THE ROT-EFFECT IN THE ANGULAR DISTRIBUTION OF PROMPT γ-RAYS IN BINARY FISSION INDUCED BY POLARIZED NEUTRONS WITH THE ENERGY OF 60 meV

Yu.N. Kopatch[1,2], D.B. Berikov[1,3], G.S. Ahmadov[1,4,5], A.M. Gagarsky[6], V.V. Novitsky[1,2], G.V. Danilyan[1,2], V. Hutanu[7], S. Masalovich[8], J. Klenke[8], and H. Deng[7]

[1]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[2]*Institute for Theoretical and Experimental Physics of National Research Centre "Kurchatov Institute", 117218 Moscow, Russia*
[3]*L.N.Gumilyov Eurasian National University,* 010000 Nur-Sultan*, Kazakhstan*
[4]*Azerbaijan National Academy of Sciences- CSSR and IRP, AZ1143 Baku, Azerbaijan*
[5]*National Nuclear Research Centre, Baku, Azerbaijan*
[6]*Petersburg Nuclear Physics Institute of National Research Centre "Kurchatov Institute", 188300 Gatchina, Russia*
[7]*Institute of Crystallography, RWTH Aachen University and Julich Centre for Neutron Science at Heinz Maier-Leibnitz Zentrum (MLZ), 85748 Garching, Germany*
[8]*Heinz Maier-Leibniz Zentrum (MLZ), Technical University of Munich, 85748 Garching, Germany*

Abstract. The investigation of the ROT effect for the fissioning nuclei in the process has been continued at the FRM-II Munich reactor (Germany). The experiment with ^{235}U target was performed at a polarized monochromatic neutron beam with an energy of 60 meV provided by the POLI instrument, in order to figure out the dependence of the effect on the incident neutron energy. Up to now all measurements of the ROT effect were performed for the cold neutron induced fission, where several fission channels are mixed with unknown weights. The correlation coefficient for 60 meV neutrons was found to be $A_\gamma = (1.25 \pm 0.31)\cdot 10^{-4}$, which is compared with the corresponding values for ^{235}U, obtained with the cold neutrons: $A_\gamma = (1.66 \pm 0.16)\cdot 10^{-4}$ (by the ITEP group).

I. INTRODUCTION

The ROT-effect in the angular distributions of prompt γ-rays emitted from neutron induced fission was measured, which is expressed as the angular correlations between the spin of the incident neutron σ, momentum direction of the light (heavy) fission fragment (FF) p_f and the direction of the prompt fission γ-ray emission of the type:

$$W(\Omega) \sim 1 + R_\gamma \cdot \sigma \cdot [p_f \times p_\gamma].$$

The ROT-effect, which is formally T-odd effect, was measured for the first time in the emission of alpha particles in ternary fission of ^{235}U induced by cold polarized neutrons [1]. It was observed as a small rotation of the angular distribution of α-particles from ternary fission relative to a plane formed by FF momentum and the neutron spin direction. This effect was explained in a semi-classical model as a result of the collective rotation of the fissile nucleus at the moment of its rupture and named as ROT-effect (from the rotation). Due to rotation of the fissioning system, fission fragments receive the orbital momentum, and the axis of fragment emission slightly rotates relative to the deformation axis of the nucleus at the moment of scission.

In ternary fission, the description of the ROT-effect of a fissile nucleus is complicated by the fact that the α-particle emitted by the fissile nucleus at the moment of its rupture can also receive the orbital momentum. In addition, its motion is significantly affected by the electric field of the emitted fragments. All this leads to the fact that the ROT-effect in ternary fission is difficult to describe in the classical approximation, without involving model parameters and trajectory calculations. Existing quantum models [3-5] explain the presence of the ROT-effect, but not its magnitude.

