Correlation between the direction of prompt neutrons and fragments in the fission process as a tool for studying rotation effect

D. Berikov
Institute of Nuclear Physics of the National Nuclear Center of Kazakhstan, Ibragimova 1, 050032 Almaty, Kazakhstan, daniyar.berikov@gmail.com

G. Ahmadov
Joint Institute for Nuclear Researches, Joliot-Curie 6, 141980 Dubna, Russia

Yu. Kopatch
Joint Institute for Nuclear Researches, Joliot-Curie 6, 141980 Dubna, Russia

S. Nuruyev
Joint Institute for Nuclear Researches, Joliot-Curie 6, 141980 Dubna, Russia

K. Mendibayev
Joint Institute for Nuclear Researches, Joliot-Curie 6, 141980 Dubna, Russia

See next page for additional authors

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Correlation Between the Direction of Prompt Neutrons and Fragments in the Fission Process as a Tool for Studying Rotation Effect

Daniyar Berikov [a,b,*] , Gadir Ahmadov [b,c,d,e], Yuri Kopatch [b], Sabuhi Nuruyev [b,c,d], Kairat Mendibayev [a,b], Farid Ahmadov [c,d]

[a] Institute of Nuclear Physics, Ibragimova 1, 050032, Almaty, Kazakhstan
[b] Joint Institute for Nuclear Researches, Joliot-Curie 6, 141980, Dubna, Russia
[c] Institute of Radiation Problems Under Ministry of Science and Education, B.Vahabzade str. 9, AZ1143, Baku, Azerbaijan
[d] Department of Nuclear Research of IDDA, Baku Shamakhy HW 20 Km, Gobu sett. of Absheron Dist., AZ0100, Baku, Azerbaijan
[e] Khazar University, 41 Mahsati Str., AZ1096, Baku, Azerbaijan

Abstract

This paper investigates the possibility of restoring the trajectory of fission fragments using thick targets that are opaque to the fragments, by analyzing the angular distribution of prompt neutrons. Employing thick targets in experimental studies with low-intensity neutron beams accelerate the accumulation of statistics, thereby facilitating the study of subtle effects, such as the rotation (ROT) effect which sheds light on the deformation and rotational behavior of fission fragments.

The paper details the experimental techniques used, presents the results of neutron yield measurements from the fission of ^{235}U with cold and "warm" (60 meV) neutrons in the range of angles from 0 to 360° (in 22.5° increments). The analysis of these is also presented.

Keywords: The angular distribution of prompt neutrons, Anisotropy of fission neutrons, Nuclear fission, ROT effect

1. Introduction

Despite decades of research, new technologies and advanced electronics continue to push the boundaries of what we can learn about nuclear fission. Modern detectors, sophisticated data acquisition systems, and enhanced computational tools enable more precise measurements and real-time particle detection [1—3]. These innovations facilitate the study of previously difficult or partially studied and understood phenomena. By integrating these advanced tools, researchers can uncover new insights and refine existing models in nuclear physics, ensuring that the study of nuclear fission remains a vibrant and evolving field, even after more than 90 years of investigation. One of the challenges in this field is obtaining radiation sources with the required flux levels. High radiation fluxes

at specific energies are crucial for investigations into various nuclear phenomena, including the ROT effect, rare fission modes, angular distributions of gamma rays and neutrons, nuclear transition levels, cross-section measurements, and angular momentum formation etc. [4—7]. These demands highlight the ongoing need for cutting-edge technology and methodologies to advance our understanding of nuclear fission and its related phenomena.

Experiments, searching and studying the so-called ROT effect in the angular distributions of alpha particles from the ternary fission of ^{235}U nuclei by cold polarized neutrons were carried out by the authors [8,9] at the ILL reactor in Grenoble (France). The effect manifests as a shift in the anisotropic angular distribution of alpha particles relative to the fission axis, depending on the direction of polarization of the

neutrons inducing the fission. In the classical model, this effect is attributed to the collective rotation of the fission nucleus at the moment of rupture. Therefore, it is called the "ROT effect" (from the word rotation).

