Rossi-α Experiment in the IPEN/MB-01 Research Reactor: Validation of Two-Region Model and Absolute Measurement of β_{eff} and Λ

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Abstract

A new method for absolute measurement of the effective delayed neutron fraction, β_{eff}, and the prompt neutron generation time, Λ, based on Rossi-α experiments and the Two-Region Model was developed at the IPEN/MB-01 Research Reactor facility. In contrast with other techniques like the Slope Method, Nelson-Number Method and ^{252}Cf-Source Method, 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. In this way, Rossi-α experiments for validation of this method were performed at the IPEN/MB-01 facility. The final results agree well with values from frequency analysis experiments and show uncertainties of 1.46% and 0.97% for β_{eff}, and Λ respectively. This work supports the reduction of the ^{235}U thermal yield as proposed by Okajima and Sakurai.

KEYWORDS: Rossi-α, Two-Region Model, effective delayed neutron fraction, prompt neutron generation time.

1. Introduction

Reflected reactors constitute one of the most important classes of nuclear reactors. During the past 50 years, several experimental data involving reflected systems has been reported in the literature [1] that cannot be satisfactorily explained using the One-Region Point Kinetic Model, in particular many have observed that the prompt decay α curves obtained from Rossi-α experiments can exhibit multiple decay modes[2]. Furthermore, it has also been observed that the kinetic behavior of some reflected systems exhibit a nonlinear relationship between α and reactivity as predicted by the Two-Region model[1].

Among the different parameters influencing the dynamic behavior of a nuclear reactor, the effective delayed neutron fraction, β, and the prompt neutron generation time, Λ, play the most important role[3,4]. Therefore, it is essential to validate neutron codes in this respect by means of absolute measurements, which are independent of any calculations or other experiments. Concerning thermal reactors fueled with slightly enriched uranium, a literature survey shows that the available experiments related to β_{eff} were performed in the TCA[5], SHE-8[6], MISTRAL-1[7] and IPEN/MB-01[8]. The β_{eff} uncertainties range from 1.6% for MISTRAL-1 to 4.6% for SHE-8. The number of experiments related to β_{eff} is quite small and consequently the need of new and accurate experiments for thermal systems in order to have the required degree of confidence in

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calculations of such systems is completely justified.

In this way, a new methodology based on the Two-Region Model was developed, which relies on the measurements of Rossi-α distributions at several subcritical levels, which allows determination of β and Λ without the need of any data from theoretical calculations.

In this work several Rossi-α measurements were performed in the IPEN/MB-01 Research Reactor facility. The Rossi-α distributions were acquired in a large subcritical interval, from -500pcm to -25000pcm approximately. At subcritical levels under -3000pcm, we observed that prompt neutron in IPEN/MB-01 die out with two decay constants rather than one, in agreement with Two-Region Model. Moreover, using the Two-Region Model the α versus reactivity curve was fitted by means of a least-square approach in order to extract β.

2. The Two-Region Model

The multiple decay modes observed in Rossi-α distributions, the non-linear behavior between α and subcritical reactivity and others anomalies[1] can be explained using a the Two-Region Model, which is based on the theory of coupled systems proposed by Avery[9,10] and subsequently adapted for reflected systems by Cohn[11,12]. In accordance to Avery's theory, Cohn separated the total neutron loss rate from the integral system into two loss rates, one from the core region and one from the reflector region. The two regions were then coupled together using coupling parameters that represent the probability that a neutron lost from one region will appear in the other region.

Assuming that the density of delayed-neutron precursors is in a steady state during the die-away time, the Two-Region Model shows that the behavior of a prompt-neutron chain with time is given by the neutron densities in the core and reflector as follow:

$$N_c(t) = A_+^c e^{\alpha_+ t} + A_-^c e^{\alpha_- t} \quad (1)$$

$$N_r(t) = A_+^r e^{\alpha_+ t} + A_-^r e^{\alpha_- t} \quad (2)$$

where the indices c and r refer to core and reflector, respectively. The decay constants α_+ and α_- are given by:

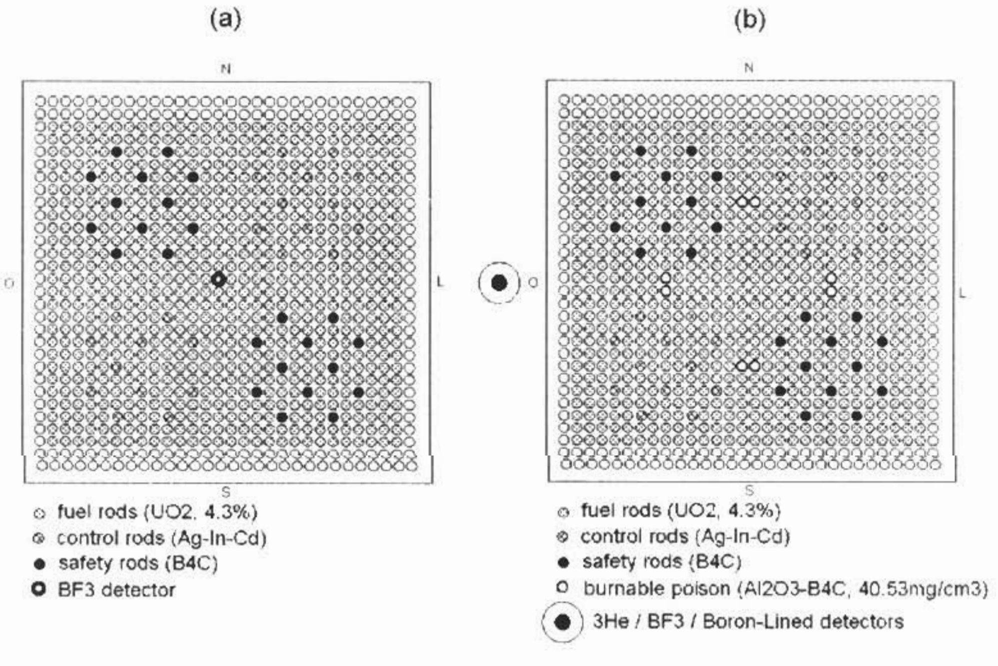
$$\alpha_\pm = \frac{1}{2\Lambda_c\Lambda_r(1-f)}\left\{\begin{matrix}\left[(1-\rho)(\Lambda_c + f\Lambda_r) + \Lambda_r(1-f)(\beta-\rho)\right]\pm \\ \pm\sqrt{\{(1-\rho)(\Lambda_c + f\Lambda_r) + \Lambda_r(1-f)(\beta-\rho)\}^2 - 4\Lambda_c\Lambda_r(1-f)(1-\rho)(\beta-\rho)}\end{matrix}\right\}, \quad (3)$$

where all symbols are the same as Ref.[1]. The constant α_+ is the prompt neutron decay constant, which is obtained in Rossi-α experiments using the One-Region Point Kinetic Model. The second decay mode, driven by α_- is related with the reflector. It is important to point out that only the amplitude A_-^r is negative. This equation shows clearly that the relationship between the decay modes and reactivity is not linear.

3. The IPEN/MB-01 Research Reactor

The IPEN/MB-01 reactor is a zero-power critical facility especially designed for measurements of a wide variety of reactor physics parameters to be used as benchmark experimental data for checking the calculational methodologies and related nuclear data libraries commonly used in the field of reactor physics. The IPEN/MB-01 reactor reached its first criticality on November 9, 1988, and since then it has been utilized for basic reactor physics research and as an instructional laboratory system. This facility consists of a 28x26 square array of UO_2 fuel rods, 4.3% enriched and clad by stainless steel (type 304) inside a light water tank. The control banks are composed of 12 Ag-In-Cd rods and the safety banks of 12 B_4C rods. The pitch of the IPEN/MB-01 reactor was chosen to be close to the optimum moderator ratio (maximum k_∞). This feature favors the neutron thermal energy region events. A complete description of the IPEN/MB-01 reactor can be found in Ref. 9. Fig. 1 shows two different configurations of this reactor core. Configuration (a) is used to in-core measurements near criticality and configuration (b) to out-core measurements in large subcritical levels.

Figure 1: IPEN/MB-01 core configurations. (a) BF_3 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.



4. Measurements Results

We have developed a data acquisition system for microscopic noise analysis called IPEN/MB-01 Correlator, which is a Virtual Instrument that records the timing of all neutrons events, allowing on-line data analysis. The main part of our timemarking system is a Multi-Channel Scaler-MCS PCI card. With dwell times from 100ns to

1300s, a memory length of 65536 channels, and input counting rates up to 150MHz, the IPEN/MB-01 Correlator provide us a high time resolution.

