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APPLICATION OF DIGITAL SIGNAL-PROCESSING TECHNIQUE TO DELAYED-NEUTRON YIELD MEASUREMENTS ON THERMAL-NEUTRON INDUCED FISSION OF ^{237}Np

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Приложение методов цифровой обработки сигналов к измерению
выхода запаздывающих нейтронов при делении ^{237}Np тепловыми нейтронами

Описана методика измерения выхода запаздывающих нейтронов деления, основанная на облучении исследуемых ядер ^{237}Np модулированным с помощью механического прерывателя потоком тепловых нейтронов. Идея метода заимствована из современной теории связи, где аналогичная процедура используется для предотвращения неавторизированного доступа к информационным потокам. Для этого поток данных, предназначенных для передачи через каналы связи публичного доступа, сначала модулируется с помощью произвольной кодовой последовательности таким образом, что только получатель, обладающий указанной кодовой последовательностью, сможет восстановить оригинальную информацию. При исследовании реакций, вызванных тепловыми нейтронами, код, использованный для модуляции нейтронного потока, применялся для демодуляции сигналов детектора запаздывающих нейтронов. Тем самым гарантировался ненулевой результат только для сигналов детектора, коррелированных с модуляцией потока тепловых нейтронов. В работе проведено сравнение разработанного метода с применяемыми обычно методами для подобных измерений и показаны особенности разработанного метода, придающие ему особую эффективность в условиях измерений с трудно контролируемыми фоновыми условиями. Использование в измерениях случайных кодовых последовательностей гарантирует качественное отделение эффектов, связанных с исследуемым явлением, от фонов, вызванных другими процессами.

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Zeynalov Sh., Zeynalova O., Smirnov V. E6-2008-27
Application of Digital Signal-Processing Technique to Delayed-Neutron
Yield Measurements on Thermal-Neutron Induced Fission of ^{237}Np

The measurement procedure based on the continuous thermal-neutron beam modulation with a mechanical chopper was developed for delayed-neutron yield measurement of the thermal-neutron induced fission of ^{237}Np. The idea of the procedure is similar to that which is widely used in modern communications for the nonauthorized data access prevention. The data is modulated with predefined pattern before transmission to the public network and only the recipient that has the modulation pattern is able to demodulate it upon reception. For the thermal-neutron induced reaction applications, the thermal-neutron beam modulation pattern was used to demodulate the measured delayed-neutron intensity signals on the detector output resulting in nonzero output only for the detector signals correlated with the beam modulation pattern. A comparison of the method with the conventional measurement procedure was provided, and it was demonstrated that the cross-correlation procedure has special features making it superior over the conventional one when the measured value difference from the background is extremely small. Due to strong sensitivity of measurement procedure on the modulation pattern of the neutron beam, one can implement the modulation pattern of specific shape to separate the effect of the thermal part of the beam from the higher energy one in the most confident way in a particular experiment.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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INTRODUCTION

The conventional measurement procedure of the delayed-neutron yield of the thermal-neutron induced reaction product can usually be considered as a three-phase procedure in which at the first phase the sample is irradiated by thermal neutrons to produce delayed-neutron emitting nuclei. At the second phase following immediately after the first one, the thermal-neutron irradiation stopped and the delayed-neutron yield measurement started. Usually both the irradiation and measurement time intervals are equal to each other and their duration should be chosen long enough for full saturation (or decay) of the investigated nuclei. The third phase, following the second phase, is used for the background measurement and it also should be not shorter than the first two phases for statistical consistency of the result. Multiple repetition of the three phase's procedure with summing of the acquired data improves the statistical accuracy of the measurement to the acceptable level. For the investigated activity to be stabilized at both the saturated and background levels one needs time usually measured in the half-life units ($T_{1/2}$) of the investigated isotope. The activity measurement should be done at the stable levels preventing the transition phase to be involved in the measurement causing additional time delays, usually (6-10) $T_{1/2}$.The cross-correlation procedure contrary to conventional one utilizes the transition phases for measurement excluding hence such time delays providing more efficient use of the neutron beam.

As is well known [1, 2], the thermal-neutron induced fission cross section for ^{237}Np is very small ($\sim$ 20 mb) in comparison with a total one (170 b). This fact causes the significant technical difficulties because of need of a huge amount of the sample material with high intrinsic neutron radioactivity (due to (α, n) and ($\mathrm{n}_{th}\,\gamma$) reactions in sample material) for the acceptable accuracy of the measurements. The insensitivity of the method to neutron signals, that are noncorrelated with modulation pattern of the beam, was its main advantage, that additionally provided automatic subtraction of the background from any intrinsic neutron radioactivity, for example, spontaneous fission or (α, n) reaction.

