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Experiment Planning of Subcritical Reactivity Measurements Using High Order Statistics of Neutron Counting

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Abstract. The reactivity measurement of subcritical fissile arrangements (subcriticality) is a featured subject among those in reactor physics, because it is necessary to handle, process, and transport fissile material from nuclear installations safely. None of the many available experimental methods of subcriticality measurements used nowadays allows its direct determination; however, the third order correlation of neutron counting allows subcriticality estimation from a fissile material without any previous knowledge of its kinetic parameters or any pulsed neutron source. Despite of its intrinsic advantages, high order statistics requires a careful planning and an optimized procedure because this type of experiment demands a long acquisition time when compared to the usual methods. It is estimated that such procedure could ask for acquisition times a few orders of magnitude longer than those required by the usual methods of subcriticality estimation (for similar uncertainties). The main experimental results of this work, undertaken in the IPEN/MB-01 facility (a zero power reactor), which agreed with the simulated results obtained by dedicated Monte Carlo codes, were: the long time for data acquisition to obtain an useful result (hundreds hours of acquisition time), and the higher efficiency of using saturation time channels different from those which were used by others researches.

Keywords: subcriticality, high order statistics, neutron counting, Monte Carlo, nuclear reactor kinetics
PACS: 28.41.Rc

INTRODUCTION

The measurement of a negative value of reactivity, subcriticality, is an important subject for nuclear reactor physics, because it is necessary operate, process and handl fissile material in a safe and economical way. Recently, this issue has been drawing increasing interest among many researchers [1, 2, 3, 4].

Subcriticality measurements and the study of statistical fluctuation of a neutron population in subcritical systems are conducted since the fifties [5, 6]. The recent interest in Accelerator Driven Systems (ADS) has increased the demand for stable and trustable subcriticality measurements. The correct measurement and monitoring of the subcriticality is an important point in the nuclear safety of ADS.

Many subcriticality monitoring techniques have been proposed [7, 8]. Some of them,

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however, need the previous knowledge of the delayed neutrons fraction, β_{eff}, or the prompt generation time, Λ, or the neutron decay constant, α. Others techniques use unusual infrastructures as a pulsed neutron source.

Nowadays, subcriticality monitoring techniques are subject of intense research. Among those techniques, some of them stand out: 1- slope fit (needs pulsed neutron source); 2- Rossi and Feynman-α (previous knowledge of β_{eff} and Λ); 3- microscopic noise analysis (previous knowledge of β_{eff} and Λ); 4- ^{252}Cf source method (needs a ^{252}Cf source); 5- neutron source multiplication method (NSMM) (which gives relatives values of k_{eff}); 6- third order correlation of neutron counting. There are, of course, others measurements methods.

The third order correlation of neutron counting is one of the simplest methods from the instrumentation and infrastructure point of view, because it needs only a usual neutron source (*Poisson* like) and detectors operating in pulse mode.

In this respect, the IPEN/MB-01 nuclear reactor (a zero power facility) offers a unique opportunity for the development experimental techniques in order to measure the subcriticality of many core configurations using different techniques. Such measurements help the development of experimental subcritical configurations data base. However, third order correlation technique has some drawbacks. Its main issue is the measurement of high statics parameters. Their measurements are much longer than the time interval required for the usual techniques.

This work addresses the main issues related subcriticality measurement using the third order correlation of neutron counting. It is used preliminary measurements and dedicated Monte Carlo codes in order to verify convergence and avoid any bias.

