

Measurement of delayed neutrons in a thermal nuclear reactor by means of a long run pile noise experiment in sub-critical state

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Abstract. The transfer function of a zero-power thermal reactor was successfully measured thanks to neutron noise techniques from 1 mHz to 160 Hz. During a month-long experimental campaign, the fluctuations of the neutron population in critical and subcritical configurations of the core were acquired using excor fission chambers and analysed through Cross-Power Spectral Density (CPSD) methodology. Firstly, the reactor's kinetic parameters, i.e. prompt decay constant, effective delayed neutron fraction and generation time, were obtained at critical state. It required calibrating the reactor's power, which was done by metal foil activation and measurement of the ²³⁵U fission rate. Secondly, these parameters were used to estimate the groups' abundances of delayed neutrons from the CPSD measured in a sub-critical state. Fitting data with a point kinetic model was done with Bayesian inference - CONRAD and Stan programs were used. A very good agreement was found between experimental abundances and the ones computed with TRIPOLI-4 Monte-Carlo transport code and JEFF3.1.1 nuclear data library. Uncertainties on prior abundances between 6 % to 101 %, held mainly by nuclear data, were lowered down to 4 % to 54 %, depending on the delayed group.

1 Introduction

The propagation of delayed nuclear data uncertainties to the effective delayed neutron fraction β and the delayed neutron average decay constant τ through neutron transport calculations raises relatively large confidence intervals. Unfortunately, these two quantities have a deep impact on reactivity measurements that rely on the inverse point kinetic equations (e.g. rod drop). The goal of this work is to provide an integral measurement of both β and τ .

The effective delayed neutron fraction can be measured using various noise related methodologies [1][2] but just a few measurements focused on the breakdown of β into delayed neutron groups since it requires much longer time [3] and a very stable reactor power. However, the abundances of the delayed neutrons groups, which allow determining the delayed neutron average decay constant τ are at least as important as the total fraction itself since reactivity measurements are almost proportional to the product $\beta\tau$ [4].

In the present paper, the transfer function of a zero-power thermal reactor was successfully measured from 1 mHz to 160 Hz in a two-steps measurement thanks to neutron noise techniques [1]. In the first step of the experiment, the high frequency portion of the measured Cross-Power Spectral density (CPSD) was used, see Eq. (1) and Eq. (2), to obtain β .

$$CPSD(\omega) = C_1 C_2 \times \frac{1}{F_0} \times \frac{2D}{\Lambda^2} \times |G(\omega)|^2 \quad (1)$$

With,

C_i : Average count rate of detector i

D : Diven factor

F_0 : Integral fission rate

G : Reactor transfer function

Λ : Neutron generation time

ω : angular frequency, $2\pi f$

In the case of thermal reactor and with $f > 1$ Hz, reactor transfer function can be simplified as,

$$|G(\omega)|^2 \approx \frac{1}{\left(\frac{\beta_{eff}}{\Lambda}\right)^2} \frac{1}{(1 - \rho_s)^2 + \left(\frac{\omega}{\alpha_p}\right)^2} \quad (2)$$

With,

α_p : Prompt decay constant

β_{eff} : Effective delayed neutron fraction

ρ_s : Relative subcritical level

In the second step of the experiment, the low frequency portion was used to fit the effective 8-group abundancies a_i of JEFF3.1.1, see Eq. (3). Abundancies are related to τ with, $\tau = \sum_i \frac{a_i}{\lambda_i}$. Reactor zero-power transfer function covering from 1 mHz to 160 Hz is

$$|G(\omega)|^2 = \frac{1}{\left(\frac{\beta_{eff}}{\Lambda}\right)^2} \frac{1}{\left(\sum_{i=1}^8 \frac{\omega^2 a_i}{\omega^2 + \lambda_i^2} - \rho_s\right)^2 + \left(\frac{\omega}{\beta_{eff}} + \sum_{i=1}^8 \frac{\lambda_i a_i \omega}{\omega^2 + \lambda_i^2}\right)^2} \quad (3)$$

With,

a_i , abundance of delayed group i

λ_i : Decay constant of delayed group i

Prior-values and uncertainties used in the calibration are respectively taken from TRIPOLI-4 with JEFF3.1.1 computation, and recent works at CEA [5][6], respectively. Prior nuclear uncertainties are reported in Table 4.

2 Experimental setup

2.1 Reactor and instrumentation

The experiment was conducted in a pool-type research nuclear reactor loaded with UOx fuel elements located at CEA Cadarache. The core had a cubic shape and a volume below 1 m³. Four CFUL-01 fission chambers detectors (Photonis) [8] located on the four faces of the core were used for the neutron noise measurement. These detectors have an efficiency around 1 count / (n/cm2/s). A calibrated CEA-made miniature fission chamber (labelled CFUR) with 3 mm in diameter and integrated mineral cable [9] was used to monitor the power throughout the experimental campaign. All fission chambers were set around core mid-plane in experimental dry channels. A rough sketch-up of the experimental setup is displayed on Figure 1.

