1. INTRODUCTION

1.1 Theoretical background

1.1.1 Reactivity and reactor kinetics

Safety and good operation of a reactor requires knowing and controlling the average time behaviour of the neutron population. The neutrons’ time behaviour is predicted using reactor kinetic equations. These equations express the neutron population as a function of neutronic and thermohydraulic parameters characteristic of the reactor. Among these parameters the reactivity $\rho$, which is the ratio of average neutron production to neutron absorption plus leakage, plays a key role.

In a zero power reactor the thermal hydraulic feedbacks are negligible because of the low power. The time dependence of the neutron population is shown to be a sum of exponential terms $N(t) = \sum_j A_j e^{\omega_j t}$ whose $\omega_j$ are solutions of the in-hour equation (1):

$$\rho = \Lambda \omega + \sum_i \frac{\beta_i \omega}{\omega + \lambda_i}$$

The time behaviour of the reactor readily depends on:
- The reactivity $\rho$,
- The generation time $\Lambda$, which is the average time between the birth of a neutron and a fission event it may cause, and
- The delayed neutrons which are usually gathered in 6 groups “i” and characterized by their delayed neutron fractions $\beta_i$ and decay constants $\lambda_i$.

As an example, the reactivity is plotted in Fig. 1 as a function of the inverse period $\omega$ using delayed neutron data and a generation time typical for the CROCUS reactor. The curve exhibits six singularities corresponding to the values $-\lambda_i$, and there is seven inverse periods $\omega_j$ solutions of a reactor having a given reactivity $\rho/\beta$, one associated with the prompt neutrons and six associated with the six delayed neutron groups. For a subcritical reactor all seven values $\omega_j$ are negative. The smaller inverse period (on the left) is the one associated with the prompt neutrons. The term due to the prompt neutrons decay rapidly in a subcritical reactor and the rate of decay depends of the reactivity. The larger inverse period (on the right) is still negative, reach zero for a critical reactor and becomes positive if the reactor is supercritical. This value is associated with the inverse asymptotic period of the reactor and governs the trend in the neutron population in the longer run.
As illustrated above, the determination of $\rho$, $\beta = \sum \beta_i$ and $\Lambda$ is of critical importance. The parameters can be inferred experimentally by inducing a transient in the reactor (e.g., moving an absorber rod) and recording the evolution of the neutron population. Another less intrusive method consists in measuring the microscopic fluctuations of the neutron population in a macroscopically stable reactor. This method is far less intrusive and is the subject of the experiment.

### 1.1.2 Probability distributions, variances of signals

Microscopic fluctuations of the neutron population can be measured by plotting a histogram of the detected neutron signal.

The histogram is typically obtained after discretization of the signal in a multi-channel scaler (MCS), i.e., after its subdivision in consecutive time channels of constant length $T$. Each channel has a value $x$ and the histogram is the plot of the number of channels $n$ having the same values $x$ as a function of $x$ (See Fig. 2). It is a measurement of the probability distribution of the signal or more exactly of its probability density function (pdf), [1].

In some neutron noise techniques we do not need to know the full probability density, but only its average and variance (e.g., Feynman method). These quantities can be determined from the discretized signal

$$X = \{x_1, x_2, \ldots, x_N\}$$

by $E(X) = \frac{1}{N} \sum_{i=1}^{N} x_i$ and $Var(X) = \frac{1}{N} \sum_{i=1}^{N} x_i^2 - \left(\frac{1}{N} \sum_{i=1}^{N} x_i\right)^2$. 

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**Fig. 1.** Plot of the In-hour equation to quantify the decay constants of the neutron population following the insertion of a reactivity $\rho$. 

