УДК 004.67 : 539.125.5

DELAYED NEUTRON YIELD MEASUREMENT ON THERMAL NEUTRON INDUCED FISSION OF ^{237}Np USING CROSS-CORRELATION TECHNIQUE

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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, widely used in modern computer communications for the non-authorized data access prevention. The data is modulated with predefined pattern before transmission to the public network and only 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 nonzero output only for the detector signals correlated with the beam modulation. The 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 especially when the measured value is extremely small in comparison with the background. 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 most confident way in the particular experiment. The remarkable property of our method is related to the unique possibility of separation the effects caused exclusively by the thermal neutrons using the neutron TOF measurement available on the IBR-2 pulsed reactor.

Experimental setup and measurement method

A simplified block diagram of the experimental setup consisted of neutron detector, the beam chopper and the thermal neutron flux modulator is shown in Fig. 1. A neutron detector was made of 450 × 450 × 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 centre (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. The 12 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.

IBR-2 pulsed reactor was used as a neutron source with the pulsing cycle and the mean power of the reactor were about 5 per second and 1.5 MW respectively. There were two kinds of the source neutron pulses inside single rector burst cycle with the time structure schematically shown in Fig 2. The neutron source pulse was created by the reactor fissile core and had width of ~320 μs. That pulse registered by the neutron detector due to the part of prompt fission neutrons, born inside the core, were able to pass trough the moderator and the surrounding materials almost without collisions. The thermal neutron pulse of the thermalized neutrons induced the fission on the target followed by prompt neutron emission. That prompt neutrons detected by the detector had 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 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 the Fig. 1) was used to reduce (by factor ~30) the fast neutron flux at the sample position declining the thermal neutrons from the beam axis to about 15 mm. Rotating mechanical chopper consisted of metallic cadmium sheet (of 1 mm thickness) with narrow slit transparent for thermal neutrons shaped the thermal neutron pulses and tailor the steady state share of the thermal neutron flux between reactor pulses. Additional thermal neutron beam shutter (modulator) created the thermal neutron beam modulation pattern as shown in the Fig. 2. When the 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 $4.0 \cdot 10^4$ n/(s · cm^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 to the beam neutron

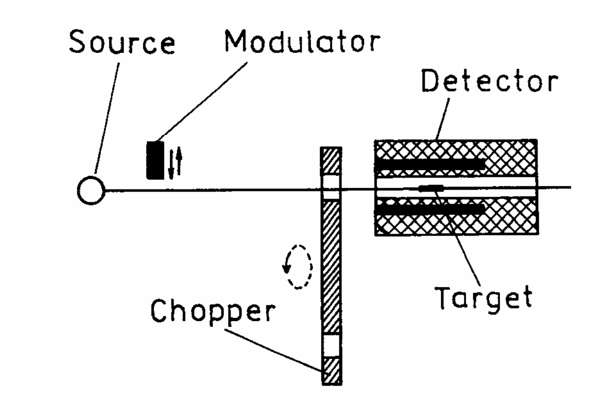

Fig. 1. Experimental Setup.

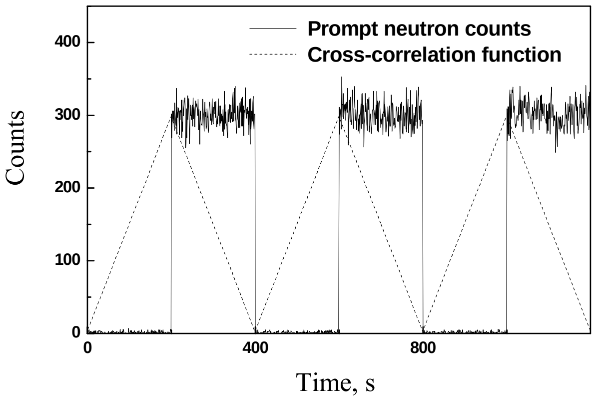

Fig. 2. Thermal neutron beam modulation pattern.

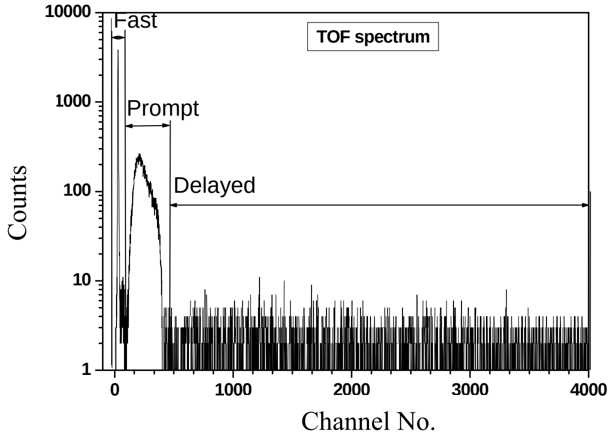

Fig. 3. The measured TOF spectrum.