Later studies by another group investigated a similar phenomenon in binary fission at the HMI reactor in Berlin and the FRM II reactor in Garching, Germany [10,11]. In these experiments, the third particle was either gamma quanta or neutrons, both exibiting anisotropic emission relative to the fission axis, albeit with a weaker anisotropy. Interestingly, the ROT effect was observed for both gamma quanta and neutrons, although with a magnitude approximately an order smaller than for alpha particles of ternary fission.

Our group also carried out a series of experiments at the POLI instrument of FRM II reactor in Garching. In these experiments, the ROT effect was measured for the first time for various energies of polarized neutrons inducing fission, including for the first isolated ^{235}U resonance at an energy of ~0.3 eV. We obtained the angular dependence of the ROT effect asymmetry coefficient for gamma quanta and determined the rotation angle of the fissile system in the fission with polarized neutrons. More detailed descriptions of these experiments can be found in Refs. [12−15].

The extension of ROT effect measurements to higher neutron energies is of great interest. In Ref. [16], the authors predicted the magnitude and sign of the effect for different target nuclei, and for each of them they determined the energy value of incident neutrons at which the magnitude of the effects should be greater. Their calculations used resonance parameters from the ENDF/B-III.0 database and the SAMMY program. Based on these results, neutron energies corresponding to resonances in specific nuclei are particularly interesting: 1.14 eV for ^{235}U, 0.305 eV and 1.272 eV for ^{241}Am, and 0.85 eV and 1.98 eV for ^{245}Cm. These resonances are relatively "clean," with minimal interference from cross-sections corresponding to other possible compound nucleus spin states. Analyzing these resonances is expected to provide a more reliable picture of physical nature of the ROT effect, leading to a clearer determination of its sign. Experimental verification of these predictions would significantly enhance our understanding of the ROT effect formation mechanism.

The lack of experimental studies of the effect for neutrons with energies greater than 1 eV is due to the unavailability of polarized neutrons with high intensity. Considering the smallness of the expected effect (10^{-4}), at low intensities it is very difficult to accumulate the necessary statistics. This article presents a method, which is probably the simplest and most affordable way to solve this problem.

2. Method

2.1. Current methodology of the experiment

In previous experiments on the ROT effect for prompt gamma rays, a stainless steel vacuum fission chamber was used at the POLI instrument of the FRM II reactor. The ^{235}U fissile target was located in the center of the chamber, between the fragment detectors. The target was deposited on both sides of a thick substrate. The size of the uranium layer was 40×100 mm^2, the thickness of each uranium layer was about 1 mg/cm^2, the totaling 82 mg of fissile material. Gamma ray detectors were located around the fission chamber at a certain distance (30 cm) from the center of the target. Fig. 1 illustrates a schematic of the detector part of the experimental setup. Fragment detection involved a system of "start" and "stop" detectors positioned on both sides of the target, parallel to it. The "stop" detectors were equipped with five independent segments, positioned at angles of 0, ±22.5, ±45° on one side and ±135, ±157.5, 180° on the other side of the target. The "start" detector is a non-segmented single detector. Eight plastic scintillation detectors were used to register prompt γ-rays and neutrons emitted in the fission. These detectors were placed at angles of ±22.5, ±67.5, ±112.5 and ± 157.5° relative to the axis of fragment detection.

The target material was irradiated with neutrons that were polarized in a specific direction (longitudinally polarized). The polarized neutron flux in front of the fission chamber for neutron wavelengths λ = 0.55 Å (0.27 eV) and λ = 1.15 Å (0.06 eV) was $3.3 \cdot 10^6$ neutron/(cm^2·sec) and $2.4 \cdot 10^6$ neutron/(cm^2·sec), respectively. The measured asymmetry of the coincidence counts was determined by the ratio:
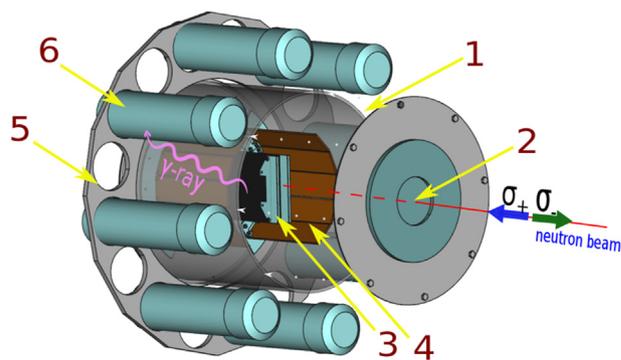

