance was from 1 m to 5 m with the meter spacing. Subsequently, measurements were made twice at each distance to a preset time (live time) of 600 s. The background was measured before and after the pair of measurements of the emitter, at each distance. The net spectrum was calculated subtracting the first background from the first measurement and the second background (after the measurement) from the second measurement, at each distance. After that, these two spectra were averaged.

The procedure was the same for all the radionuclides, types of detectors and PMT.

RESULTS AND DISCUSSION

To compare the efficiency of plastic scintillators in connection with 2" PMT, a 3" NaI:T1 scintillation detector was selected, as a standard. Due to the absence of full energy peak (FEP) in plastic scintillators, it is impossible to calibrate plastic detectors in a classical way. The most commonly used method to perform energy calibration for those types of detectors is to utilize the Compton edge. The quality (slope) of the Compton edge determines the quality of energy calibration and semi-spectrometric determination of radionuclides, or dose/dose rate calculation.

As can be seen in tab. 3, the large-volume detectors in connection with 2" PMT achieved at least 4 times better efficiency than an inorganic 3" NaI:T1 detector at 3 m distance, for all the radionuclides. The highest efficiency was achieved using detector with 25 L of detection volume followed by 4 L detector. The lowest detection efficiency exhibited the cylindrical detector. Considering the very similar shape, but almost 2 times bigger detection volume (573 cm^3 *vs.* 348 cm^3), the detection efficiency was more than 4 times worse than the efficiency achieved using NaI:Tl. The results indicated the irreplaceable role of large-volume detectors, which are widely used in radiation monitoring and portal monitors.

The first detector which was tested was a cylindrical detector with a similar shape as the standard NaI:Tl crystal. The highest detection efficiency (fig. 3) was achieved using 2" PMT, especially when low energy radiation was measured (59.5 keV), where the efficiency was more than 2 times higher than when 1" PMT were used. The difference between detection efficiency of 2" and 1" PMT is approximately 30 % in favor of 2" when high energy photons were measured. The variance among 1" PMT with different types of the photocathodes, is almost negligible.

Due to the larger volume (750 cm^3) the detection efficiency is higher, but still followed the previous trend, at least in terms of low energy detection. The difference was still more than 2 times higher. When measuring medium and high-energy photons, the difference among all PMT was not uniform, as in the previous case. As can be seen in fig. 4, the type of the photocathode exhibited greater importance than in the previous case. Because the detection efficiencies of 1" PMT and 2" PMT were close to each other, it can be presumed that the use of 1" PMT in block type detectors is possible without significant loss of detection efficiency.

Figure 5 shows a graph of the efficiency of the bar detector. Results clearly confirm that the best detection efficiency was undoubtedly achieved using 2"

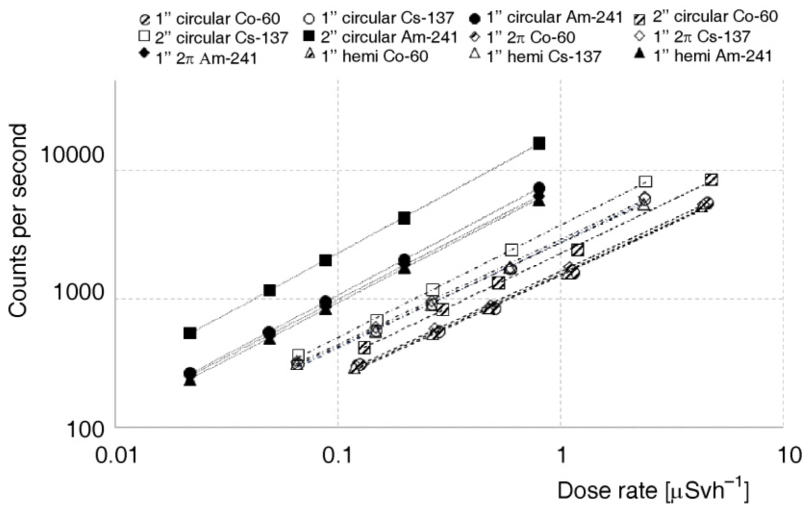

Figure 3. Detection efficiency of the cylindrical detector (9 cm 9 cm) in connection with different types of PMT

Table 3. Absolute detection efficiency of selected NaI:Tl and plastic scintillators in connection with 2" PMT

