Measurements and simulations to investigate the feasibility of neutron multiplicity counting in the current mode of fission chambers

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Abstract—**In two earlier papers [1], [2] we investigated the possibility of extracting traditional multiplicity count rates from the cumulants of fission chamber signals in current mode. It was shown that if all neutrons emitted from the sample simultaneously are also detected simultaneously, the multiplicity rates can be retrieved from the first three cumulants of the currents of up to three detectors, but the method breaks down if the detections of neutrons of common origin take place with a time delay spread wider than the pulse shape. To remedy these shortcomings, in this work we extended the theory to two- and three-point distributions (correlations). It was found that the integrals of suitably chosen two- and three-point moments with respect to the time differences become independent of the probability density of the time delays of detections. With this procedure, the multiplicity rates can be retrieved from the detector currents for arbitrary time delay distributions. To demonstrate the practical applicability of the proposed method, a measurement setup was designed and built. The statistics (shape and amplitude distribution) of the detector pulse were investigated as important parameters of the theoretical model. Simulations were performed to estimate the expected value of the multiplicity rates in the built setup. Measurements were performed and two types of moments (the mean and the covariance function) of the recorded detector signals were calculated. Values of singles rates were successfully recovered.**

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Keywords—**nuclear safeguards, multiplicity counting, fission chambers**

I. Introduction

The primary objective of multiplicity counting is to determine the mass of small fissile samples which is extracted from the detection rates of single, double and triple coincidences (S, D and T count rates) with pulse counting techniques [3]. The development of a method that extracts these multiplicity rates from the first three cumulants of the current of fission chambers is the subject of this paper and its two predecessors [1], [2]. The basic idea was introduced in Ref. [1], in which the neutrons emitted simultaneously from the sample were assumed to be detected simultaneously. It was shown that the S, D and T count rates could be retrieved from the first three cumulants of the detector current, provided that certain parameters of the detector (such as its pulse shape and amplitude distribution is known. In reality, though, detection of neutrons of common origin does not take place simultaneously. Incorporation of this phenomenon into the theory was made in the sequel paper [2], by assuming a random arrival time to the detector. The results showed that when the width of the density function of the time delay is much wider than the pulse width (which is a typical case is thermal detection systems), the coefficients of the D and T rates (analogues of the doubles and tripes gate factors in pulse counting methods) will become vanishingly small, hence only the S rates can be unfolded from the cumulants. To remedy this problem, the theory has recently been extended to the use of the double and triple covariance functions of the detector signals derived from their two- and three-point distributions (in time). In this paper, the main results of this extension are reported. In order to demonstrate the use of the proposed method and to investigate its practical applicability, an experimental configuration has recently been prepared in the Training Reactor Facility at the Budapest University of Technology and Economics in Hungary. Extensive measurements are currently in progress in various configurations. At the end of the paper, some preliminary experimental results will be presented as well.

II. Traditional Multiplicity Counting

In this section the traditional method of multiplicity counting is summarized briefly using the terminology of [4]. In a multiplicity counting measurement, the detection rates of the first three k-tuplets (k detected neutrons originating from the same sample emission) are determined. These rates are called the *singles* (S), *doubles* (D) and *triples* (T) rates, respectively and they can be written as:

$$\begin{aligned} S &= F\,\varepsilon\,\widetilde{\nu}_1 \\ D &= \frac{F\,\varepsilon^2\,f_d\,\widetilde{\nu}_2,}{2} \\ T &= \frac{F\,\varepsilon^3\,f_t\,\widetilde{\nu}_3,}{6}, \end{aligned} \tag{1}$$

Here F is the intensity of spontaneous fission in the sample, ε is the detection efficiency, $\widetilde{\nu}_i$ is a modified form of the so-called Böhnel moments, the factorial moments of the number of emitted neutrons per one source event. f_d and f_t the so-called doubles and triples "gate factors" which are introduced empirically in order to account for the non-coincident detection of neutrons of common origin, and the loss of detection outside the measurement windows.

Using these equations, the sought sample quantities (including the fissile mass of the sample) can be obtained from the measured values of the S, D and T rates using algebrain inversion [4].

III. Multiplicity counting using fission chamber signals

The theory of the newly proposed method of multiplicity counting is based on a formalism describing the fluctuating signals of neutrons detectors [5]. The key element of the formalism is a stochastic model of the detector response, which describes the pulse by a deterministic (constant) pulse shape $f(t)$ with a random amplitude **a**, whose nth moment is denoted by $\langle a^n\rangle$. It is assumed that the detection of neutrons occurs with a random time delay τ, which is independent and identically distributed for each neutron, and is characterized by a density function $u(\tau)$.

Using these quantities as building blocks, various low order cumulants of the detector signals can be calculated with a master equation formalism. In [1] and [2] expression were derived for the one-point cumulants. In this paper calculations for the two and three point cumulants will be presented. We shall see that as in the one-point case, the two- and three point cumulants can also be expressed with the Böhnel moments hence they are also related to the traditional multiplicity rates. As it was already discussed in the previous papers, when interpreting the cumulants in terms of the multiplicity rates, with the purpose of unfolding the Böhnel moments from the cumulants, one has to substitute $f_d = f_t = 1$ in (1). This is because the effect of non-coincident detection of neutrons of common origin, which is described by the empirical gate factors in the traditional method, is explicitly included in the theory of the new method. Nevertheless, as it will be seen, the analogies of the gate factors appear in the cumulants as well.