1. THE EXPERIMENTAL SET-UP

We present the slightly modified experimental set-up described already in [3–6]. A simplified block diagram of the set-up consisting of neutron detector, the beam chopper, and the thermal-neutron flux modulator is shown in Fig. 1. A neutron detector was made of $450 \times 450 \times 700$ mm polyethylene block with cylindrical channel passing through centers of both the quadrant sides of the block. The axis of the hole with the diameter of 150 mm was oriented in parallel to the neutron beam axis. The sample during the measurement was located at the center of the hole and was irradiated homogeneously by the neutron beam of approximately rectangular 15×150 mm shape. The distance between sample location and the neutron source center (flight path) was about 30 m and the inner side of the hole was covered by the metallic cadmium (Cd) sheet to protect the detector from the thermal neutrons scattered on the sample. Twelve cylindrical ^{3}He-proportional counters with dimensions of 32×500 mm were placed at equal distances from each other on the cylinder surface with diameter of 225 mm which was coaxial with the central cylindrical hole.

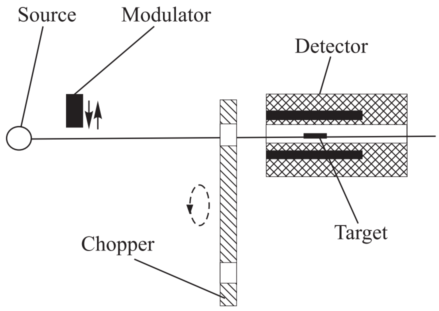

Fig. 1. Experimental set-up

IBR-2 pulsed reactor was used as a neutron source with a pulsing cycle and the mean power of the reactor about 5 per second and 1.5 MW, respectively. There were two kinds of the source neutron pulses inside single reactor burst cycle with the time structure schematically shown in Fig. 2. The neutron source pulse was created by the reactor fissile core and had the width of $\sim 320 \mu$s [7]. That pulse registered by the neutron detector due to part of prompt fission neutrons born inside the core was able to pass through the moderator and surrounding materials almost without collisions. The thermal-neutron pulse of the source was created by neutrons thermalized inside the reactor core and could not be seen directly by the neutron detector, but they caused prompt fission neutrons on the target. These prompt neutrons reproduced the TOF structure of the thermal-neutron pulse at the detector location. The reactor intensity between succeeding bursts was considered as consisting of three main parts: sharp fast neutron pulse, followed by wider

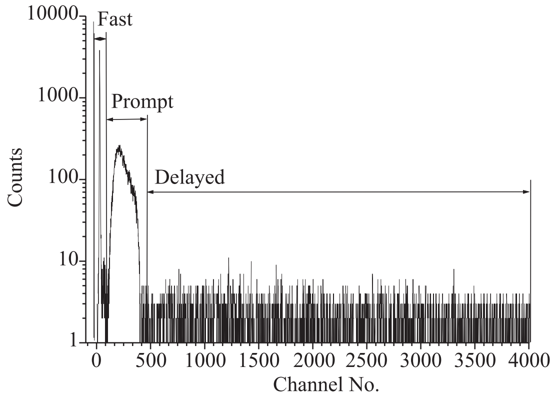

Fig. 2. TOF spectrum obtained for ^{237}Np(n_{th}, f). The allocation of the sampling intervals is schematically shown in the figure

thermal-neutron pulse and the steady state flux of the source which was generated by the reactor core continuously with the same energy spectrum as burst neutrons but with intensity of about 7% of the total neutron flux of the IBR-2. A bent mirror neutron guide (not shown in Fig. 1) was used to reduce (by a factor of ~ 30) the fast neutron flux at the sample position declining the thermal neutrons from the beam axis to about 15 mm. Rotating mechanical chopper consisting of metallic cadmium sheet (1 mm thick) with narrow slit transparent for thermal neutrons, served to shape thermal-neutron pulses and tailor the steady state share of the thermal-neutron flux between reactor pulses. Additional thermal-neutron beam shutter (modulator) controlled by the data acquisition system was used to create the thermal-neutron beam modulation pattern as shown in Fig. 3. When the