Distance [m]	Absolute efficiency [10^{-3} %]														
	Harshaw			9 cm 9 cm			15 cm 10 cm 5 cm			80 cm 10 cm 5 cm			100 cm 50 cm 5 cm		
	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co
0.5	133	344	708	32	103	215	45	134	279	–	–	–	–	–	–
1	36	101	216	8	30	61	15	47	94	258	1039	2186	215	1654	3638
1.5	17	54	110	4	15	33	6	21	43	–	–	–	–	–	–
2	10	35	75	2	9	21	4	14	27	70	293	654	54	443	981
3	5	19	42	1	5	11	2	7	15	33	151	313	25	225	479
4	3	12	26	–	–	–	–	–	–	19	89	201	14	136	306
5	2	8	19	–	–	–	–	–	–	8	46	98	10	92	199

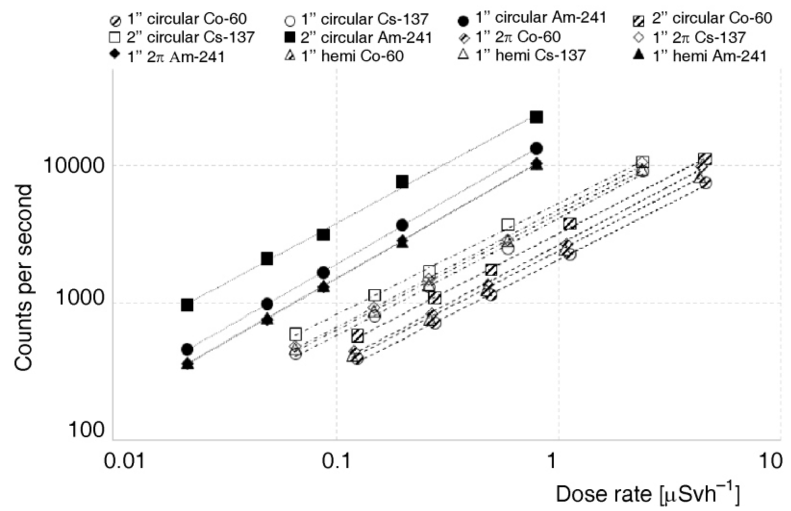

Figure 4. Detection efficiency of block detector (15 cm 10 cm 5 cm) in connection with different types of PMT

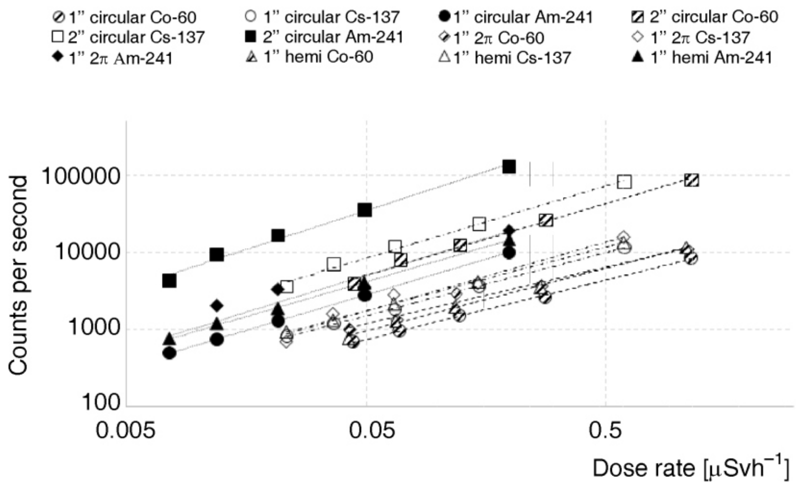

Figure 5. Detection efficiency of the bar detector (80 cm 10 cm 5 cm) in connection with different types of PMT