In the plot, the Inhour equation is represented for different $\rho/\beta$ values, illustrating the transition from prompt super-critical to delayed super-critical and finally to sub-critical reactors. The inverse periods $\omega$ (s$^{-1}$) are depicted on the x-axis, while $\rho/\beta$ is on the y-axis. The curve highlights how the reactor's stability changes with varying reactivity.
Mathematically the relative likelihood of a continuous random variable $X$ is given by its probability density function (pdf) $f_X(x)$. If the variable $X$ can only take discrete values the relative likelihood is given by the probability mass function (pmf) $g_X(x)$. If the expression of the pdf/pmf is known, then the mean and variance can be obtained as:

$$E(X) = \int x f_X(x) \, dx$$
$$E(X) = \sum x g_X(x)$$

and

$$Var(X) = \int x^2 f_X(x) \, dx - (\int x f_X(x) \, dx)^2$$
$$Var(X) = \sum x^2 g_X(x) - (\sum x g_X(x))^2$$

1.1.3 Characterization of the count rate statistical distributions in a multiplying media such as CROCUS

In a multiplying media, such as a reactor, the probability distribution of the detected neutrons is more complex than in a non-multiplying media. In a reactor we have for example to account for fission events (generating 1 to 5 neutrons), capture events (eliminating one neutron) and the neutrons coming from a startup or external source.

As an illustration Fig. 3 shows a neutron chain in blue. The neutron chain has fission (f), captures (c) and detection (d) events. The exact detection time is shown on the uppermost time scale. Using these time the histogram of time differences between the detections can be plotted. For example, with the neutron chain of Fig. 3, the channel $T_b-T_a$, $T_c-T_a$ and $T_c-T_b$ of the histogram would be incremented. It can be intuitively understand than the probability to detect two neutrons from the same neutron chain will not remain constant with the time difference between the detection. And that the time behaviour of the histogram might be characteristics of the reactor, for example of the average time between fission events or between fission and capture in a neutron chain.

This method is the Rossi–α method and is actually used in practice. It has been showed that, indeed, the histogram of time difference is of the form $f(T) = Ae^{\alpha T} + B$ where $\alpha = (\rho-\beta)/\Lambda$ is the prompt decay constant and $T$ is the time difference between two detections [2]. The term $Ae^{\alpha T}$ characterizes detections of two neutrons belonging to the same neutron chain (as in Fig. 3). It varies with $T$ and is for example decaying in time in a subcritical reactor. The second term is constant and characterizes the detection of two neutrons belonging to two different neutron chains.

Fig. 2. Histogram plot of a time dependent signal discretized in a multi-channel scaler.
Another way to characterize the probability distribution of the detected neutrons is to plot its variance-to-mean ratio (as for measurement 1). Using the lower time scale of Fig. 3, we can subdivide the time in equal chunks of length $T$, discretize the signal on it and compute the variance and mean. By repeating the same operation for different dwell time $T$ we can obtain a curve $Y(T)$.

Again from Fig. 3 one could expect that the variance and mean will vary with $T$ and quantify the neutron chain properties in the reactor. This method is Feynman-α method and its theoretical expression for a single detector is [2]:

$$Y_{\text{var}}(T) = \frac{\text{var}(T)}{\text{mean}(T)} - 1 = \frac{\varepsilon}{(\beta-\rho)^2} \left(1 + \frac{1-e^{\alpha T}}{\alpha T}\right) - 2Rd$$

where $T$ is the time length of the channel, $\varepsilon$ is the detector efficiency i.e. the number of counts per fission in the core, $D = \langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$ is the Diven factor, $\beta$ is the delayed neutron fraction, $\rho$ the reactivity, $\alpha = (\rho-\beta)/\Lambda$ the decay constant, $d$ the detector dead-time and $R$ the average detector count rate.

