A Simple Way to Overcome the Shortage of ^{3}He Detectors in the IPEN/MB-01 Nuclear Reactor

E. Gonnelli, L. N. Pinto, H. R. Landim, R. Diniz, R. Jerez, and A. dos Santos

***Abstract*— In order to overcome the shortage of ^{3}He detectors for subcritical experiments in the IPEN/MB-01 reactor, some experiments were performed employing less sensitive detectors, such as BF_3, and a logic input module, which sums the counts from different detectors. Through microscopic and macroscopic neutron noise technique, it was possible to obtain, respectively, Rossi-α distribution and Auto Power Spectral Densities (APSD) for each detector configuration and various subcritical levels, and the prompt neutron decay constant (α) was extracted through a least squares procedure. In addition, Cross Power Spectral Densities (CPSD) were acquired for different types of detectors and the correlation among those detectors was confirmed. It was also observed that there was no loss of correlation among the neutron pulses, and therefore, the CPSD curves demonstrated the presence of correlated events. The α parameter was used as an indicator for the comparison of the results and for the quality of the experimental data. The obtained values demonstrate that the sum of counts technique does not present loss of information (correlated neutrons) even for different models and types of detectors, suggesting that the technique may be employed in neutron noise measurements for subcritical reactivity.**

***Index Terms*— Auto power spectral density, cross power spectral density, neutron noise technique, reactor instrumentation, Rossi-α.**

I. Introduction

THE increasing demand for neutron detection systems based on ^{3}He is generating a huge problem in its production and supply worldwide [1]–[3], mainly in the last decade [4]–[7]. Considering this context, alternative solutions must be thought and developed [8], [9], since the ^{3}He neutron detector is extensively used in strategic fields as scientific research [6], public security (airport and seaport monitoring) [10] and industry applications [6] and mainly in nuclear reactors experiments [11].

The nuclear reactor physics program developed at the Nuclear and Energy Research Institute (IPEN/CNEN – Brazil) performs a series of experiments which the employment of neutron detectors is crucial [12]–[18]. The experiments carried out at the IPEN/MB-01 nuclear reactor facility use several types of thermal neutron detectors – boron lined, boron trifluoride (BF_3) and helium-3 (^{3}He) proportional detectors – for the traditional nuclear reactor physics experiments, including important benchmark works for ICSBEP (International Criticality Safety Benchmark Evaluation Project) [19]–[23] and IRPhEP (International Reactor Physics Evaluation Project) [24] which validate essential parameters.

Subcriticality has been of great experimental and theoretical relevance with the development of Accelerator Driven Systems (ADS) [25]–[29]. Regarding subcritical systems, the IPEN/MB-01 reactor may provide useful results through a series of experiments where new subcritical arrangements for the reactor core are being proposed [23]. In these new configurations, where subcriticality ranges from -3000 pcm to -6000 pcm, BF_3 and Boron Lined counters have not enough sensitivity to give reliable results, and ^{3}He detectors must be employed due to their higher neutron sensitivity.

The aim of this work is to use of a logic input module (ORTEC® Quad 4-Input Logic Unit) [30] to sum the counts from 2 or more BF_3 detectors and to verify if the results of macroscopic and microscopic noise analysis are reliable in comparison to the ^{3}He results. For this purpose, the APSD curves and the Rossi-α distribution of one detector and the combination of two and three detectors were used to obtain the prompt neutron decay constant, α, for 13 subcritical levels, ranging from near critical up to -4000 pcm. The α parameter for each subcritical level and for each Bf_3 detector arrangement, and also for the ^{3}He detector, is obtained by a least squares approach in a purely experimental way. It should be noted that the α parameter is the only parameter that may be used for the comparison of the "detectors performance", since it depends only on the experimental data. The results for ^{3}He detectors presented here are supposed correct for all subcritical levels based on earlier experiments [13], [14], [31].

CPSD curves were also acquired for the 13 subcritical levels aforementioned in order to show that the correlation measurements with three different detectors (two BF_3 and one He^3) are possible. In this case, the sum of two detectors of BF_3 was correlated with the signal of a third detector of ^{3}He. In other words, the sum of two detectors was cross-correlated with the signal of a third detector. The results also show that the logic unit does not provide any significant delay in the process of summation.

