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Study of the Influence of Source Type in the Kinetics Measurements in a Subcritical System

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1. Introduction

The interest in Accelerator Driven Systems (ADS) has increased the attention for the measurements of kinetic parameters in subcritical assemblies driven by an external source. A pulsed source is time-dependent, thus the corresponding methods based on the fluctuation measurements are reformulated ([1] and [2]). Because the time distribution of the neutron's population is used to obtain the reactivity of the subcritical system, we must consider the time dependent propagation of the external source in space and energy. The time distribution of a pulsed source give us information not only about the fission time distribution but about the reflector influence in the reactor system and its material composition.

One of the goals of the MUSE 4 program at the Cadarache Center of CEA (France) is to investigate methods to measure and monitor the reactivity in an ADS. A deuterium accelerator (GENEPI) with a deuterium and a tritium target has been coupled to a subcritical reactor (MASURCA). To study the influence of a source driven subricitical system we have performed measurements at the same reactivity with 3 different type of sources: Cf-252 (spontaneous source), deuterium-deuterium and deuterium-tritium pulsed sources.

2. Experimental Set-Up

For the experiments studied, the MASURCA fast reactor at Cadarache was loaded with MOX fuel and sodium pins to simulate the coolant [15]. Furthermore, the core contains a vacuum beam tube, at the end of which a deuterium or tritium target is positioned. A lead buffer zone surrounds the target to simulate the influence of a spallation target on the neutron spectrum that would be present in ADS driven by a high-energy proton beam. A stainless steel-sodium reflector surrounds the core. Axially the core is shielded with stainless steel and in the radial direction with iron. Some kinetic parameters of the reactor are the generation time (Λ) which is about $0.61\mu s$ and β_{eff} which is about 334 pcm (1 pcm = 10^{-5} $\Delta K_{eff}/K_{eff}$).. Both parameters have been obtained at critical and we assume that they don't change much at subcriticalities of interest.

GENEPI is a deuteron accelerator producing neutrons at the core center from either the D(d,n)^{3}He or the T(d,n)^{4}He reaction [3]. It can operate with a repetition rate between 50 Hz and 4.5 kHz and with a width less than 1 μs (gaussian shape), providing about 3 10^4 $neutrons/pulse$ of an energy of 2.67 MeV in case of the deuterium target and for the tritium 2 10^6 $neutrons/pulse$ of about 14.1 MeV.

Measurements have been performed with a Cf-252 source located in the east-west experimental channel at the center position. The Cf-252 source emits, via spontaneous fission, about 2 10^9 $neutrons/\sec ond$ with a fission spectrum.

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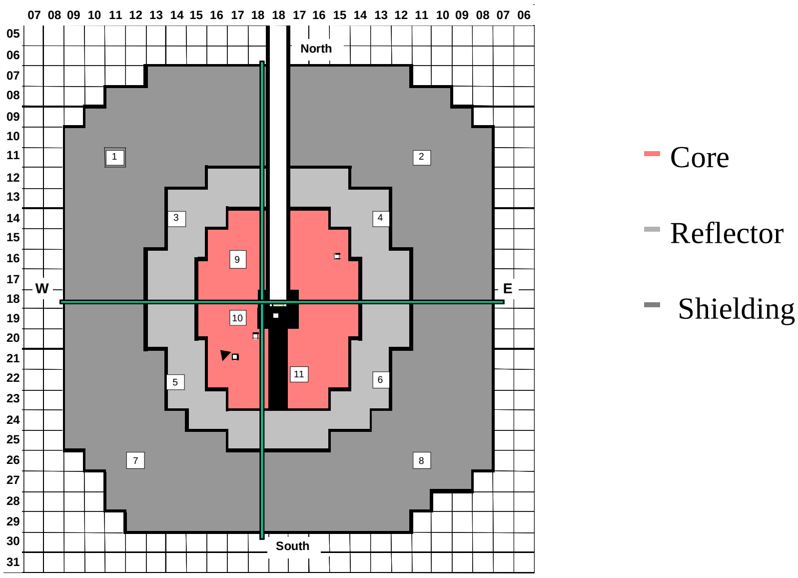

Fig. 1: Horizontal cross section at mid-plane of the MASURCA core with the detector positions indicated.