When two detectors are available, we can synchronize them and measure their covariance. This results in a formula featuring the two detector efficiencies $\varepsilon_1$ and $\varepsilon_2$ and the same reactor parameters [2]:

$$Y_{\text{cov}1,2}(T) = \frac{\text{cov}1,2(T)}{\sqrt{\text{mean}_1(T) \cdot \text{mean}_2(T)}} = \varepsilon_1\varepsilon_2 \frac{D}{(\beta-\rho)^2} \left(1 + \frac{1-e^{\alpha T}}{\alpha T}\right)$$

Equations (2) and (3) are valid only if the time length $T$ is small enough for the delayed neutrons to have a negligible influence because we are just characterizing the variance and covariance between prompt neutrons. As can be seen from Fig. 1, this requires the inverse period to be larger (in absolute value) to about $3 \text{s}^{-1}$, i.e. a time constant $T < 0.1 \text{s}$.

![Fig. 3. Example of neutron chains with fission, capture and detection events.](image-url)
2. PURPOSE

The purposes of this experiment are:

- Characterization of the count rate statistical distributions in non-multiplying media:
  Characterize the statistical distribution of the gamma ray emitted by a Co-60 source and detected by a sodium iodine detector facing the source.
- Characterization of the count rate statistical distributions in a multiplying media such as CROCUS: Characterize the statistical distribution of the neutrons in the reactor using its variance and its mean, and infer parameters of the reactor such as the decay constant $\alpha=(\rho_S+\beta)/\Lambda$.

3. SAFETY MEASURES

In order to work under the standard regulations for control of radiation exposure the safety measures during the experiment are:

- Personal dosimeter for each participant of the experiment (teachers, students and reactor operators) provided by the radiation safety group.
- Drinking and eating is not allowed in the control area.
- Use lab coat and gloves for the manipulation of the lead container with the Co-60 source in the CROCUS reactor hall.

4. INSTRUMENTS AND MATERIALS

Characterization of the count rate statistical distributions in non-multiplying media

- A sodium iodine (NaI) detector positioned in front of a $^{60}$Co source.
- The detector is connected to an OSPREY combined pre-amplifier/amplifier unit which sends the signal via USB to the multi-channel analysis (MCA) program GENIE2000 on the PC in the control room [3].
- The pre-amplifier and amplifier shape the detector signal such that the GENIE2000 can order and display the signal. It operates in two modes: pulse height analysis (PHA) and multi-channel scaler (MCS). The PHA mode is designed to record the number of gamma-rays as a function of their energy (summed during the whole measurement time), whereas the MCS mode records the number of gamma rays in a given energy range as a function of time. In the MCS mode, the duration of each time channel is the same and is named the dwell time “dt”. It can be adjusted from some micro seconds to some seconds, depending on the precision desired by the experimentalist. The total number of time channel available can also be adjusted from 128 to 65356 in order to have a recorded time sequence of the desired length.

Characterization of the count rate statistical distributions in multiplying media

- The CROCUS reactor at the critical state with a power of 50 mW.
- The instrumentation is similar to that of the measurement in non-multiplying media.
- Four neutron detectors (BF$_3$) inserted in the CROCUS core in the position shown in Fig. 4 - left (Periphery 1, 2 and CR1 and 2), connected to pre-amplifiers, amplifiers, discriminators (Fig. 4 – right), and fed to four multi-channel scaler (MCS) cards installed at the back of the acquisition PC.
The detectors identification numbers, their locations, the used cables, the amplifier model, the MCS cards and the acquisition channels are summarized in Table 1.

**Table 1. Setup of the detectors and instrumentations**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Core Position</th>
<th>Cables from Reactor (Channel #)</th>
<th>Amplifier</th>
<th>MCS Card</th>
</tr>
</thead>
<tbody>
<tr>
<td>G45006</td>
<td>CR1</td>
<td>Blue (1)</td>
<td>ORTEC 572</td>
<td>MCB-121</td>
</tr>
<tr>
<td>G47349</td>
<td>Periphery 1</td>
<td>Black (2)</td>
<td>ORTEC 572</td>
<td>MCB-122</td>
</tr>
<tr>
<td>G45269</td>
<td>CR2</td>
<td>Yellow (3)</td>
<td>CANBERRA 2022</td>
<td>MCB-123</td>
</tr>
<tr>
<td>G45270</td>
<td>Periphery 2</td>
<td>Blue (4)</td>
<td>CANBERRA 2022</td>
<td>MCB-124</td>
</tr>
</tbody>
</table>