Nevertheless, after the discovery of the ROT effect for α-particles in ternary fission, it was clear that it can also manifest itself in the angular distribution of prompt γ-rays and neutrons accompanying the binary fission, where its theoretical description can be simpler. The ROT-effect for gamma-rays and neutrons is possible, because the angular distribution is anisotropic with respect to the deformation axis of the fissioning nucleus at the moment of scission, and the asymmetry with respect to the initial direction of the deformation axis is fully or partly conserved after the escape of the fragments to infinity. Indeed, a similar effect has been observed in the emission of prompt γ-rays and neutrons in fission of ^{235}U and ^{233}U, although its value was an order of magnitude smaller than in the α-particle emission from ternary fission [6-8]. As for the ROT-effect in the angular distribution of α-particles of ternary fission of ^{235}U and ^{233}U nuclei [2], the ROT-effect in the angular distribution of prompt γ-rays and neutrons for these two uranium isotopes was very different.

At present, there are several theoretical models which can describe the ROT-effect. These models use two fundamentally different approaches to the description, “classical” and “quantum”. In the classical model, due to the impossibility of dividing the process of ternary fission into two consecutive stages, trajectory calculations are used. And quantum models at the moment suffer from a lack of predictive power.

Further study of the ROT-asymmetry in the angular distribution of prompt γ-rays and neutrons from fission may shed light on the question of the applicability of various models describing the ROT-asymmetry in the angular distribution of α-particles from the ternary fission. At present, one of the main problems is to understand why two very similar uranium isotopes ^{235}U and ^{233}U exhibit a quite different behavior with respect to the effects of T-odd asymmetry in ternary fission. According to the authors of [4], the reason for this difference lies in the different phase factors of the interfering neighboring neutron resonances. In any case, it seems important to clarify this issue. Obviously, the most direct way to answer this question is to provide the measurement of Todd effects for isolated resonances with well-known spins.

The next problem is the dependence of the magnitude of the ROT-effect on the energy of neutrons causing the fission. The study of this dependence can help understanding such details of the fission mechanism as the transition of the nuclear polarization at the angular momentum of fission fragments. According to the model proposed in [10], the ROT-effect depends on the quantum numbers J and K (angular momentum and its projection on the deformation axis, respectively), which characterize the fission channels introduced by A. Bohr [9]. Up to now, all measurements of the T-odd effects were performed for the cold neutron induced fission, where several fission channels are mixed with unknown weights [10]. In order to disentangle different spin states and get “clean" data on the J and K channel-weights one can perform measurements with different incident neutron energies. The FRM-II reactor at MLZ in Garching with its unique hot neutron source provides an almost perfect instrumentation for such measurements.

II. DESCRIPTION OF THE EXPERIMENT

The experiments on binary fission were carried out for (n, f) reactions with ^{235}U as a target and a neutron beam from the POLI diffractometer at the FRM-II reactor at the Maier-Leibnitz Zentrum in Garching (Germany). The experimental setup shown below (Fig. 1) was similar to the previous experiment discussed in [11]. The main difference was the neutron polarizer. In the current experiment, the neutrons were polarized using in-situ SEOP (Spin Exchange Optical Pumping) polarizer [12]. The polarizer employs a high opacity ^{3}He neutron spin filter with continuous ^{3}He polarization provided by two laser array bars frequency narrowed by an ultra-compact volume Bragg grating. The degree of neutron beam polarization was close to 100 % and kept constant during the experiment.