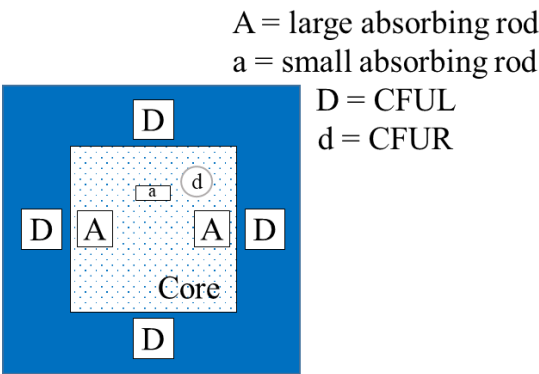


Figure 1: Sketch up of the pile noise experimental setup.

SPECTRON is a CEA-developed acquisition system dedicated to measuring the low frequency fluctuations in the current issued by fission chambers. The frequency bandwidth (0-36 kHz) and signal to noise ratio (SNR) were adapted to meet the pile noise requirements [9]. SPECTRON is well suited for critical measurement above 1 W. For low power measurements in critical or sub-critical experiments, the X-MODE acquisition is used [10]. It works with pulse train signal shaped by amplifier-discriminator modules (standardly Canberra ADS7820 NIM cards).

2.2 Power calibration

From equation (1), one can see that the core integral fission rate F_0 (averaged over the measurement) is required in order to obtain β . In practical, the reactor power is monitored during the experiment with a neutron detector to obtain an average power level. Then a

calculated factor is used to convert that value into an estimation of F_0 . The Diven factor has been calculated using a spatial expression first given by Bennett [11] and implemented in TRIPOLI-4 [12],

$$D = D_v \times D_s = 0.800 \times 1.1 = 0.880$$

The calibration of the reactor was done using a gold foil with 6.5 mm in diameter and a thickness of 50 μm. The foil was stuck on the CFUR. After irradiating the foil, the activity was standardly obtained by gamma spectrometry. The activity was converted into a reaction rate and then into a fission rate by means of a calculated factor given by a TRIPOLI-4 simulation of the experimental setup [12]. The CFUR with the gold foil are shown in Figure 2.



Figure 2: In-core fission chamber and gold foil dosimeter for power calibration.

2.3 Delayed critical experiments

The kinetic parameters, α , β and Λ , were obtained in critical configuration with both SPECTRON and X-MODE acquisition systems. The large absorbing rods were raised until delayed criticality and locked until power drift correction was needed. Two measurements per acquisition system were done in order to ensure repeatability. The characteristics of the measurements are reported in Table 1.

Table 1: Critical measurements characteristics.

Acq. system	Day	Power (W)	Duration
X-MODE	1	0.1226 (4)	4h
SPECTRON	1	0.838 (1)	2h
X-MODE	2	0.1278 (3)	4h
SPECTRON	2	0.871 (1)	2h

2.4 Subcritical experiments

The group of long-lived delayed neutron precursors is associated to a time constant of 51 to 55 s, depending on the nuclear data library. To observe the impact of this group of precursors, is it necessary to record signals on a large time scale (typically 500 s) and to reproduce the

measurement a large number of time to build statistics, with no interference of any kind in the reactor setup. This is the reason why it was chosen to perform the experiment in a slightly subcritical configuration, and to follow a strict procedure to monitor the day-to-day reactivity of the reactor.

The delayed neutron abundances, a_i , were measured from noise signal acquired with X-MODE. The following procedure was applied for each measurement run:

- The first large absorbing rod was raised and locked around core mid plane.
- The small absorbing rod was set in its highest position.
- The second large absorbing rod was raised and locked in its highest position.
- The small absorbing rod was drop to reach a slight sub-criticality.

This last rod-drop allowed to derive sub-criticality level and verify that every measurement was done at the same level of sub-criticality. The measurement characteristics are reported in Table 2.

Table 2: Delayed neutron abundances measurement reactivity and average daily temperature.

Day	ρ (\$)	T (°C)	Day	ρ (\$)	T (°C)
1	-0.170	19.66	7	-0.167	19.95
2	-0.169	19.87	8	-0.168	20.14
3	-0.173	20.06	9	-0.167	20.11
4	-0.168	20.05	10	-0.170	20.02
5	-0.170	19.94	11	-0.171	20.05
6	-0.171	20.03	12	-0.172	19.92
		σ_{rel}			0.98 % 0.77 %

2.5 Computational tool

The experiment was simulated with the version 11 of TRIPOLI-4® [12] transport code together with JEFF3.1.1 nuclear data library [7]. The IRDF-2002 nuclear data library dedicated for dosimetry application was used for the gold foil reaction rate computation [13]. For that latter case, the fission chamber and the gold foil were exactly simulated as can be seen on Figure 3. Geometry sensitivity study yielded a total relative uncertainty on dosimeter reaction rate of 1.4 % (1σ), accounting also for Monte-Carlo convergence.

