NEUTRON NOISE MEASUREMENT IN THE CROCUS REACTOR

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ABSTRACT

This paper reports on the measurements of kinetics parameters at the teaching reactor CROCUS. The prompt decay constant, $|\alpha| = (\beta-\rho)/\Lambda$, was measured in several sub-critical configurations using the Feynman-α reactor noise technique and the reduced generation time Λ/β was deduced. The CROCUS facility is a zero-power reactor operated at EPFL. It is mainly used for educational purposes. Among all neutron noise measurement techniques, the focus was put on the Feynman-α technique. The intrinsic neutron population fluctuations were recorded in macroscopically stable sub-critical states and the prompt decay constants α were derived by fitting the Feynman-α experimental distributions with the point kinetic theoretical expression. The prompt decay constant at critical state $\alpha_0=\beta/\Lambda$ was deduced in two ways: by extrapolation of the sub-critical prompt decay constant to the critical state, and by direct measurement of the sub-critical reactivity using rod-drop techniques. The neutron population was measured by two BF_3 detectors located in the reactor. Data acquisition was performed simultaneously with two ORTEC multichannel scaler cards (MCS-pci) controlled by specially developed LabView programs. The post-processing of the data was done in LabView and Matlab. The prompt decay constant (β/Λ) at criticality was found to be $146.6 \pm 6.3\ s^{-1}$. Monte Carlo predictions calculated with MCNP5-1.6 are in a good agreement being within 2σ of the experimental results.

1. Introduction

Neutron noise measurement methods allow for the extraction of safety and kinetic parameters of the reactor, such as reactivity, the prompt neutron decay constant (α), the delayed neutron fraction (β) or the mean neutron generation time (Λ). The main goal of this experiment was to determine the prompt neutron decay constant at criticality, $\alpha_0=\beta/\Lambda$, of the CROCUS reactor using the Feynman-α method.

Several recent studies have presented neutron noise experiments in zero-power reactors using the Feynman-α technique [1-6]. Multichannel scalers are generally used for the neutron noise acquisition. Modern multichannel scalers have negligible dead time between consecutive channels allowing the bunching of the channels counts –the bunching technique – and speeding up the measurements [7, 8]. We decided to use this technique for the Feynman-α analysis. The measured prompt decay constant (β-ρ)/Λ and its critical value $\alpha_0 = \beta/\Lambda$ are reported and compared to MCNP5-1.6 predictions.

2. Neutron noise measurement theory and the Feynman-α technique

In neutron-noise measurement experiments, a detector is placed in a nuclear reactor and neutron counts are recorded. Because of the nature of the chain reaction, the individual counts are dependent on each other and the statistical properties of the count sequence depend on the kinetic characteristics of the specific or particular reactor. A reactor signal can be macroscopically considered as being a Poissonian signal in which the mean equals the variance. At a small time scale, for time $T \leq 10/\alpha$, this does not hold anymore and the ratio of the signal variance to the mean differ from unity. In a zero-power reactor, it can be assumed that sources of noise due to temperature, mechanical and hydraulic effects are absent and that the noise source arises entirely from nuclear origins. Therefore, in a zero-power reactor the noise sources are the fluctuations in the number of neutrons per fission, in the time between nuclear events, known as the mean lifetime for absorption, fission and scattering, and finally in the probability that an event is either a fission, an absorption or a scattering reaction. The Feynman-α measurement technique is dedicated to the measurement and interpretation of the random process affecting the steady-state of a reactor. This technique, denoted by *Y*, calculates the ratio of the signal variance to the mean as a function of *T*:

$$Y(T) = \frac{\left(\overline{Z(T)^2} - \overline{Z(T)}^2\right)}{\overline{Z(T)}} - 1 \qquad ,$$

(1)

where *Z* is the neutron count and *T* the gate width. During the acquisition, the signal is recorded in consecutive channels having a small dwell time *dt*. During the post processing, consecutive channels are bunched together to form series of samples having durations *T* that are multiples of *dt*. The time sizes, *T*, of interest are comprised between 0.1/α and 10/α and *Y(T)* is calculated for these values. The point kinetic expression of the variance-to-mean ratio as a function of *T* had been derived as:

$$Y(T) = \frac{\varepsilon_f \cdot D}{(\beta - \rho)^2} \cdot \left\{ 1 - \frac{(1 - e^{-\alpha T})}{\alpha \cdot T} \right\} \qquad ,$$

(2)

where *D* is the Diven factor and ε_f the fission detection efficiency of the detector.

Two MCS-pci cards were used in order to perform the noise measurement experiment whose channel start and advance were synchronized. This authorizes us to compute the variance-to-mean ratio of the two cards (Eq. 1) on the sum of the raw signal of the two detectors – as if it was a larger detector with double efficiency, which is a valid assumption in the point kinetics model. The synchronization also allows us to compute the covariance-to-mean ratio of the two cards as:

$$Y_{\mathrm{cov}}(T) = \frac{\langle Count(T)_1 \cdot Count(T)_2 \rangle - \langle Count(T)_1 \rangle \cdot \langle Count(T)_2 \rangle}{\langle Count(T)i \rangle}$$

(3)

In conclusion it is possible to measure *Y (T)* using the variance-to-mean ratio with one and two cards and using the covariance-to-mean ratio with two cards. Ultimately the α parameter is derived using a least-squared fitting of the measured *Y(T)* curves. An illustration of such *Y(T)* curve can be seen in Figure 1 where the theoretical expression for the Feynman-α has been used with parameters corresponding to our experimental situation.