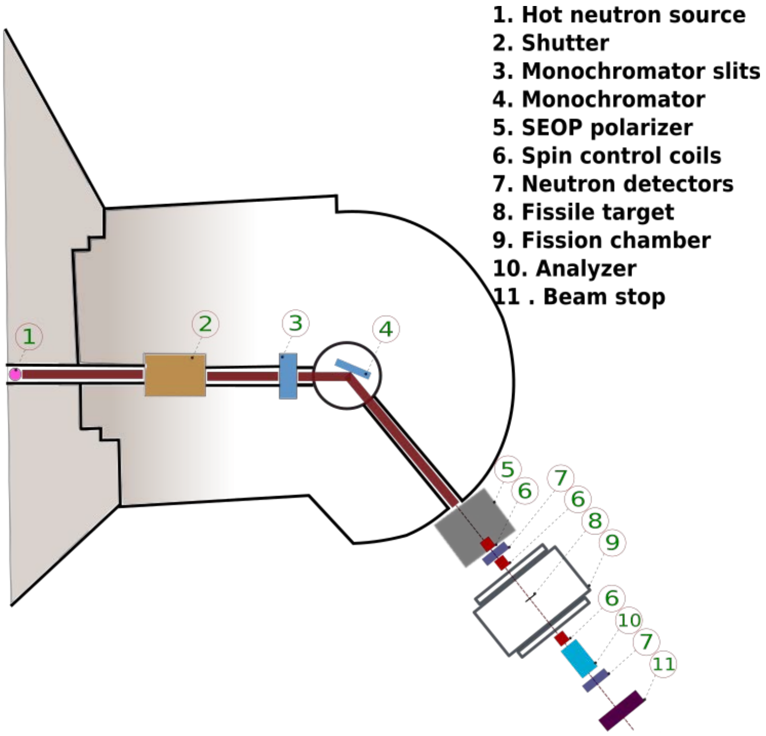

FIG. 1. Schematic view of the experimental setup with POLI instrument at MLZ.

The monochromatic polarized neutron beam passes through a thin Al window into the cylindrical fission chamber filled with tetrafluoromethane gas (CF_4) at a pressure of about 10 mbar. Si(311) non-polarizing variable double-focusing monochromator was used to produce an intense monochromatic narrow neutron beam with the wavelength of 1.15 Å (62 meV). The value for the maximal non-polarized neutron flux was estimated as $1.8 \cdot 10^7$ n/sm^2/sec.

The two-sided fissile target, containing about 82 mg of ^{235}U oxide-protoxide deposited on the thick 40×100 mm^2 aluminum backing is mounted on the axis of the chamber along the longitudinally polarized neutron beam direction. Two low-pressure angular sensitive multiwire proportional counters (LPMWPC) facing each other to the left and right of the target at a distance 3 cm (start detector) and 11 cm (stop detector) were recorded fission fragments. Each stop counter consists of five independent segments at the angles of 0, ±22.5, ±45 degrees on the left and ±135, ±157.5, 180 degrees on the right side of the target to increase the angular sensitivity of the detector. Prompt fission γ-ray and neutron detectors are located outside the fission chamber. Each of these detectors is a scintillation counter. As a scintillator, plastic and NaI(Tl) crystals were used, which made it possible to effectively register not only γ-quanta, but also neutrons, separating them by the time-of-flight. Eight cylindrical plastic scintillators with a diameter of 70 mm and a length of 120 mm and four NaI scintillators optically connected to a photomultiplier tube, wrapped with an antimagnetic screen and placed in a sealed aluminum case were inserted in a rotatable holder at a distance of about 30 cm from the target center. The schematic view of the used detector array inside/outside the fission chamber is shown in Fig. 2.

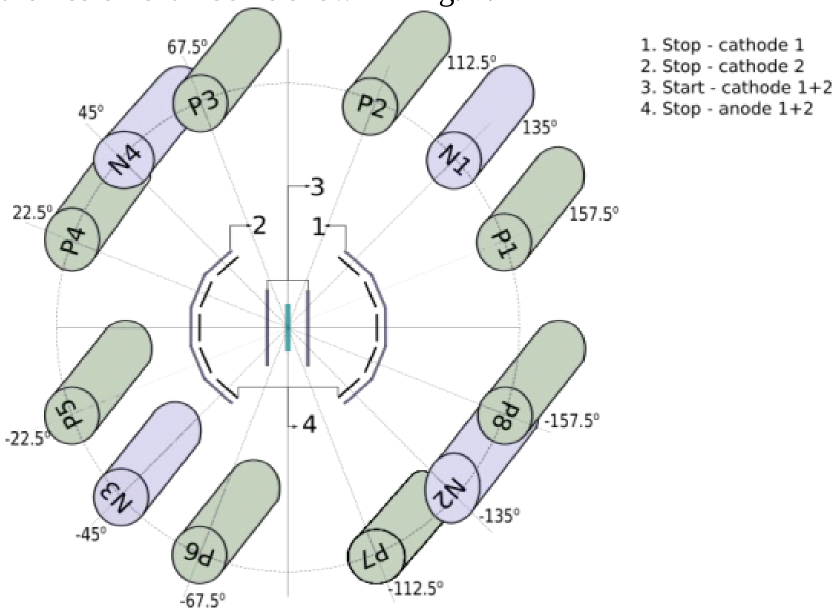

FIG. 2. The layout of the detector positioning around the target inside/outside the fission chamber. view from the beam direction. 1, 2 – stop MWPC, 3 – start MWPC, 4 – target. P1-P8 – plastic scintillators, N1-N4 – NaI scintillators.