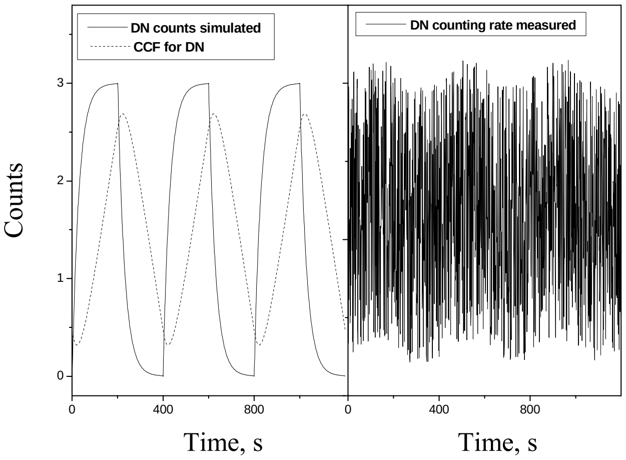

Fig. 4. The calculated (left) and the measured DN counting rates functions (right) for one reactor burst.

TOF values as shown in Fig. 3. 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 increased continuously until reaching the saturation level as schematically shown in Fig. 4. Then the modulator phase was 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 as the reference. 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 s, so for the both phases 1000 TOF distributions was recorded. As was described in 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 was divided into three groups related to the fast ($0 < \mathrm{TOF} < 1.5$ ms), prompt ($1.5 < \mathrm{TOF} < 24$ ms), and delayed ($24 < \mathrm{TOF} < 180$ 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. 2 (solid line) along with the cross-correlation function (CCF) between the beam modulation and the PN rate (dashed line) calculated using the formula:

$$PN_{CCF}(t)=\frac{1}{M_N}\int_0^T PN(\tau)M(t-\tau)d\tau,$$

$$\text{where } \mathrm{M_N}=\frac{1}{T}\int_0^T M(t)dt\,. \qquad (1)$$

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

$$DN_{CCF}(t)=\frac{1}{N}\int_0^T DN_N(\tau)M(t-\tau)d\tau,$$

$$\text{where the } \mathrm{N}=\frac{1}{T}\int_0^{\mathrm{T}} M(\tau)d\tau\,. \qquad (2)$$

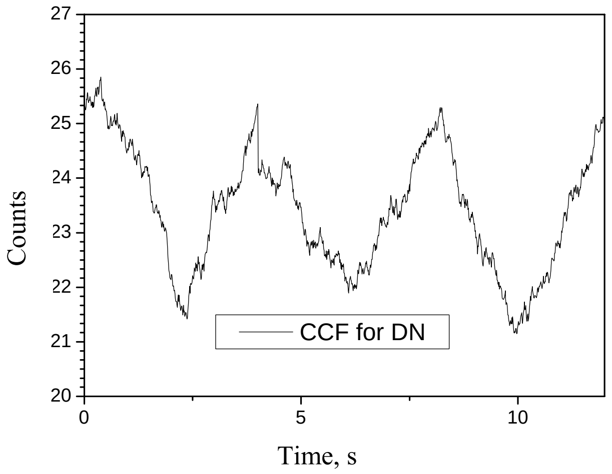

Fig. 5. Measured CCF for DN after 40 averaging.

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 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.

Data analysis and results

Analyzing the correlation of the FN counting rate with the neutron beam modulation we found the modulation pattern similar to that presented in Fig. 6 for PN.