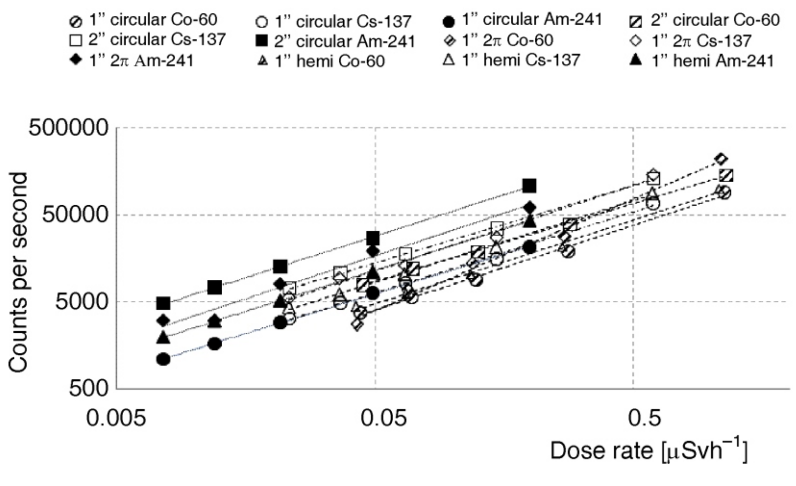

Figure 6. Detection efficiency of the board detector (100 cm 50 cm 5 cm) in connection with different types of PMT

PMT, with very low efficiency for 1" photomultipliers. The results obtained from this type of detector were burdened by a considerable error, which, even after repeated measurements, showed a very poor linearity of the results. This behavior is probably caused by a damage of the detector structure, a crack or a scratch on the surface, or in the volume of the detector, resulting in variation in behavior and scintillation reflection. This could result in distorted measurement results. Another possibility is that the detector could have been poorly grounded, resulting in accidental charging and discharging of the detector, consequently resulting in unclear results or low efficiency.

Due to the interaction of ionizing radiation in the volume of the detector, when there is no photoelectric effect for higher photon energies, but only Compton

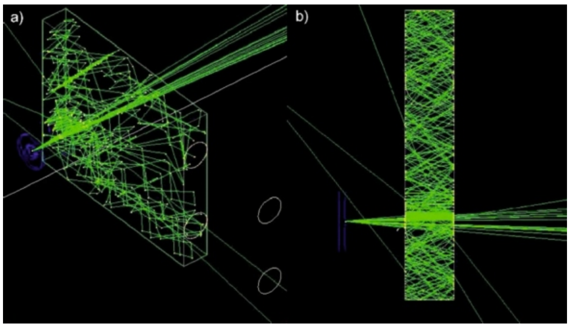

Figure 7. A visualization showing the tracks of twenty 662 keV photons incident on a polyvinyl toluene detector; (a) oblique view, (b) side view [21]

scattering takes place, thus no photopeak arises in the spectrum, it was very difficult to properly adjust the settings. Even the Compton edge was not clearly visible, thus the settings were taken from the bar detector. The reason can be found in multiple reflections and a relatively small area of the photocathode, in comparison with the volume of the detector (25 L). The highest detection efficiency (fig. 6), when dealing with low energy (59.5 keV), was observed using 2" PMT. Unlike the other detectors, the 1" PMT with 2 photocathode reached the highest detection efficiency for middle and high energies. Although the settings were indicative, results indicated the better use of 2 photocathode for a given type of detector. The simulation of reflection is given in fig. 7. As shown in the figure, there are countless reflections in the volume of the detector affecting the resulting spectrum.

A summary of the obtained data is given in tab. 4, where the calculated detection efficiencies of the investigated detectors in connection with different types of photomultipliers, normalized to the detection efficiency of Harshaw, at a dose rate of 1 Svh^{-1}, are listed. The stated results were computed based on regression lines equation, obtained using data from figs. 3-6.

CONCLUSIONS

The plastic scintillation detectors with different shapes and volumes were selected for this work, for which the detection parameters were measured. The main attention was paid to 1" photomultipliers type 9900B, 9107B, and 9114B, which were measured at different distances, along with the selected detectors. The comparison was performed using an inorganic NaI:Tl Harshaw scintillation detector, which was primarily used as a standard for comparison with detection efficiencies of 2" photomultiplier (ET Enterprises, GB), specifically the type 9266KB50, as a standard type of PMT, which is widely used today. The detection efficiency of 1" photomultiplier was related to the detection efficiency of 2" PMT, in conjunction with the respective types of plastic detectors.

It has been confirmed that approximately similar volumes of plastic scintillation detectors have lower detection efficiency, up to 80 % on average. On the other hand, plastic detectors are significantly lighter. In the following overview, the efficiency of the compared 1" photomultiplier normalized to the efficiency of 2" PMT, is numerically expressed. The average of the detection efficiencies at the measured distances, normalized to the detection efficiency of 2" PMT, at given distances, is shown in tab. 5.