Fig 1 shows the horizontal cross section at core mid-plane with some of the detector positions. Fission chambers, BF_3 and ^{3}He counters are present. We used ^{235}U fission chambers located in the reflector for the fluctuation technique and a small ^{235}U fission chamber in the east-west experimental channel to study the time evolution of the neutron source.

3. Cross Correlation method

The analysis technique is the time correlation of detection events between two detectors located in the reflector region. The two-detector cross correlation is defined as the joint probability of one neutron detection at time t_2 in dt_2 and another detection at time t_1 in dt_1 following a pulse or spontaneous fission event of the Cf-252 source at time t_0 in dt_0.. In this, we observe that the correlation function is enhanced by the pulsed distribution of the external source.

Because of the MOX fuel used in MASURCA, a second source of neutrons coming from spontaneous fissions and also the (α, n) reaction is present. This source has less importance than the pulsed source or Cf-252 in the contribution to the correlation function, nevertheless it must be considered in a quantitative analyses. In order to simplify the analyses performed in this paper we do not consider the inherent source contribution. Because of the high neutron energy (14.1 MeV) from the deuterium-tritium reaction, the source neutrons can also be multiplied by the (n,2n) reactions in the lead buffer[4]. It means that an extra correlation factor can appear for the tritium target. From the calculations performed with the Monte Carlo code MCNP-DSP [7] it was observed that their contribution to the amplitude is not very important and to neglect it simplifies the understanding.

The correlation function converges faster when the tritium target drives the subcritical reactor because a greater number of neutrons arrive at the detectors in short time periods (relative to DD). We simplify our analysis by studying configurations not deeply subcritical (about 550 pcm).. Point kinetics can been considered as a reasonable approximation for the MASURCA reactor operating at such reactivities [1]. However, some reservation to this hypothesis must be retained knowing that there is a 10 % uncertainty in the alpha-prompt value measured at this sub-criticality [6].

Eq. 1 is the joint probability to have one count in detector D_1 at time t_1 when a count is obtained in detector D_2 at t_2 upon a source neutron inserted in the system at time t_o

$$P(t_2, t_1, t_0)d\tau = \frac{\varepsilon_1\varepsilon_2\left[\frac{F_P(t_0)}{\alpha\Lambda}\overline{\nu(\nu-1)}\right]}{(\overline{\nu}\Lambda)^2}\frac{\exp(-\alpha(t_2+t_1-2t_0))}{2\alpha}d\tau dt_0 \quad (1)$$

$F_P(t)$ is the number of pulsed-induced fissions in Δt, with a time dependence coming from the pulsed source time distribution. $\tau = t_2 - t_1$ is the time difference between the detections at detectors D_1 and D_2. The number of neutrons produced per neutron–induced fission is ν, the neutron generation time and the detector efficiency are given by Λ and ε_i.. The pulse time distribution convolutes with the reactor transfer function, a good knowledge of the pulse shape allow us two separate both functions and get the reactor response.

Because of the relation between pulse width (1 μs) and window period (800 μs), we consider a Dirac delta function for the time pulse distribution and a source frequency (f) lower than the characteristic reactor frequency. The window size for the analyses is choose to have one source pulse per time window. For each pulse the detectors see a burst of neutrons and the correlation amplitude is favored. From these approximations we can integrate the equation 1 over t_0 from $-\infty$ up to the first detection event at t_1.

$$P(\tau)d\tau = \frac{\varepsilon_1\varepsilon_2\left[\frac{F_P}{\alpha\Lambda}\overline{\nu(\nu-1)}\right]}{(\overline{\nu}\Lambda)^2}\frac{\exp(-\alpha|\tau|)}{2\alpha}d\tau \quad (2)$$

F_P is the integral over all possible values of t_0 up to t_1 of $F_P(t_0)$.