The detector high voltage is provided by two ORTEC 556 units and is to be set to 1100 V. The ORTEC 572 and CANBERRA 2022 amplifier have a coarse gain of 10, a fine gain of 0.8 and a shaping time of 0.5 μs. The coarse gain potentiometer is set to 100 due to an internal gain multiplication factor of 0.1 in the ORTEC572 Amplifier.

5. **EXPERIMENTAL PROCEDURES**

**Characterization of the count rate statistical distributions in non-multiplying media**

1. Log in as "Master Experiment" User (no password) on the Neutron Noise Measurement PC in the CROCUS reactor hall.
2. Launch the program GENIE2000 on the PC – the manual is available on the desktop for more information [3].
3. Open the local detector DET01.08 (File Menu/Open Datasource/Detector, see [3] p. 41).
4. Power the detector high voltage at 400V (MCA Menu/Adjust/HPVPS, see [3] p. 56) and verify that the control LED on the PMT is on.
5. Take the 60Co source #57, which had an activity of 37 MBq on 31.12.1968, and place it at 5–6 cm from the surface of the detector.
6. What is the current activity of the source?
7. Measure the dose rate of the source with an ADC-6 in contact of the source and behind the lead bricks. How does it compare with the annual dose rate limit of 1 mSv/year for person non-exposed to radiation during their work?

8. Selection of the 1.33 MeV gamma rays:
   8.1. Launch the acquisition and stop it after a minute.
   8.2. Observe the acquired spectra (number of counts as a function of the energy/channel). Comment on the spectra features.
   8.3. Note the channel delimiting the highest energy peak of the spectra
   8.4. Open the local detector as in step #1 but chose MCS instead of DET01.08
   8.5. Go to MCA Menu/Adjust/MCS and select Disc. Mode to ROI and input the noted channel numbers for the start and end of the ROI (see [3] pp. 58–59). Confirm each time by pressing OK. We are selecting only the highest energy gamma rays for the recorded signal.

9. Set the dwell time of the measurement to 0.1 s and start the acquisition and stop it after 3–5 minutes.

10. What is the signal behaviour?

11. Plot the histogram of the signal and determine its average and its variance. For this you can use Excel and the video instruction [4], whose link is also on the PC desktop.

12. What probability density function (pdf) can be observed?

13. What are the variance, the mean and their ratio?

14. Repeat the measurement with a dwell time of 0.01 and 0.001 seconds. How those dwell times change the probability distribution and the variance-to-mean ratio?

**Characterization of the count rate statistical distributions in multiplying media**

1. Make CROCUS critical with a power of 50 mW without the startup neutron source (operator).

2. Power ups the instrumentation and set parameters according to the settings given in the previous section (BE CAREFUL never to turn the high voltage of the detector on before turning on the low voltage of the pre-amplifier).

3. Test the detectors by observing the signal after the pre-amplifier and the amplifier using an oscilloscope.

4. Acquisition dry run
   a. On the acquisition PC6010 open the folder Exp09 and launch the acquisition program Slow_Acquisition.vi in the folder Algorithm (see Fig. 5)
   b. Fill out the Card Settings block with the card names and threshold values shown in Fig. 5. It is important to select the card MCB121 as the card #1 (i.e. the master card). Set the dwell-time to 500 μs, the pass length (number of channel in the card) to 60 000 channels and the total number of sweep to 5.
   c. Fill out the TDMS File Settings block with the directory and root filename for the output (see Fig. 5 for an example).
   d. Click the right arrow below the Edit menu to activate the vi and start the acquisition by pressing the START button.
   e. Adjust the number of sweeps (i.e. repetition of the measurement) to have a total acquisition time of 30 minutes.
   f. After the acquisition is finished (LED finished on) open the .tdms files created for each card using the excel importer with aright click.
5. Acquisition  
   a. Repeat step 4 but increasing the number of sweeps to measure during 30 minutes