The work demonstrates that the achievement of good quality measures is viable without the employment of more sensitive detectors. The data acquisition technique, where the signals

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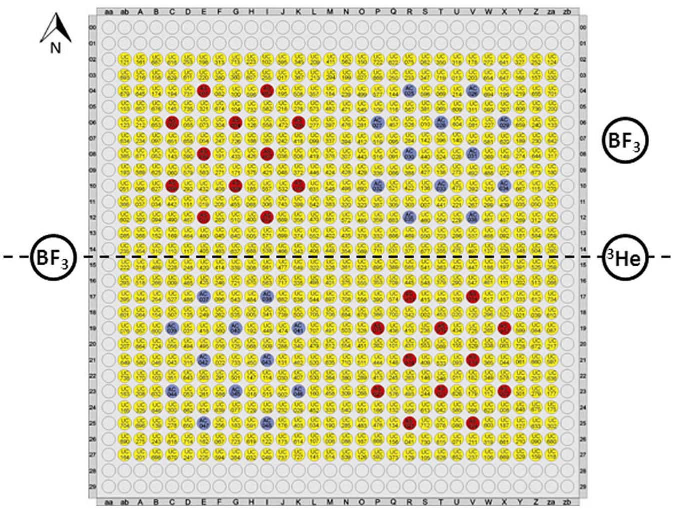

Fig. 1. Standard core configuration of the IPEN/MB-01 reactor. This upper view shows the fuel rods in yellow, the control rod banks (BC#1 and BC#2) in blue and the safety rod banks in red. The black circles (right and left side) represent the location in the reflector region. The dashed line is the central position which the two detectors combination was used.

of detectors are summed, could allow the possibility to overcome the ^{3}He detectors shortage by using less sensitive, less expensive and more accessible neutron detectors, as BF_3.

II. Experimental Procedure

Thirteen subcritical levels were considered in this work where the movement of control banks BC#1 and BC#2 occurs in steps of 2.50% of insertion. Both control banks initiated their positions in 55.00% withdrawn (near critical state) and finished in the 25.00% withdrawn (-4000 pcm subcritical).

The experiment employed BF_3 and ^{3}He detectors, each one having their own set of electronic equipment (standard equipment for pulse mode detectors). Hereafter, the superscripts (a) and (b) will be used for different detectors of the same type (or the same gas), as BF_3^a, BF_3^b, $^3He^a$ and $^3He^b$.

The main properties of these detectors are as follows:

BF_3^a: Reuter Stokes, model RS-P1-0820-201.
Gas pressure: 40 cm Hg
Thermal neutron sensitivity: ~ 13 cps/nv

BF_3^b: Reuter-Stokes, model RS-P1-0836-201
Gas pressure: 40 cm Hg
Thermal neutron sensitivity: ~ 11 cps/nv

$^3He^a$: Centronic, model 31-He3-380/25
Gas pressure: 380 cm Hg
Thermal neutron sensitivity: ~ 54 cps/nv

$^3He^b$: Centronic, model 50-He3-760/38E
Gas pressure: 760 cm Hg
Thermal neutron sensitivity: ~ 186 cps/nv

The Fig. 1 illustrates the core configuration and the detectors position for the case where three detectors are employed. For the configurations employing two detectors, the central position was used (dashed line).

The standard core configuration with 28×26 fuel rods was used for the whole set of experiments. In this way it was possible to achieve a large range of subcritical levels and, for

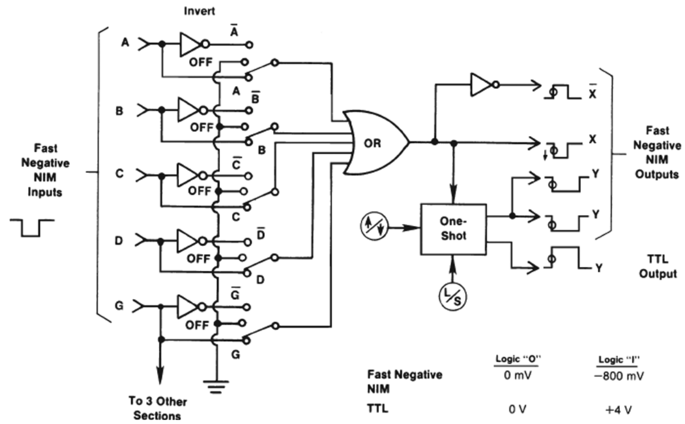

Fig. 2. Block Diagram of the Model CO4020 Logic Unit.

this particular experiment, the reactivity ranged about -70 up to -4000 pcm, which corresponds to 55.00% and 25.00% of control banks withdrawn, respectively.