The ^{252}Cf source emits the fission neutron randomly in time and amplitude and it can be considered as a constant source, which means a constant induced fission rate F_I. Equation 3 is the integral over t_0 from $-\infty$ up to the first detection event at t_1 of the correlated term of the equation 1:

$$P(\tau)d\tau = \frac{\varepsilon_1\varepsilon_2\left[\frac{F_I\overline{\nu}_I}{\alpha\Lambda}\overline{\nu(\nu-1)}\right]}{(\overline{\nu}\Lambda)^2}\frac{\exp(-\alpha|\tau|)}{2\alpha}d\tau \quad (3)$$

F_I as the number of ^{252}Cf spontaneous induced fissions over all possible values of t_0 up to t_1, $\overline{\nu_I}$ the mean number of neutrons from the spontaneous fission of the ^{252}Cf..

The comparison of equation 2 and 3 results in the equivalence between two formulas changing only the amplitude. However, the eq. 2 is limited to a fitting window of the same size of pulsed source period, for a Dirac pulse shape and we didn't consider the time the source needs to distribute homogeneously in the fuel reactor zone.

From the correlation functions 2 and 3 we extract the prompt time decay constant which is related with the reactivity, ρ , by the point kinetics expresion:

$$\alpha = \frac{\rho - \beta}{\Lambda} \tag{4}$$

The three sources in this study are considered as point sources and they are located at the same position, at the center of the target in the center of the core. The Cf-252 continuous source is compared with the pulsed neutron source produced with the two targets (D-D and D-T) at a frequency of 1kHz et 500Hz respectively. The number of neutrons per second from the spontaneous fission of the Cf-252 source is about twice the neutrons produced per second in the tritium target ($2\ 10^9$). Because the number of neutrons produced in the two targets ($3\ 10^7$ for the deuterium target) is different we compare that influence on the kinetic parameter used. The increasing in the source amplitude translates to a rise in the correlations,Eq (1)-(3), which means a decreasing in the measuring time needed to get the statistics for a correct prompt time decay constant. On the other hand, the comparison between the correlation fonction allow us to confirm the better ratio signal to noise when a pulsed source drives the subcritical system. In Fig 2, we compare the cross-correlation function of two U-235 detectors located in the reflector region of the MASURCA reactor.

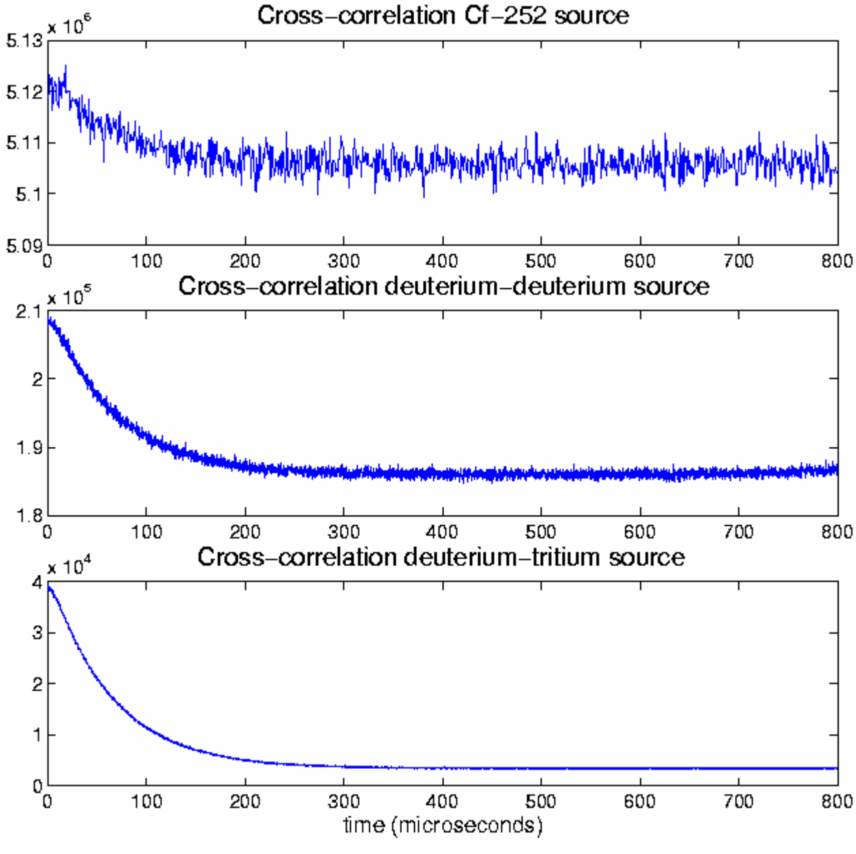

Fig 2 Cross Correlation of a source driven system with 3 different sources

The duration of the measurements presented at the figure above are different and depend on the source. For the Cf-252 correlation curve we performed the measurements for about 6000 seconds, 8000 seconds for the deuterium target and 2400 seconds for the tritium.

