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A New Method for Absolute Measurement of β_{eff} based on Microscopic Noise Experiments and the Two-Region Model in the IPEN/MB-01 Research Reactor

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Abstract. A new method for absolute measurement of the effective delayed neutron fraction, β_{eff}, based on Microscopic Noise Experiments and the Two-Region Model was developed at the IPEN/MB-01 Research Reactor. In contrast with other techniques, the main advantage of this new methodology is to obtain the parameters in a purely experimental way, eliminating all parameters that are difficult to measure or calculate. Consequently, the uncertainties associated to these parameters are eliminated and the accuracy in β_{eff} is improved. Experimentally, several Rossi-α and Feynman-α measurements were performed in the IPEN/MB-01 in a large subcritical interval. By adopting the present approach, the final results show that uncertainties of 0.67% and 0.97% on, respectively, β_{eff} and Λ are achievable. The theory/experiment comparison of β_{eff} shows that among the available nuclear data libraries JENDL3.3 has the best performance.

1 Introduction

Since 1990, it has been observed that delayed neutron data uncertainties may result in undesirable conservatism in the design and operation of nuclear reactor control systems[1]. Among these data, the effective delayed neutron fraction β_{eff}, play the most important role. Currently, a target accuracy of ±3%(1 s.d.) has been requested for the experimental β_{eff}[2]. Nowadays, there are fewer measurements of β_{eff} available for validating the calculations for thermal systems[3]. In such a way, a collaborative effort to improve the β_{eff} measurements in thermal systems has been recommended.

Currently, all the β_{eff} measurement techniques[4] cannot directly give the β_{eff}, but they yield it using several calculated and/or semi-experimental parameters. Uncertainties of these parameters are critical uncertainty sources in these techniques. It is apparent that when a physical quantity needs to be known to a few-percent accuracy then an absolute experimental determination is essential.

For these reasons, a new methodology for absolute measurement of the β_{eff} is proposed. This methodology combines the well-known microscopic noise analysis techniques, Rossi-α and Feynman-α[5], with the Two-Region model[6]. By adopting this approach, values for β_{eff}, and other kinetic parameters may be obtained without any calculations or other experiments results. Consequently, the accuracy in β_{eff} was improved and the proposed target accuracy could be reached. Through this methodology, other parameters such as the prompt neutron generation time Λ may also be estimated.

2 The Two-Region Model

The Two-Region Model was developed on previous works[6-8] and describes the time-dependent behaviour of multiplying systems comprised of two distinct regions, the core and a non-multiplying, source-free reflector.

If six groups of delayed neutrons are assumed the inhour equation derived from the Two-Region Model will have eight roots with an additional asymptote at $-1/\tau_r$[9], where τ_r is the adjoint-weighted neutron lifetime in the reflector region.

The ω_7 and ω_8 roots can be obtained from the reflected core inhour equation neglecting delayed neutrons ($\omega \gg \lambda_1$)[9]:

$$\omega_{7,8} = \frac{1}{2\Lambda_c\Lambda_r(1-f)}\left\{\begin{array}{l} -\left[(1-\rho)(\Lambda_c + f\Lambda_r) + \Lambda_r(1-f)(\beta_{eff}-\rho)\right] \pm \\ \pm\sqrt{\begin{array}{l}\left\{(1-\rho)(\Lambda_c + f\Lambda_r) + \Lambda_r(1-f)(\beta_{eff}-\rho)\right\}^2 \\ -4\Lambda_c\Lambda_r(1-f)(1-\rho)(\beta_{eff}-\rho)\end{array}}\end{array}\right\} \quad (1)$$

where the positive and negative signs go with ω_7 and ω_8 respectively. This equation shows clearly that the relationship between the roots ω_7 and ω_8, and reactivity is not linear. The ω_7 root is obtained in conventional one-region Rossi-α and Feynman-α measurements and is designated as prompt neutron decay constant, α. The ω_8 root is related to the reflector effect and introduces an additional decay mode in Rossi-α and Feynman-α distributions.

In contrast to One-Region Model, the reflected core Rossi-α and Feynman-α distribution shows two exponential terms, and may be written as[9,10]:

$$p_{Rossi}(\tau) = A_7 e^{\omega_7 \tau} + A_8 e^{\omega_8 \tau} + BG \qquad (2)$$

$$Y(T) = B_7\left(1 + \frac{1 - e^{\omega_7 T}}{\omega_7 T}\right) + B_8\left(1 + \frac{1 - e^{\omega_8 T}}{\omega_8 T}\right) + BG \qquad (3)$$

where the amplitudes A_7, A_8, B_7 and B_8, and the background term BG, are fitting parameters.

