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# A potential alternative/complement to the traditional thermal neutron based counting in Nuclear Safeguards and Security

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ABSTRACT

A new concept for thermal neutron based correlation and multiplicity measurements is proposed in this paper. The main idea of the concept consists of using 2.223 MeV gammas (or 1.201 MeV, DE) originating in the $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{D}$-reaction instead of using traditional thermal neutron counting. Results of investigations presented in this paper indicate that gammas from thermal neutron capture reactions preserve the information about the correlation characteristics of thermal (fast) neutrons in the same time scale. Therefore, instead of thermal neutron detectors (or as a complement) one may use traditional and inexpensive gamma detectors, such as NaI, BGO, CdZnTe or any other gamma detector. In this work we used D8 × 8 cm$^2$ NaI scintillator to test the concept. Thus, the new approach helps to address the problem of replacement of $^3$He-counters and problems related to the specific measurements of spent nuclear fuel directly in the spent fuel pool. It has a particular importance for Nuclear Safeguards and Security. Overall, this work represents the proof of concept study and reports on the experimental and numerical evidence that thermal neutron capture gammas may be used in the context of correlation and multiplicity measurements. Investigations were performed using a $^{252}$Cf-correlated neutron source and an $^{241}$Am-Be-random neutron source. The related idea of the Gamma Differential Die-Away approach is investigated numerically in this paper as well, and will be tested experimentally in future work.

## 1. Introduction

Thermal neutron-based detectors, such as $^3$He gas proportional detectors, have been already around for decades and are used in a variety of Nuclear Safeguards and Security applications, portal monitors, coincidence counters, waste assay systems. Therefore, the present problem of the global shortage of $^3$He [1] (the total $^3$He demand is $\sim 65 \cdot 10^3$ l/y, while the total supply is $\sim 10\text{–}20 \cdot 10^3$ l/y [2]) led to a number of international programs initiated to find a possible replacement for the $^3$He detection technology. A number of different new detectors and systems are suggested as a replacement, a good overview of each of them can be found in a recent report of [3]. In this work we approach the problem from another perspective and investigate the possibility to instead of using thermal neutrons to use 2.223 MeV gammas which are produced during the thermalization process by epithermal and thermal neutrons in hydrogen-containing material. This depends mostly on the yield of 2.223 MeV gammas (ratio between thermal neutrons and capture gammas) and the ability of 2.223 MeV gammas to carry the same time-related information as thermal neutrons. If 2.223 MeV gammas perform satisfactorily in these two aspects then traditional and inexpensive gamma detectors can be used as an alternative to the $^3$He thermal neutron detectors for correlation measurements and counting.

## 2. The main concept

The main idea of the concept consists of using 2.223 MeV gammas or 1.201 MeV gammas (Double Escape (DE)) originating in the $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{D}$-reaction instead of using traditional thermal neutron counting. The high-energy neutrons from the fissionable material or spent nuclear fuel slows down to epithermal and thermal energies in hydrogen-containing material (water, polyethylene etc.). Some of these thermal neutrons undergo $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{D}$-reaction with the release of 2.223 MeV gammas which are finally detected by the gamma detector, as shown in Fig. 1. It is important to notice that out of all emitted neutrons (for the case of $^{252}$Cf in the 40 × 40 × 30 cm$^3$ water tank, as shown in Fig. 2) approximately half undergo $^{1}\mathrm{H}(n,\gamma)^{2}\mathrm{D}$ reaction after thermalization. Our results indicate that

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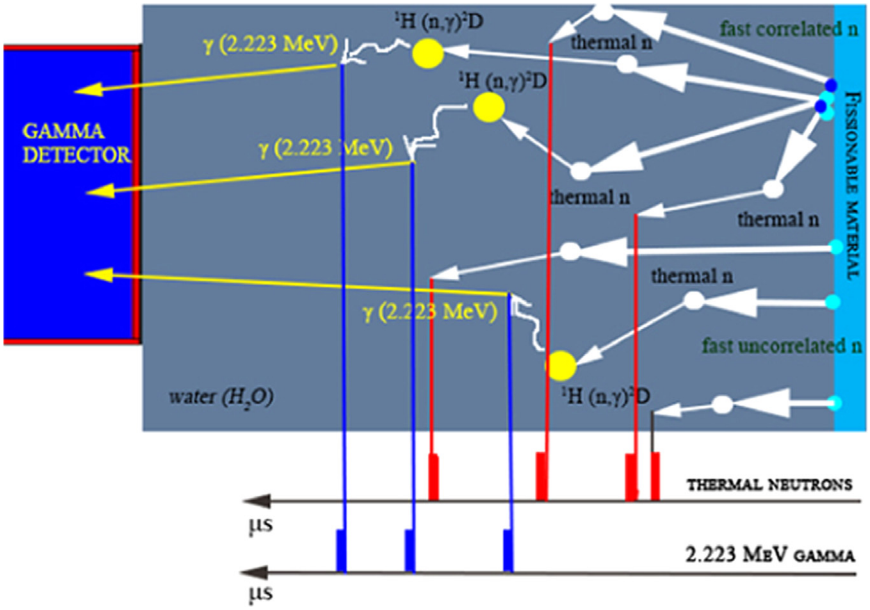