A. *One-point Distributions*

To serve as a reference of comparison with the expressions of the two- and three point cumulants presented in the following subsection, a brief overview of the theory concerning the one-point distribution is given here based on [2].

By omitting the details of the derivations, the first three cumulants (the mean, variance and skewness) of the detector signal are given by

$$\kappa_1 = S\,\langle a\rangle I_1, \tag{2}$$

$$\kappa_2 = \Big(S\,\langle a^2\rangle + \xi_{1,1}\,2D\,\langle a\rangle^2\Big)\,I_2, \tag{3}$$

$$\kappa_3 = \Big(S\,\langle a^3\rangle + \xi_{1,2}\,6D\,\langle a\rangle\langle a^2\rangle + \xi_{1,1,1}\,6T\langle a\rangle^3\Big)\,I_3. \tag{4}$$

Following similar considerations, the expressions for the double and triple cross-covariances between two and three detectors read as

$$\kappa_{1,1} = 2D\,\langle a\rangle^2\,\xi_{1,1}\,I_2, \tag{5}$$

$$\kappa_{1,1,1} = 6T\,\langle a\rangle^3\,\xi_{1,1,1}\,I_3. \tag{6}$$

Here, I_n as well as $\xi_{1,1}$, $\xi_{1,2}$ and $\xi_{1,1,1}$ are integrals of the pulse $f(t)$ shape and the delay density function $u(\tau)$ and their definitions can be found in [2]. Because it will appear in the two-and three point cumulants, we include here the definition of I_1:

$$I_1 = \int_0^\infty f(t)\,\mathrm{d}t. \tag{7}$$

We will refer to the ξ's as "gate factors" because they play a similar role in the above formulas as the traditional gate factors in (1). From Equations (2)–(6) it is seen that if I_n and the ξ's are known from calibration, the detection rates can be obtained from the measured cumulants by simple algebraic inversion. However, as it was also shown in [2], if the spread of the density of the time delay is much larger than the pulse width (which is typical in thermal detection systems), the gate factors become vanishingly small. In such a case, only the S rates can be extracted.

B. *Two- and Three-point Distributions*

To explore the temporal correlations in the detector signals, their distribution must be described at two or even three points in time: besides time t, a second time $t-\theta$ and a third time

$t-\theta-\rho$ is considered as well. Regarding a single detector, our goal is to determine the integrals

$$\mathrm{Cov}_2 = \int_0^\infty \mathrm{Cov}_2(\theta)\,\mathrm{d}\theta \tag{8}$$

and

$$\mathrm{Cov}_3 \equiv \int_0^\infty \int_0^\infty \mathrm{Cov}_3(\theta,\rho)\,\mathrm{d}\theta\mathrm{d}\rho \tag{9}$$

of the second and the third order cumulants of the signal, the covariance function $\mathrm{Cov}_2(\theta)$ and the bi-covariance function $\mathrm{Cov}_3(\theta,\rho)$ defined as

$$\begin{aligned}\mathrm{Cov}_2(\theta) = \lim_{t\to\infty} \mathbb{E}\left[(y(t)-\mathbb{E}[y(t)])\right.\\ \left.\times\,(y(t-\theta)-\mathbb{E}[y(t-\theta)])\right],\end{aligned} \tag{10}$$

and

$$\begin{aligned}\mathrm{Cov}_3(\theta,\rho) = \lim_{t\to\infty} \mathbb{E}\left[(y(t)-\mathbb{E}[y(t)])\right.\\ \times\,(y(t-\theta)-\mathbb{E}[y(t-\theta)])\\ \left.\times\,(y(t-\theta-\rho)-\mathbb{E}[y(t-\theta-\rho)])\right].\end{aligned} \tag{11}$$

Detailed calculation of the moments can be found in [6]; here only the final results will be provided. One finds that the integral of the covariance function $\mathrm{Cov}_2(\theta)$ has the form

$$\mathrm{Cov}_2 = \frac{1}{2}\left(S\left\langle a^2\right\rangle + 2\,D\langle a\rangle^2\right)\,I_1^2, \tag{12}$$

whereas the integral of the bicovariance function $\mathrm{Cov}_3(\theta,\rho)$ has the form

$$\begin{aligned}\mathrm{Cov}_3 = \frac{1}{6}\left(S\,\langle a^3\rangle + 2D\,\langle a\rangle\langle a^2\rangle(\xi_A+\xi_B+\xi_C)\right.\\ \left. +\,6\,T\,\langle a\rangle^3\right)\,I_1^3.\end{aligned} \tag{13}$$

Here I_1 is the same as (7) in the previous Section, whereas the three point doubles gate factors ξ_A, ξ_B and ξ_C are also integrals of the pulse shape and the delay density function; their definitions can be found in [6]. The corresponding integrals of the covariance function $\mathrm{Cov}_{1,1}(\theta)$ of two detectors and the bi-covariance function $\mathrm{Cov}_3(\theta,\rho)$ of three detectors read as

$$\mathrm{Cov}_{1,1} = D\langle a\rangle^2\,I_1^2 \tag{14}$$

$$\mathrm{Cov}_{1,1,1} = T\,\langle a\rangle^3\,I_1^3. \tag{15}$$

One can see that the expressions (12)–(15) have, with minor differences, the same form as the one-point cumulants (3)–(6). The difference is that, except in the doubles term of Cov_3, all the gate factors (hence the density of the unknown time delay distribution) have disappeared.