METHOD AND EXPERIMENTAL SET UP

Method

The third order correlation of neutron counting allows the direct measurement of subcriticality without the previous knowledge of β_{eff}, Λ, α (kinetics parameters), or unusual infrastructures. This method is an extension of the Feynman-α one. The Feynman-α method uses the ratio between the neutron counting variance, $m_2(T)$ (T is the dwell time), and its respective mean, $m(T)$, by means of the second order correlation $Y(T) = m_2(T)/m(T) - 1$. The third order correlation method uses, besides $Y(T)$, the third order correlation $X(T) = m_3(T)/m(T) - 3m_2(T)/m(T) + 2$. Using the following approximations [9]: 1- one group of energy and point kinetics; 2- disregarding delayed neutrons; 3- subcritical and homogeneous system with subcriticality (-ρ), detection and fission probabilities per unit time, λ_d and λ_f, respectively, which emits ν prompt neutron per fission; 4- fission source with constant activity and Poison like, it can be shown that:

$$X(T) = X_{2\infty}\left(1 + e^{-\alpha T} - 2\frac{1 - e^{-\alpha T}}{\alpha T}\right) + \; X_{3\infty}\left(1 - \frac{3 - 4e^{-\alpha T} + e^{-2\alpha T}}{2\alpha T}\right) \quad (1)$$

where,

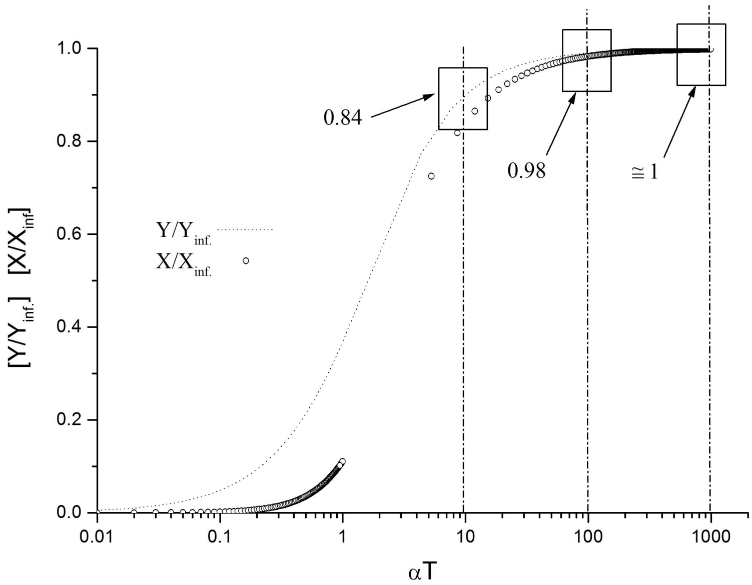

FIGURE 1. The corrections of X and Y values for two different saturation regimes. In the region of 100/ α, the bias is about 2%. A Feynman-α evaluation could be done in order of evaluate αT which allows one to estimate the bias correction.

$$X_{2\infty} = \frac{3\lambda_d^2\lambda_f^2\langle\nu(\nu-1)\rangle^2}{\alpha^4}$$
$$X_{3\infty} = \frac{3\lambda_d^2\lambda_f\langle\nu(\nu-1)(\nu-2)\rangle^2}{\alpha^3},$$
$$X_\infty = X_{2\infty} + X_{3\infty},$$
$$Y_\infty = \frac{\lambda_d\lambda_f\langle\nu(\nu-1)\rangle}{\alpha^2}$$

$\alpha = \langle\nu\rangle\ \ \lambda_f\ \ (-\rho)$, and ∞ refers to saturation values ($T \to \infty$). Using eq. 1 it is possible to show that: show that:

$$\frac{X_\infty}{Y_\infty^2} = 3 + \frac{\langle\nu\rangle\langle\nu(\nu-1)(\nu-2)\rangle(-\rho)}{\langle\nu(\nu-1)\rangle^2} \quad (2)$$

The saturation dwell time suggested by [10] is 1000/α, because the resulting bias is very small. Figure 1 shows the corrections of X and Y values for two different saturation regimes. In the region of 100/α, the bias corrections are not quite sensitive to the $X_{3\infty}/X_{1\infty}$ value, as shown in Fig. 2. If, however, one obtains small uncertainties ($\sim$1%), it is strongly suggested to use a bigger dwell time. It is not advisable to use $\alpha T \sim 10$.