Through the acquired neutron signals the Auto Power Spectral Densities were obtained using a Multichannel Scaler (MCS-pci^{TM} board) attached in a desktop computer by a PCI Local Bus standard. The MCS board, which has no dead time between adjacent channels [32], records the counting rate of events in a given time bin (dwell time), and the APSD is obtained by a Fast Fourier Transform (FFT) algorithm using a LabView^{TM} software. In all cases, the APSD curves were obtained with 500 averages.

The Rossi-α distribution was acquired using the same electronic system described above. The Rossi-α method is based on the time distribution of the acquired neutron pulses followed by a trigger pulse from the detector [31].

The prompt neutron decay constant (α) is then derived by a least squares fitting of the experimental APSD curves and Rossi-α distribution through the theoretical model based on the standard point kinetic equations [22].

A. Nuclear Module

The ORTEC Model CO4020 Quad 4-Input Logic Unit [30] may provide several logic functions without the necessity of other logic modules in the electronic system acquisition. The more useful function for this work is the *Fan-in* and it represents the *OR* logic operation. The selected function sums the neutron negative logic pulses, fast NIM, from the amplifier module. In a simplified mode the equation below represents the logic operation *OR*:

$$X = A + B + C + D. \tag{1}$$

X is the fast-NIM logic output signal and A, B, C and D are the input fast-NIM logic signals

The Fig. 2 represents the block diagram of the CO4020 Model Logic Unit and it shows all the possible combinations of logic functions that could be implemented [30].

III. Results

The results for the α parameter achieved from single detectors and pair combinations through the APSD curves and Rossi-α distribution are shown in Figs. 3 and 4, respectively.

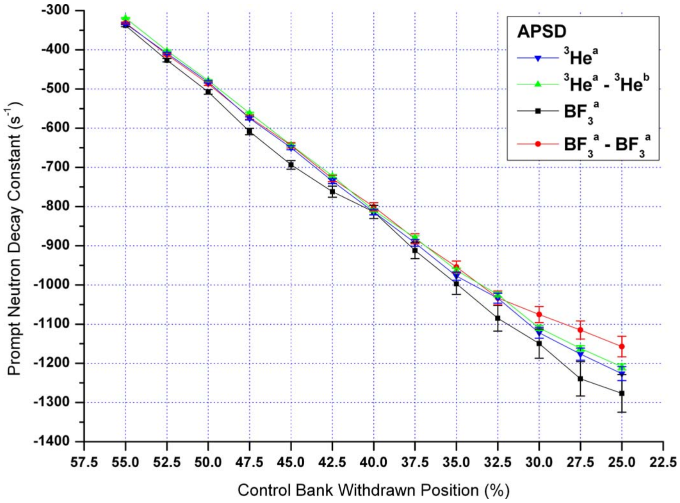

Fig. 3. The alpha results obtained by the experimental APSD curve fitting for all subcritical reactivity steps.

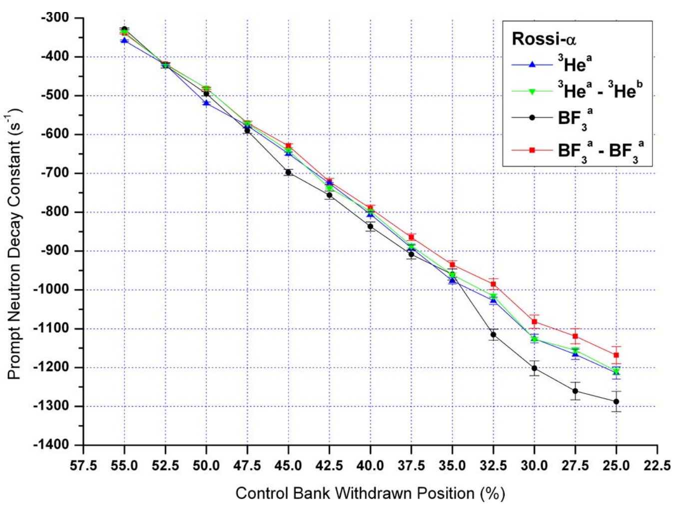

Fig. 4. The alpha results obtained by the experimental Rossi-α curve fitting for all subcritical reactivity steps.