Plastic detectors, located at the angles of ±22.5, ±67.5, ±112.5 and ±157.5 degrees ensures subsequent measurements of coincidences of prompt fission gamma rays and fission fragments with respect to the mean axis of the detection of fragments. The centers of gamma/neutron and fragment detectors are located in the plane orthogonal to the longitudinally polarized neutron beam direction. Prompt neutrons and prompt γ-rays from fission were separated in plastic scintillators using the time-of-flight technique. The start signal was the signal from the fission fragment detectors, which also served as a trigger indicating the fission event. The incoming polarization is periodically flipped between parallel and antiparallel to the beam propagation. The spin was flipped by 180° every 1.3 seconds, the flipping frequency was controlled by the quartz clock.

The data acquisition system (DAQ) includes preamplifiers (PAM), timing filter amplifiers (TFA), constant fraction discriminators (CFD) for time pick-up, Time-to-Digital Converters (TDCs), logical modules AND, OR, Logic fan-in/fan-out (FIFO), Analog-to-Digital Converters (ADCs), delays, scaler, and the VME-PC interface running on the Linux operating system [13]. The DAQ consisted of three signal lines of pulse processing: recording event times in TDC boards, recording pulse heights via ADC and counting events in scaler. Every event matching coincidence of the signals from the γ/neutron and fragment detectors is digitized by TDC and stored together with the information about the direction of polarization of the neutron beam. The input of the TDC was inhibited by the transition time of the neutron spin flip. The coincidence count rates of γ-rays and fission fragments were recorded by the counters for two opposite directions of the neutron-beam polarization. These count rates were used to monitor the status of the setup and instrumental asymmetry. The frequent spin flip of the incident neutron beam served as one of the main mechanisms for suppressing instrumental asymmetry. Therefore, special attention was paid to the stability of the measurement time for opposite values of the neutron spin. The scaler controlled the data acquisition time with an accuracy of 10^{-6} sec. For each triggered event (coincidence between one of the FF detectors and one of the γ-ray/neutron detectors) the data from the TDC and ADC were stored as list-mode-data together with the information about the spin sign. During one day of measurements, about 5 GB of compressed data were collected, divided into 5-minute expositions, which were then analyzed off-line.

III. EXPERIMENTAL RESULTS

The main goal of the data processing was to determine the T-odd asymmetry coefficients of the number of coincidences of prompt fission γ-rays and fission fragments with respect to the direction of neutron beam polarization for each angle, calculated by the formula:

$$R(\theta) = [N^{+}(\theta) - N^{-}(\theta)]/[N^{+}(\theta) + N^{-}(\theta)], \tag{1}$$

where $N^{+}(\theta)$ and $N^{-}(\theta)$ are the γ-ray count rates for a selected angle between the detectors at two opposite directions of neutron polarization. In the Table I presented the asymmetry coefficient R_{γ} determined from the experimental data according to Eq. 1, measured for coincidences of the pulses from eight independent plastic detectors with each pulse from ten stop counters. Thus data were accumulated for 16 different angles between the axes of the fission fragment and γ-ray detectors in the experiment.

TABLE I. Angular dependence of the ROT asymmetry

Angle	R_{γ}, 10^{-4}	Angle	R_{γ}, 10^{-4}
0	-0.6± 0.9	180	-0.2± 0.9
22.5	-0.4± 0.8	202.5	-0.8± 0.9
45	-2.0± 0.9	225	-0.1± 0.9
67.5	-0.3± 0.9	247.5	-0.8± 0.9
90	1.8± 0.9	270	-0.5± 0.9
112.5	1.5± 0.9	292.5	0.3± 0.9
135	2.2± 0.9	315	1.4± 0.9
157.5	0.7± 0.9	337.5	1.3± 0.8

The coefficient of γ-ray emission anisotropy A with respect to the fission axis for the fragments of binary fission of a polarized $^{236}U^{*}$ compound nucleus was measured in the same experiment (Fig. 3).