When the α-parameter is known for different subcritical states it is possible to derive α_0 by mean of knowing the reactivity level in dollars of each subcritical state (Eq. 4) or by extrapolation at criticality using the linear behavior of the reactivity for slightly sub-critical states (Eq. 5).

$$\alpha_0 = \alpha \cdot (1 - |\rho_\$|)$$

(4)

$$|\alpha| = \frac{\beta}{\Lambda} \cdot (1 - \rho_\$) = \frac{\beta}{\Lambda} \cdot (1 - K \cdot \frac{1}{C})$$

(5)

K is a proportionality constant and C stands for the neutron count rate.

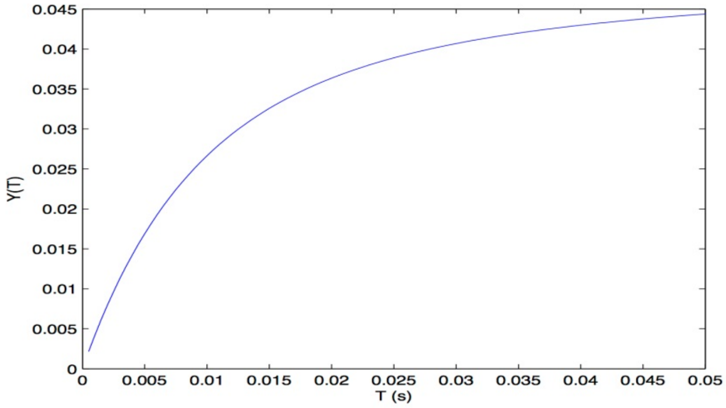

Figure 1: Theoretical Feynman-alpha distribution

3. CROCUS reactor

CROCUS is an experimental nuclear reactor. It is a zero-power reactor and the maximum permitted power is limited to 100 W. It is intended for education in reactor physics. The core has the approximate shape of a cylinder 60 cm in diameter and 1 m in height. It consists of 336 rods of uranium oxide enriched to 1.8%, surrounded by 176 rods of metallic uranium enriched to 0.95%. The uranium is in the form of cylindrical pellets cladded in aluminum. The core reactivity is controlled by a variation of the water level with an accuracy of ±0.1 mm (equivalent to ±0.4 pcm).

4. Experimental set-up and measurement procedure

The prompt decay constant α was measured in different sub-critical states, i.e. for different water levels, during several one-day measurements. Each experiment corresponded to a particular subcritical level, lasting about six to seven hours, and using two independent acquisition lines. Each acquisition line included a BF_3 detector, a preamplifier, and an amplifier whose output was connected to an MCS-pci card. The two MCS-pci cards were embedded in the same computer and controlled by Labview routines during the acquisition. The two cards signals were synchronized using a master-slave architecture. The available detector positions in the CROCUS reactor can be seen from Figure 2, namely the Control Rod (CR) positions and the peripheral positions. The two peripheral positions were chosen for the reported experiments.

The exact same procedure was used for each experimental day. First, the reactor was brought to criticality to measure and control the critical water level and then the water was lowered to the desired level. Indeed, one of the methods used to derive α_0 requires measuring the reactivity in dollars. This was done by using the standard resolution of an inversion of the kinetics equation implemented in a Matlab routine. This method required that the signal from a critical state to a stable, subcritical state, which corresponds to the water level drop, to be recorded. This was done using one of the fission chamber embedded in the CROCUS reactor protection system (RPS). Once the signal recorded the introduction of the start-up source for the purpose of the neutron counts statistic, the true collection of neutron counts data began.

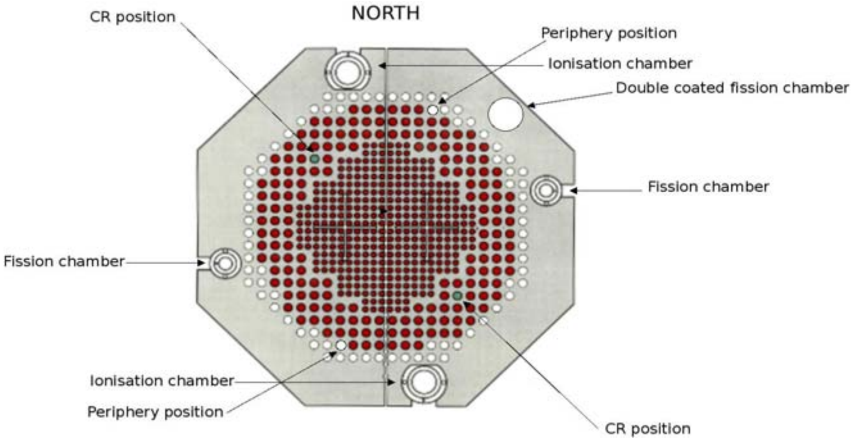

Figure 2: CROCUS reactor upper view and detector position

5. Results and analysis

The Feynman-α formula presented in Eq. 2 assumed mono-energetic prompt neutrons coming from a point reactor and also perfect detectors and acquisition systems. In practice several modifications were introduced to account for delayed neutrons [8, 9], detector dead time and the finite number of channels of the MCS-pci cards [9].

