Investigation of organic scintillators for neutron-gamma noise measurements in a zero power reactor

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***Abstract*—Noise measurements in light water reactor systems aid in generating validation data for integral point kinetic parameter predictions and monitoring parameters for reactor safety and safeguards. The CROCUS zero-power reactor has been used to produce both data types to date, using thermal neutron detectors to observe neutron noise and inorganic scintillators to observe gamma noise. Also, the cross-correlation of gamma and neutron noise has been investigated at CROCUS with separate gamma and neutron detectors. Organic scintillators can be used to cross-correlate gamma and neutron noise with only one detector type, within a single detector volume, and provide nanosecond timing resolution for time-correlated measurements. Dual-particle measurements require particle-type discrimination and are hence possible with organic scintillators since such detectors have the property of presenting statistically different pulse shapes for gamma rays and fast neutrons. The fine timing precision increases the signal-to-noise ratio relative to moderated thermal neutron detectors for correlated measurements and the dual-particle sensitivity allows for multiple modalities of estimating the prompt neutron decay constant. In this work, we present data obtained with 5.08 cm-length by 5.08 cm-diameter trans-stilbene cylindrical detectors set in the water reflector of CROCUS. Preliminary results estimate the prompt neutron decay constant to be (155 ± 5) s^{-1} at delayed critical.**

***Keywords*—power spectral density, organic scintillators, pulse-shape discrimination**

I. INTRODUCTION

NOISE measurements offer a powerful non-invasive technique to observe a given fissile system's kinetic parameters. The kinetic parameters hereby refer to the coefficients of the differential equations describing the temporal behavior of a neutron population in a neutron multiplying medium. These equations are often derived using the so-called point kinetics assumptions, leading to a set of equations that can be solved cost-efficiently and, if the system indeed allows for the used assumptions, offer a precise predictor for time-dependent phenomena of neutron populations [1]. Noise measurements typically refer to a method to estimate the prompt decay constant, $\alpha = (\beta_{\text{eff}} - \rho)/\Lambda$ [2], [3] - where β_{eff} is the effective delayed neutron fraction, and Λ is the mean neutron generation time - via the analysis of a time series signal from a detector set close to a fissile system. More advanced noise measurements can also include the determination of β_{eff} and Λ [4], [5]. These measurements can then be used for code validation [6], integral parameter databases [7], and potentially for nuclear data assimilation [8].

In previous work, estimates of the prompt neutron decay constant from neutron noise measurements of the CROCUS zero power reactor at critical were completed with thermal neutron detectors and inorganic scintillators [4], [9]–[11]. Power spectral density analysis (also known as Cohn-α [2]) was used to estimate α using the gamma-ray sensitive inorganic scintillators ($CeBr_3$) and neutron sensitive thermal neutron detectors (^{235}U fission chambers and ^{3}He). Additionally, the two detector types were cross-correlated to obtain (γ,n) correlations [12]. The estimates compared well to simulated values using iterative fission probability (IFP) predictions in Serpent 2 [13], where the highest accuracy per unit measurement time was found with (γ,γ) correlations [14].

This work uses organic scintillator measurements of the CROCUS zero-power reactor to leverage dual-particle sensitivity in a single detector volume for combined (γ,n) noise analysis. We set a single cylindrical 5.08-cm-diameter by 5.08-cm-length trans-stilbene detector [15], [16] in the water reflector of CROCUS, and analyzed time stamp data with the power spectral density technique to estimate α.