The cross correlation function converges faster for the pulsed source and it depends on the intensity of the neutron pulse used. The prompt time decay constant value, α, obtained from the fitting to the fundamental mode for the three functions are coherent, although a great variance is obtained in the case of the Cf-252 because of the poor statistics.

Source type	**Cf-252**	**Deuterium-deuterium**	**Deuterium-Tritium**
α	15699 ± 868 s^{-1}	15183 ± 74 s^{-1}	15824 ± 12 s^{-1}
Fitting window	7-700 μs	28-700 μs	32-700 μs

Table 1: Comparison prompt decay constant

One explanation of the difference between the values obtained with two targets on the pulsed source can be the better statistics of the tritium data, an energy effect caused by the harder spectra of the tritium target but also the stronger influence of the source in the last case. In Fig 2, we observe that accidental correlations are more important in the case of the deuterium source confirming that correlations will be favored with a stronger pulsed source.

During the fitting process we observed that the starting point of the fitting window used changes from one source to the other. For the pulsed source we consider the time the neutrons need to be distributed homogeneously considering also the gaussian time distribution for the pulse [3]. The distance between the source and the detector is large enough to consider that the contribution of direct neutrons from the source is negligible.

The higher intensity of the tritium target produces a strong influence in our kinetic parameters the very first microseconds after the pulse has been emitted. In practice it translates to a decreasing of the fitting window and in an uncertainty in estimation of the starting point of the fitting. At deeper subcriticalities the area of interest will be very much reduced because MASURCA is a fast core. At reactivities with strong spatial effects the space-time source distribution seems to compete with the higher harmonics contribution, which translates to a new source of uncertainty.

4. Time Evolution of the Pulsed Neutron Source

In order to study the pulsed source distribution over the system, we performed measurements at different positions of a U-235 fission chamber located in the experimental channel east-west. For all measurement data presented in this section the target used was the tritium target because of the better statistics. The detector was moved with steps of 106 mm, in Fig 1., from the center of an assembly to the next one.