3 The IPEN/MB-01 Research Reactor and core configurations

To examine the present methodology, a series of Rossi-α and Feynman-α experiments were conducted at the IPEN/MB-01 research reactor[11]. The IPEN/MB-01 reactor is a zero-power critical facility which consists of a 28x26 square array of UO_2 fuel rods, 4.3% enriched, inside a light water tank. The reactivity is controlled by control and safety rods. The maximum operating power of the facility is limited to 100W.

Rossi-α and Feynman-α distributions were recorded in two different core configurations. Figure 1 displays a schematic view of each configuration and the detector locations.

The core configuration given in Fig. 2a was used to perform Rossi-α and Feynman-α measurements at subcritical levels near the critical state in order to obtain the β_{eff}/Λ value. In order to reduce the count rate of the BF_3 detector near the critical state, the startup source (Am-Be, 1*Ci*) was removed from the bottom of the core.

The core configuration given in Fig. 2b, was implemented to perform Rossi-α and Feynman-α measurements in a very large range of reactivity (nearly from -500pcm to -25000pcm). This large subcritical level is achieved employing eight burnable poison rods in order to reduce the reactivity excess of the core to nearly zero. Due to the large subcritical reactivity interval, Rossi-α and Feynman-α measurements were conducted with two detectors with different sensitivities positioned in the reflector region. To increase the count rate of the detector to a more reasonable value, the start up source was positioned in the bottom of the core to drive the system during the measurements.

The main part of our timemarking system is a Multi-Channel Scaler-MCS PCI-bus card. This acquisition card records the elapsed time between a trigger and subsequent pulses. Software written in LabVIEW™ *G*-Language is used to control the acquisition. Our system provides an on-line data analysis of Rossi-α and Feynman-α simultaneously.

4 Measurements results

According to Fig. 2a, Rossi-α and Feynman-α distributions were recorded at three different subcritical levels near the delayed critical state, in order to measure the ratio β_{eff}/Λ. Each subcritical level was achieved by changing the control rods positions. According to the Two-Region Model predictions[9], near criticality the component driven by ω_7 root is dominant. In this way, α values were obtained by fitting each Rossi-α and Feynman-α distributions using a typical least-square algorithm to functions which includes only one exponential term. Since we are only interested in relative changes in reactivity level due to changes in the control rod position, the subcritical reactivity ρ can be obtained through the Neutron Source Multiplication Method (NSMM)[12] In this method the inverse count rate $1/C$ can be directly related to ρ. Figure 4 and 5 show the fitted α values vs. inverse count rate of the BF_3 detector used to perform the measurements. These data were extrapolated to the critical condition and β_{eff}/Λ values were estimated as -235.28(1.70)s^{-1} and -235.57(0.66)s^{-1}, for Rossi-α and Feynman-α measurements, respectively.

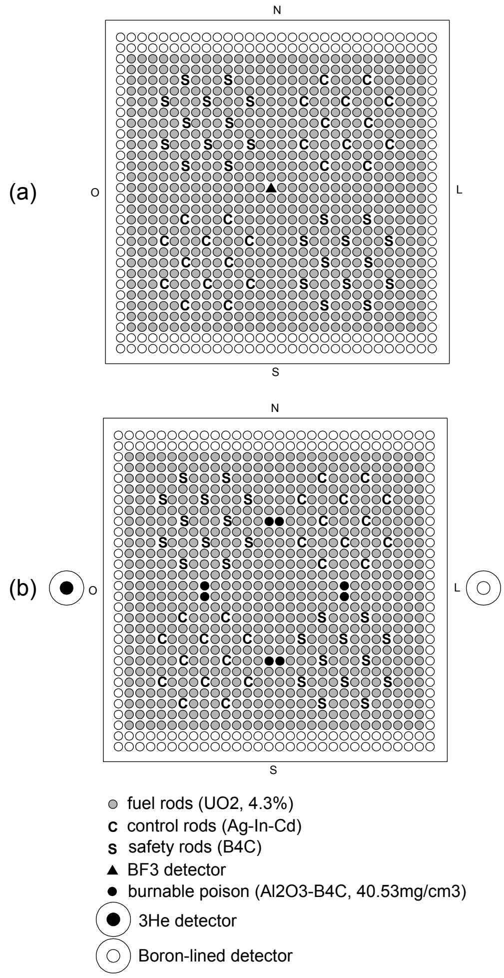

Fig. 1. IPEN/MB-01 core configurations. (a) BF3 detector positioned in the center of the active core. (b) Eight burnable poison rods positioned in the active core and three different detectors in the reflector region.

