ON THE ROT-EFFECTS IN TERNARY AND BINARY FISSION OF ^{233}U and ^{235}U NUCLEI INDUCED BY POLARIZED COLD NEUTRONS

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Abstract

For the first time the ROT-effect was manifested in ternary fission of ^{233}U nuclei induced by polarized s-neutrons as a small shift of the angular distribution of long-range α-particles at the reversion of the neutron beam polarization. This shift is caused by the rotation of the fissile nucleus at the scission, thus fission fragments and α-particles acquire orbital velocity. In the experiment, the direction of the rotation and, consequently, the direction of the shift (i.e., the sign of shift) is determined by the value of the compound nucleus spin. The latter is formed by summing up of the captured neutron spin with the spin of the target-nucleus. The experimental data shows that in ternary fission signs of ROT-effects for target nuclei ^{233}U and ^{235}U are the same, while in binary fission they are opposite. That means that ternary both fission-prone nuclei pass through the same transition quasi-stationary states at the saddle, while in the case of binary the transition states are different. It is well known that ternary and binary modes of fission are different final states of the fission process, which is run by the quantum number of quasi-stationary states at the saddle. A possible source of such contradiction is being discussed.

ROT-effect (from «rotation») was manifested in the experiment [1], performed with the aim of detailed study of previously discovered at ILL, the so-called, TRI-effect in ternary fission of ^{233}U by polarized cold neutrons [2]. The asymmetry of long-range α-particles emission relative to the plane, formed by the momentum of light fragment and spin of longitudinally polarized neutrons was measured. This asymmetry, at a first approximation, could be described by the expression:

$$N = \text{Const.}\ (1 + D\cdot\mathbf{P}_\alpha\,[\mathbf{P}_{lf}\,,\,\boldsymbol{\sigma}_n\,]). \qquad (1)$$

Here D is the asymmetry coefficient, $\mathbf{P}_\alpha$ and $\mathbf{P}_{lf}$ are the momenta of α-particles and light fragment, correspondingly, $\boldsymbol{\sigma}_n$ is spin of the neutron captured by nucleus. All vectors are normalized.

In the experiment, the coefficient D was found by measurements the asymmetry

$$A = (N^+ - N^-)/\,(N^+ + N^-) \qquad (2)$$

at the reversing of the neutron beam polarization direction (sign + and -). It was surprising that under this operation the angular distribution of α-particles is shifted at a small angle to the left or to the right depending on the direction of the neutron beam polarization. As a result of this shifting, which looks like an instrumental effect, an additional asymmetry appears, and the measured total asymmetry coefficient A is not equal to coefficient D in expression (1). The authors of [1] understood that the effect was the result of fissile nucleus rotation at scission point and called it "ROT-effect". Due to fissioning nucleus rotation at the scission point, fission fragments and α-particles acquire orbital velocity and their trajectories, instead of a straight-line in the absence of rotation, becomes hyperbolic. This means that momenta of fragments and α-particle deviates from the initial direction of the fissioning nucleus deformation axis. The sign of deviation depends on the direction of the nucleus rotation, which is determined by the spin value of compound nucleus. For the value J=I+1/2 (I is the spin value of target nucleus) the direction of nucleus polarization coincides with the direction of neutron beam polarization, while for the spin value J=I–1/2 it is the opposite. Usually, the obtained data processing algorithm attributes the positive sign of the measured asymmetry to the right-handed rotation of the fissioning nucleus, which takes place at the coincidence of fissioning nucleus polarization direction with the neutron beam polarization direction. In the experiment [3] it was found that the signs of ROT-effect in ternary fission of ^{233}U and ^{235}U are the same. Data, concerning TRI- and ROT-effects in ternary fission of ^{233}U and ^{235}U nuclei are shown in Table 1.

Table 1. The results of the measurements for ternary fission of ^{233}U and ^{235}U [3]

Target nucleus	I	TRI–effect (asymmetry)	ROT – effect (shifting angle)
^{233}U	5/2	– 3.90 (12)	0.021(4)°
^{235}U	7/2	+ 1.7(2)	0.215(5)°

It is worth noting that the coefficients D (TRI-effect) in ternary fission of these nuclei have opposite signs. Contemporary models describing TRI-effects also require rotation of the fissioning nucleus at scission point, because the three-vector correlation (expression (1)) is described by Coriolis mechanism. Thus, it seems unlikely that there is asymmetry in the signs of TRI-effects in ternary fission of ^{233}U and ^{235}U, while the signs of ROT-effects in ternary fission of the same nuclei are the same. In this regard, another group performed control experiment aimed to measure ROT-effects in binary fission of ^{233}U and ^{235}U. ROT-effect in binary fission is “pure” so the results should not be corrected. To be confident in identifying the signs of the effects in the fission of these nuclei, the measurements were carried out simultaneously for both targets using the same set-up. The target was composed as a "sandwich" made of ^{233}U and ^{235}U targets having the same parameters. The detectors of the fragments on one side of the fission chamber recorded only the fission fragments of ^{233}U, while the detectors located in the second half of the chamber, recorded the fission fragments of ^{235}U. The coincidences of pulses from the detectors of the fragments with pulses of 12 scintillation detectors of prompt fission γ-rays and neutrons, located around the fission chamber, were measured [4]. The results of this experiment are presented in Table 2.