As may be seen from Figs. 3 and 4, the agreement of only one BF_3 detector (black line) with the ^{3}He detectors (blue and green lines) is not good, but there is an improvement when one more BF_3 detector is added (red line). However, the agreement is still not good for 30.00%, 27.50% and 25.00% of banks withdrawn, which represent more subcritical states. This means that the sum of the counts from two BF_3 detectors is not enough to give reliable results for these three subcritical states.

Figs. 3 and 4 also show that the results for one ^{3}He detector and for the sum of two ^{3}He detector are almost the same, indicating that the individual ^{3}He detectors (a) and (b) already have enough sensitivity to give reliable results up to -4000 pcm, as expected [13], [14].

Figs. 5 and 6 show the results for α obtained with one ^{3}He detector and the sum of three BF_3 detectors for the APSD and Rossi-α, respectively. As may be seen in the Figs. 5 and 6, there was a good improvement when three BF_3 detectors are employed.

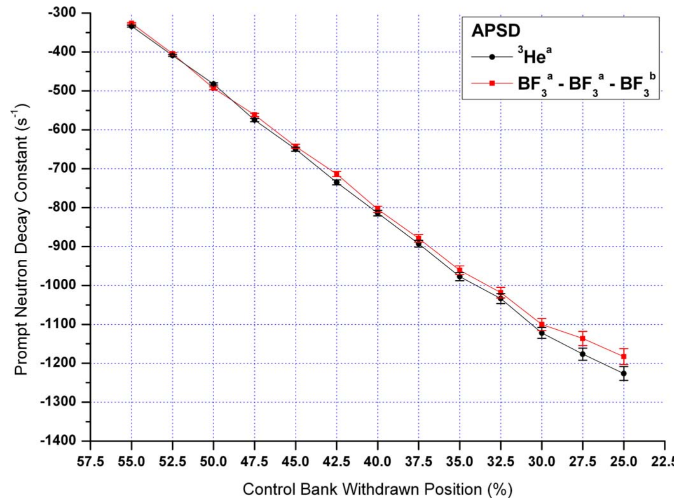

Fig. 5. α results from a set of three BF_3 detectors and one single ^{3}He detector from the APSD.

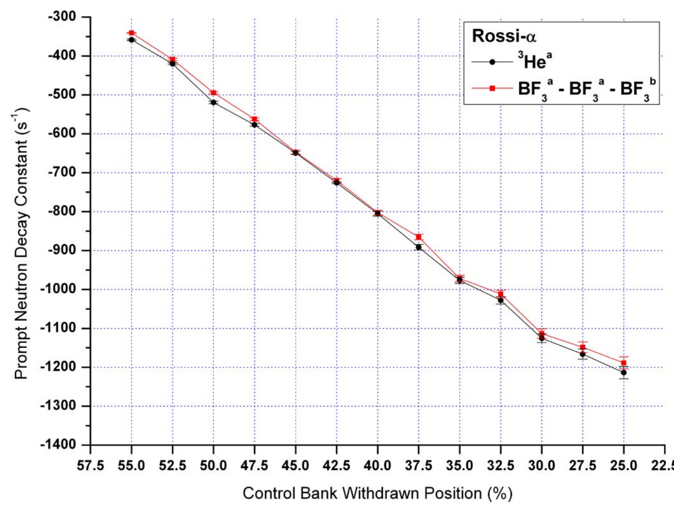

Fig. 6. α results from a set of three BF_3 detectors and one single ^{3}He detector from the Rossi-α.

In the Fig. 5 there is still some disagreement for the last two bank positions but to a lesser extent than the earlier case. Even so, the tendency for reach the ^{3}He detector results are clear. As expressed in Fig. 6, the Rossi-α results are more in agreement with the ^{3}He results than the results of the APSD for the last three subcritical reactivity steps.

The uncertainty of the α parameter, obtained from the fitting procedure, also decreases as more detectors are employed. The decrease in the uncertainty of the α parameter may be seen in Tables I and II for the APSD and Rossi-α, respectively.

For a given state of the reactor, a low sensitivity detector has also a low efficiency (in detected neutrons per all neutrons in the reactor) and this efficiency is a limiting factor for the discrimination of correlated neutrons to uncorrelated neutrons, i.e., the first plateau to the second plateau of the APSD. The relative proportion of correlated noise to uncorrelated noise is crucial for the determination of any parameter from spectral densities [33]. Thus, the addition of more detectors is equivalent to increase the sensitivity and the efficiency of a single detector, and so increasing the correlated noise to uncorrelated noise ratio.