With the results presented above, it possible to design an experimental procedure such that all selected moments (cumulants and covariances) are independent of the time delay distribution. This makes the method applicable for multiplicity counting with thermalised neutrons, for which the detector efficiency is much higher than for fast neutrons. In particular, one can use the first cumulant κ_1 to determine the singles rates, the covariance $\mathrm{Cov}_{1,1}$ or Cov_2 to determine the doubles rate, and the bi-covariance $\mathrm{Cov}_{1,1,1}$ to determine the triples rate.

IV. Experimental Investigation

An experimental configuration has been prepared in the Training Reactor Facility at the Budapest University of Technology and Economics in Hungary in order to demonstrate the use of the newly proposed method. Strictly speaking, the applied measurement setup corresponds to the active version [7] of multiplicity counting as opposed to the passive version described in the first part of this paper. The reason for this is that no spontaneous fissionable materials are available at our facility, therefore the only option is to use low enriched uranium samples irradiated by an isotopic neutron source to induce fission in the sample. Although the two versions of multiplicity counting provide different formulas for the detection rates [7], the relationship between the moments of the detector signals and the detection rates is expected to be the same in the two cases. Therefore as our primary goal is not to unfold the fissile mass of an unknown sample, but only to show the possibility of extracting detection count rates from the time-resolved signals of fission chambers, we shall disregard the differences of the two versions and use the formulas for the signal moments as presented in the preceding sections.

A. Description of the measurement set-up

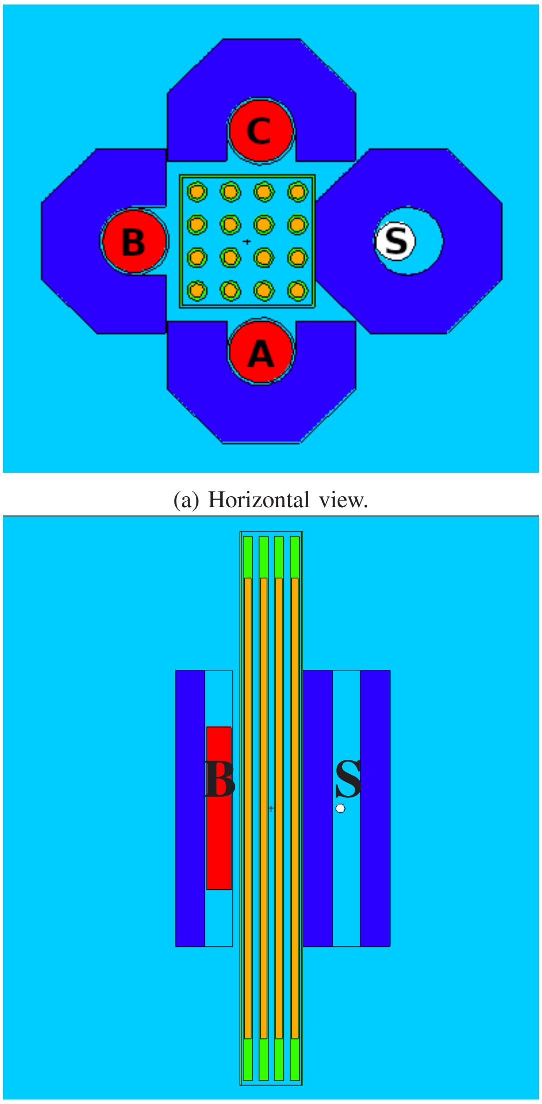
Fig. 1 shows the MCNP 6.1 [8] model of the measurement geometry whereas Fig. 2 shows a picture of the built setup.

The central element of the setup is an EK-10 type fuel assembly. Different variants of the same assembly type are available in the facility which differ in their shape, in the number of fuel rods they contain, and the arrangement of the rods within the assembly. The one shown in the figures is a square shaped assembly with 68 mm side length containing 16 fuel rods in a square lattice. Each rod is filled with fresh fuel pins of 10% enriched uranium oxide in metal magnesium matrix yielding 7.94 grams of ^{235}U per rod. The rods have a 50 cm active length and a 7 mm active diameter. The cladding of the fuel pin is 99.5% purity aluminum alloy, with an outer diameter and thickness of 10 mm and 1.5 mm, respectively.

The fuel assembly is surrounded by three KNT-31-1 type fission chambers labeled with A–C on the Figure. The fission chambers have a 17.6 cm length, a 32 mm outer diameter and 500 cm^2 area of sensitive layer covered with 90% enriched uranium. The thermal neutron sensitivity of the detectors is 0.25 pulse per one neutron/cm^2.