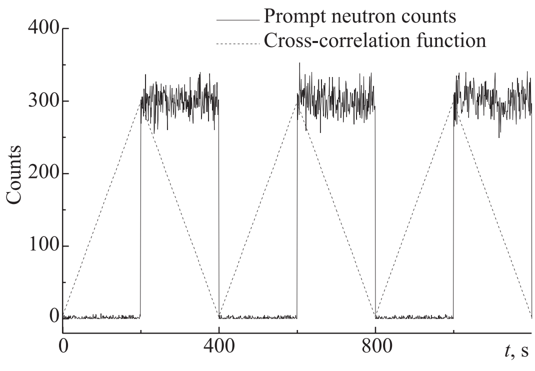

Fig. 3. Time dependence of the PN counting rate when beam modulation was applied (full line). The CCF between PN and beam modulation pattern (dashed line) is normalized to total number of PN detected per modulation cycle

modulator was at the «Beam-On» state, the thermal neutron flux at the sample location was estimated from measurement of fission rate of the ^{235}U sample (~ 12.5 mg of 0.9999 enrichment) found to be 4.0×10^4 n/(s $\cdot$ sm^2) with the stability value no worse than 1%.

Neutron signals detected inside each reactor burst cycle were assigned to the fast, prompt, and delayed neutrons in respect of the beam neutron TOF values as shown in Fig. 2. These signals were normalized to the 5 neutron source burst cycles creating fast, prompt, and delayed neutron counting rate samples per source cycle. The sequence of the samples versus the source cycle number was treated as discrete analog of the corresponding continuous neutron counting rate function sampled with the neutron source cycle. During the open state of the modulator, the delayed neutron counting rate was continuously increasing until reaching the saturation level as schematically shown in Fig. 4. Then the modulator phase was

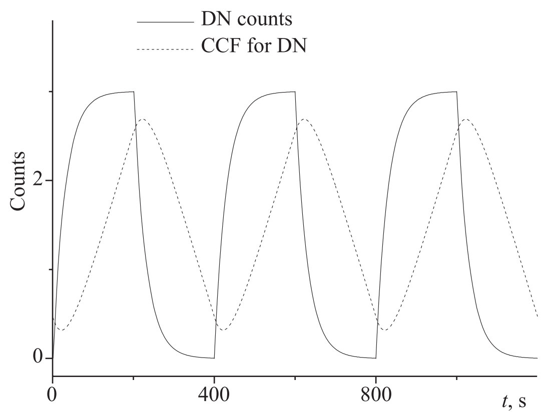

Fig. 4. The simulated time dependence of DN counting rate (full line) along with CCF (dashed line) between DN counting rate and the beam modulation pattern

turned to the «Beam-Off» phase terminating the thermal neutron flux for the same time interval as at the «Beam-On» phase. At the «Beam-Off» phase of the modulator the fast neutron intensity was not terminated, but weakened by the scattering on the modulator to the ~ 0.98 of the value at the «Beam-On» phase as it was evaluated from the attenuation of the fast neutron pulse. The delayed-neutron counting rate at the saturation level in respect to the background level for the given target depended on the fission rate of the target nuclei. The fission rate of the target can be evaluated from simultaneously measured total number of prompt and delayed neutrons using the $\bar{\nu}_p$ value available from the literature and using ^{235}U(n_{th},f) reaction for the calibration as explained in the next chapter.

2. DATA ACQUISITION AND DATA ANALYSIS SYSTEM

The specialized data acquisition system based on IBM-PC plug-in card associated with the data acquisition and data analysis software was developed for measurement and evaluation of the prompt and the delayed neutron counting rate functions. In the present report only a brief review of the electronics was provided, the detailed description is available in [3]. The data acquisition electronics was triggered by the reactor «T-Zero» signal for the thermal neutron TOF measurement. The data acquisition card had 4096 channels of 48 μs each, and it sampled neutron intensity function during $\sim$ 197 ms out of the 200 ms time interval between successive bursts of the reactor. After collecting 5 successive bursts of the reactor, the acquired TOF spectrum was recorded to the PC hard disk along with the information on the beam modulation phase. The beam modulation phase was controlled by the part of the data acquisition software for the synchronization of the beam modulation with the data acquisition. The duration of the beam modulation phase was chosen to be 200 seconds, so for both the phases 1000 TOF distributions were recorded. As was described in the previous chapter, the TOF distributions were used to produce fast (FN), prompt (PN), and delayed neutron (DN) counting rates. All signals making up the TOF distribution were divided into three groups related to the fast ($0 <$ TOF < 1.5 ms), prompt ($1.5 <$ TOF < 24 ms), and delayed ($24 <$ TOF < 180 ms) neutrons according to the TOF values. The numbers of counts in the individual groups were considered as discrete samples of the corresponding counting rates. The prompt neutron counting rate measured for ^{237}Np(n_{th}, f) reaction is shown in Fig. 3 (solid line) along with the cross-correlation function (CCF) between the beam modulation and the PN rate (dashed line) calculated using the formula:

$$PN_{\rm CCF}(t) = \frac{1}{M_N}\int_0^T PN(\tau)M(t-\tau)d\tau,\ \text{where } M_N = \frac{1}{T}\int_0^T M(t)dt. \quad (1)$$

