Comparison of prompt and delayed photofission neutron detection techniques using different types of radiation detectors

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Comparison of prompt and delayed photofission neutron detection techniques using different types of radiation detectors

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***Abstract*—For several years, detection of various threats on country borders plays a significant role in the frame of Homeland Security applications. One of this threat is the illicit trafficking of nuclear materials (especially including Special Nuclear Material – SNM – ^{235}U, ^{233}U or ^{239}Pu), which can be potentially used for production of nuclear weapon as well as radiological dispersal device (RDD) – known also as a "dirty bomb". In order to detect the potentially hidden nuclear material, systems using linear accelerators and a group of detectors are developed by several scientific groups around the world. Besides solutions focusing on detection of delayed γ-rays or neutrons, also the systems dedicated for prompt neutron detection were proposed. One of the possible prompt neutron detection technique is known as Threshold Activation Detection (TAD). This technique relies on activation of ^{19}F nuclei in the scintillator medium by fast neutrons and registration of high-energy β particles and γ-rays from the decay of reaction products (for example, ^{19}F(n,α)^{16}N or ^{19}F(n,p)^{19}O). Recent studies in the frame of the European Horizon 2020 C-BORD project showed that, despite the low ^{19}F(n,α)^{16}N or ^{19}F(n,p)^{19}O reaction cross-section, the method could be a good solution for detection of shielded nuclear material. A benchmark of the TAD technique based on fluorine detectors with reference method focused on delayed neutron detection with ^{3}He detectors will be presented in this paper. These experimental results were obtained using 9 MeV Varian Linatron M9 linear accelerator (LINAC).**

***Index Terms*—photofission, prompt neutrons, BaF$_2$, delayed neutrons, threshold activation detection, TAD, LINAC, special nuclear materials, SNM, scintillators.**

I. Introduction

The aim of the study is to carry out a comparative study of nuclear material detection techniques basing on prompt and delayed neutron registration. The first technique, applied for prompt neutron detection, is based on Threshold Activation Detection (TAD) using scintillators containing ^{19}F. The incident fast neutrons activate the ^{19}F nuclei, resulting in (n,α) or (n,p) reaction and emission of high energy β particles (up to 10.4 MeV) and γ-rays (in example 6.1 MeV). Potential scintillators of interest for this application are liquid fluorocarbon based EJ-313 [1], [2], [3] or BC-508, BaF$_2$ [4] or fluorine based plastic scintillators based on pentafluorostyrene [5]. The second technology is focused on the detection of delayed neutrons using ^{3}He detectors [6], having a very low sensitivity to γ-rays and high cross section for thermal neutrons of 5530 barns. In this paper we investigated the performance of ⌀5" $\times$ 1" BaF$_2$ scintillator and compared with that for ^{3}He detector, Canberra 150NH100 model [7]. Particularly, BaF$_2$ scintillators present many advantages comparing to fluorocarbon liquid scintillators, such as non-flammability and lack of hydrogen in the scintillator medium, decreasing the efficiency of threshold reaction due to neutron scattering. In addition, the risk of leakage of the liquid fluorocarbon scintillators is a significant disadvantage, promoting the BaF$_2$ scintillator as an interesting alternative.

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II. Results

A. Measurements of the BaF$_2$ response to the ^{252}Cf

The BaF$_2$ scintillator was coupled to an Electron Tubes ET9390 series ⌀130 mm photomultiplier with silicone grease in order to improve light transportation to a photocathode. Finally, detector was mounted into laboratory-made housing designed and manufactured at NCBJ. The test site at NCBJ, where the detector was exposed to neutrons from a ^{252}Cf source is presented in Fig. 1.

Primarily, the response of the BaF$_2$ to neutrons was measured for ^{252}Cf neutron source at NCBJ, emitting 30000 neutrons per second in 4π. Source was shielded with 5 cm thick Pb brick in order to absorb high-energy prompt and delayed γ-rays. The ^{252}Cf was placed 15 cm from the front of the detector. Anode pulses from the photomultiplier were recorded by CAEN V1730 VME-type digitizer offering sampling rate of 500 MS/s and accuracy of 14 bits. Pulses were integrated by a DPP-PSD firmware implemented to the digitizer FPGA. The net spectrum recorded after 4 h was showed in Fig. 2. It can be noticed that fast neutron detection efficiency of the