The detection efficiencies of the cylindrical and the block type detector were relatively high, ranging from 77 up to 81% of the 2" PMT detection efficiency for the energy of 661.62 keV. The biggest difference was observed when low energy photons (59.5 keV) were measured, where the detection efficiency dropped to 40 %. On the other hand, using bulky detectors together with 1" photomultipliers, did not come close to the efficiency achieved by low-volume detectors. The only exception was the configuration of 1" PMT with 2 photocathode, where the detection efficiency was particularly high for cobalt and HV corresponded to the bar detector. This result should be taken

Table 4. Relative detection efficiencies [%] of the selected plastic scintillators and PMT, normalized to detection efficiency of NaI:Tl , at a dose rate of 1 Svh^{-1}

Detector	2" circular $_{eff}$ [%]			1" circular $_{eff}$ [%]			1" 2 $_{eff}$ [%]			1" hemi $_{eff}$ [%]		
	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co
Cylinder	24	30	31	11	22	21	9	23	22	9	21	21
Block	34	41	43	20	33	29	16	39	37	16	35	33
Bar	776	1156	1162	62	162	116	109	220	163	85	196	163
Board	647	1839	1933	123	956	1218	362	2096	2996	26	1287	1411

Table 5. Average detection efficiencies of 1" PMT normalized to detection efficiency of 2" PMT

Detector type	1" circular PMT (9107B)			1" 2 PMT (9900B)			1" hemi PMT (9114B)		
	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co	^{241}Am	^{137}Cs	^{60}Co
Cylinder	47.2 1.5	77.4 6.4	66.2 4.2	43.4 3.3	81.4 7.4	68.8 4.1	41 2.8	77.6 7.2	64.8 3.3
Block	50.6 5.4	74.4 7.4	65 3.5	39.8 4.1	85.2 8.7	79.4 6.1	40.2 4.1	80 5.2	71.6 3.4
Bar	8.8 1.8	17 3.5	12.4 3.3	19.4 5.4	20.2 2.7	19 5.7	12.8 3	19.6 3.6	15.8 2.7
Board	22.4 1.3	46.4 3.2	51 6.7	38.8 10	57.8 5.4	87.4 28.6	41 1	61.6 4.5	56.8 7

very indicatively, because the gain and HV correspond to the bar detector settings.

Due to the measurement results, it is possible to consider the miniaturization of the system and the use of these diminished devices in applications that are unable to displace or use often heavy systems. The difference in the weight of 2" PMT with a circular photocathode and 1" PMT with a hemispherical photocathode, all with active divider, preamplifier and BNC type of connectors, is threefold in favor of 1" PMT. In addition, the outer dimensions play in favor of 1 "PMT. The length of 1" hemi PMT is two and a half times smaller than 2" circular PMT.Due to the low weight and small dimensions, it would be possible to incorporate plastic detectors utilizing 1" PMT into the detecting means of first responders, such as robots, UAV, *etc*.

ACKNOWLEDGEMENT

The authors of the article would like to express their gratitude to the company Nuvia CZ, plc, for the co-operation on development of active dividers, preamplifiers, and modification of plastic scintillators.

AUTHORS' CONTRIBUTIONS

The idea for the study was put forward by J. Janda. The measurements and the theoretical calculations, data evaluation and interpretation were carried out by S. Hohnova and J. Janda.

REFERENCES

[1] Sartini, L., *et al*., GEMS: Underwater Spectrometer for Long-Term Radioactivity Measurements, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers*, *Detectors and Associated Equipment, 626-627* (2011), May, pp. S145-S147

[2] Beddar, A. S., *et al.*, Water-Equivalent Plastic Scintillation Detectors for High-Energy Beam Dosimetry: I. Physical Characteristics and Theoretical Considerations, *Physics in Medicine and Biology, 37* (1992), 10, pp. 1883-1900

[3] Beddar, A. S., *et al*., Water-Equivalent Plastic Scintillation Detectors for High-Energy Beam Dosimetry: II. Properties and Measurements, *Physics in Medicine and Biology, 37* (1992), 10, pp. 1901-1913

[4] Kubota, S., *et al*., A New Scintillation Material: Pure CsI with 10 ns Decay Time, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 268* (1988), 1, pp. 275-277

[5] Fajardo, Y., *et al*., Automation of Radiochemical Analysis by Applying Flow Techniques to Environmental Samples, *TrAC Trends in Analytical Chemistry, 29* (2010), 11, pp. 1399-1408