A ^{241}Am–Be source, labeled with S on the Figure, is located close to the fuel assembly to provide neutrons that cause induced fission in the fuel. The isotopic source has an emission intensity of $2{\cdot}10^6$ neutrons/s. Both the source and the detectors are covered (at least partially) by a paraffin-wax coating which serves as a moderator for the fast neutrons originating from the isotopic source and the fuel. The thickness of the coating was chosen to maximize the fission intensity in the detectors; based on MCNP simulations with different thicknesses, 3 cm was found to be optimal.

The signal of each detector is sent to an in-house-built high-frequency pre-amplifier which produces a voltage signal ranging between -1 and 1 V. The pre-amplifier circuit has a small time constant (compared to the charge collection time of the detector), hence the shapes of the amplified voltage pulses reflect the shapes of the current pulses in the detector. The voltage signals of three detectors are then registered by a pair of Red Pitaya STEMLab 125-14 type FPGA-based A/D converters. Each converter has two analogue inputs and provides a 14 bit vertical resolution as well as 125 MHz maximal sampling frequency (corresponding to a 8 ns maximal resolution in time).



(a) Horizontal view.

(b) Vertical view.

Fig. 1: The MCNP model of the measurement setup.

The complete experimental investigation is divided into three steps:

1) First, by recording relatively short segments of the detector signals, the relevant properties of the pulses were determined: the mean amplitude $\langle a \rangle$, as well as the integral I_1 of the pulse shapes.

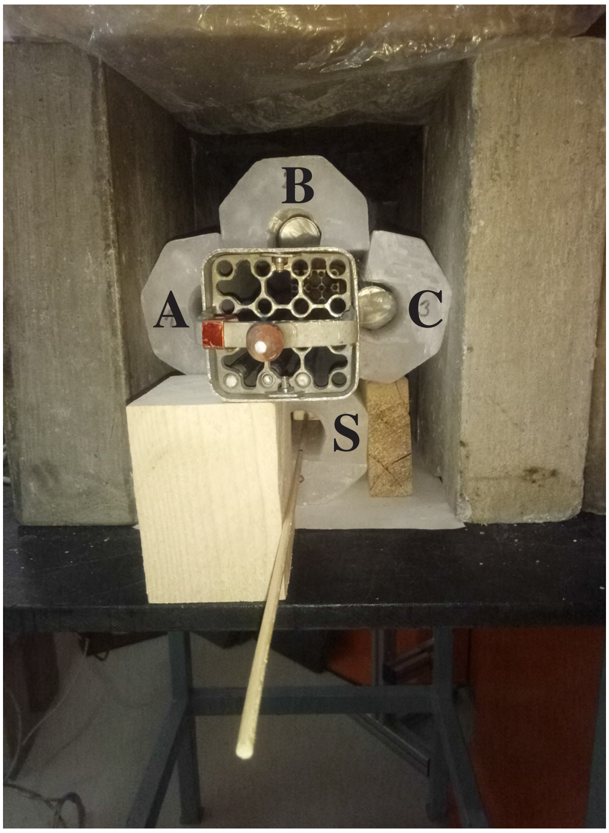


Fig. 2: A picture of the measurement setup.

2) Next, by running MCNP simulations, the detection efficiency ε of the measurement configuration is determined, furthermore, the expected number of singles, doubles and triples detection events is estimated.
3) Finally, by running long measurements and analyzing signals, the mean value and the covariance function of the detector signal is determined. From the mean value, the singles rate is also recovered.

B. *The properties of the detector pulse*

The properties of the impulse of the detectors (their shape and amplitude distribution) were determined by analyzing a large number of recorded pulses. Signals were recorded for 5 minutes with a time-resolution of 48 ns; Fig. 3 shows a short segment of the recorded signal of two detectors. From all the registered pulses, the non-overlapping ones were selected and analyzed. An other set of signals were recorded without the isotopic source being present in order to characterize the background noise. The results are summarized on Figures 4 and 5 for one of the three detectors. Fig. 4 shows the probability density function of the amplitudes of the selected pulses, i.e. the pulse amplitude spectrum. There is a consider-able background below 150 mV which originates partly from the α-decay in the fissile deposit of the fission chamber and partly from electronic noise. The mean amplitude of the pulses generated by neutrons is around 272 mV. On Fig. 5 the shapes of three individual registered pulses is shown together with the average pulse shape calculated from the complete set of selected pulses. One can see that the average pulse has a characteristic length of around 10 μs. The integral of the pulse shape is 3.09 μs.

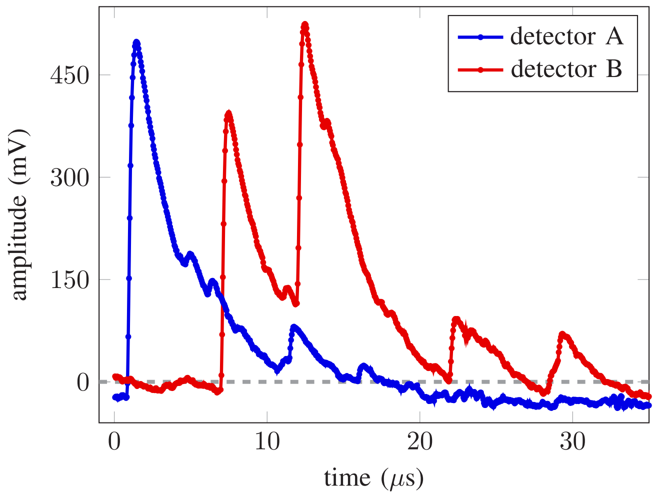


Fig. 3: Short segments of the recorded signals of two detectors.