II. METHODS

A. The CROCUS research reactor

The CROCUS zero-power research reactor is a two-region, water-moderated uranium core operated by the Laboratory for Reactor Physics and Systems Behaviour (LRS) at the Swiss Federal Institute of Technology Lausanne (EPFL). It is housed in a concrete shielding of about 1.3m thickness, see Figure 1. It is a zero-power reactor, with a maximum power of up to 100 W. The reactor core is an approximately cylindrical configuration with a diameter of about 58 cm and a height of 100 cm, consisting of two fuel zones (see Figure 2). The central zone is loaded with 336 UO_2 fuel rods (1.806 wt.%-enriched), set in a square lattice with a pitch of 1.837 cm. The peripheral zone is loaded with up to 176 thicker, U_{met} fuel rods (0.947 wt.%-enriched) with a pitch of 2.917 cm, also in a square lattice. The core is brought to criticality by introducing water from below via pumps, with an excess reactivity at

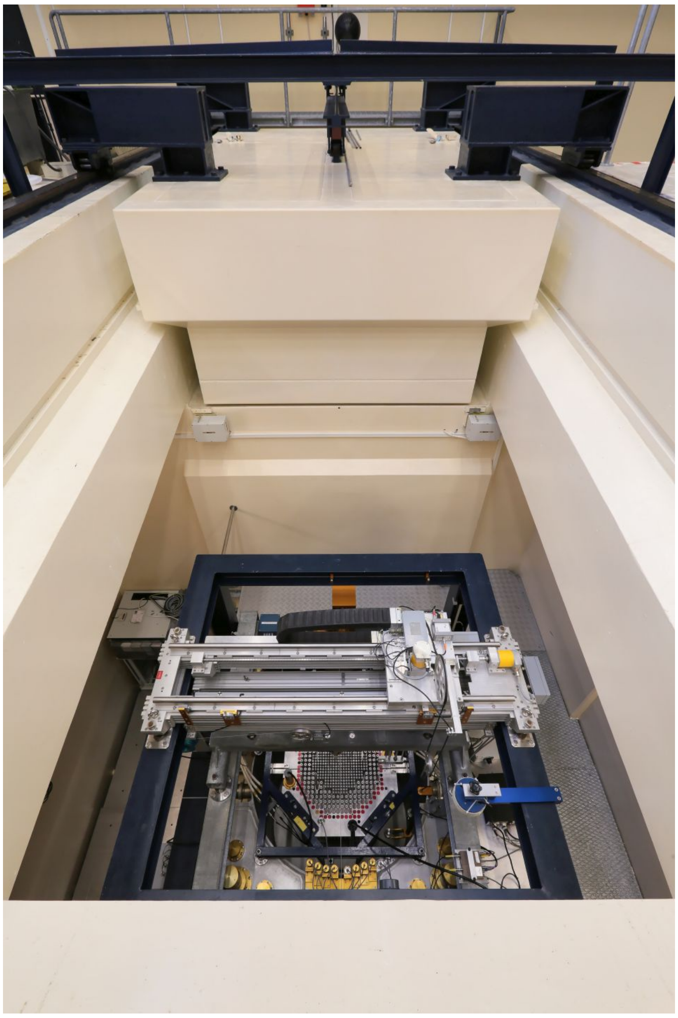

Fig. 1. Top-down view of the CROCUS reactor from above the concrete containment. The top wall may be opened when the reactor is shut down.

the maximum water level being 200 pcm. The water level is controlled by a spillway that allows for 0.1 mm accuracy on the control of the water level (equivalent to about 0.4 pcm). The core is located in an aluminum water tank, its diameter is 130 cm and its thickness is 1.2 cm [9].

B. *Organic scintillators*

Organic scintillators are a dual-particle sensitive detector. The hydrocarbon volume is sensitive to gamma rays mainly via Compton scattering and neutrons mainly via proton elastic scattering. The Compton scattering interaction provides the information for light-output calibration via a measured, monoenergetic source. The neutron light output relative to gamma-ray light output is quenched, non-linear, and delayed. For this reason, the detectors are only sensitive to fast neutrons (as low as 700 keV) with a detection threshold of about 50 keV electron equivalent (keVee).

The incident neutron and gamma ray radiation may be discriminated on-the-fly with a charge integration based pulse-shape discrimination. By quantifying the delayed light-output of neutrons in comparison to gamma-rays, we can discriminate the two types of radiation [16].

