T-ODD ANGULAR CORRELATIONS IN THE EMISSION OF PROMPT NEUTRONS IN ^{235}U FISSION INDUCED BY POLARIZED NEUTRONS

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In 1998, the collaboration of Russian and German institutes performed at the high-flux reactor of the Institut Laue-Langevin (ILL) an experiment on search for the T-odd three-vector correlation in ternary fission of ^{233}U by cold polarized neutrons. The investigated angular correlation can be represented by expression

$$W = 1 + D_\alpha \left(\vec{p}_\alpha \cdot [\vec{\sigma}_n \times \vec{p}_{LF}]\right). \qquad (1)$$

Here D_α is the correlation coefficient; $\vec{\sigma}_n$ is the spin of the neutron captured by ^{233}U; and $\vec{p}_\alpha$ and $\vec{p}_{LF}$ are the momenta of the α particle emitted in ternary fission and of the light fission fragment, respectively. All the vectors are normalized.

Such an experiment to test the time reversal invariance of nuclear forces had been proposed earlier in [1]. But the violation of time reversal invariance in the inelastic nuclear reaction cannot be observed due to unavoidable final states interaction, which can imitate the T-odd correlations. So, unexpectedly large magnitude of the coefficient D_α (10^{-3}) [2] was very surprising. It can result from interference effect in strong and/or electromagnetic interactions of α particle with fragments in final states. The most simple theoretical model explained the observed correlation by the Coriolis mechanism [3].

Later, a detailed study of the correlation (1) showed that the angular distribution of α particles relative to the fission axis is shifted when inversing the polarization direction of neutrons inducing fission [4].The direction of shifting is determined by the direction of neutron beam polarization. Being unable to find any systematic effects which could explain the observed phenomenon, the authors concluded that the effect is caused by the rotation of polarized fissioning nucleus before it splits into the fragments, and called it ROT effect. Analysis showed that it is not the shift of the angular distribution of α particles, which is formed with respect to the axis of deformation of the fissioning nucleus, but the rotation of the fission axis by a small angle with respect to which the angular distribution of α particles is measured. This axis deviates from the original direction of the deformation axis due to the composition of radial and tangential velocities of the fragments. The trajectory of the fragments, instead of linear in the absence of rotation, becomes hyperbolic. The polarization of the neutron beam determines the direction of polarization of the fissioning nucleus and sets the direction of its rotation; this determines the direction of the deviation of the fragment trajectory. Such a correlation of light charged particles emission directions with the direction of neutron beam polarization can also be formally represented by a T-odd function (five-vector correlation):

$$W = 1 + R\left(\vec{\sigma}_n \cdot \left[\vec{k}_\gamma \times \vec{p}_{LF}\right]\right)\left(\vec{k}_\gamma \cdot \vec{p}_{LF}\right). \tag{2}$$

In contrast to the correlation (1), the momentum of the fragment is squared in (2), and therefore, the effect has the same sign for both light and heavy fragments. The correlation coefficient R is proportional to the rotation angle of the fission axis during the acceleration of the fragments due to Coulomb repulsion and to the derivative of the angular distribution of the α particles, detected at an angle ϑ to the fission axis.

From the above semiclassical description of the ROT effect, it follows that a similar phenomenon can be found in the angular distribution of any other particles accompanying fission of the nucleus into two fragments. Therefore, once data were published in [4], an experiment has been set up at the beam of polarized cold neutrons of the BER-II reactor of HMI in Berlin in order to measure the ROT effect in the emission of prompt γ rays in binary fission of ^{235}U by polarized cold neutrons [5, 6]. The sought effect was found, but about an order of magnitude smaller than for α particles. The angular distribution of γ rays emitted by fragments is anisotropic with respect to the direction of the momentum of the fragment, and this experimental fact was explained by Strutinsky [7] as a consequence of the spin alignment of the fragments during breakup of the nucleus in a plane orthogonal to the deformation axis of the fissioning nucleus. So γ rays emitted by the fragments are anisotropic with respect to the axis of the fissioning nucleus deformation. And although they are emitted not at the moment of scission, however, they may demonstrate the ROT effect.

Similar effect can be expected in the emission of prompt fission neutrons, assuming that the angular distribution of prompt neutrons in the rest frame of the fragments is anisotropic.

