Neutron Channel of the FOBOS Spectrometer for the Study of Spontaneous Fission∗


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Abstract—The 4π spectrometer FOBOS has been completed with the multidetector system for registration of neutrons aimed at experiments to search for collinear tripartition of heavy spontaneously fission nuclei. A simple empirical model developed for the description of the measured neutron multiplicity is tested on the data block comprising 6 × 10⁷ events. © 2003 MAIK “Nauka/Interperiodica”.

The 4π spectrometer FOBOS [1] has been completed with the multidetector belt for registration of neutrons. Of course, the application of neutron detectors at the FOBOS setup is limited to some special experiments due to methodological problems, e.g., thick metallic and hydric matter constructions of the detectors, the large size of the spectrometer, an intensive neutron background from the U-400M cyclotron during in-beam experiments, etc. Bearing in mind these complications, we have found a suitable solution for experiments to search for collinear cluster tripartition (CCT) of heavy spontaneously fissionable nuclei [2]. According to the model [3], such process should be accompanied by almost isotropic emission of postscission neutrons in the laboratory system of the multiplicity as high as ∼10. This agrees with the previous results on spontaneous decay of ²⁴⁸Cm and ²⁵²Cf obtained at the FOBOS setup [3]. Therefore, the CCT events could be separated by considering those with a large number of fired neutron detectors, which reflects a high multiplicity.

The neutrons emitted from the moving fission fragments (FF) are focused along the fission axis. Hence, the optimal configuration of neutron detectors for the separation of the CCT events seems to be a belt of high-efficiency counters assembled in a plane perpendicular to the symmetry axis of the spectrometer configuration, which is obviously the mean fission axis under these conditions. The symmetry center of this belt must coincide with the location of the FF source [4]. This general disposition is illustrated in Fig. 1. Two groups containing five big and one small FOBOS modules each are used as a double-armed TOF-E spectrometer which covers ∼29% of the hemisphere in each arm.

The neutron detector consists of 140 separate hexagonal modules [5] comprising a ³He-filled proportional counter, a moderator, a high-voltage input, and a preamplifier. The counters operate under a gas pressure of 7 bar, being 50 cm in length and 3.2 cm in diameter. The moderator is made of polyethylene. The spacing between the parallel planes of a module is 5 cm. The neutron counters are composed into eight arrangements of 16 counters each and one of 12 counters and they cover altogether effectively ∼19% of the complete solid angle of 4π. The electronics of the “neutron belt” is operated in the slave mode, being triggered by the event selector of the gas part of the FOBOS detector. The view of the spectrometer surrounded by the neutron belt is represented in Fig. 2.

In order to test the results obtained, in particular, the neutron multiplicity distribution, the following approach was used. Three of a total of four different sources of neutrons have been taken into account and the partial contribution of each source to the experimental spectrum of the number of fired neutron detectors (i.e., experimental or measured multiplicity distribution) has been calculated. These sources are as follows:

(1) The moving FF originated from conventional binary fission and detected in coincidence in the opposite arms of the spectrometer. Note that the time gate (128 µs) for the registration of neutrons

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is opened just at the point of time when the FF fire the “stop” detectors.

(2) The FF originated from the fission events coinciding randomly with the gate. This source will be named below the “random source.”

(3) The neutron background.

(4) The central fragment of the chainlike prescission nuclear configuration in CCT [3], which is almost at rest. This source has not been taken into consideration at the present stage of simulations.

The probability $P_k$ of registration of $k$ neutrons from the first source is given by the following expression [4]:

$$P_k = \sum_{N \geq k} P_N C_N^k \varepsilon^k (1 - \varepsilon)^{N-k},$$

(1)

where $P_N$ is the emission probability of $N$ neutrons known from the literature and $\varepsilon$ is the detection efficiency. In the first approximation, $\varepsilon$ can be estimated directly from the measured multiplicity distribution.

In order to take into account the influence of the second (random) source, let us imagine that, at some time point $t_0$ (Fig. 3), the gate $[0; T]$ for detecting of neutrons is already opened as a result of registering the coincident FF. At any point of time $\tau$, an independent fission event can occur. This event is then interpreted as a random coincidence and each neutron emitted by the corresponding FF spends some time $t_d$ until it is detected. The latter is under the condition that the neutron hits the detector belt covering $\eta$ part of the whole sphere. From the physical point of view, the time $t_d$ is spent both for moderation and for secondary diffusion until absorption in one of the $^3$He counters. Time intervals $t_d$ are distributed by an exponential law with the timing constant $\lambda$. The parameter $\lambda$ was derived from the experimental spectrum of neutron detection times (Fig. 4). It should be noted that the neutron registration efficiency is appreciably lower than the geometrical one due to the leaking-out and absorption of neutrons in the moderator. Using the well-known MCNP code, we have estimated the registration efficiency $f$ of the neutron belt during infinite time for an isotropic source. The obtained value of $f$ for the neutron energy of 0.5 MeV is about 60%. The value of $f$ decreases slightly with increasing neutron energy to 1 MeV.