The correction for delayed neutrons introduces additional exponential terms to Eq. 2 (one in the simplest case) with smaller decay constants. Fitting the model with and without additional exponential terms for different time intervals showed that the delayed neutron term was negligible for T values smaller than $10/\alpha$. In practice we chose to fit the $Y(T)$ expression for T comprises between $0.1/\alpha$ and $10/\alpha$ and did not consider delayed neutrons. The corrections for detector dead time and the finite number of channels of the MCS card are more easily implemented and were considered for both variance and covariance-to-mean formulas.

Decay constants obtained with the variance and covariance-to-mean formulas are shown in Table 1 for the four subcritical states. Variance-to-mean results obtained with the different detectors were found to be in good agreement (1σ) for each subcritical state. But covariance-to-mean results were found to be significantly lower.

Table 1: Prompt decay constants (s-1)

Water level (mm)	Variance Det. 1	Variance Det. 2	Variance Both Det.	Covariance Both Det.
920	210.2 ± 5.0	211.6 ± 7.5	208.4 ± 3.6	202.0 ± 2.7
930	187.6 ± 3.1	186.4 ± 2.9	186.8 ± 1.7	172.5 ± 1.1
938.6	169.8 ± 3.3	165.1 ± 3.4	167.1 ± 1.2	160.4 ± 1.5
945	165.7 ± 3.2	162.5 ± 3.1	164.4 ± 1.0	160.0 ± 1.0

The critical prompt decay constant $\alpha_0=\beta/\Lambda$ can be derived from the values in Table 1 by extrapolation or in knowing the reactivity of the subcritical level (see Section 2). The extrapolation technique is not adapted to the selected subcritical states and will require several additional measurements close to critical to yield results with adequate uncertainties. On the other hand, the α_0 results deduced from each subcritical level by knowing its reactivity were found to be in good agreement (2σ) with an exception for the covariance-to-mean ratio results which are significantly lower (see Figure 3). For this reason we did not used the covariance-to-mean ratio results to derive the final α_0 value. This final value was derived by doing a weighted mean on the α_0 values and its uncertainty accounts for the fitting uncertainties and the observed scattering between the different day results. The final value for α_0 is $146.6 \pm 6.3\ s^{-1}$. It is in agreement within 2σ of the MCNP predictions of $155.0 \pm 1.6\ s^{-1}$ [10].

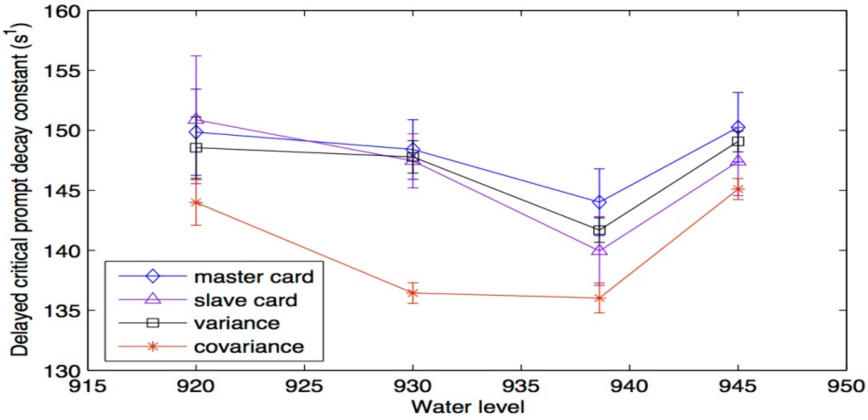

Figure 3: Dependence of the delayed critical prompt decay constant on the subcriticality corresponding to different water levels.

6. Conclusion

The prompt decay constant, $|\alpha| = (\beta-\rho)/\Lambda$, was measured in several sub-critical configurations ($50<\rho<150$ pcm) using the Feynman-α variance-to-mean and covariance-to-mean ratios values. The prompt decay constant at critical $\alpha_0 = \beta/\Lambda$ was then deduced either by measuring the reactivity of the sub-critical state or by extrapolating the α-values to infinite power. The experimental values were compared to Monte Carlo predictions. A coherent set of fits demonstrated the robustness of the chosen method when relevant corrections were applied in accordance with the delayed neutron theory and the properties of our acquisition system and algorithms. Almost all estimates of α_0 are comprised between 140 and 151 s^{-1} with 1σ uncertainties from 1 to 4 s^{-1}. The final value for α_0 is $146.6 \pm 6.3\ s^{-1}$. It is in agreement within 2σ with the MCNP predictions of $155.0 \pm 1.6\ s^{-1}$.

7. References

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