The CCF was normalized to the total number of PN detected per period of modulation function. Because the DN counting rate measured in the same experiment had significant constant background and noise basement, the simulated DN counting rate is presented in Fig. 4 along with the CCF for reference. The time dependence of the measured DN counting rate is shown in Fig. 5, and the corresponding CCF presented in Fig. 6 was calculated using the following formula:

$$DN_{\rm CCF}(t) = \frac{1}{N}\int_0^T DN_N(\tau)\times M(t-\tau)d\tau,\ \text{where the } N = \frac{1}{T}\int_0^T M(\tau)d\tau. \quad (2)$$

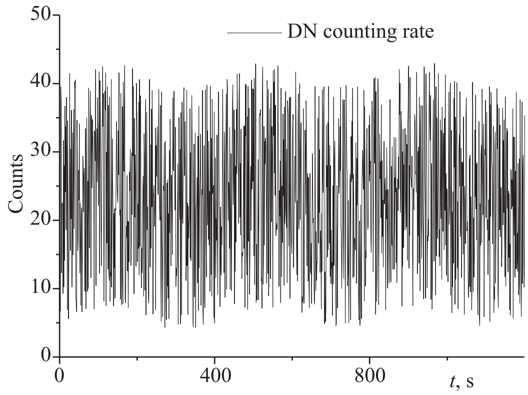

Fig. 5. The time dependence of DN counting rate measured in ^{237}Np(n_{th}, f) reaction with 20 g neptunium sample when beam modulation was applied

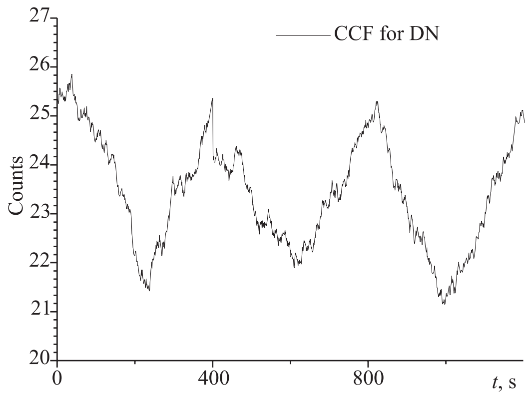

Fig. 6. The time dependence of the CCF between DN counting rate and beam modulation pattern measured in ^{237}Np(n_{th}, f) reaction with 20 g neptunium sample when beam modulation was applied

It is clear from the comparison of the CCF with the original counting rate functions that the CCF had better signal-to-noise ratio due to that CCF is suppressing the frequency components in the original signal which are not present in the modulation function. For further improvement of the signal-to-noise ratio, the CCF and ACF functions were reduced to the single period of the modulation function by summing. We used the ACF for the DN because it produced better signal-to-noise ratio than the CCF. Analyzing the correlation of the FN counting rate with the neutron beam modulation we found the modulation pattern similar to that presented in Fig, 3 for PN. That fact we explained by loss of the fast neutrons after scattering on the cadmium sheet of the beam modulator. The value of the modulation was found to be compatible with the delayed-neutron counting rate and it was taken into account in data analysis for correct evaluation of the delayed-neutron yield as follows. As was mentioned earlier the constant background in the TOF spectrum was created by the steady state flux of the IBR-2 core and it had the same spectrum as the pulsed flux. That is why the same flux reduction due to scattering at the modulator can be expected for the steady state background as for the FN pulse. When the correlation functions are properly normalized, then their average values for the period of modulation function are equal to the number of FN, PN, or DN detected per period plus the average constant background counting rate. Denoting the integral values of PN and DN counts per period as $N_{\rm PN}$ and $N_{\rm DN}$, respectively, one can write the following equation:

$$\frac{N_{\rm PN}}{\nu_p \varepsilon_p} = \frac{N_{\rm DN}}{\nu_{\rm d} \varepsilon_d}. \tag{3}$$

