Search for Scission Neutrons Using Specific Angular Correlations in $^{235}$U Fission Induced by Slow Polarized Neutrons

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Abstract—The experimental data concerning scission (or prescission) neutrons are very contradictory—the relative part of these neutrons in the prompt fission neutrons varies from 1 to 35% owing to arbitrary assumptions made in different analyses. To solve this problem, we have used a new alternative method to search for the scission neutrons. We have found the left—right asymmetry of prompt-fission-neutron (PFN) emission caused by $sp$-wave interference in the entrance channel of the reaction and the $P$-odd asymmetry of the PFN emission caused by parity nonconservation at the exit channel of the fission process. Both effects cannot reside in PFN evaporated by excited fission fragments. The scission (or prescission) neutrons are responsible for these effects.

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1. INTRODUCTION

Six years ago, the collaboration of ITEP–Tuebingen University–Darmstadt TU–PNPI–ILL–Kurchatov Institute searched for the formally $T$-odd triple correlation

$$W = \text{const} \cdot (1 + DP_{\alpha}[P_{1f}, S_{n}])$$

(1)

in ternary fission of $^{233}$U induced by cold polarized neutrons of ILL HFR.

In expression (1), $D$ is the correlation coefficient; $P_{\alpha}$ and $P_{1f}$ are the unit vectors in directions of ternary $\alpha$ particle and light fission fragment momenta, respectively; and $S_{n}$ is the unit vector in the direction of cold neutron beam polarization.

It was found that there was an unexpectedly large left—right asymmetry of $\alpha$-particle emission relative to the plane formed by vectors $P_{1f}$ and $S_{n}$. The measured value of the asymmetry coefficient turns out to be equal to $(-2.74 \pm 0.07) \times 10^{-3}$ [1]. Corrections for geometry of the experiment and for average compound nucleus polarization degree will increase the module of this coefficient up to $10^{-2}$.

The angular part of (1) changes its sign under a time reversal operation, but it is not evidence for violation of time-reversal invariance. There are three interacting charged particles at the final state of ternary fission (heavy and light fission fragments and $\alpha$ particle). Therefore, it is more probable that correlation (1) arises owing to Coulomb or strong interactions in final states of reaction. To distinguish between them, it is necessary to search for the same correlation for a neutral particle, emitted via the same mechanism as a long-range $\alpha$ particle in ternary fission. It looks very strange that the emission of neutrons was not included in the process in which light charged particles were emitted, like $p$, $d$, $t$, $^{3}$He, $\alpha$, $^{5}$He, etc. It was a historical misunderstanding. The probability of neutron emission must be higher, for example, than the probability of proton emission because the neck must be enriched by neutrons owing to the Coulomb repulsion of protons and for the neutron there is no Coulomb barrier. Many years ago, such neutrons were indeed found in binary fission and they were called “scission” neutrons. The angular distribution of scission neutrons relative to the fission axis should be approximately spherically symmetric, while neutrons evaporated by completely accelerated excited fragments are elongated with the fission axis owing to summation of velocities. Only through fitting of the prompt fission nucleon angular distribution by two components is it possible to find scission neutrons. In such analysis, many arbitrary suppositions are made and results are very contradictory. The relative part of...
scission neutrons in prompt fission neutrons obtained in different works varies from 1% up to 35% [2]. Thus, to solve this problem, it is necessary to work out an alternative method to search for the neutral component of ternary fission.

2. SPECIFIC ANGULAR CORRELATION AS A TOOL TO STUDY THE MECHANISM OF THE REACTION

According to the theory of angular correlation, the module and the sign of all coefficients of the angular distribution expansion, in the general case, depend on the quantum characteristics of initial and final states as well as on quantum numbers of outgoing particles. Thus, in the case of fission when the number of final states for fragments (and, therefore, the number of initial states for evaporated neutrons) is equal to \( N \) \((\approx 10^6)\), the coefficients will be suppressed by \( \sqrt{N} \) times owing to summation or averaging over all \( N \) states.\(^3\). For this reason, the fragment’s neutrons will hardly show any angular correlation. As for the scission neutrons, they are evaporated by the fissile nucleus and, therefore, it can be supposed that the number of initial states for them is not so large. These arguments encouraged us to search for the specific angular distributions of scission neutrons in binary fission of \(^{235}\text{U}\) induced by low-energy polarized neutrons.