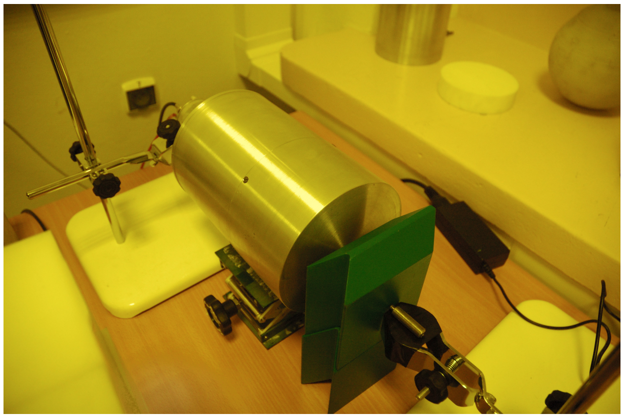

Fig. 1. Test of the prototype BaF_2 detector designed at NCBJ with ^{252}Cf neutron source.

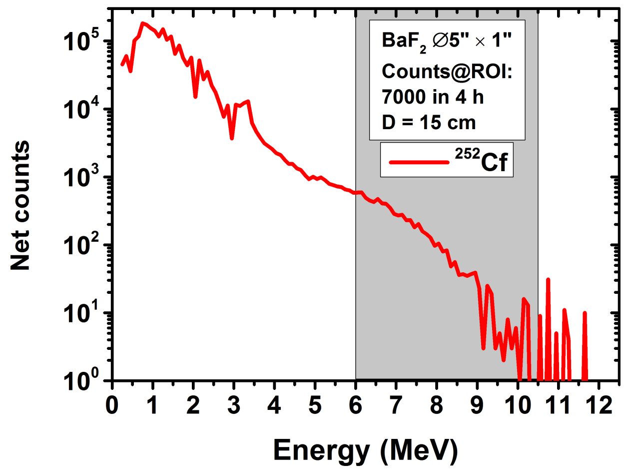

Fig. 2. The BaF_2 detector response to ^{252}Cf neutron source. The β continuum up to 10.4 MeV is clearly seen.

$\varnothing$5" $\times$ 1" BaF_2 based photodetector is significantly better than that for the detector presented in [3].

B. Tests with 9 MeV LINAC at SAPHIR facility

After examination of the detector efficiency at NCBJ, the performance of depleted uranium (DU) detection were investigated at SAPHIR facility in CEA LIST Saclay, France. The test site is shown on Fig. 3. We used the commercially produced Varian Linatron M9 LINAC, emitting bremsstrahlung radiation with endpoint at 9 MeV, in order to induce photofission in DU samples. Both BaF_2 and ^{3}He detectors were placed one meter from DU samples, which in turn were placed one meter from the LINAC tungsten conversion target. Measurements were performed for shielded and unshielded DU. A 5 cm thick Pb brick was used as the shielding. The Teflon in front of the BaF_2 detector was used as an additional TAD material containing ^{19}F, emitting 6.1 MeV γ-rays. During cargo inspection it is convenient to provide as low dose as reasonable possible due to potential exposition of illegal human transportation to radiation. Thus, the LINAC beam frequency was set to 40 Hz. Short time of inspection was introduced; irradiation lasted 10 s, then after 1 s of cooling time, the acquisition with the BaF_2 lasted 20 s. Spectra were

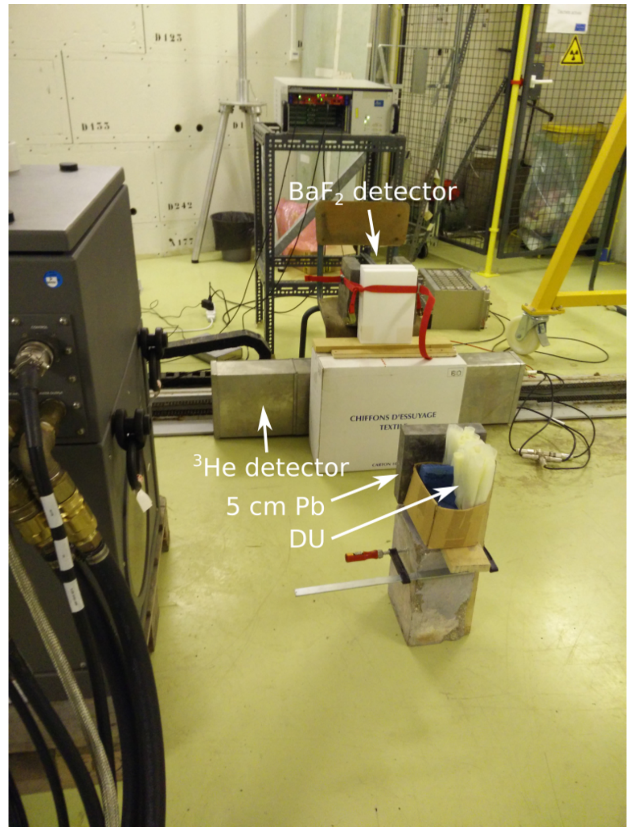

Fig. 3. Test site at SAPHIR facility, CEA LIST, France.