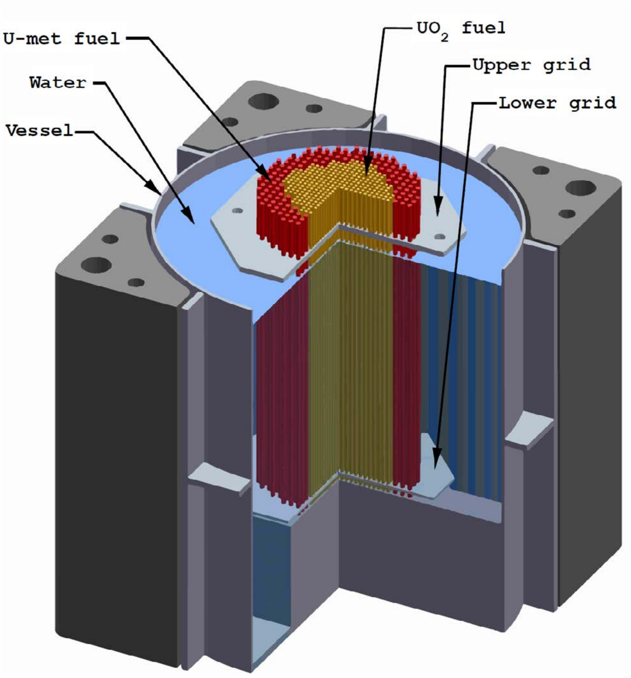

Fig. 2. Schematic view of the CROCUS reactor, showing the vessel, fuel grids, fuel elements, and water level when in operation.

C. *Neutron-gamma noise experimental setup*

We placed one 5.08-cm-diameter by 5.08-cm-length trans-stilbene detector in the water moderator offset 20 cm from the edge of the U_{met} zone, as detailed in Figure 3, with the active volume of the stilbene centered about the mid-height of the active fuel volume. A sealed, clear plastic tube fastened to the grid held the detector in position and protected the assembly from water. The detector was connected to a CAEN DT5730S 500-MHz 14-bit digitizer and a CAEN DT1470ET high-voltage unit in the reactor control room through diagnostic channels connecting the control room and containment while maximizing shielding [16]. After a gradual search for the critical water level, we measured the reactor for 60 minutes at critical.

D. *Power spectral density technique*

The time dependent behavior of the neutron flux $n(t)$ can be described by the point kinetics approximation [1]:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{\text{eff}}}{\Lambda} n(t) + \sum_i \lambda_i c_i + S, \qquad (1)$$

with the quantities ρ, the reactivity, β_{eff}, the effective delayed neutron fraction and Λ, the prompt generation time. The beta-delayed neutron precursor concentrations c_i and decay constants λ_i are derived via a balance equation, also known as the Bateman equation. The prompt neutron decay constant is defined as

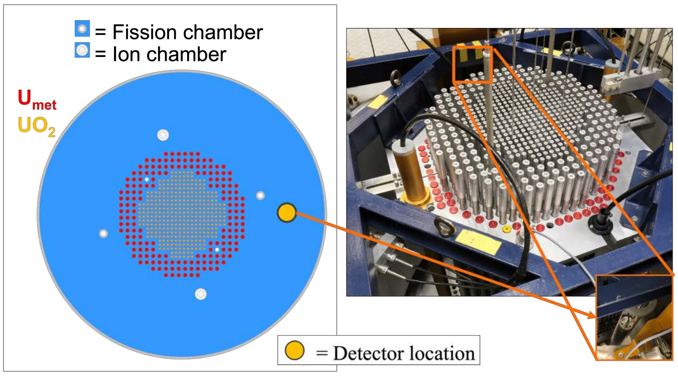

Fig. 3. The axial stilbene detector placement in the CROCUS reflector.