Let us investigate how the experimental multiplicity is formed. Let $k$ neutrons originated from the fission event opening the gate be detected during the gate $[0; T]$. Let during the same gate $r$ neutrons emitted from the FF of the random fission event be detected as well. Then, the number $k_\Sigma = k + r$ is written by the data acquisition system. The distribu-
tion \( P(\tau) \) should be a convolution:

\[
P(\tau) = P_k * P_r,
\]

where the function \( P_k \) is calculated by the expression (1). The function \( P_r \) can be obtained by the serial threefold application of the binomial transformation (1) to the function \( P_N \) (which is the probability of emission of \( N \) neutrons in fission of a \(^{252}\text{Cf}\) nucleus) using \( \eta, f \), and \( \eta_r(t) \), respectively, as the parameters.

As the probability \( \eta_r(t) \) of registration of the neutron hitting the detector at the time point \( \tau \) (Fig. 3) depends on time according the expression

\[
\eta_r(t) = \frac{T - \tau}{T} \int_0^T \lambda \exp(-\lambda t) dt,
\]

it is necessary to integrate function \( P_r \) with the weight function \( n \exp(-nt) \) within the limits \([0; T]\), where \( n \) is the fission rate of the source. The function \( P_N \) obtained above deals with positive times only. At the same time, those neutrons emitted earlier, i.e., at negative times (Fig. 3), can also be detected in the frame of the gate. One can obtain the distribution \( P_{\Sigma} \) conditioned by such events in the same way as above.

The full contribution from the random source \( P_{\Sigma \Sigma} \) is obtained as the sum

\[
P_{\Sigma \Sigma} = P_{\Sigma} + P_{\Sigma -}.
\]

The third source of neutrons, namely, the background, was estimated experimentally. As can be judged from Fig. 4, the count rate at a time later than \( 80 \mu s \) looks like a plateau specified by the contributions of both the background of the experimental hall and the fission neutrons appearing formerly at a negative time and roaming in the neutron belt until the time gate under discussion. In our case, the background is low enough to be omitted.

The proposed model still does not include a contribution of the CCT as a source of neutrons. The existence of such a source itself could be tested by a comparison of the calculated and experimental multiplicity distribution with the calculated one.

Summarizing, the model multiplicity distribution is calculated according the formula:

\[
P_{\text{lin}} = (1 - c) P_k + c P_{\Sigma \Sigma},
\]

where \( c \) is the probability of the random coincident fission events. In the framework of such a definition, the function \( (n/2) \exp(-nt) \) should be normalized to unity and \( c \) is the integral of this function in the limits \([-\infty; T]\).

The calculated spectrum \( P_{\text{lin}} \) is compared with the experimental one in Fig. 5. A good agreement for the major contribution of low multiplicity observed can appraise us of evidence of the model adequacy. The discrepancy observed for high multiplicity seems to be consistent with the idea of an isotropic neutron source, which was not considered in the simulations.

The most critical point for the results of simulations with the model discussed is the efficiency of registration. Therefore, as was already mentioned, in addition to its empirical estimate, numerical simulations by the MCNP code have been performed. These simulations are also aimed at the optimization of the experimental conditions. The overall registration efficiency for neutrons from ordinary fission and from CCT events amounted to 4.1 and 10.8%, respectively. The latter is in good agreement with an empirical
estimate, bearing in mind that the efficiency of the 16-detector array is close to 60%.

The reliability of our MCNP simulations are checked by reproducing the experimental values of the timing constant $\lambda$ of $\sim 20 \mu$s (Fig. 4) and the count ratio of 1.3 for the detectors from inner and outer layers of the 16-detector array. The simulation delivers 1.25, 1.35, and 1.3 for detector arrays positioned at angles of 79° and 101° with respect to the direction of the FF motion and on the average, respectively.

Such good agreement of MCNP simulations with the experimental data already at the preliminary phase together with success of our empirical modeling ensures the reliability of the measured distribution of the neutron multiplicity for the analysis. Although further simulations are in progress, the multiplicity filter is already being successfully applied for the analysis of the FF data [2].

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