TABLE I

THE PERCENTAGE DECREASE OF THE STANDARD ERROR FOR THE PROMPT NEUTRON DECAY CONSTANT. THE RESULTS WERE OBTAINED FROM THE APSD

Control Banks Position (%)	Standard Error			Percentage decrease of Standard Error (%)	
	BF_3^a A	BF_3^a- BF_3^a B	BF_3^a- BF_3^a BF_3^b C	A - B	B - C
55.00	3.13	2.36	2.04	24.69	13.56
52.50	4.45	3.11	2.66	30.08	14.47
50.00	6.06	4.01	3.46	33.79	13.72
47.50	8.28	5.23	4.26	36.88	18.55
45.00	11.06	6.57	5.36	40.56	18.42
42.50	14.04	8.29	6.60	40.96	20.39
40.00	16.79	10.33	8.01	38.46	22.46
37.50	20.71	12.56	9.72	39.36	22.61
35.00	27.22	14.96	11.38	45.05	23.93
32.50	32.79	17.71	13.84	46.00	21.85
30.00	37.35	20.63	15.50	44.76	24.87
27.50	43.88	23.07	18.03	47.41	21.85
25.00	47.97	26.15	20.35	45.49	22.18

TABLE II

THE PERCENTAGE DECREASE OF THE STANDARD ERROR FOR THE PROMPT NEUTRON DECAY CONSTANT. THE RESULTS WERE OBTAINED FROM THE ROSSI-α

Control Banks Position (%)	Standard Error			Percentage decrease of Standard Error (%)	
	BF_3^a A	BF_3^a -BF_3^a B	BF_3^a- BF_3^a BF_3^b C	A - B	B - C
55.00	2.31	1.81	1.02	21.53	43.44
52.50	6.57	3.84	3.14	41.49	18.41
50.00	5.78	2.82	2.79	51.19	0.91
47.50	7.05	4.58	3.42	34.95	25.33
45.00	7.84	5.05	4.86	35.58	3.79
42.50	10.48	8.43	4.48	19.54	46.87
40.00	11.86	8.13	6.09	31.48	25.03
37.50	11.62	8.72	7.14	24.94	18.21
35.00	14.42	10.76	8.05	25.35	25.20
32.50	17.68	14.16	9.85	19.90	30.48
30.00	19.22	17.02	12.42	11.44	27.05
27.50	22.54	19.52	13.79	13.39	29.36
25.00	26.10	21.99	15.55	15.78	29.28

The increase of correlated to uncorrelated ratio may be seen in Fig. 7. It shows the APSD for the most subcritical state (banks 25.00% withdrawn) obtained from two individual BF_3 detectors (in red and in black) and for the neutron pulses sum of both detectors (in blue).

The improvement of α results, when the signals of two or three detectors are summed, occurs due to the increase in neutron sensitivity. For a single detector, it is needed that its sensitivity has a minimum value in order to discriminate between correlated and uncorrelated neutron noise [33]. For the two individual BF_3 detectors (red and black), the ratio of correlated to uncorrelated noise is about 1.21, and the ratio for the sum of counts (blue) is about 1.39, which shows an increase in the difference between the correlated and the uncorrelated noise. Considering that, the improvement of results comes from this fact.

The error bar in each frequency point of the APSD is given by $1/\sqrt{N} = 1/\sqrt{500} = 4.5\%$, (N = 500 is the number of averages, not the counts of a given detector), i.e., each point of the APSD has an error bar of magnitude 4.5% of its value. The error bars of the APSD are frequency independent, while those of the CPSD are not, being given by $1/\sqrt{\gamma N}$, where γ is the coherence function ($\gamma \leq 1$) and N is the number of averages [34]. The data that originated the APSD, related to the banks position in 25.00%, are shown in Fig. 8.