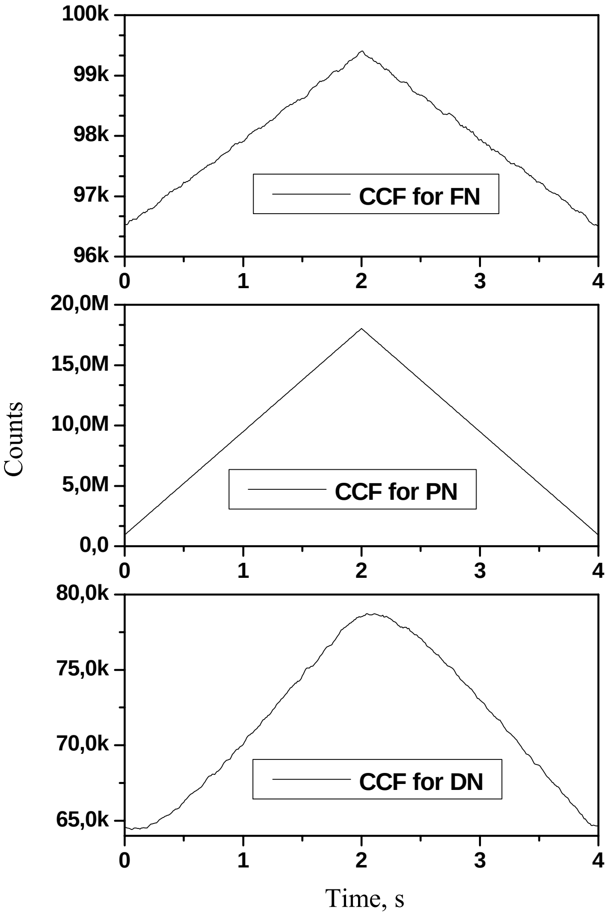

Fig. 6. Measured CCFs after ~$1.6 \cdot 10^6$ averaging.

That fact we explained by lose of the fast neutrons after scattering on the cadmium sheet of 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 period of modulation function are equal 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_{PN} and N_{DN} respectively one can write the following equation:

$$\frac{N_{PN}}{\nu_p \varepsilon_p} = \frac{N_{DN}}{\nu_\mathrm{d} \varepsilon_d}. \qquad (3)$$

Right and left sides of the equation represented the thermal neutron induced fission rates calculated using PN and DN counts for the same measurement time interval. The values ν_p, ε_p – are average number of prompt neutrons per fission event and neutron detector efficiency for PN and ν_d, ε_d – corresponding values for DN. Rewriting formula (3) to the following form:

$$\nu_\mathrm{d} = \frac{N_{PN}}{N_{DN}} \cdot \frac{\varepsilon_p}{\varepsilon_d} \nu_p \ , \qquad (4)$$

one can find ν_d using measured values N_{PN}, N_{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 the formula (5) as the equation in respect to $\frac{\varepsilon_p}{\varepsilon_d}$ using value of ν_d for the ^{235}U from the literature. Finally the measurement of delayed neutron yield reduces to measurement of values N_{PN}, N_{DN}. 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: $\nu_d = 0.0114 \pm 0.0009$.

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ЗАСТОСУВАННЯ МЕТОДІВ ЦИФРОВОЇ ОБРОБКИ СИГНАЛІВ ДО ВИМІРЮВАННЯ ВИХОДУ ЗАПІЗНІЛИХ НЕЙТРОНІВ ПРИ ПОДІЛІ ^{237}Np ТЕПЛОВИМИ НЕЙТРОНАМИ

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Описано методику вимірювання виходу запізнілих нейтронів поділу, що базується на опроміненні досліджуваних ядер ^{237}Np потоком теплових нейтронів, модульованим за допомогою механічного переривника. Ідея методу запозичена із сучасної теорії зв’язку, де подібна процедура застосовується для запобігання неавторизованому доступу до інформаційних потоків. Для цього потік даних, призначених для передачі каналами загального доступу, спочатку модулюється за допомогою довільної кодової послідовності таким чином, щоб тільки одержувач, який знає вказану кодову послідовність, зміг відновити оригінальну інформацію. При дослідженні реакцій, викликаних тепловими нейтронами, код, що використовувався для модуляції нейтронного потоку, застосовувався для демодуляції сигналів детектора запізнілих нейтронів. Таким чином гарантувався ненульовий результат тільки для сигналів детектора, що корелюють з модуляцією потоку теплових нейтронів. Проведено порівняння розробленого методу з методами, що звичайно застосовуються для подібних вимірювань, та показано особливості цього методу, що надають йому особливу ефективність при вимірюваннях у фонових умовах, які важно контролювати. Застосування у вимірюваннях випадкових кодових послідовностей гарантує ефективне відокремлення ефектів, пов’язаних з досліджуваним явищем від фонових подій, викликаних іншими процесами.

ПРИЛОЖЕНИЕ МЕТОДОВ ЦИФРОВОЙ ОБРАБОТКИ СИГНАЛОВ К ИЗМЕРЕНИЮ ВЫХОДА ЗАПАЗДЫВАЮЩИХ НЕЙТРОНОВ ПРИ ДЕЛЕНИИ ^{237}Np ТЕПЛОВЫМИ НЕЙТРОНАМИ

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Описана методика измерения выхода запаздывающих нейтронов деления, основанная на облучении исследуемых ядер ^{237}Np потокам тепловых нейтронов, модулированным с помощью механического прерывателя. 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. Проведено сравнение разработанного метода с применяемыми обычно методами для подобных измерений и показаны особенности этого метода, придающие ему особую эффективность при измерениях с трудно контролируемыми фоновыми условиями. Использование в измерениях случайных кодовых последовательностей гарантирует эффективное отделение эффектов, связанных с исследуемым явлением, от фоновых событий, вызванных другими процессами.

Received 09.06.08,
revised - 25.03.09.