The second core configuration illustrated in Fig. 1b was loaded in order to validate the Two-Region Model predictions and obtain β_{eff} in an absolute experimental way. In order to achieve the different reactivity levels, the system was perturbed with the insertion of all control and safety rods simultaneously in steps of 5%. Above -3000pcm approximately, only one decay mode was identified in Rossi-α distributions. On the other hand, below -3000pcm two decay modes were considered to fit the distributions (see Eq. 2). This behaviour is in agreement with the Two-Region Model predictions. In the Feynman-α distributions, the correlated component governed by the ω_7 root is dominant, and only one exponential term could be observed. Thus, α was obtained by fitting these curves to Eq. 3 with only the first exponential term. Figure 6 and 7 show the Rossi-α and Feynman-α curves recorded at -3363.76pcm, respectively. In Fig. 8, the α values, obtained from the Rossi-α curves, were plotted as a function of the inverse count rate. In Fig. 9, the same procedure was done for the α values obtained from the Feynman-α curves.

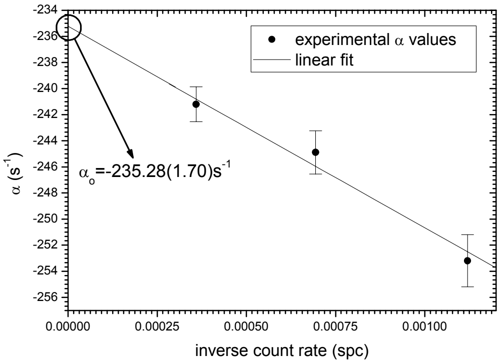

Fig. 4. Plot of the α values versus the inverse count rate.

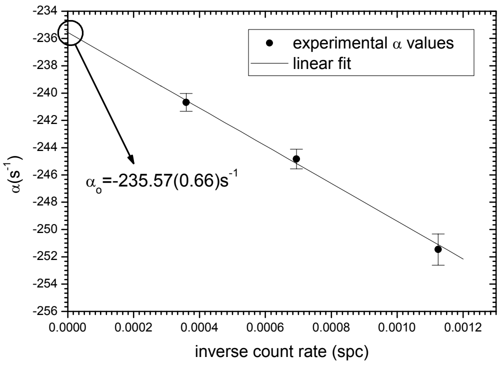

Fig. 5. Plot of the α values versus the inverse count rate.

The parameters α_0, τ_c, τ_r, f and β_{eff} were directly obtained by fitting the data illustrated in Figs. 8 and 9 to the Eq. 2 by the least-squares method. The fitted quantities τ_c, τ_r, and f can be combined to yield Λ, as follow[6,9]:

$$\Lambda = \frac{1}{1-f}\left(\tau_c + f\tau_r\right) \tag{3}$$

Tables 1 and 2 summarizes the obtained parameters.

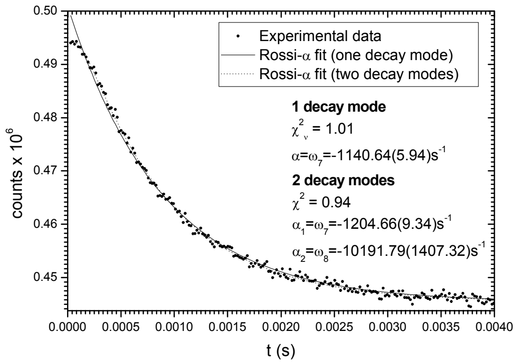

Fig. 6. Rossi-α distribution for a subcritical level of -3363.76pcm.

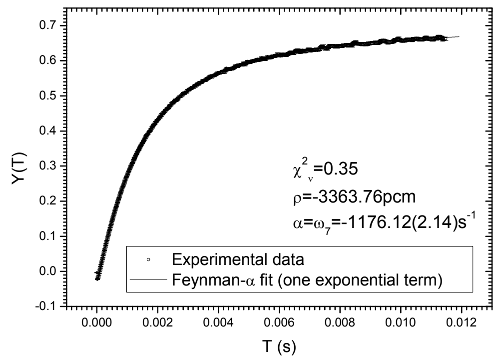

Fig. 7. Feynman-α distribution for a subcritical level of -3363.76pcm.