3. INTERFERENCE EFFECT IN ENTRANCE CHANNEL OF REACTION

In a slow neutron capture process, all neutron waves are involved. Practically, for thermal energies, the \( s\)- and the \( p\)-wave capture are significant. Interference between them will reveal itself as left—right (for the case of polarized slow neutron capture) and forward—backward (for unpolarized neutron capture) asymmetries of the outgoing particle angular distribution. The first one is given by the expression

\[
W = \text{const} \cdot (1 + B\mathbf{P}_{\text{out}}[\mathbf{P}_{\text{in}}, \mathbf{S}]),
\]

where \( B \) is the left—right asymmetry coefficient; \( \mathbf{P}_{\text{in}} \) and \( \mathbf{P}_{\text{out}} \) are unit vectors in the direction of momenta of the incident slow neutron and outgoing prompt fission neutrons, respectively; and \( \mathbf{S} \) is a unit vector in the direction of incident neutron beam polarization.

\(^3\)The fission process is the unique exception to the rule. The quasistationary transitional states at the saddle point are considered as the final states where only a few states are involved at low excitation energy above the barrier. Owing to that, the \( P\)-even and \( P\)-odd asymmetries are not washed out. Of course, quantum mechanics is not valid for this case. There must be some unknown mechanism which makes phases for different final states the same and, thus, all signs of the correlation coefficients turn out to be the same.

The measurement of left—right asymmetry of prompt—fission-neutron emission in binary fission of \(^{235}\text{U}\) induced by thermal polarized neutrons has been performed on the MEPhI reactor. The result is [3]

\[
B = (-5.8 \pm 1.4) \times 10^{-5}.
\]

The same asymmetry of the angular distribution of \(^{235}\text{U}\) light fragments is equal to \( 3 \times 10^{-4} \). Therefore, the suppression of the asymmetry coefficient by the removable background of a fragment’s neutrons is equal to about 5 and, thus, the ratio of \((N_{\text{sc}}/N_{\text{tot}}) \equiv \eta\) is equal to 0.2. Of course, this evaluation is not correct because there are no data showing that the asymmetries for fragments and for prompt neutrons or \( \gamma \) quanta must be the same. The correct way to evaluate \( \eta \) is the measurement of the angular dependence of asymmetry. The result of the measurement presented above was obtained at an average angle of 90° between the fission axis and the direction on neutron detector. At this angle, the background of a fragment’s neutrons is minimal, while at an angle of 0° it must be maximal. But in the last case, \( \mathbf{P}_{\text{out}} \) will be parallel to \( \mathbf{S} \), and thus the angular function in (1) will be equal to zero. So it is reasonable to measure asymmetry at an angle of 45°. From the ratio of asymmetries at 90° and 45°, it is possible to evaluate the correct magnitude of \( \eta \). Of course, the accuracy with which \( \eta \) will be obtained depends on the accuracy of measurements of \( B(90°) \) and \( B(45°) \). The MC simulation shows that the accuracy must be equal to \( 5 \times 10^{-6} \) to obtain \( \eta \) with 30% precision. It is impossible to obtain this accuracy in measurements at the MEPhI reactor because it will take too much beam time.

4. INTERFERENCE EFFECT IN EXIT CHANNEL OF REACTION

Another possibility to search for the scission neutrons using the specific angular correlations is the measurement of the \( P\)-odd asymmetry of prompt—fission-neutron emission:

\[
W(\theta) = \text{const} \cdot (1 + A\mathbf{S} \cdot \mathbf{P}_{\text{out}}) = C(1 + A \cos \theta).
\]

The reason why scission neutrons can show such asymmetry while a fragment’s neutron will play the role of background is the same as for the interference effect in the entrance channel of the reaction. Indeed, the fissile nucleus has mixed parity due to weak interaction in the compound nucleus and it conserves the compound nucleus polarization. Therefore, this will manifest itself as \( P\)-odd asymmetry of the angular distribution of any particles emitted by fissile nuclei. As was described in the previous paragraph, the magnitude of the coefficient \( A \) will be defined not only by