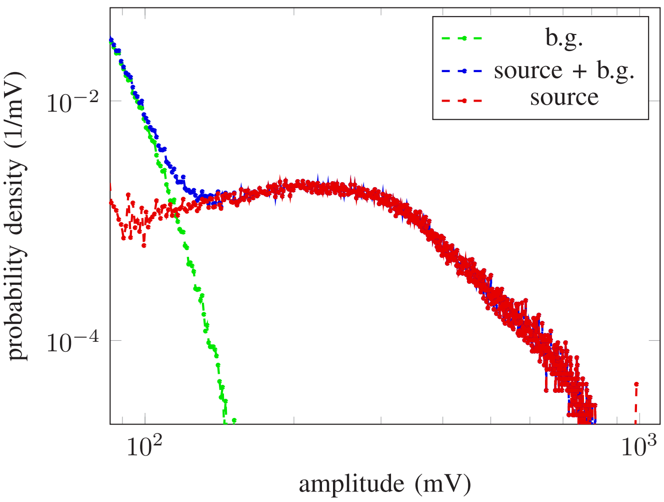


Fig. 4: Probability density function of the amplitude of the detector impulse.

C. The efficiency of detection

The efficiency of detecting single neutrons, as well as doubles and triples was investigated with MCNP simulations using the model shown on Fig. 1. Each simulation was performed with the PTRAC option which, provided listed information on (among many others) the location and time of fission events. This data was then processed and used to determine the quantities discussed in this subsection.

In order to estimate the efficiency of the detectors, that is, the probability of detecting a neutron coming from the fuel assembly after an induced fission, source neutrons were initiated from the fuel region. Their position and direction

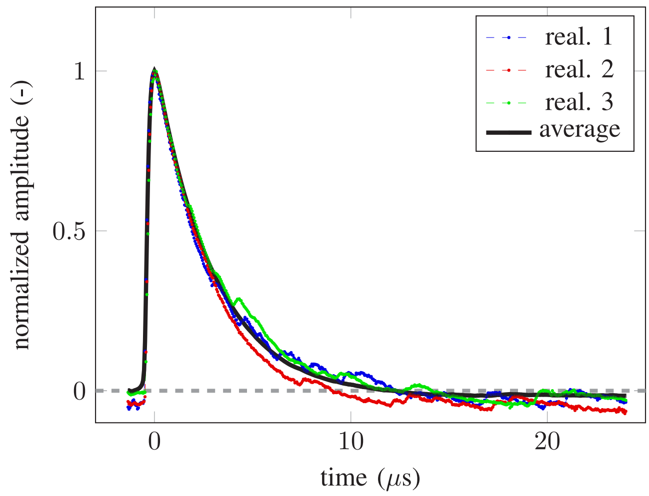


Fig. 5: Some realizations of the shapes of the detector impulse and the calculated average shape.

followed uniform and isotropic distributions, respectively, whereas their energy followed the Watt spectrum specific to ^{235}U. To eliminate the effect of internal multiplication, which is of no interest in determining the detection efficiency, the fuel pins were replaced by void space. After initiating $3 \cdot 10^9$ source particles in total, the number of fission events in the detectors were counted, from which the detection efficiency could be easily estimated. The results are summarized in Table I. One can see that the efficiency of all three detectors is around 0.07% yielding an overall detection efficiency of around 0.21%. This is a very low value (especially when compared with the usual 40–60% efficiency of traditional multiplicity counters [3]) primarily caused by the unfavorable geometrical conditions in the system. As a consequence, by recalling expressions (1) of the detection rates, we expect that the observed doubles and triples rates will be several orders of magnitudes smaller than the singles rates, which can make their determination difficult or even impossible.

TABLE I: The probability of detecting neutrons arriving from the fuel.

detector	detection probability (%)
A	0.0710
B	0.0703
C	0.0707
total	0.212

There is an additional effect related to the detection of neutrons, which is not included in the theoretical model presented in the first part of the paper, nevertheless it affects the statistics of the measured signals. Namely, in a fission chamber the detection of a neutron generates further neutrons, which might then get detected in this particular detector or in a neighboring one, thus increasing observed rates of singles, doubles and triples detections. To estimate the probability of such events, simulations were performed in which source neutrons were initiated from one of the detectors (distributed uniformly in space, isotropically in direction and with Watt energy spectrum), and the number of fission events in all detectors were counted. This same procedure was repeated with all three detectors, and the probabilities of detecting neutrons originating from any of the three detectors were estimated. The results are shown in Table II, where the rows represent the detectors where the neutrons starts from, and the columns represent detectors where the neutrons arrives to. Considering a neutron generated during the detection process in one of the detectors, the probability that it will be detected by the same detector is around 0.033–0.035%, whereas the probability that it will be detected by an other detector is around 0.016%. Since these probabilities are quiet low, the number of such "false counts" and hence their contribution to the singles, doubles and triples is expected to be negligible. Nevertheless, in order to gain a better understanding of this process and its consequences, we are planning to incorporate it into the theoretical model in the near future.