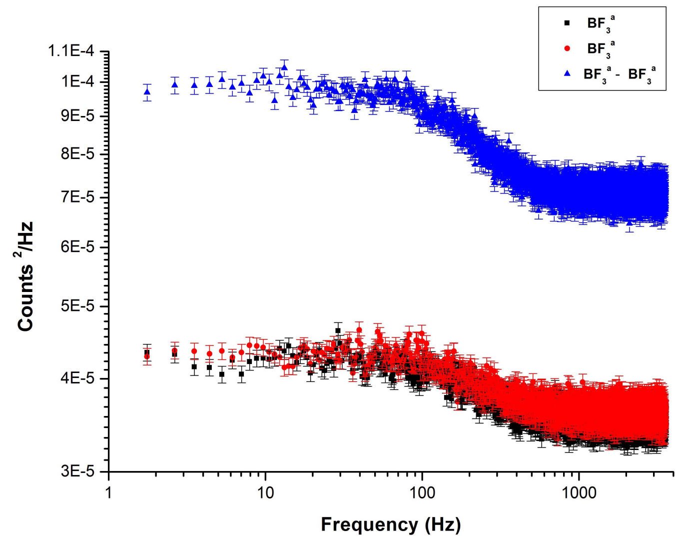

Fig. 7. APSD obtained from two individual BF_3 detectors and for the neutron pulses sum of both detectors (banks position in 25.00%). Each point has an error bar, in %, given by [1/SQRT(500)], were 500 is the number of averages.

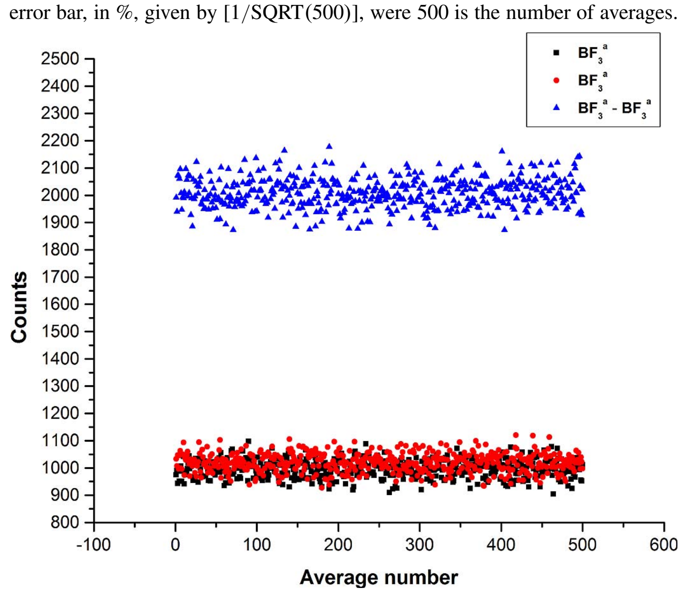

Fig. 8. Raw data for obtaining the APSD of Fig. 7.

Fig. 8 shows the counting (1.0 second measurement time and 500 samples) for three detectors and Control Banks (CB) positions 25% withdrawn. These CB positions correspond to about −4.000 pcm subcritical and all the three counts are normally distributed at 0.05 (5%) level of significance - Shapiro-Wilk and Kolmogorov-Smirnov tests [35], [36]. The mean counting for each detector and respective standard deviation (all uncertainties are within the interval of one standard deviations, i.e., 1σ) are:

BF_3 (red):

$$\text{Mean counting (in 500 samples)} = 1019.82 \pm 34.88$$

BF_3 (black):

$$\text{Mean counting (in 500 samples)} = 995.58 \pm 32.94$$

Sum of the two BF_3 (blue):

$$\text{Mean counting (in 500 samples)} = 2007.99 \pm 54.24$$

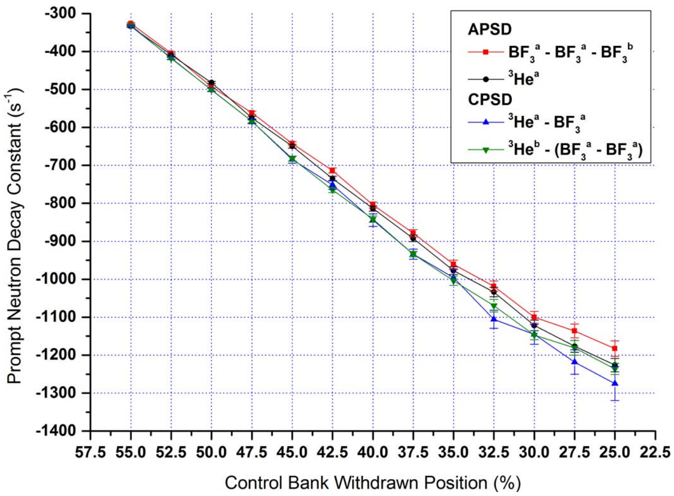

Fig. 9. The alpha results obtained by the experimental CPSD curve fitting for all subcritical reactivity steps. The green data represent the alpha values from the correlation between the sums of neutron pulses from two BF_3 detectors and one ^{3}He detector.