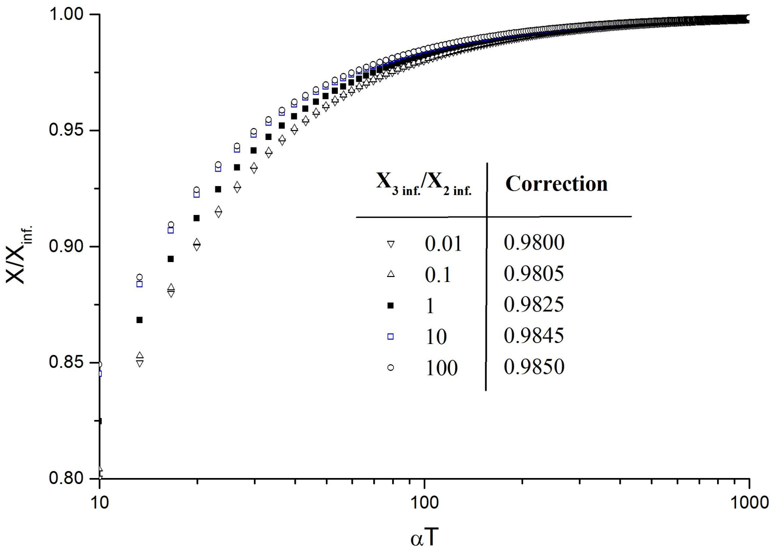

FIGURE 2. In the saturation regime ($100/\alpha$ - $1000/\alpha$), the $X_{3\infty}/X_{1\infty}$ is not quite sensitive to the dwell time, which allows the usage of the $100/\alpha$ saturation regime without the previous knowledge of $X_{3\infty}/X_{1\infty}$.

Experimental set up

The experimental set up is simple. A BF_3 (a BF_3 is advisable, mainly because of its better gamma discrimination features) or ^{3}He proportional counter is positioned in the reflector as close to core as possible. The boundary conditions to the detector positioning are: dead time and space effect issues. The electronics is usual: 1- pre-amplifier (ORTEC 142C); 2- amplifiers (CANBERRA 2024), 0.25-0.5 μs shaping time; 3- Single Channel Analyzer (SCA) ORTEC 551; 4- PCI bus counter (100 ns-1300 s time channel). The main experimental concern is to increase the gamma rejection and to decrease the system dead time or evaluate its influence.

RESULTS

IPEN/MB-01 Reactor Monte Carlo Point Kinetics Simulations

A former experiment performed by [9]: presents the following difficulties related to measurement of the third order counting correlation: 1- divergence from known reference results for subcriticality levels lower than 4500 pcm; and 2- high uncertainties values. In order to show those measurement problems, it was developed a dedicated Monte Carlo point kinetics model which emulates a particular configuration of the IPEN/MB-01 point kinetics.

The first problem which those simulations reveal is the measurement subtleness. The