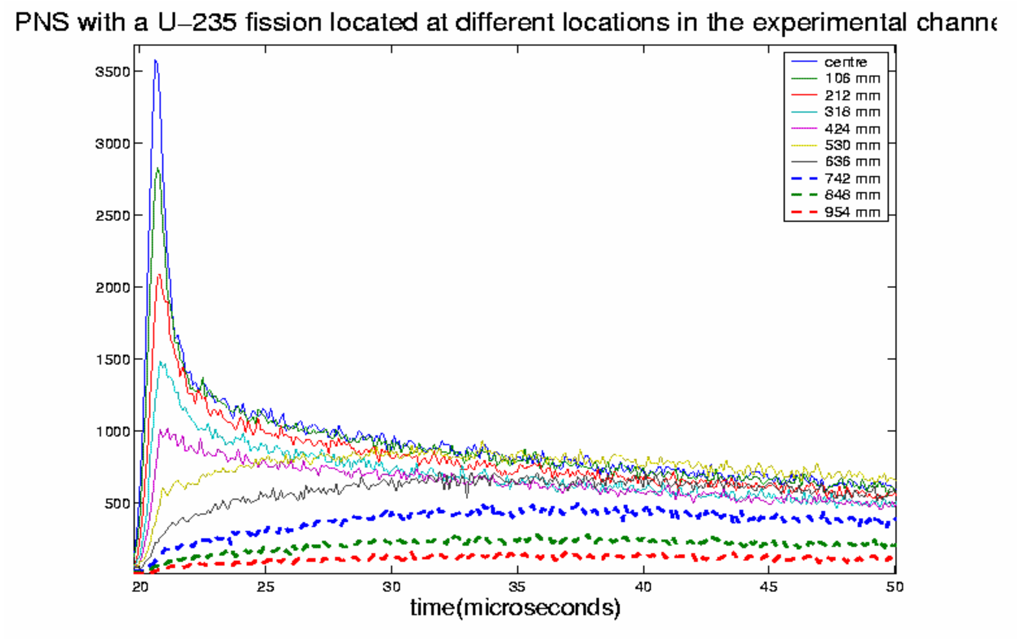

Fig 3: Time evolution at different detector locations

In Fig 3, we observe that the delta Dirac approximation is not valid if we want to study a time window of the first microseconds of the pulse. For fission chamber positions close to the source we observe a fast response for the source and its pulse shape, for further locations the source needs longer time to be distributed homogeneously. From inspection of Fig 3, the fitting window must start after the pulse decays completely and the detector only observes the fission chain time distribution. Because of the non-static characteristic of the pulsed driven system, this starting point must be determined at each measuring position.

The time distribution of the source in the system depends also on the subcriticality level. A homogeneous distribution is achieved faster when the system is more subcritical. The detector location doesn't change from one configuration to the other but the fuel region changes, reducing in radius from the low subcritical (-500 pcm) to the deeper one (-3000pcm). We illustrate this phenomena in figures 4 for detectors located at core, reflector and shielding respectively.

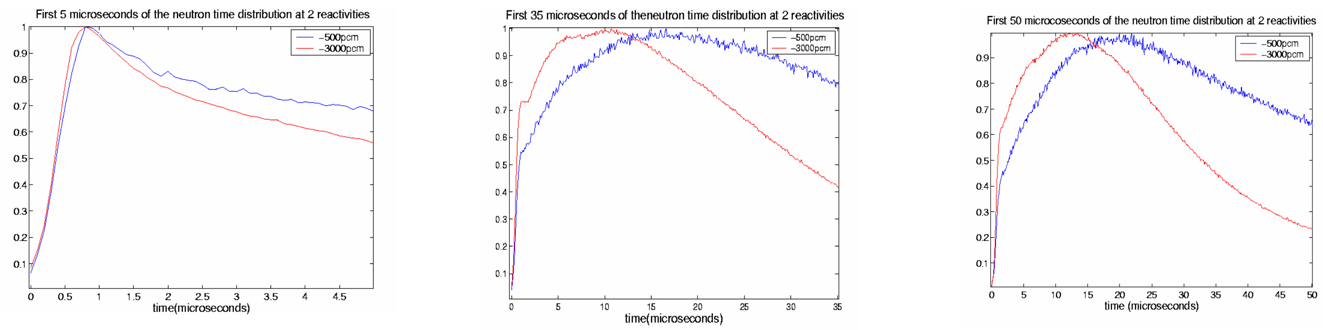

Fig 4 Comparison first microseconds at 2 reactivities et 3 detector locations

For a detector located in the core region the dependency of the source time distribution reactivity is less important that in the reflector and shielding. This is probably because a detector in the core sees the pulse propagation much more directly due to proximity. The pulse passes by rapidly. In the reflector and shield, phenomena are much more complicated by spectral effects. Also in the reflector and shield we see a depression at about 9 microseconds. This effect is stronger as we go deeper in subcriticality, and this is under study.

5. Conclusions

The time distribution in a pulsed driven subcritical system can be quite complicated as it is a combination of source propagation and multiplication. We can therefore use data like these to help to validate neutronics codes, whether used for ADS systems or not.

We observe strong effects of the source time distribution that limit our ability to measure the kinetic parameters as reactivity or beta-effective.

Extrapolating to a future ADS where the neutron source is from spallation, the source importance and the neutron energy will be higher than in MUSE. This means a stronger influence by the time distribution principally in the first microseconds and quite probably more resonance effects will exist. The fact we are seeing such source related phenomena that are clouding the desired measures (reactivity or kinetics parameters such the β_{eff}) at relatively low energies like 14 MeV does not bode well for measures using spallation neutron sources at very high energies. We hope that the TRADE program will contribute to our further understanding.

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