The Rossi-α measurements were performed in a twofold approach. Initially a miniature BF_3 detector was placed in the center of the active core (see Fig. 1a). The Rossi-α distributions were recorded using the IPEN/MB-01 Correlator. Fig. 2 shows a typical measured Rossi-α distribution. In total, three different measurements were performed with the core system driven by its intrinsic source and different control rods positions. The prompt decay constants were obtained from these three subcritical levels via a least-square fit procedure using only one decay mode. In this way, a linear extrapolation to $\rho=0$ gave α_0 of the system as $235.12 \pm 1.76 s^{-1}$, see Fig. 3.

Figure 2: Typical Rossi-α distribution for a subcritical level of –4.77pcm.

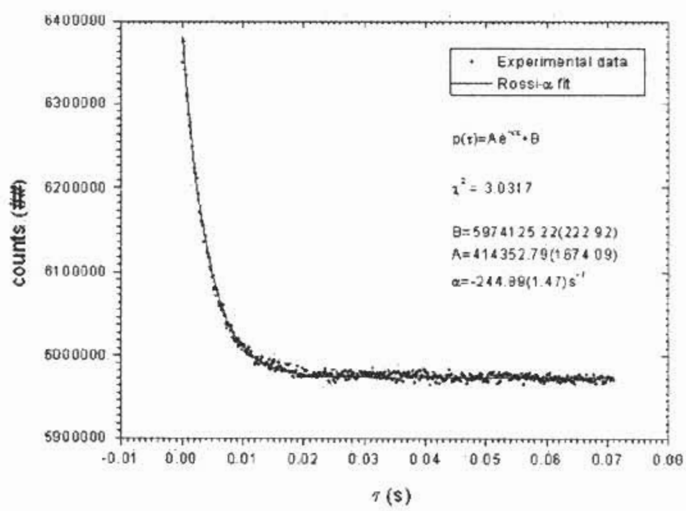
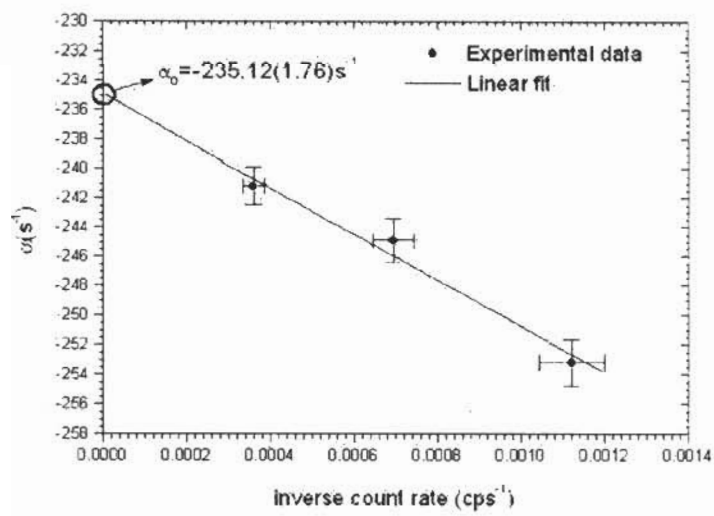


Figure 3: Plot of the α values versus the inverse count rate.



The second approach considered the measurements of the prompt neutron decay constant 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 (see Fig. 1b). Each rod is filled with 52 pellets of Al_2O_3-B_4C with 40.53 milligram of Boron per cubic centimeter. The second mean to reduce the reactivity was the simultaneous introduction of all control and safety rods of the reactor in steps of 5% insertion. The Rossi-α measurements were performed with the reactor being driven by the start-up source (Am-Be, 1Ci). Three detectors with different sensitivities (^3He, BF_3 and Boron-Lined) were placed in the reflector region.

Above -3000pcm approximately, only one decay mode was identified in Rossi-α distributions. On the other hand, under -3000pcm two decay modes were considered to fit the distributions. Rossi-α distributions fitted with one and two decay modes are showed in Figs. 4 and 5, respectively. The residue analysis in Fig. 5 shows that two decay modes fit is better than one decay mode fit. The small drop of the Rossi-α distribution at the beginning of the curve is characteristic of this distribution in the reflector region. It can be shown by a straightforward solution of the reflected core Cohn´s equations that the coefficient A_r is negative then giving rise to the drop in the distribution. This aspect is verified experimentally.

Figure 4: Rossi-α distribution for a subcritical level of –499.88pcm.