TABLE II: The probabilities of detecting neutrons born in the detection process in one of the detectors.

	detection probability (%)		
	A	B	C
A	0.035	0.016	0.016
B	0.016	0.033	0.016
C	0.016	0.016	0.035

The detection probability presented above is a simple way to characterize the detection efficiency in the measurement setup. An other, more direct approach is to estimate the expected number of single, double and triple detection events in a given period of time. To get this information, neutrons were initiated from the ^{241}Am–Be isotopic source region, and the number of events when one, two and three neutrons were detected (excluding the detection of neutron born in the fission chambers) were counted. The simulations were performed with $3 \cdot 10^9$ source neutrons in total which, taking into account the strength of the isotopic source, corresponds to a measurement time of 25 minutes. This simulation was repeated with four different number of fuel rods (8, 10, 13 and 16) in the assembly, in order to investigate the sensitivity of the detection rates on the amount of fissile material. The results are summarized in Table III. Two types of singles are shown: source singles are neutrons detected directly from the isotopic source, whereas sample singles originate from induced fission in the fuel assembly. No values are presented for the triples, because their number was zero in each case due to the very low detection efficiency of the system. As expected, with increasing amounts of fuel the number of sample singles and sample doubles increases, because the probability of inducing fission in the fuel also increases. The expected number of source singles shows the opposite tendency which can be explained by the shielding property of the fuel: the more fuel is present, the lower the probability that source neutrons reach the detectors without causing induced fission in the fuel. In general, as it is expected from the detection probabilities shown earlier, the expected number of singles is several order of magnitudes higher than the expected number of doubles. Additionally, the expected number of source singles is much higher than that of the sample singles. As a result, one expects that the source single counts will have a dominating contribution to the measured detector current and to its moments, as we will see in the following subsection.

TABLE III: Number of detection events with different amounts of uranium in the fuel assembly.

# rods (-)	number of detection events per 25 min		
	source singles	sample singles	sample doubles
8	3152978 ± 1775.7	261434 ± 511.3	227 ± 15.1
10	2989616 ± 1729.1	301605 ± 549.2	272 ± 16.5
13	2804619 ± 1674.7	346319 ± 588.5	279 ± 16.7
16	2623345 ± 1619.7	379215 ± 615.8	331 ± 18.2

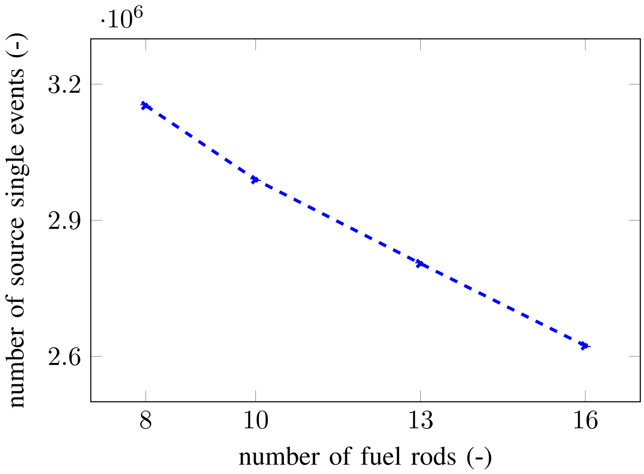


Fig. 6: Number of source single events per 25 min as function of the number of fuel rods in the assembly.

D. The mean value and the covariance function of the signals

As a simple preliminary demonstration of the proposed method, measurements were performed using three different types of fuel assemblies, containing 0, 5 and 16 rods. The mean values and the covariance functions of the registered signals were then determined which, according to (2) and (14), are related to the (sample) singles and (sample) doubles rates, respectively. The bicovariance functions were not calculated due to the low expected value of the triple events.

Since, as we saw earlier, detection events (especially doubles) are rare, long measurements lasting several hours are necessary to gain usable statistics. Considering the 48 ns time resolution of the AD converter, the recorded signals would require a large amount of disk space. In order to save space, a compression technique was developed and applied. The technique utilizes the fact that – due to the low detection intensity – neighboring pulses in the signal are often fare from each other and separated by background noise which, however, contains

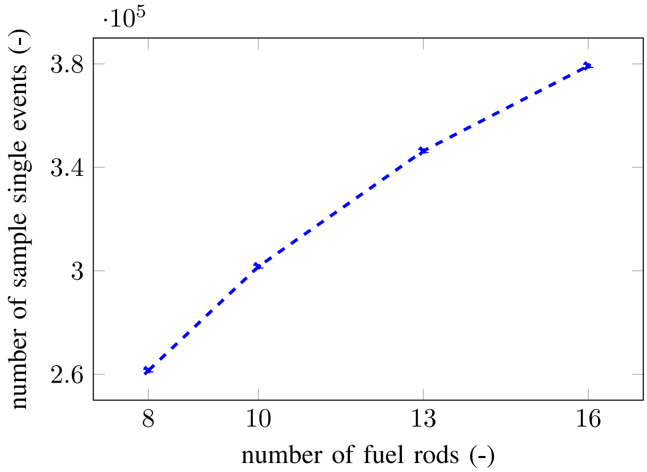


Fig. 7: Number of sample single events per 25 min as function of the number of fuel rods in the assembly.