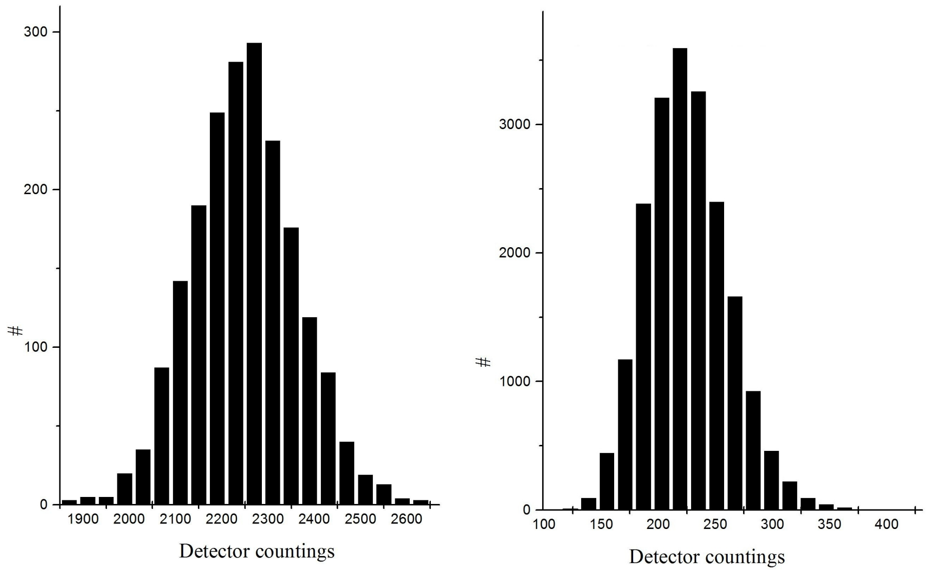

FIGURE 3. Frequency counting in two saturation regimes (αT=100-1000) of a Monte Carlo point kinetics model with a true subcriticality level, ρ_0, of 300 pcm and a true neutron prompt decay constant, α_0, of 1200 s^{-1}. Left - gate time: 1000/α=0.833 s, skewness = $m_3/m_2^{3/2} = 0.090(86)$ and 2000 counting channels. Right - gate time: 100/α=0.0833 s, skewness = $0.41(03)$ and 20000 counting channels.

main phenomenon to be observed is the counting distribution asymmetry around its mean value. This asymmetry is a direct measurement of subcriticality.

Figure 3 shows two simulations of a Monte Carlo point kinetics model with a true subcriticality level, ρ_0, of 300 pcm and a true neutron prompt decay constant, α_0, of 1200 s^{-1}, each simulation uses a different saturation regime. The αT=100 saturation regime has proven to be a better choice for asymmetry observation at this subcriticality level. Both models emulate a 30 min experiment. The asymmetry observation was performed by the skewnees, $m_3(T)/m_2^{3/2}(T)$, estimation.

In the αT=100 saturation regime the reactivity is statistically different from zero and the estimated subcriticality was 0.21(20). This result is statistically equivalent to the true value 0.003, but useless from a practical point of view. On the other hand, the αT=1000 saturation regime has not shown any asymmetry. Both models emulate a 30 min experiment. Compared to the usual uncertainty relative to the X measurement, the bias introduced by the lack of knowledge $X_{3\infty}/X_{1\infty}$ value is not relevant, at least in the αT=100 regime.

Other simulations in deeper subcriticality levels (i.e., 3000 pcm) have shown similar results. The uncertainty magnitude problem, or the necessary data acquisition time, grows with the subcriticality. Figure 4 presents the estimated time of measurement necessary to get a useful result for an 8000 pcm subcritical configuration [11], using a Monte Carlo dedicated program.

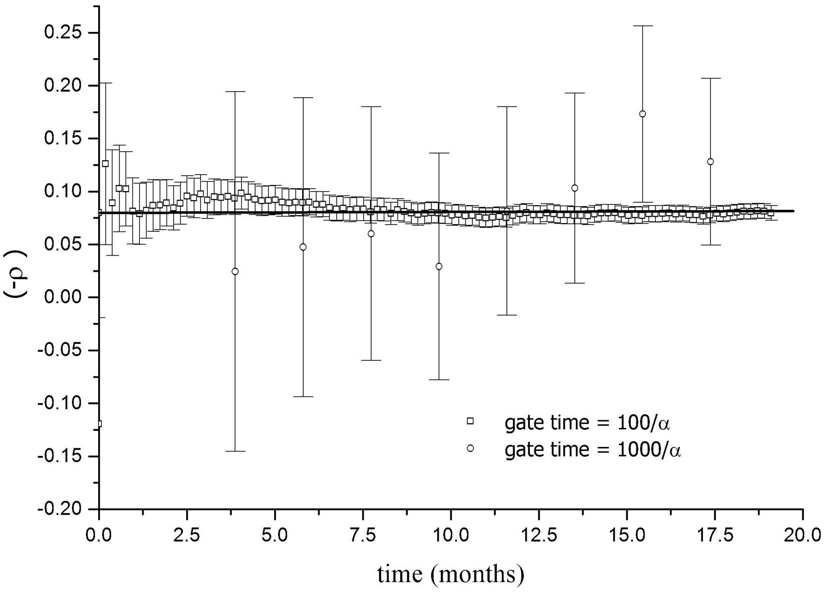

FIGURE 4. Estimated time of measurement necessary to get a useful result, for an 8000 pcm subcritical configuration, using a Monte Carlo dedicated program and the advantage of using a saturation dwell time of $100/\alpha$ (mean counting rate = 1750 cps).