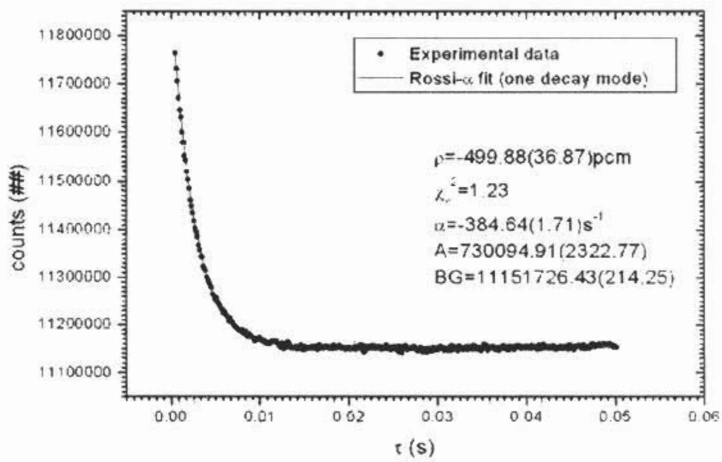
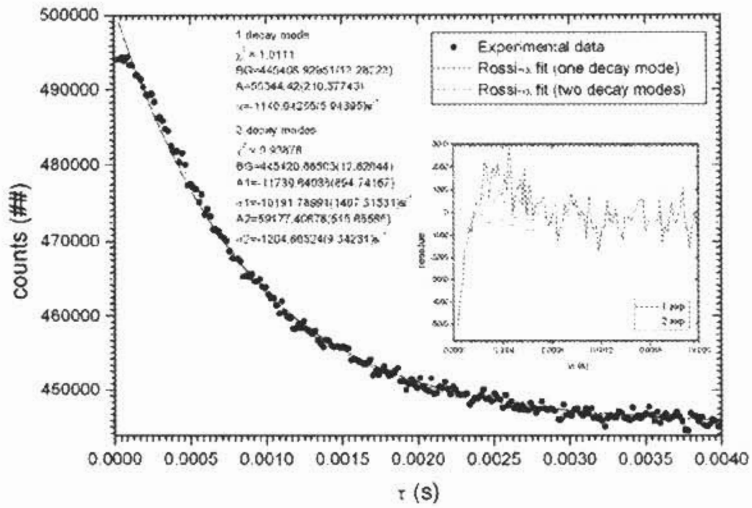


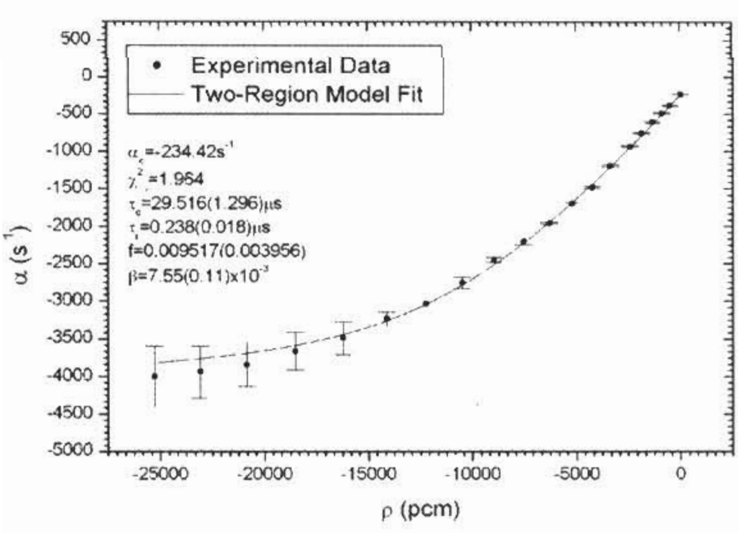
Fig. 6 shows the measured α values vs. the subcritical reactivity. The subcritical levels were determined by the Neutron Source Multiplication Method-NSMM[13,14] using the counting of the detector that gave rise to the distribution normalized to the control rod calibration near critical. However, our new technique for measurement of β and Λ is independent of the absolute value of the reactivity. The important aspect is only the shape of the reactivity scale versus the control rod position. As mentioned, we recognized that the variation of α with reactivity is not linear, but shows a behavior described by Eq. 1. Fig. 6 shows that there is a stabilization of the prompt decay constant for higher reactivities as predicted by the Two-Region Model. This plateau value is according to the Two-Region Model equal to the reflector decay constant, λ_r, which corresponds to the inverse neutron lifetime in reflector, $1/\tau_r$.