$$\alpha = \frac{\beta_{\text{eff}} - \rho}{\Lambda}. \tag{2}$$

Using [17], the autocorrelation of a point-like reactor can be written as:

$$P_{ii}(\tau) = \frac{1}{2} Y \alpha e^{-\alpha|\tau|}, \tag{3}$$

with Y being

$$Y = \frac{\epsilon D_\nu}{(\beta_{\text{eff}} - \rho)^2}, \tag{4}$$

where ϵ is the detector efficiency in counts (C_i) over fission rate (F_0), and D_ν is the Diven factor [18]. When accounting for the overlap of uncorrelated fission chains, an autocorrelation term $\delta(\tau)$ needs to be added, here neglecting delayed neutrons for illustrative purposes [14]:

$$P_{ii}(\tau) = \epsilon F_0 \ (\frac{1}{2} Y_1 \alpha e^{-\alpha|\tau|} + \delta(\tau)). \tag{5}$$

This formulation, called the "Rossi-α method", is a common noise analysis technique using time interval distributions [3], [19]. It describes the correlation of a given detection with one later in time - which evidently shows a relation that is linked through the prompt fission chain, i.e., detecting a neutron now will have a high likelihood of resulting in another neutron detected as the fission chain continues to propagate. The time correlation is hereby exponential in nature: the fission chain will eventually die out - thus the name prompt decay constant for the coefficient of the exponent.

The auto power spectral density method (APSD) is an arguably more (unwanted) noise-resistant method to estimate α. The APSD of a detector is found by Fourier-transforming the Rossi-α function, yielding a Lorentzian [14]:

$$G_{ii}(\omega) = \int_{-\infty}^{\infty} dt e^{-i\omega t} P_{ii}(t) = \\ \epsilon_i F_0 + \frac{\epsilon_i^2 F_0 D_\nu}{(\beta_{\text{eff}} - \rho)^2} \frac{1}{1 + \omega^2/\alpha^2}. \tag{6}$$

By Fourier transforming the time series of a detector signal, one may directly fit this expression to obtain α, in this case not an exponential decay, but the Fourier transform of it: a Lorentzian bell curve with cut-off frequency.

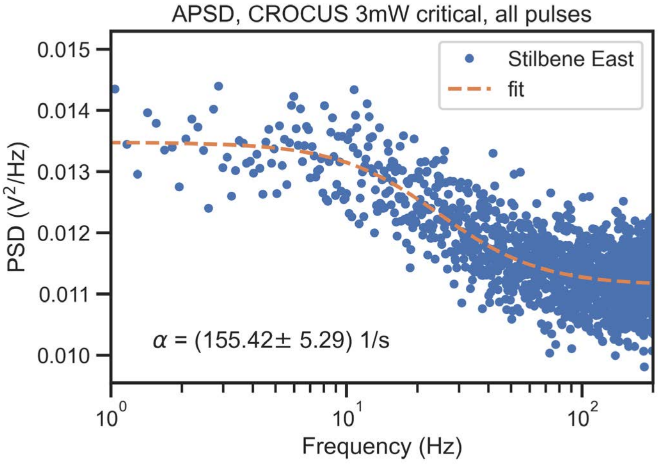

Fig. 4. Auto power spectral density (APSD) of the stilbene detector signal pulse time stamps.

III. RESULT

The resultant APSD distribution yields a precise estimate of $\alpha = 155.42 \pm 5.29$ when fit with equation 6 (see Figure 4). The total data for both neutron and gamma-ray detection time stamps were analyzed together without discrimination.

IV. CONCLUSIONS AND FUTURE WORK

The result presented in this work represents a precise estimate of the prompt neutron decay constant of CROCUS at critical in a relatively brief, 60-minute measurement time. This measurement time was shorter and compares well to previous measurements and simulations [4], [10], [12], [13]. Exact simulation modeling of this reactor configuration will be needed to support this estimate of α due to the unique perturbation caused by this detector configuration. A successful comparison would be an additional benchmark for code validation.

Analysis utilizing pulse-shape discrimination and multiple trans-stilbene detectors will be analyzed to increase modalities and improve precision. Small volume, 6-mm edge, cubic organic scintillators placed next to the reactor U_{met} (less than 1 cm offset) that exhibit lower relative magnitudes of pulse pile-up will be analyzed for the same purpose.

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