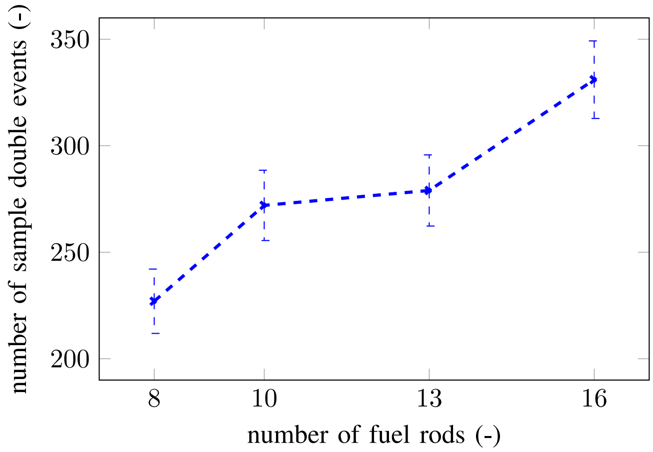


Fig. 8: Number of sample double events per 25 min as function of the number of fuel rods in the assembly.

no useful information on the system. Therefore, a triggering procedure was implemented on the FPGA module of the AD converter to disregard the unnecessary parts of the signal. The procedure is illustrated on Fig. 9 and is explained in the following. An arbitrary threshold level is defined for the input analogue signal coming from the detector to the converter. By default, the digitized signal values are not written to files, instead they are collected in a memory buffer within the FPGA. When the signal goes above threshold, the values start being written to files from 40 samples earlier. When the signal goes below threshold and stays there for at least 200 samples, they stop being written to files. During analysis of the signals, these unrecorded segments were considered to be zero.

Using the described compression technique, a single 8 hour long measurement was performed with each of the three assemblies. The threshold values for the triggering were determined individually for each detector based on their amplitude spectrum, just like the one seen on Fig. 4.

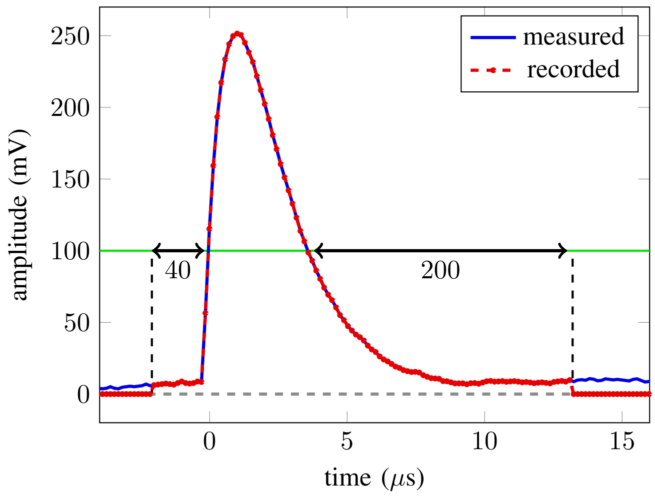


Fig. 9: Illustration of the triggering technique applied in the recording of the detector signals.

The mean values of the registered signals of all three detectors are shown on Fig. 10. One immediately sees, that they show a decreasing tendency with increasing amounts of fuel, just as the source singles in Table III. This is not surprising if we recall that the mean value is proportional to the singles detection rate and – as shown in the previous subsection – singles events are dominated by the so called source singles. Table IV lists the singles rates (number of singles per 1 second) calculated with formula (2) from the mean values of detector A. To serve as a comparison with the simulated values shown in Table III, the number of singles per 25 minutes were also calculated. We see that the measured singles rates are in the same order as the simulated (and dominating) source singles.

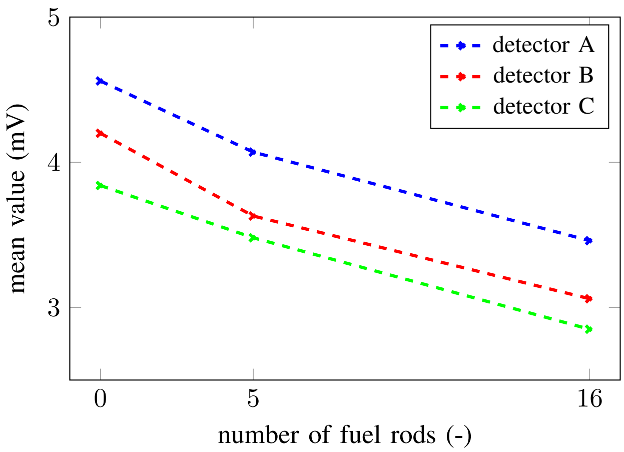


Fig. 10: The mean value of the recorded detector signals at different number of fuel rods in the assemblies.