Table 2. The results of simultaneous measurements of ROT-asymmetry in binary fission of ^{233}U and ^{235}U [4]

Fission products	**Average angle between particle momentum and the fission axis**	**R(^{233}U)·10^5**	**R(^{235}U)·10^5**
Prompt γ-rays	22.5°	– 2.5 ± 1.7	6.8 ± 2.1
Prompt γ-rays	45°	– 3.3 ± 1.4	10.1 ± 1.7
Prompt γ-rays	67.5°	– 6.3 ± 2.6	10.3 ± 3.1
Prompt neutrons	22.5°	– 2.9 ± 1.8	5.4 ± 2.1

The accuracy of the measurements was not high enough. Nevertheless, it is obvious that the signs of ROT-effects in binary fission of ^{233}U and ^{235}U are opposite. Thus, the contradiction arises between the data on the relative signs of the ROT-effects in ternary and binary fission of ^{233}U and ^{235}U nuclei. The difference between the ternary and the binary fission refers to the final state of the fission process. It is known, that ternary and binary modes of fission pass through the same quasi-stationary transition states at the saddle point [5]. So, as it was previously noted, the direction of the polarized fissioning nucleus rotation is uniquely determined by the value of its spin and the spin projection on the deformation axis. These parameters, characterizing the transitional state, are set at the saddle point, and they are the same for both ternary fission and binary fission. Therefore, it is likely, that this contradiction is not of physical nature. It is more likely to be found in the experimental method or in the algorithm of the measurement results processing. For example, it may be the result of the existence of sufficiently large apparatus asymmetry of negative sign in the experiment [4], which can change the sign of ROT-effects at binary fission of ^{233}U, and therefore to reduce the values of asymmetries in the binary fission of ^{235}U. In fact, the values of ROT-effects in ^{235}U binary fission are approximately two times less than those reported in [6]. However, in this experiment, the fission fragments were collimated, and the start-stop registration method was used for the identification of light and heavy groups of fragments. While in the experiment [4], which was carried out in a short session of measurements, the collimators of fragments were removed, and only pulses from the start detectors were used. It is obvious, that in this case the measured asymmetry will be less than true. It also should be noted, that such a big apparatus asymmetry might arise only due to the changeable magnetic field of the spin-flipper influence on PMT of the scintillator counter of γ-rays and neutrons. But in all experiments, all PMT's were thoroughly shielded by the soft iron and mumetal, and apparatus asymmetry of the scintillator counts was always controlled by on-line measurements of the count rates asymmetry of all detectors situated around the fission chamber. In the first experiment, in order to search for the ROT-effect in prompt γ-rays emission at ^{235}U fission [7], γ-rays detectors were also installed at angles of 90° and 180° and the measured asymmetry occurred to be zero within statistical error in full accordance with the model of ROT-effect. Finally, here is the last positive factor: the values of ROT- asymmetries given in Table 2 are the average values for the four detectors situated in four quadrants around the target. It is important that the signs of the asymmetries in adjacent quadrants must be opposite to each other in accordance with the geometry of the set-up. So, at the averaging of the results, the signs of the results from the detectors situated at even quadrants were inversed. Nevertheless, the resulting signs of ROT-asymmetries turned out to be opposite for ^{233}U and ^{235}U nuclei. Thus, the suggestion that an apparatus effect is a possible cause of the misalignment of the signs of the effects can be considered as unlikely.

If we do not revise our understanding of ROT-effect, there is the only possibility left to explain the misalignment of the signs of ROT-effects in ternary fission of ^{233}U. The authors of [3], who published their result for ROT-effect in ternary fission of ^{233}U, noted that it was obtained under the assumption that the TRI-effect does not depend on the angle between the momentum of α-particle and the fission axis. In accordance with the expression (1), if it actually describes the TRI-effect discovered in the experiment, the angular dependence must be sinusoidal in the absence of Coulomb focusing of α-particles. Although, it is yet unknown how it is perturbed by the Coulomb field. Unfortunately, the angular dependence was measured in the experiment with insufficient accuracy. It is therefore possible that the assumption of the independence of TRI-effect on the angle is wrong. The magnitude of the ROT-effect in ternary fission of ^{233}U is small compared to the magnitude of the TRI-effect, and for this reason, a slight dependence of the TRI-effect on the angle can be the reason of the ROT-effect sign change. The problem can be solved by the high accuracy measurement of this angular dependence.

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