6. Preparation of fit routines  
   a. During the measurement, prepare the routines to fit the Feynman–α expression of Eq. (2) and (3 as a function of T in order to derive the decay constant value α and its uncertainty.  
   b. Input data is in the form of three columns of number (T, Y(T), sigma(T)).  
   c. Available programs are Excel, Matlab and Mathematica. If you are not familiar with any of these programs we suggest you to use either the "cftool" toolkit from MATLAB, which has a user-friendly GUI interface or Excel Solver add-ins (see Appendix D, [5]).

7. Post-processing of the data  
   a. When the acquisition is finished launch the program Y_Postprocessing.vi in the folder Algorithm (see Fig. 6).  
   b. Fill out the Input Data block to process the four cards.  
   c. Don’t resize the TDMS file, selecting a sweep and channel offset of 0.  
   d. Chose the maximum number of grouped channels (Dwell Time) such that T<0.05 s.  
   e. Activate the vi with the white arrow (below the Edit menu).  
   f. TDMS and ASCII files have been created for the variance and covariances.

8. Share the variance and covariance results \{Yvar_i\}_{i=1:4} and \{Ycov_{1,i}\}_{i=1:4} between the two groups and fit the results with your routines.

9. What are the decay constants and their uncertainties? Are the results consistent with one another? How do they compare with the code predictions given in Appendix F [5]?  

10. Derive the decay constant for all detectors (1+2+3+4) taken together Yvar_tot. Does the result improve?

11. Bonus questions:  
   a. How would the Feynman–α curves change if the reactivity was lower (i.e., in subcritical states)?  
   b. Could you extract more characteristics of the reactor from the Feynman–α curves than just α, assuming that you know the fission rate in the reactor?
Fig. 5. Acquisition program front panel.
6. MAIN PARAMETERS MEASURED

Characterization of the count rate statistical distributions in non-multiplying media
- The PHA mode is used first to select the energy range of interest for the gamma rays and then the MCS mode to record the time distribution of the gamma ray signal. The probability distribution of the signal will be extracted from this time distribution.

Characterization of the count rate statistical distributions in multiplying media
- Theoretically, the measurements for different value of the channel width T is needed to be repeated. In practice, however, the measurement is done only once with a small value of T=dt (e.g., 500 μs). The adjacent channels of the MCS are then regrouped after the measurement to directly yield values for T=2dt, 3dt, 4dt, etc.
7. TYPICAL REAL DATA COLLECTED

Examples of the typical real data collected to obtain the count rate statistical distribution

The count rate from an iodine crystal detector is measured, using different dwell times, i.e., each channel of the analyser corresponds to a fixed period (=dwell time) and the graph displays the count rate (number of counts) for each channel.

The following Figs. 7 and 8 present the count rate histograms for different dwell times of 0.1 s, 0.01 s and 0.005 s. The x axis corresponds to the different values of count rate during one period and the y axis is the number of the realizations.

![Fig. 7. Count rate histogram for a dwell time of 0.1 s.](image1)

![Fig. 8. (a) Count rate histogram for a dwell time of 0.01 s; (b) Count rate histogram for a dwell time of 0.005 s.](image2)

Examples of the statistical count rate distribution in CROCUS

The following figures display $Y_{var}$ (Fig. 9 and 10) and $Y_{covar}$ (Fig. 11) versus time for the different detectors placed in the reactor core.
Fig. 9. Feynman–α method with the variance of the detector 3.

Fig. 10. Feynman–α method with the sum variance from all the detectors.