We have performed such an experiment at a beam of cold polarized neutrons MEPHISTO at the FRM II reactor of the Technical University of Munich [8]. The threefold and fivefold correlations in the emission of prompt neutrons from fission of ^{235}U were measured simultaneously. The neutrons were detected by plastic scintillators placed at angles $90^\circ \pm 22.5^\circ$ and $270^\circ \pm 22.5^\circ$ to the fission axis in coincidence with light and heavy fragments. The detectors recorded γ rays and neutrons being separated from γ rays by time of flight from the target to the detector. To control the operation of the equipment, threefold and fivefold correlation in the emission of γ rays were measured. ROT effect in the emission of γ rays has been confirmed with high precision, but other effects were not found within the experimental errors of the order of $(2 - 3) \times 10^{-5}$. Since the desired effects were measured only at an angle of 67° to the fission axis, the setup was slightly modified and measurements were continued.

Collimated beam of cold polarized neutrons passes through a system of controlling the direction of the longitudinal polarization and, being guided by leading magnetic field, enters into a fission chamber filled with isobutane to a pressure of 8 mbar. It hits the target, which is a 1-mm-thick zirconium plate, covered by a layer of oxide-protoxide of ^{235}U with a thickness of 500 μg/cm^2. The start and stop multiwire proportional counters are placed parallel to the target plane at a distance of 2.5 and 12.5 cm from the target, respectively. Start-stop technique allows identifying the mass of the detected fragment, i.e., separating the light and heavy fragment groups (Fig. 1). Eight neutron detectors, which are plastic scintillators with a diameter of 70 mm and a length of 120 mm, supplied with a photomultiplier EMI 9839A, are placed outside the chamber at a distance of 25 cm from the target center. Neutron detectors are located at angles of ±22.5°, ±67.5°, ±112.5°, ±157.5° relative to the direction of registration of the fragments. Centers of neutron detectors and detectors of the fragments are located in the plane orthogonal to the direction of the neutron beam passing through the center of the target. Neutron detectors allow for the registration of γ rays as well. Separation of neutron and γ rays could be done using time-of-flight technique (Fig. 2). Every event matching coincidence of the signals from the neutron and fragment detectors is digitized by multichannel TDC CAEN V775N and stored together with the information about the direction

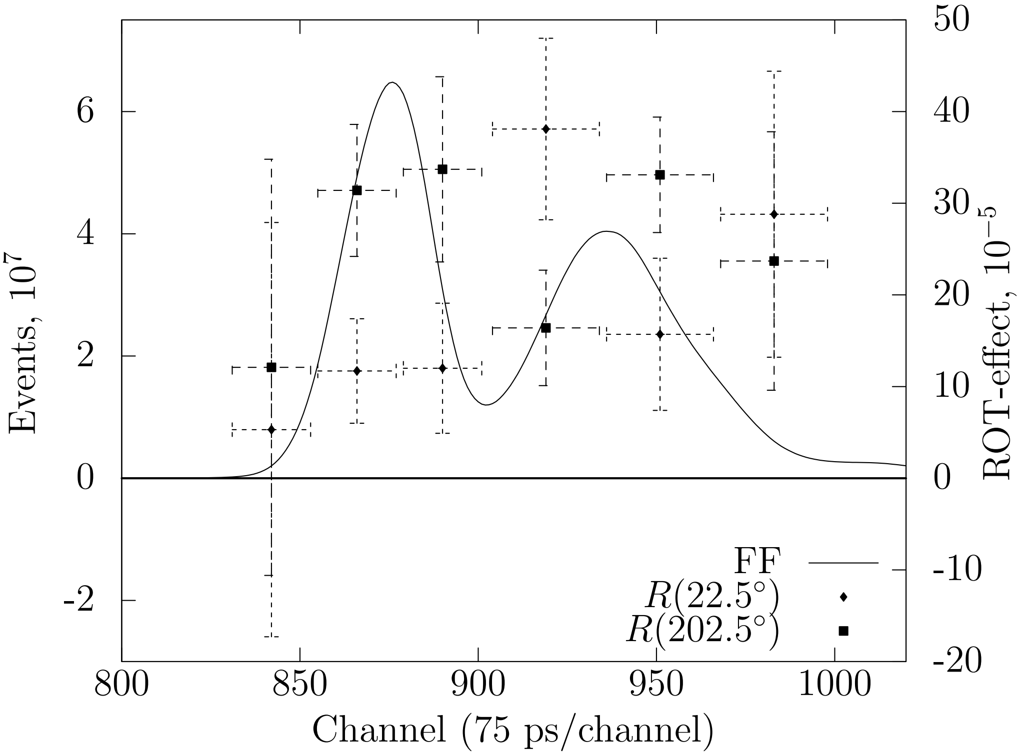

Figure 1: ROT effect for different groups of fission fragments.
FF – time-of-flight spectrum of ^{235}U fission fragments at 10 cm base;
$R(\vartheta)$ – ROT effect at angle of ϑ relative to the direction of the fragment's motion.