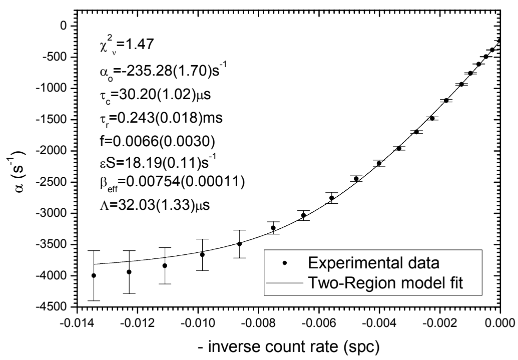

Fig. 8. α Values obtained from the Rossi-α curves vs. the inverse count rate. The parameters were obtained via least-square fit using Eq. 2.

All the fitted parameters measured by Rossi-α and Feynman-α agreed well with each other when the standard deviations are considered. Moreover, the measured values for α_0, β_{eff} and Λ are well in accordance with a previous results from frequency analysis experiments [13,14].

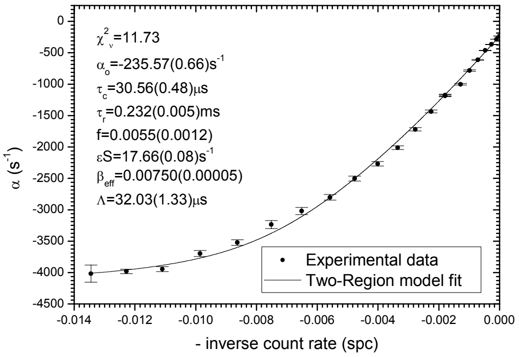

Fig. 9. α Values obtained from the Feynman-α curves vs. the inverse count rate. The parameters were obtained via least-square fit using Eq. 2.

Table 1. Rossi-α measured results.

parameter	Rossi-α (core)	Rossi-α (reflector)
α_o	-235.28(1.70)s^{-1}	-234.75(2.34)s^{-1}
τ_c	-	30.20(1.02)μs
τ_r	-	0.243(0.018)ms
f	-	0.0066(0.0030)
β_{eff}	-	7.54(0.11)x10^{-3}
Λ	-	32.03(1.33)μs

Table 2. Feynman-α measured results.

parameter	Feynman-α (core)	Feynman-α (reflector)
α_o	-235.57(0.66)s^{-1}	-235.25(0.96)s^{-1}
τ_c	-	30.56(0.48)μs
τ_r	-	0.232(0.005)ms
f	-	0.0055(0.0012)
β_{eff}	-	7.50(0.05)x10^{-3}
Λ	-	32.02(0.58)μs

The small standard deviations show that precise absolute measurements for β_{eff} and Λ can be obtained. More precisely, the uncertainty in β_{eff} is 1.46% for the Rossi-α measurements and 0.67% for the Feynman-α. Both results are smaller than the proposed target accuracy of ±3%(1 s.d.).

Table 3 lists theory/experiment comparisons for the β_{eff} measured in this work. According to these results, JENDL3.3 presented the best performance and meets the desired accuracy for the calculation of this parameter. This result is in complete agreement with the adjustment study carried out by Sakurai and Okajima where the ^{235}U yield was reduced by 0.9%[15].

Table 3. Comparison of the calculated β_{eff} with the experimental values.

		ENDF/B-VI.8[a]	JEFF-3.1	JENDL 3.3
β_{eff} (C/E)	TORT	1.0565	1.0325	1.0082
Rossi-α	MCNP-4C3	1.0421	1.0289	1.0074
β_{eff} (C/E)	TORT	1.0509	1.0270	1.0028
Feynman-α	MCNP-4C3	1.0366	1.0234	1.0021

5 Conclusions

On the basis of the Two-Region model and microscopic noise experiments, a new methodology for absolute measurement of β_{eff} was successfully developed in the IPEN/MB-01 Research Reactor. By adopting this approach, an absolute experimental determination of β_{eff} could be carried out with the required accuracy and without knowledge of any other parameter. In order to implement this technique, several Rossi-α and Feynman-α distributions were recorded in core and reflector regions. According to the Two-Region model predictions, two decay modes were noticed in the Rossi-α curves, while only one exponential component was observed in the Feynman-α distributions. Furthermore, it was noticed a nonlinear behaviour between α and the inverse count rate of the detector, which is also in agreement with the Two-Region Model predictions. The prompt neutron generation time Λ and other parameters, were also measured in a purely experimental way. The C/E values for the β_{eff} measured in this work show that JENDL3.3 presented the best agreement, which justifies the adjustment study performed by Okajima and Sakurai where the ^{235}U yield was reduced by 0.9%.

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