It is possible to estimate that a use ful measurement would require a few months, considering a 1Ci (3.7×10^{10} Bq) Poisson like source. The utilization of αT=100 saturation regime (with bias correction) was considered satisfactory.

Preliminary Experiments

From the experimental set up and data used in Kuramto et al. [11], it was possible to measure the subcriticality of three configuration of the IPEN/MB-01 reactor ($-\rho \sim$ 2850, 5725 and 8000 pcm). For each configuration, a Feynman-α experiment was performed to determine the saturation dwell time from the estimated α. In all configurations, the neutron detection rate was kept low enough to limit the dead time effects of the data acquisition system.

The three experiments given the following results for the subcriticality measurements: 1- 0.06(50) (reference value: 0.028); 2- 0.12(06) (reference value: 0.057); and 3- 0.86(80) (reference value: 0.088). Figure 4 shows the formation of a new plateau, and the introduction of a large bias in the results, after the dwell time has become greater than MCS registration capability ($T \times N$ of time channels) by means of counting bunching technique, for configuration 3.

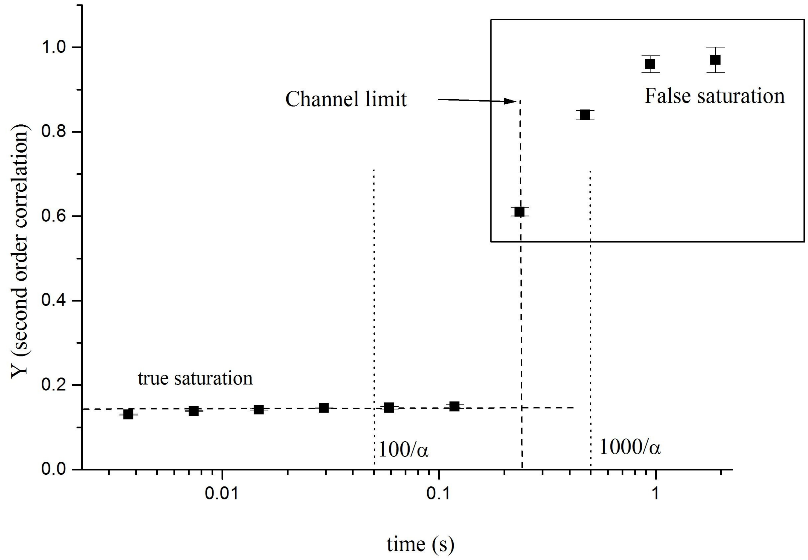

FIGURE 5. Preliminary results for one IPEN/MB-01 reactor configuration [11] ($-\rho_0 \sim$ 8831 pcm, $\alpha = 2100(15)$ s^{-1} and 3h of acquisition). Those results show how bunching techniques may introduce bias in the results if it is not properly used. The uncertainty of the reactivity measurement, -0.86(80), shows the measurement difficulty.

CONCLUSIONS

The third order correlation of neutron counting was studied by means of Monte Carlo simulations of the IPEN/MB-01 reactor point kinetics models, whose kinetics parameters are identical to those of previous works. The main results of this work are the subtleness of the phenomena, the high data acquisition time for a useful result (may be a couple of months), and the effectiveness of using the αT=100 saturation regime. Preliminary experiments were conducted which indicate a limitation in the bunching technique which introduces a relevant bias into the measurements by means of what it is believed to be the MSC restart during the measurement. One of the main limitations of this work was the detector's low counting rate which was chosen in order to avoid dead time effects. In a future work, it will be studied the role of acquisition system's dead time in the measurement results.

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