Fig. 11. Feynman–α method with the covariance between detectors 1 & 2.
The first part of the experiment consists in demonstrating that the radioactive decay follows a Poisson distribution law:

\[ P(N, t) = \frac{(\lambda t)^N}{N!} e^{-\lambda t} \]

The results demonstrate this assumption in a proper way. The histogram of the fluctuation for high dwell time doesn’t show the Poisson characteristic of the emission, as the correlation between two successive events is lost. The Poisson distribution is revealed for dwell times, which are small enough compared to the count rate.

In a multiplying media, events can occur between the birth of a neutron and its detection, such as fission, capture or scattering. In order to determine the characteristic time of these events, the goal is to detect two events resulting from the same neutron chain. This can be performed by measuring the events recorded in given time steps. Intuitively, the probability to detect an event right after another event is detected should be higher, as the neutrons coming from the same chain reach the detector with a time lag related to their proximity in the chain (neutrons from the same disintegration may reach the detector with a very brief time lag). Apparently, for large time steps, this behaviour cannot be revealed, as the number of events detected is high due to the high uncorrelated events constant background. As the time step is reduced in order to get either zero or one event per step, then such a probability can be easily determined.

This is practically done using the Rossi–\( \alpha \) or the Feynman–\( \alpha \) methods, which model the described probability as a function of the time step. The latter is shown in the results section, as it is easily applied in practice: the variance of the signals mean is computed for different dwell time. This is performed for one single detector (Fig. 9) and all the four detectors (Fig. 10). Two observations can be made:

- The spreading of the points is less important for the two detectors, due to the larger amount of measurements reducing the uncertainty.
- The variance of the mean for both measurement is shifted to lower values by a constant parameter which is the expression of the dead time in the following equation:

\[ Y_{var}(T) = \frac{Var(T)}{mean(T)} - 1 = \frac{\epsilon D}{(\beta - \rho)^2} \left( 1 + \frac{1 - e^{\alpha T}}{\alpha T} \right) - 2Rd \]

For an extremely reactive detector without any dead time, the variance at an infinitesimal time step should be zero.

Another way to characterize the distribution is to synchronize the two detectors and measure their covariance on the mean for different time steps, as shown in Fig. 11. As it can be clearly seen on the graph, the constant term of the dead time does not contribute anymore, as the covariance is zero for an infinitesimal time step. The covariance has a constant asymptotic limit for large time step, which shows the constant non-correlated events background.
9. PRE-KNOWLEDGE REQUIRED FROM STUDENTS

The students should be familiar with following contents:

- Nuclear measurements: instrumentation and data acquisition system (gamma and neutron detectors, basic experimental set up).
- Reactor physics: neutron noise measurement theory, reactivity and reactor kinetics.
- Probability distributions, variances of signals
- Radiation protection: dose rates, limits and all aspects regarding radiological protection, necessary to perform the experience under high security standards.

10. RESULTS

The obtained distributions are fitted with the following expression:

\[
Y_{var}(T) = \frac{Var(T)}{mean(T)} - 1 = A \left( 1 + \frac{1 - e^{\alpha T}}{\alpha T} \right) - C
\]

\[
Y_{cov1,2}(T) = \frac{Cov1,2(T)}{\sqrt{mean_1(T) mean_2(T)}} = B \left( 1 + \frac{1 - e^{\alpha T}}{\alpha T} \right)
\]

The above two equations are valid only if the time length T is small enough to neglect the influence from delayed neutrons due to characterisation of the variance and covariance between prompt neutrons. Thus, all the fittings of measured data (Figs. 12–19) are exclusively applied to the time ranges of interest from 0.0005 s to 0.05 s, which give lower uncertainties. The following Table 2 lists all the derived values of the decay constant by fitting curves and their uncertainties obtained from the curve-fitting tool in MATLAB.