The covariance function of the signals of detectors A and B are shown on Fig. 11. Regardless of the number of fuel rods in the assembly, the covariance function appears to be a

TABLE IV: Singles rates estimated from the mean value of detector A with different amounts of uranium in the fuel assembly.

# rods (-)	number of singles (-)	
	per 1 second	per 25 minutes
0	5425.5	8138206.7
5	4842.5	7263706.5
16	4116.7	6175042.8

constant zero function buried in noise, whose integral will also practically be zero, making it impossible to recover the doubles detection rate using formula (14). This is most likely a result of the low rate of doubles events, which are suppressed by the much more frequent singles events and by the background noise.

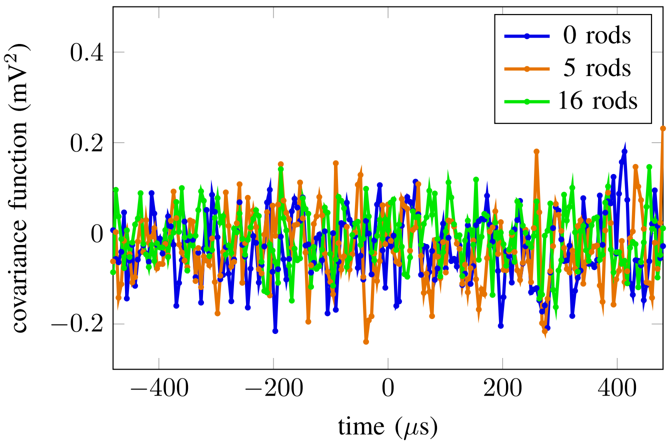


Fig. 11: The covariance function of the signals of detectors A and B at different number of fuel rods in the assemblies.

V. Conclusions and Future Plans

A new form of neutron multiplicity counting has been developed with the possibility of extracting traditional multiplicity count rates (namely the singles, doubles and triples rates) from the cumulants of fission chamber signals in current mode. It was shown that, at least in theory, by using two- and three-point statistics of the currents of one to three fission chambers, the detection rates can be recovered even in the case when the detection of neutrons of common origin does not take place simultaneously. The proposed method has the advantage that it does not suffer from the dead time problem, on the other hand it requires the knowledge of the detector pulse statistics (shape and amplitude distribution), which are though only the properties of the detector and can be determined from calibration. An experimental setup was designed and built to demonstrate the practical usability of the method. The properties of the detector pulse required by the theoretical model have been successfully determined. Monte Carlo simulations were performed to estimate the detection efficiency in the built setup. It was found that the probability of detecting a single neutron is much smaller than in a traditional multiplicity counter and as a consequence, the expected number of doubles and triples events is almost negligible compared to that of the singles events. Measurements were performed and the mean values as well as the covariance functions of the signals were estimated. Values for the singles rates were successfully extracted from the mean current, but the measured covariance functions were found to be zero, making it impossible to recover any doubles rates.

These latter results indicate that in order to effectively demonstrate the use of the proposed method of multiplicity counting, the detection efficiency should be significantly increased. There is two obvious choice to achieve this: one possibility is to use three groups of detectors where each group contains several small-sized detectors whose signals are unified; the other possibility is to use three large fission chambers. Coordination is in progress with partner institutes to realize such measurements.

References

[1] I. Pázsit, L. Pál, and L. Nagy, "Multiplicity counting from fission chamber signals in the current mode," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 839, pp. 92–101, 2016.

[2] L. Nagy, I. Pázsit, and L. Pál, "Multiplicity counting from fission detector signals with time delay effects," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 884, pp. 119–127, 2018.

[3] N. Ensslin, W. C. Harker, M. S. Krick, D. G. Langner, M. M. Pickrell, and J. E. Stewart, "Application guide to neutron multiplicity counting," *Los Alamos Report LA-13422-M*, 1998.

[4] I. Pázsit, A. Enqvist, and L. Pál, "A note on the multiplicity expressions in nuclear safeguards," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. **603**, pp. 541 – 544, 2009.

[5] L. Pál, I. Pázsit, and Z. Elter, "Comments on the stochastic characteristics of fission chamber signals," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 763, no. 0, pp. 44–52, 2014.

[6] L. Nagy, I. Pázsit, and L. Pál, "Two- and three-point (in time) statistics of fi
ssion chamber signals for multiplicity counting with thermal neutrons," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 929, pp. 148–155, 2019.

[7] M. Krick, N. Ensslin, D. Langner, M. Miller, R. Siebelist, J. Stewart, R. Ceo, P. May, and L. Collins Jr, "Active neutron multiplicity analysis and monte carlo calculations," Los Alamos National Lab., NM (United States), Tech. Rep., 1994.

[8] J. T. Goorley, M. R. James, T. E. Booth, F. B. Brown, J. S. Bull, L. J. Cox, J. W. Durkee Jr, J. S. Elson, M. L. Fensin, R. A. Forster III *et al.*, "Initial mcnp6 release overview," *Nuclear Technology*, vol. 180, pp. 298–315, 2012.