**Fig. 1.** A simplified illustration of the proposed concept.

these gammas carry the same information about correlations as thermal neutrons. Moreover, due to the origin of gammas, since it takes on average microseconds for a neutron to be slowed down and captured, the time scale stays the same as for thermal neutrons. As our previous research [4,5] show, the source gamma will be correlated on the ns scale which makes the analysis somewhat cumbersome. Therefore, the advantage of using 2.223 MeV gamma lines is partly related to the microseconds time scale since there will be no interference with other lines in the gamma spectrum which will be correlated on the same time scale, unless another strong neutron absorber is present in the system which can lead to the production of highly energetic gamma lines. Though, even in this case the overall information will be improved.

## 3. Description of the simulation process and the experimental set-up

The new concept was investigated experimentally and numerically. The experiments were performed with a weak $^{252}$Cf ($\sim$17.3 kBq) spontaneous fission source of correlated neutrons and an $^{241}$Am-Be ($\alpha$, n)-source of random neutrons with a neutron yield of approximately $1.1 \cdot 10^7$ neutrons per second. Due to the lack of access to real spent fuel assemblies and a portable neutron generator (at the moment), the potential of the method for spent nuclear fuel measurements directly in the spent fuel pool and the related idea of the Gamma Differential Die-Away approach were investigated only numerically in this paper. Future experimental work on these issues is foreseen.

### 3.1. Geometry of the experimental set-up

A Plexiglas water tank was constructed specifically for experimental investigations, as shown in Fig. 2.

Dimensions of the tank was $40 \times 40 \times 30$ cm$^3$. The tank was equipped with a water tight Plexiglas sample (source) holder to avoid direct contact between the sample and the water in the tank and provide the possibility to vary the distance between the source and the detector. One NaI scintillator (D8 $\times$ 8 cm$^2$) was used in the measurements.

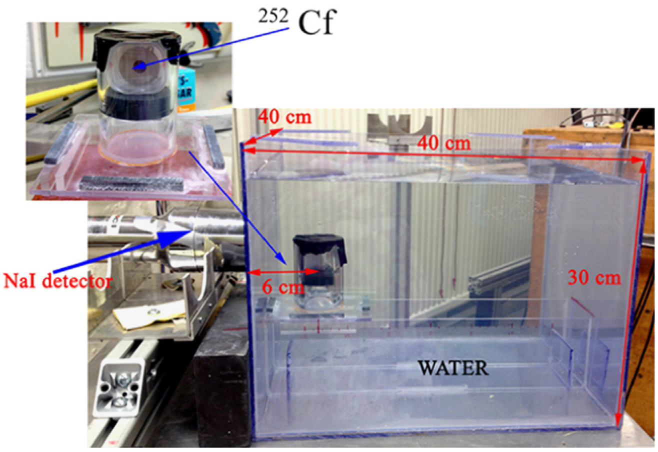

**Fig. 2.** An illustration of the test setup.

Two sources were used for the calibration procedure to cover the energy range from 511 keV to 2.5 MeV, i.e. a $^{22}$Na ($<$1 MBq) source giving the 0.511 MeV, 1.274 MeV lines and a coincident line of 1.785 MeV; a $^{60}$Co source with lines of 1.17 MeV, 1.33 MeV and a coincident line of 2.5 MeV.

### 3.2. Electronics and settings used in experiments

The NaI detector was connected to an 8 channel, 12 bit 250 MS/s, VX1720E CAEN digitizer. The high voltage bias for the detector was adjusted to +1365.4 V using a CAEN (Mod. SY403) 64 channel high voltage supply system.

### 3.3. Data processing procedure

The experimental evaluation of the Rossi-alpha distribution and the Feynman-alpha (variance-to-mean) ratio for thermal neutron-induced gammas was performed with one detector in a traditional way [6,7], as shown in Fig. 3.

Originally, the digitized waveform and corresponding timestamps were collected during a time interval varying from 30 min