of polarization of the neutron beam. Reverse of polarization occurs at a frequency of 1 Hz, the input of the TDC being inhibited by the time of the neutron spin flip. At the same time, for the on-line control of the installation, the coincidence count rates of neutrons/γ rays and the light/heavy fragments were recorded by counters, which were read out every 5 min for each detector. The values of asymmetries, calculated by the formula $R = \frac{N^{+}-N^{-}}{N^{+}+N^{-}}$, were constantly monitored. Here N^{+} and N^{-} are the coincidence count rates for opposite directions of neutron polarization. Simultaneously, the asymmetry of the fragment count rates was measured and controlled.

Table 1 shows the values of ROT effect in the angular distribution of prompt neutrons and γ rays from fission, obtained in this study, [5] and [8]. Figure 2 shows the results of measurements of ROT effect in separate intervals of the TOF spectrum of coincidences of the signals from neutron/γ

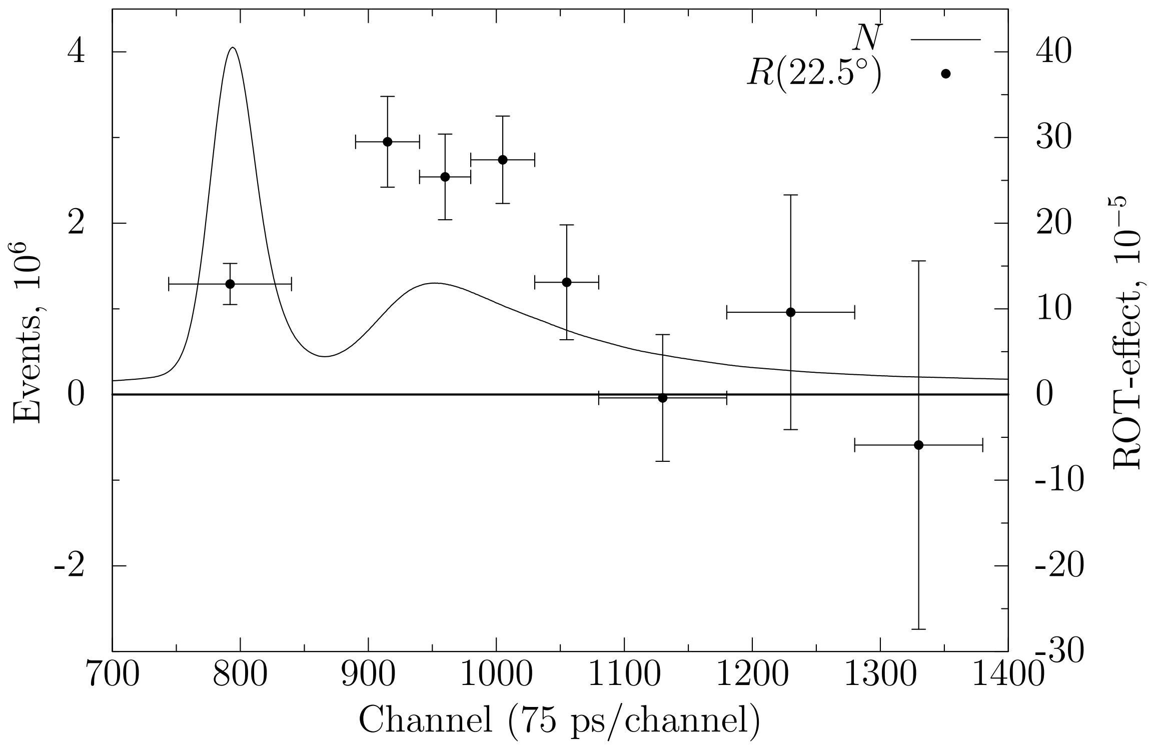

Figure 2: TOF spectrum of neutrons and γ rays, ROT effect in fission of ^{235}U for different intervals of the time-of-flight spectrum.
Left – the prompt γ ray peak; right – the peak of prompt fission neutrons; $R(\vartheta)$ – ROT effect at angle of ϑ relative to the direction of the fragment's motion.