<table>
<thead>
<tr>
<th>Detector:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>1,2</th>
<th>1,3</th>
<th>1,4</th>
<th>1,2,3,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha) [s(^{-1})]</td>
<td>-158</td>
<td>-142</td>
<td>-160</td>
<td>-126</td>
<td>-143</td>
<td>-150</td>
<td>-153</td>
<td>-130</td>
</tr>
<tr>
<td>(\sigma_{\alpha}) [s(^{-1})]</td>
<td>15</td>
<td>24</td>
<td>20</td>
<td>16</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Decay constants derived from the fitting of measured data (Figs. 12–19) are consistent with each other. The results are within 1 or 2 standard deviations compared to the predicted value of \((-154.4\pm1.6)\) s\(^{-1}\) [6], which eliminate a significant systematic error of the method.

The position of the inserted detectors, detector 1 and detector 3 are almost placed symmetrically, which can account for the better consistency between detector 1 and detector 3, likewise to the detector 2 and detector 4. The decay constants derived from the covariance are more precise with lower uncertainties than using the variance for a single detector. However, the decay constant derived by taking all detectors together does not yield to a value with a better precision. Nevertheless, the uncertainty was lowered by this consideration.

Although, the predicted value of \((-154.4\pm1.6)\) s\(^{-1}\) [6] is not within a few standard deviations of the obtained result, it can be assumed that this is due to the fact that results from single detectors were add up and treated effectively as one detector. Moreover, it is possible that the systematic error occurs in the simulation, as it can be seen that the symmetry between the detectors plays only a minor role and the noise measurements are indeed independent of symmetrical considerations.
In order to characterize the reactor with the decay constant and other parameters like $A$, $B$ and $C$ derived from the fitting equations, the reactor fission rate $R$ has to be known. Then, the following relations can be used:

$$A = \frac{\varepsilon D}{(\beta - \rho)^2}; \quad B = \frac{\sqrt{\varepsilon_1 \varepsilon_2 D}}{(\beta - \rho)^2}; \quad C = 2Rd \rightarrow (\beta - q)^2 = \frac{\varepsilon D}{A} = (\alpha \Lambda)^2,$$

where $\varepsilon$ is the detector efficiency, the Diven factor $D$ is known to be around 0.8 and $d$ is the detector dead time. Thus, we can easily determine the detector efficiency by the ratio of the measurement to the real neutron flux derived from the fission rate. Moreover, using the value of $A$ and decay constant $\alpha$, we can calculate the neutron generation time $\Lambda$. For a critical reactor the reactivity is zero, and then the delayed neutron fraction can also be calculated. Therefore, the reactor characteristics can be determined by measuring the neutron noise.

![Fig. 12. Feynman–α method with the variance of the detector 1.](image)

![Fig. 13. Feynman–α method with the variance of the detector 2.](image)

![Fig. 14. Feynman–α method with the variance of the detector 3.](image)
Fig. 15. Feynman–α method with the variance of the detector 4.

Fig. 16. Feynman–α method with the covariance between detectors 1 & 2.

Fig. 17. Feynman–α method with the covariance between detectors 1 & 3.

Fig. 18. Feynman–α method with the covariance between detectors 1 & 4.
11. CONCLUSIONS

The results obtained with the $^{60}$Co source in a non-multiplying media are in accordance with the theory, as the emission distribution is found to follow a Poisson law. This result is analytically proven.

In a multiplying media, the total of eight sets of decay constants of the CROCUS reactor were derived. The decay constant value of ($-153.0\pm8.0$) s$^{-1}$ was calculated from the covariance of the detector 1 and detector 4. This value is the closest to the predicted value of ($-154.4\pm1.6$) s$^{-1}$ [6]. The results obtained by summing up the measurements from all four BF$_3$ detectors - assuming that only one detector is present - were not in a better agreement with the simulated value. However, the uncertainty was lowered by this consideration.

This experiment proved that it is possible to characterize a reactor without any safety risks from intrusive means, i.e. moving control rods, but only by observing flux fluctuations and deriving their statistical properties. It is evident that the reactor tends to leave characteristic information about its properties in the neutron noise.

12. REFERENCES