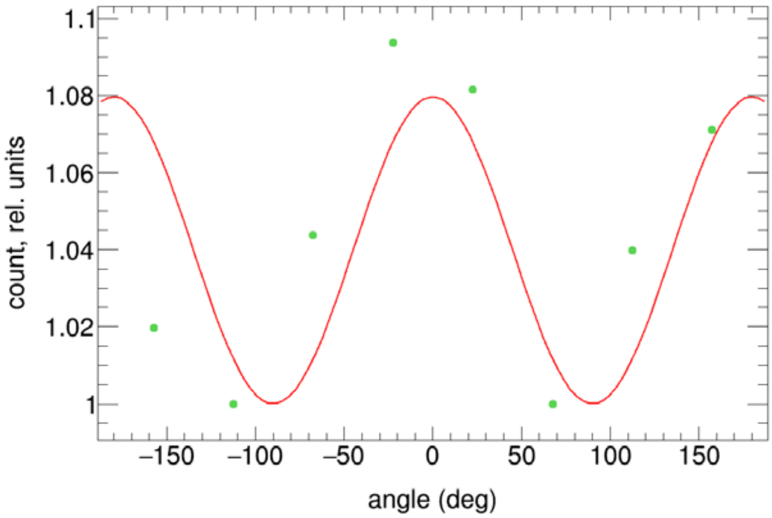

FIG. 3. Prompt γ-ray angular distribution. The curve is the result of approximation by Eq. (2).

The number of γ-quanta and their energy distribution in the process of ^{235}U nuclei fission by thermal neutrons was studied in more detail in [14]. According to this work, on average, 6.51±0.3 γ-quanta, the average energy of which is 0.99±0.07 MeV, fall on the act of fission. The angular distribution of the prompt γ-rays relative to the fission axis is anisotropic. The simplest integral parameter characterizing this anisotropy is the anisotropy coefficient A, defined as $A = 1 – W(0^{\circ})/W(90^{\circ})$. The value of the anisotropy coefficient for the angular distribution of prompt fission γ-rays of ^{235}U is $A \approx 0.13$ [15]. Although this value is significantly lower than in the angular distribution of α-particles of ternary fission, such a noticeable anisotropy nevertheless makes it possible to search and study the ROT-effect of the fissile nucleus in the angular distribution of prompt fission γ-rays. For gamma radiation of an unpolarized fissioning system, the angular distribution can be expressed by [16]:

$$N(\theta) = N(90^{\circ})\cdot(1 + A\cdot\cos^2\theta), \qquad (2)$$

where A is the angular anisotropy coefficient. The obtained experimental value of the anisotropy coefficient in this work was A = 0.08(2). It has to be noted that this value is not corrected for the angular spread of the fission fragments and γ-rays in the detectors. For the analysis of the ROT effect this uncorrected value has to be used, as all possible effects, connected with the geometry of the experimental setup are the same in both cases.

When a polarized fissioning system rotates around its polarization direction the axis before the moment of emission and detection of the γ-rays rotates by a small angle ±δ [17]. The sign of δ depends on the captured neutron polarization direction. Taking into consideration a smallness of the angle δ for fission axis rotation, the angular dependence of the T-odd asymmetry coefficient of prompt fission γ-rays can be written by this equation:

$$R(\theta) = -A\cdot\delta\cdot\sin(2\theta)/[1 + A\cdot\cos^2(\theta)]. \qquad (3)$$

The results listed in the table 1 are shown in Fig. 4. These experimental data were approximated by Eq. (3). The given expression makes it possible to obtain the angle of rotation δ of the polarized fissioning system. The angle of rotation of the $^{236}U^*$ nucleus was found to be $\delta = 0.09(2)^0$. The result is still preliminary, as not all systematic errors are taken into account.