[6] Meresova, J., *et al*., Determination of Natural and Anthropogenic Radionuclides in Soil-Results of an European Union Comparison, *Applied Radiation and Isotopes, 70* (2012), 9, pp. 1836-1842

[7] Chakraborty, S., *et al*., Tracer Level Radiochemistry to Clinical Dose Preparation of 177 Lu-Labeled Cyclic RGD Peptide Dimer, *Nuclear Medicine and Biology, 40* (2013), 7, pp. 946-954

[8] Nowotny, R., LiF: W as a Scintillator for Dosimetry in Diagnostic Radiology, *Physics in Medicine and Biology, 49* (2004), 12, pp. 2599-2611

[9] Rosenthall, L., Applications of the Gamma-Ray Scintillation Camera to Dynamic Studies in Man, *Radiology, 86* (1966), 4, pp. 634-639

[10] Vieux, G., Rougeot, H., U. S. Patent No. 4,803,366. Washington, DC: U.S. Patent and Trademark Office, 1989

[11] Melcher, C. L., Perspectives on the Future Development of New Scintillators, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 537* (2005), 1-2, pp. 6-14

[12] Gupta, C. K., Krishnamurthy, N., Extractive Metallurgy of Rare Earths, *International Materials Reviews, 37* (1992), 1, pp. 197-248

[13] Garcia-Torano, E., *et al*., Characterization of a CeBr 3 Detector and Application to the Measurement of Some Materials from Steelworks, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 837* (2016), pp. 63-68

[14] Summerhayes, C. P., *et al*., Phosphorite Prospecting Using a Submersible Scintillation Counter, *Economic Geology, 65* (1970), 6, pp. 718-723

[15] Smith, A. Y., Pournis, S., Exploration for Uranium Ore Deposits, Proceedings Series, *Nuclear Energy Agency, 75* (1976), pp. 185-209

[16] Borkowski, C. J., Clark, R. L., Gamma-Ray Energy Resolution with NaI-TlI Scintillation Spectrometers, *Review of Scientific Instruments, 24* (1953), 11, pp. 1046-1050

[17] Dolan, J. L., Safeguarding Special Nuclear Material by Detecting Fast Neutrons in Liquid Scintillators, 2013

[18] Fehlau, P. E., Brunson, G. S., Coping with Plastic Scintillators in Nuclear Safeguards, *IEEE Transactions on Nuclear Science, 30* (1983), 1, pp. 158-161

[19] Kuroda, Y., *et al*., A Mobile Antineutrino Detector with Plastic Scintillators, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 690* (2012), pp. 41-47

[20] Cespirova, I., *et al*., New Generation Detector for Monitoring Using Remote-Controlled Ground-Based and Airborne Systems, *Bezpechnost Yaderne Energie, 23* (2015), 5-6, pp. 159-162

[21] Rakes, K. D., Evaluating the Response of Polyvinyl Toluene Scintillators Used in Portal Detectors (No. AFIT/GNE/ENP/08-M04), Thesis, Air Force Inst. of Techn. Wright-Patterson Air Force Base, Dayton, O., USA, 2008, p. 55

Received on August 9, 2017
Accepted on December 29, 2017

Јиржи ЈАНДА, Сабина ХОХНОВА

ПОРЕЂЕЊЕ ПАРАМЕТАРА ДЕТЕКЦИЈЕ ФОТОМУЛТИПЛИКАТОРА У ЗАВИСНОСТИ ОД ОБЛИКА СЦИНТИЛАТОРА

Овај рад расветљава питања ефикасне минијатуризације очитавања пластичних сцинтилатора уз одржавање њихове високе ефикасности детекције и осетљивости. Поређење ефикасности детекција обављено је на основу вредности мерења за изабране гама емитере (^{60}Co, ^{137}Cs, ^{241}Am) на различитим удаљеностима. За мерења су одабрани органски пластични сцинтилатори са тројним системом различитих облика и запремина. Експериментално су утврђени параметри детекције једноинчних фотомултипликаторских цеви са промењивом геометријом фотокатоде и упоређени са стандардно коришћеним двоинчним фотомултипликаторским цевима са кружним типом фотокатоде. Примарни циљ овог рада је верификација могућности замене гломазне и веома тешке електронике са минијатурном верзијом уз одржавање параметара детекције у мобилним применама као што су беспилотне летелице.

Кључне речи: ефикасност детекције, фотомултипликаторска цев, фотомултипликатор, сцинтилациони детектор, пластични детектор