Right and left sides of the equation represent the thermal neutron induced fission rates calculated using PN and DN counts for the same measurement time interval. The values ν_p, $\varepsilon_{\rm p}$ are the average number of prompt neutrons per fission event and neutron detector efficiency for PN, and ν_d, $\varepsilon_{\rm d}$ are corresponding values for DN. Rewriting formula (3) to the following form:

$$\nu_{\rm d} = \frac{N_{\rm PN}}{N_{\rm DN}} \times \frac{\varepsilon_p}{\varepsilon_d} \nu_p, \tag{4}$$

one can find ν_d using measured values $N_{\rm PN}$, $N_{\rm DN}$ and available from the literature the ν_p value. The remaining parameter $\frac{\varepsilon_p}{\varepsilon_d}$ can be obtained from calibration measurement with ^{235}U sample considering formula (5) as the equation in respect

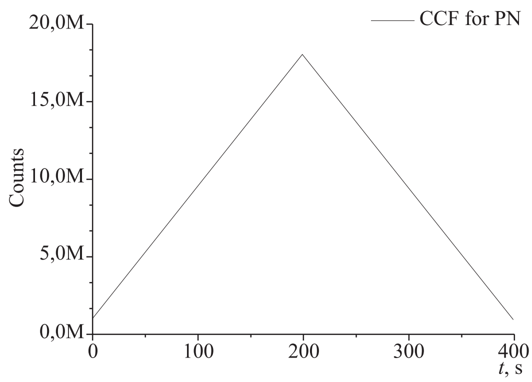

Fig. 7. The time dependence of the CCF between PN counting rate and beam modulation pattern measured in ^{237}Np(n_{th}, f) reaction with 20 g neptunium sample reduced to the one cycle of the beam modulation pattern

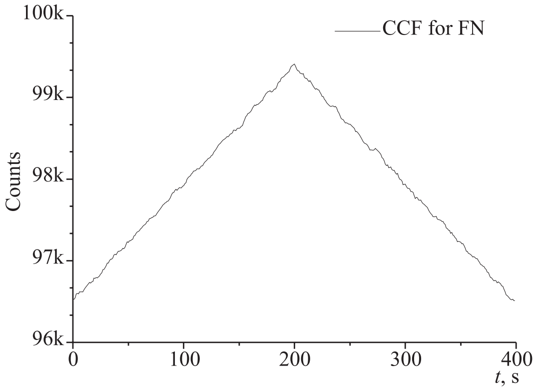

Fig. 8. The time dependence of the CCF between FN counting rate and beam modulation pattern measured in ^{237}Np(n_{th}, f) reaction with 20 g neptunium sample reduced to the one cycle of the beam modulation pattern

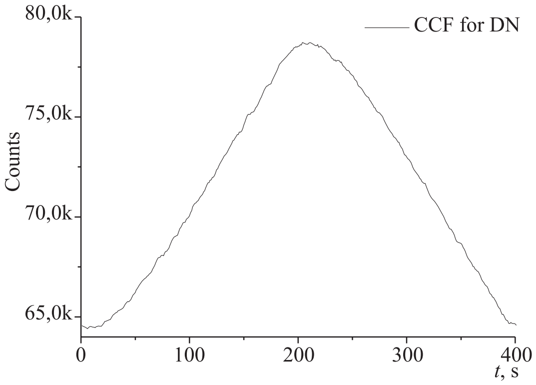

Fig. 9. The time dependence of the CCF between DN counting rate and beam modulation pattern measured in ^{237}Np(n_{th}, f) reaction with 20 g neptunium sample reduced to the one cycle of the beam modulation pattern

to $\dfrac{\varepsilon_p}{\varepsilon_d}$ using value of ν_d for the ^{235}U from the literature. Finally the measurement of delayed neutron yield reduces to the measurement of values $N_{\rm PN}$, $N_{\rm DN}$, which evaluated using functions measured for ^{237}Np(n_{th}, f) reaction and presented in Figs. 7–9.

3. RESULTS AND DISCUSSION

The method discussed above was applied to delayed-neutron yield measurement of thermal-neutron induced fission of ^{237}Np and the following result was found for ~ 90 hours measurement:

$$\nu_d = 0.0114 \pm 0.0009.$$

Comparing the value ν_d for the ^{237}Np(n_{th}, f) reaction with the previous result reported in [6], one can found difference of about 3% which we explain by the neglecting in [6] of the background modulation by the beam shutter described above.

To demonstrate the power and the sensitivity of the developed method, a series of special measurements was carried out with very small ~ 1 mg sample of the ^{235}U with background conditions as for ^{237}Np target. Under this condition measured in the different series, the delayed-neutron yield for thermal-neutron induced fission of ^{235}U was in good agreement with the results obtained with a ^{235}U sample of 12.5 mg measured in normal background conditions.

Finally, the presented method provides at least twice higher value of the thermal-neutron beam utilization efficiency in comparison with the traditional procedure as was implemented in [6].

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