Table 1: ROT effect R for different angles relative to the fission axis in ^{235}U fission

ϑ	R_n, 10^{-5}	R_γ, 10^{-5}
22.5°	21.2 ± 2.5	12.9 ± 2.4
35°	10 ± 5	15 ± 4
55°	0 ± 6	23 ± 4
67.5°	-0.3 ± 2.2	20.0 ± 1.8

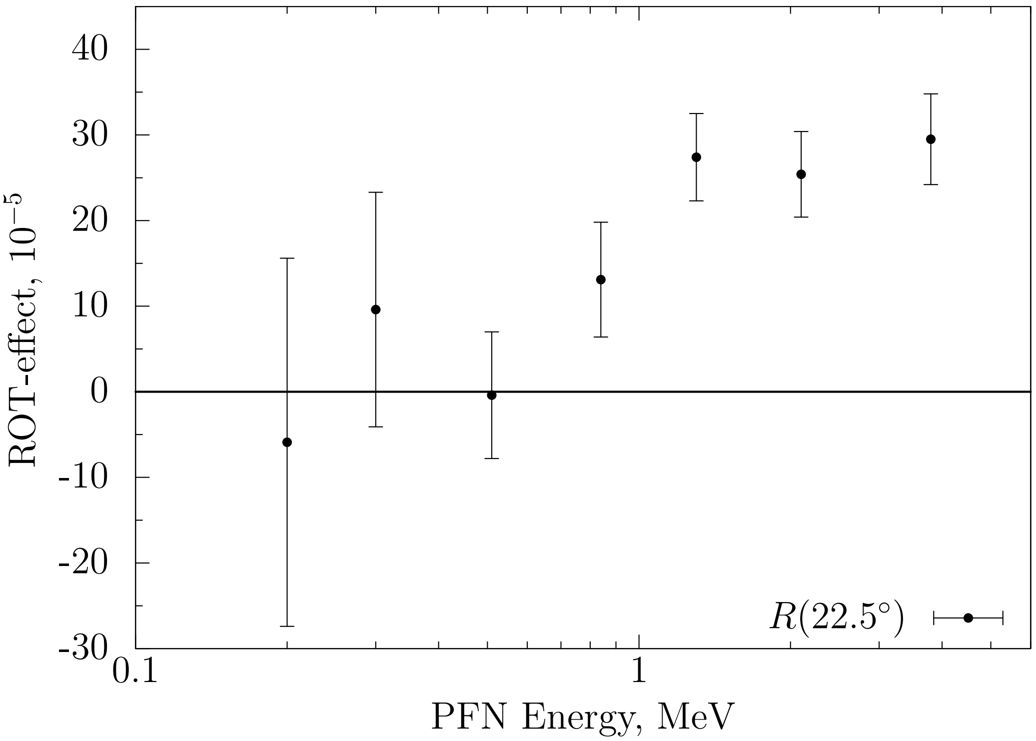

Figure 3: Energy dependence of ROT effect in ^{235}U fission

ray detectors and the fragments. The effects in the maximum of neutron peak are about two time larger than the effect in the γ peak, which can be explained by a larger anisotropy of the neutron emission in the rest frame of the fragment, compared to that of the γ rays. The ROT effect is showing for prompt fission neutrons of 1 MeV and higher (see Fig. 3).

Since the setup allowed us to distinguish between light and heavy fission fragments, we were able to compare values of ROT effect at angles of 22.5° relative to the direction of light and heavy fragments motion. One can see in Fig. 4 that magnitude of ROT effect is higher at angle of 22.5° relative to the direction of heavy fragment motion. We tried to obtain more detailed dependence of ROT effect on fragment's mass, and the result is shown in Fig. 1. Higher statistics and better mass resolution are necessary to make up any conclusion.