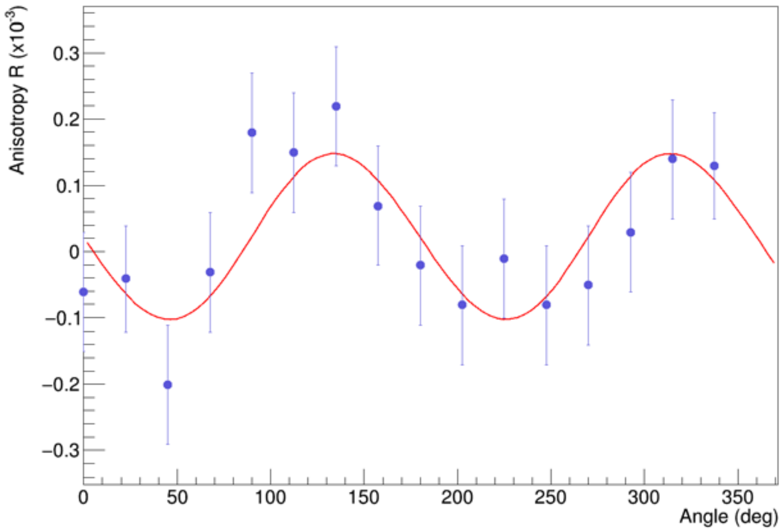

FIG. 4. Experimental angular dependence of the T-odd asymmetry coefficient R of γ-ray emission in $^{236}U^{*}$ fission.

Acknowledgments

This work has been supported by the Russian Ministry for Science and Education, German Ministry for Education and Research BMBF through the project 05K13PA3. The instrument POLI is operated by RWTH Aachen in cooperation with JCNS FZ Jülich (Jülich Aachen Research Alliance JARA). We are grateful to K. Lehmann, P. Stein, H. Saul and W. Luberstetter for their help in setting up and conducting the experiment.

REFERENCES

1. F. Goennenwein, M. Mutterer, A. Gagarski, et al., Phys. Lett. B **652**, 13 (2007).
2. G.A. Petrov, A.M. Gagarski, I.S. Guseva, et al., *Proceedings of the XVI International Seminar on Interaction of Neutrons with Nuclei*, Dubna, 2009, p. 362.
3. V.E. Bunakov and S.G. Kadmensky, Phys. At. Nucl. **66**, 1846 (2003).
4. V. Bunakov, S.G. Kadmensky, and S.S. Kadmensky, Phys. At. Nucl. **71**, 1887 (2008).
5. V.E. Bunakov and S.G. Kadmensky, Phys. At. Nucl. **74**, 1655 (2011).
6. G.V. Danilyan, J. Klenke, V.A. Krakhotin, et al., Phys. At. Nucl.**72**, 1812 (2009).
7. G. Danilyan, J. Klenke, V. Krakhotin, Y. Kopach, et al., Phys. At. Nucl.**74**, 671 (2011).
8. G.V. Danilyan, J. Klenke, Yu.N. Kopach, et al., Phys. At. Nucl.**77**, 677 (2014).
9. A. Bohr, in *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy*, Geneva, August, 1955, Vol. 2 (UN, New York, 1956), p. 151.
10. A. Gagarski, F. Gonnenwein, I. Guseva, et al., Phys. Rev. C **93**, 054619 (2016).
11. Yu. Kopatch, V. Novitsky, G. Ahmadov, et al., EPJ Web of Conf. **169**, 00010 (2018).
12. Z. Salhi, E. Babcock, et al., J. Phys. Conf. Ser. 1316, 012009 (2019).
13. D. Berikov, V. Hutanu, Yu. Kopatch, et al., JINST 15, P01014 (2020).
14. F. Pleasonton, R.L. Ferguson, H.W. Schmitt, Phys. Rev. C **6**, 1023 (1972).
15. S.S. Kapoor, R. Ramanna, Phys. Rev. **133**, B598 (1964).
16. V. Strutinskii, Zh. Eksp. Teor. Fiz. **37**, 861 (1959).
17. G.V. Valsky, A.M. Gagarski, I.S. Guseva, et al., Bull. Russ. Acad. Sci. Phys. **74**, 767 (2010).