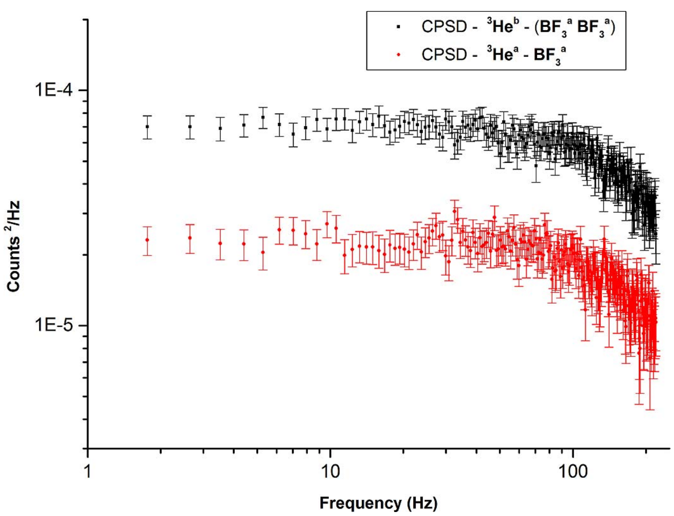

Fig. 10. CPSD obtained for two different combinations of detectors in a frequency range of 250 Hz. The presented power spectral densities were obtained for a total frequency interval of 4 kHz. The black data represent the achieved CPSD employing the neutron pulses summation while in the red data represent the CPSD without the summation system.

The alpha results obtained by the experimental CPSD curve fitting for all subcritical reactivity steps are shown in Fig. 9.

The CPSD considering the combination of different detectors can be seen in Fig. 10. The comparison between the CPSD obtained for the most subcritical state (banks 25.00% withdrawn) is showed. The red data represent the CPSD between two individual detectors ($^3He^a$ and BF_3^a) without the process of neutron pulses summation. The black data represent the CPSD between three detectors ($^3He^b$, BF_3^a and BF_3^a) which the process of neutron pulses summation was employed.

For all cross-power spectral densities were observed the correlated neutron events and uncorrelated events which also show that the correlation measurements with three different detectors are possible. In this case, the sum of two detectors was correlated with the signal of a third detector. The sample rate used for all CPSD and APSD was of 4 kHz. However, the frequency interval chosen to apply the least-square method was about 250 Hz exclusively for the CPSD, i.e., the frequency range that represents the correlated events. Regarding the uncorrelated events for the CPSD curves, the uncorrelated noise begins in 350 Hz, approximately.

In CPSD curves, for banks position in 25.00%, uncorrelated events are 10 times lower than correlated events. It should be highlighted that the ratio between correlated and uncorrelated events is much higher in CPSD curves than in APSD curves, thus the uncorrelated events must be neglected to perform the CPSD fit. In a decibel scale this relation represents a decrease of 10 dB in uncorrelated events in comparison to correlated events. Comparatively, the banks position in 55.00% for the CPSD, represents a ratio between the correlated and uncorrelated events of more than 300.

IV. Conclusions

The experimental determination of the prompt neutron decay constant (α) was successfully performed at the IPEN/MB-01 reactor and the presented methodology demonstrated that the logic pulse module may be employed to sum the neutron counts of three detectors in subcritical states.

Adopting this approach, the neutron counts were enhanced, the experimental data were statistically improved and the standard errors of the α parameter were decreased. In addition, it should be emphasized that in deeply subcritical states, where the macroscopic neutron noise technique tends to fail, the summation of the neutron counts contributed positively over the plateaux difference of the auto power spectral densities. The greater the difference between the plateaux, the more reliable the α parameter result will be. This may be seen while employing the three BF_3 detectors. The results are in agreement with one ^{3}He detector, though the last three subcritical states have coincided within the interval of two standard deviations. The Rossi-α experiments provided better results for the last three subcritical states than those of the APSD. The cross correlation (CPSD) also shows equivalent results for the α parameter when in comparison with the APSD results.

The obtained values demonstrated that the summation of counts technique does not present loss of information (correlated neutrons) even for different models and types of detectors, showing that the technique may be employed in neutron noise measurements for subcritical reactivity.

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