Figure 5: Rossi-α distribution for a subcritical level of -3363.76pcm.



In order to determine some kinetic parameters, in particular β and Λ, we developed a new methodology based on the Two-Region Model. In contrast with other techniques like the Slope Method, Nelson-Number Method and ^{252}Cf-Source Method [15], the main advantage of this new methodology is to obtain the parameters in a purely experimental way. In other words, this methodology eliminates all parameters that are difficult to measure or calculate, and the accuracy of kinetic parameters obtained is dependent just on the quality of experimental data. In this new methodology, the parameters α_o, τ_c, τ_r, f and β can be obtained by fitting the measured α vs. reactivity curve using Eq. 1. This procedure is indicated by the solid-line in Fig. 6, and the results are showed in Tab. 1.

Figure 6: The prompt neutron decay constant, α, vs. reactivity. The parameters were



parameter	Rossi-α (core measurements)	Rossi-α (reflector measurements)	Frequency Analysis[a]	Frequency Analysis[b]
α_0	$-235.12(1.76)s^{-1}$	$-234.42s^{-1}$	$-234.61(3.26)s^{-1}$	$231.00(0.94)s^{-1}$
τ_c	-	$29.516(1.296)\mu s$	$21.145\mu s$	-
τ_r	-	$0.238(0.018)ms$	$1.415ms$	-
f	-	$0.009517(0.003956)$	0.0059	-
β	-	$7.55(0.11)x10^{-3}$	$7.47(0.11)x10^{-3}$	$7.39(0.07)x10^{-3}$
Λ	-	$32.08(0.31)\mu s$	$32\mu s$	$31.99(0.33)\mu s$

[a] With delayed neutron[8]
[b] Without delayed neutron[17]

According to Tab. 1, we demonstrated the consistency of the measurement of α_o both in the core and in the reflector region. The reflector value was obtained by extrapolating the data of the curve for the critical state.

The measured quantities τ_c, τ_r and f, can be combined to yield the prompt neutron generation time, Λ, by the following relation[1]:

$$\Lambda = \frac{1}{1-f}(\tau_c + f\tau_r) \tag{4}$$

and the obtained value is $\Lambda=32.08(0.31)\mu s$.

As observed in Tab. 1., the measured values for $\beta=7.55(0.11)x10^{-3}$ and $\Lambda=32.08(0.31)\mu s$ are well in accordance with a previous results from frequency analysis methods[8,17]. The small standard deviations show that precise absolute measurements for β and Λ can be obtained.

Tab. 2 was extracted from Ref. 14 and shows calculational results from TORT and MCNP-4C3. The theory/experiment comparison (Tabs. 1 and 2) shows that the JENDL3.3 has the best performance. This is a direct consequence of a adoption of a smaller ^{235}U Thermal yield as proposed by Okajima and Sakurai [18].

Table 2 Final calculated results for β_{eff} and Λ given by TORT (S_{16} and 16 groups)

		ENDF/B-VI.8[(a)]	JEFF-3.1	JENDL 3.3
β_{eff} (pcm)	TORT	792.38	774.38	756.16
	MCNP-4C3	781.6 ± 4.1	771.7 ± 4.1	755.6 ± 4.0
^{235}U Thermal yield		1.670×10^{-2}	1.620×10^{-2}	1.585×10^{-2}

(a) LANL review

5. Conclusions

Rossi-α experiments for validation of Two-Region Model and absolute determination of β and Λ were successfully performed at the IPEN/MB-01 Research Reactor facility. The observation of two decay modes in Rossi-α distributions recorded in reflector region and the non-linear behavior between α and reactivity, demonstrated that the kinetic behavior of this core is governed by the Two-Region Model. To assure a correct validation of nuclear data library and neutron transport codes, a new methodology for absolute measurement of β and Λ based on Two-Region Model was developed. By adopting this approach, values for β and Λ are derived without any calculations or other experiments. The obtained results agree well with values from frequency analysis experiments. The results also show that uncertainties of 1.46% and 0.97% on, respectively, β and Λ are achievable, and a precise absolute measurements for these parameters using this new technique can be obtained. The theory/experiment comparison of β_{eff} shows that among the available nuclear data libraries JENDL3.3 has the best performance. The reduction of the ^{235}U Thermal yield as proposed by Okajima and Sakurai is completely justified according to the β_{eff} measurements performed in this work.

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