TRI effect in the emission of prompt fission neutrons at angle of 67.5° relative to fission axis $D_n^\star(67.5°) = (-0.7 \pm 2.3) \times 10^{-5}$, so the correlation coefficient D_n in formula

$$W = 1 + D_n \left(\vec{p}_n \cdot [\vec{\sigma} \times \vec{p}_{LF}]\right)$$

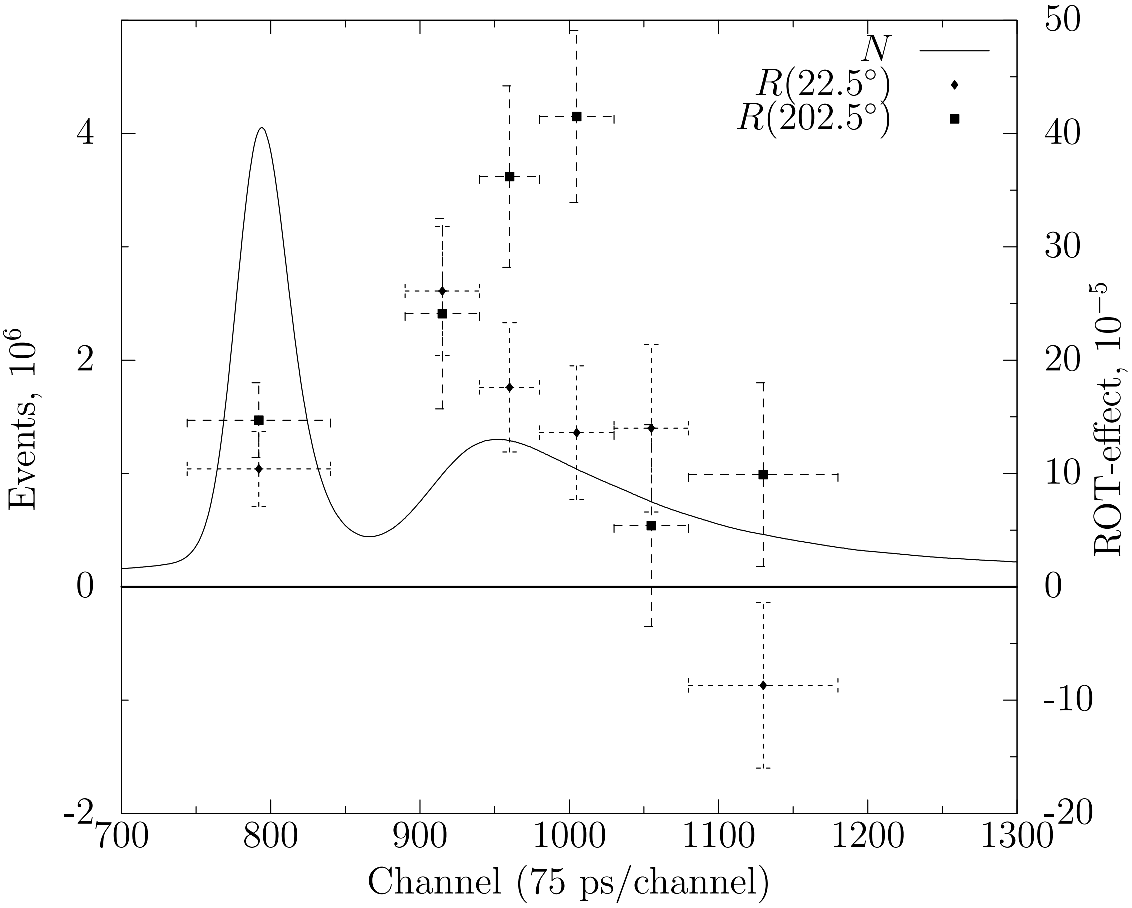

Figure 4: TOF spectrum of neutrons and γ rays, ROT effect in fission of ^{235}U for different intervals of the time-of-flight spectrum for light and heavy fragments separately. $R(\vartheta)$ – ROT effect at angle of ϑ relative to the direction of the light fragment's motion.

$D_n = (-0.8 \pm 2.5) \times 10^{-5}$.

Main result of this work is observation of the ROT asymmetry in the emission of prompt fission neutrons. There is significant asymmetry at angle 22.5° relative to fission axis, while the effect at angle 67.5° has not been observed. ROT effect increases with increase of the energy of prompt fission neutrons. It is higher in the direction of heavy fragment's motion.

In a first approximation, the results are consistent with the calculations of the effects at angles of 22.5° and 67.5°, represented in the work of Guseva [9]. Calculations were performed under the assumption that the angular distribution of fission neutrons in the rest frame of the fragment is anisotropic. Mechanism for the appearance of anisotropy in neutron emission from excited fragments is similar to the mechanism of anisotropy of prompt γ rays and can be explained by alignment of the spins of fission fragments in the plane orthogonal to the deformation axis of the fissioning nucleus. Thus, both the emission of neutrons and γ rays from fission fragments are anisotropic with respect to the axis of deformation of the fissile nucleus, which leads to the observed ROT effects.

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