acquired three times, then results were summed. Summarizing, the total time of acquisition lasted 93 s. In the case of ^{3}He detector, after single 10 s of irradiation, the measurement lasted 60 s.

Fig. 4 and Fig. 5 show the obtained net spectra for the BaF_2 and ^{3}He detector. The results expressed in the net number of counts were presented in Table I. The sensitivity of the TAD technique is definitely lower than the detection of delayed neutrons after irradiation with LINAC. The decrease of the

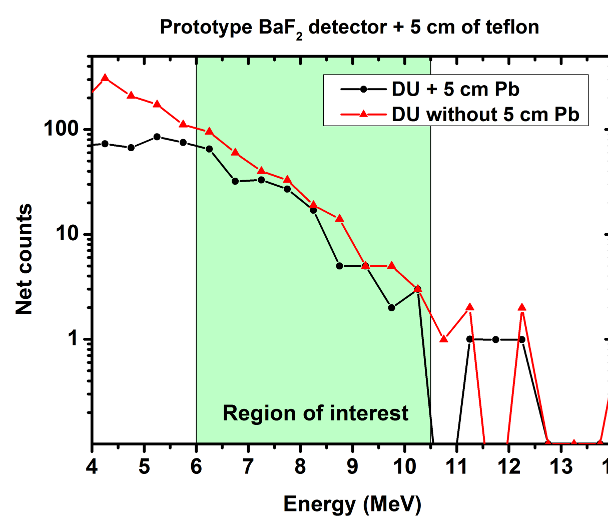

Fig. 4. Net spectra obtained from the BaF_2 detector after three irradiations and counts summing. Data were binned with step of 500 keV.

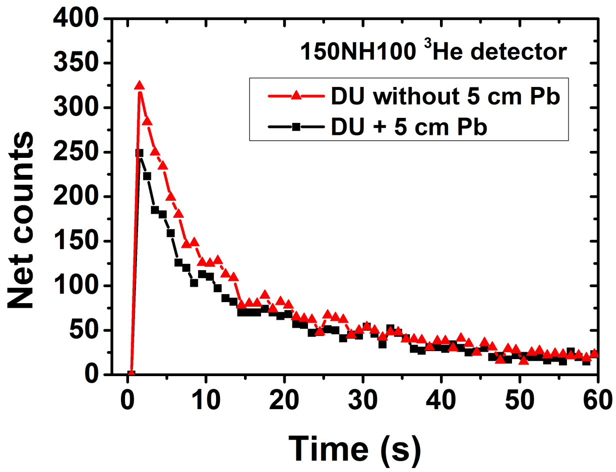

Fig. 5. The net counts registered with the ^{3}He detector in the time scale limit set to 60 s.

TABLE I
NUMBER OF NET COUNTS REGISTERED WITH THE BaF_2 AND ^{3}HE DETECTORS.

Detector	Size	Counts
BaF_2 + 5cm Pb	⌀5" × 1"	189 ± 14
BaF_2	⌀5" × 1"	275 ± 17
^{3}He 150NH100 + 5cm Pb	⌀1 m × 1"	3600 ± 60
^{3}He 150NH100	⌀1 m × 1"	4450 ± 67

sensitivity of shielded DU detection is rather similar for these two techniques and varies between 20 - 35%. However, the worldwide shortage of ^{3}He caused significant price increase of ^{3}He gas detectors. Thus, the BaF_2 detector can be considered as an alternative solution offered for considerable price.

III. CONCLUSION

The prompt neutron detection efficiency of the BaF_2 scintillator is significantly lower in comparison with the sensitivity of the 1 m long ^{3}He detector, used for delayed neutron detection. However, it is important to point out that the ^{3}He detector is much more expensive than ⌀5" × 1" BaF_2 detector used in the present study. Thus, comparison tests with alternative delayed neutron detectors as well as detector geometry optimization will be continued.

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