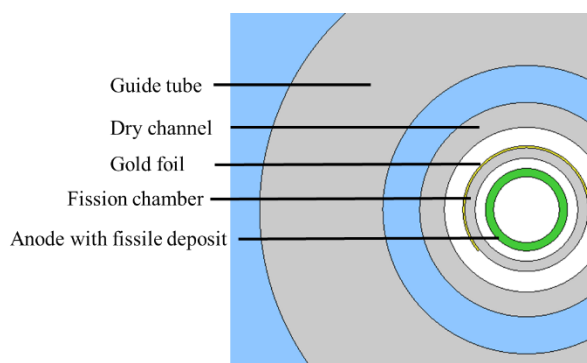


Figure 3: Gold foil activation simulation geometry.

Kinetic parameters α_p and β_{eff} were derived from the prompt domain of CPSD obtained at critical state. The frequency ranged from 1 Hz to 160 Hz. The curves obtained with X-MODE and SPECTRON were fitted with a least-square method. Results from the four experiments reported in Table 1 were then averaged.

The delayed neutrons abundances were fitted with Bayesian inference and Markov chain Monte Carlo programs, namely CONRAD [14] and Stan [15], respectively. CPSD ranged from 1 mHz to 1 Hz. Priors were centred on TRIPOLI-4 computed values and their distribution was Gaussian. Their standard deviation, σ , was taken from recent work on nuclear data [5-6]. Note that prior knowledge information is helpful to converge to a physical solution and that λ_i are fixed in JEFF3.1.1.

3 Results and discussion

Both low and high frequencies CPSD are plotted in Figure 4 and show an acceptable agreement with the prior reactor transfer function.

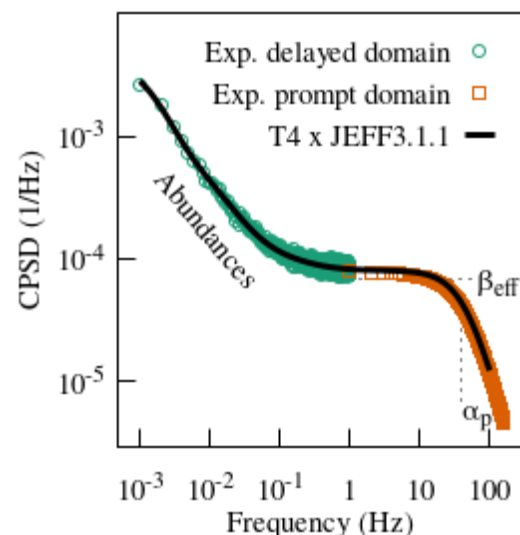


Figure 4: Full CPSD in sub-critical state measured with X-MODE.

Numerical parameters obtained by fitting critical experiment data using equation (2) are reported in Table 3. A slight overestimation of α_p as calculated by TRIPOLI-4 with JEFF3.1.1 is observed. The delayed neutron fraction β_{eff} is well consistent with the calculated one.

Table 3 : Relative differences (C/E-1) between fitted kinetic parameters and simulations. C is obtained with TRIPOLI4 and JEFF3.1.1.

Parameters	C/E-1 (%)
α_p	2.5 ± 0.1 %
β_{eff}	1.7 ± 1.7 %

Abundances obtained by fitting sub-critical experiment data using equation (3) are reported in Table 4. One can observe a good agreement between experiment and JEFF3.1.1 computation. Also, uncertainties are

remarkably reduced on longest lived groups. The older JEF2.2 library produces large discrepancies, especially on groups 2, 3 and 5 where a bias and compensations are evidenced.

Table 4 : Priors nuclear uncertainties and relative differences (C/E-1) between fitted abundances and simulations.

Group	JEFF3.1.1		JEF2.2	
	Prior nuclear uncertainty (%) [5-6]	C/E-1 (%)	Prior nuclear uncertainty (%)	C/E-1 (%)
1	5.6 %	0.3 ± 5.6	10 %	-4.6 ± 3.5
2	5.6 %	-0.2 ± 4.5	10 %	-16.8 ± 2.0
3	13 %	-3.2 ± 8.9	14 %	-17.1 ± 4.2
4	9.2 %	-2.7 ± 6.6	21 %	3.5 ± 4.3
5	12 %	0.9 ± 6.7	40 %	54.8 ± 20.8
6	54 %	1.1 ± 25.2	112 %	3.5 ± 9.9
7	77 %	4 ± 30.9		
8	130 %	4.6 ± 56.1		
τ		-0.8 ± 1.3		-11.4 ± 1.0

4 Conclusion

This experiment demonstrates that it is possible to conduct long run pile noise experiment in sub-critical state to extract the delayed neutron average decay constant.

Coupled with a more traditional delayed neutron fraction measurement of β_{eff} , this technic allows a better integral validation of the kinetic parameters calculated with JEFF3.1.1 and TRIPOLI-4.

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