Fig. 1. Schematic of the detector setup used in the experiment at the FRM II reactor. 1 — fission chamber, 2 — input Al chamber window, 3, 4 — fission fragment detectors based on position-sensitive low-pressure multiwire proportional counters (start and stop detectors), 5 — holder, 6 — scintillation plastic detectors for γ-quanta and neutrons. The fissile target is located in the center, between the start detectors.

$$D(\theta) = \frac{N^+(\theta) - N^-(\theta)}{N^+(\theta) + N^-(\theta)}, \qquad (1)$$

where $N^+(\theta)$ and $N^-(\theta)$ is the number of coincidences of signals from γ-quanta detectors and from fragment detectors, located at an angle θ to each other in the plane orthogonal to the axis of the longitudinally polarized neutron beam, measured at two opposite directions of polarization of the neutron beam.

Measurements continued for a month. During the measurement period, the total number of recorded fission events was 2.8×10^7.

2.2. Proposed methodology

On tangential channel № 1 [17] of the IBR-2M pulsed reactor of the Frank Laboratory of Neutron Physics (FLNP) JINR, experiments are planned to measure the ROT effect for prompt gamma quanta in the isolated ^{235}U resonance with the energy of 1.14 eV. However, the neutron flux and spectrum differ significantly from the FRM II reactor where previous experiments were performed. The flux of polarized neutrons with an energy of 1.14 eV in experimental channel № 1 is $\sim 10^2 \div 10^3$ neutron/(cm^2·sec). Obviously, using thin targets, ideal for fragment detection, becomes impractical due to the low neutron flux, resulting in insufficient data collection. Therefore, directly recording fragments to measure the ROT effect for resonance neutrons on channel №1 is not feasible. A novel approach proposed by senior researcher V.L. Kuznetsov from FLNP aims to overcome this limitation by using a thicker target, even though it prevents fragment detection. Previous experimental studies aimed at studying the mechanism of neutron emission in nuclear fission show that neutrons are emitted mainly in the direction of motion of the fragments [18—20]. The presence of such strong neutron anisotropy allows to reconstruct the trajectory of the fragments. The proposed methodology is explained in detail below.

A fission chamber is not needed in case of using a thick (mass several tens of grams) target. A collimated neutron beam from the reactor passes through a polarizer made of Co—Fe single crystals. These single crystals are used simultaneously as a monochromator to select a narrow beam of neutrons with the required energy, and as a polarizer. After the polarizer, the neutrons pass through spin transport and control systems (spin flipper) and hit a target surrounded by scintillation detectors (see Fig. 2).

The experiment utilizes scintillation detectors specifically chosen for their ability to efficiently detect both fast neutrons and gamma rays across a wide energy range. Additionally, these detectors can
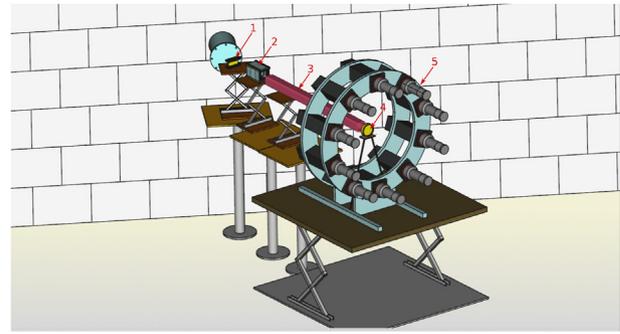

Fig. 2. Experimental setup for measuring the ROT effect. 1 — neutron polarizer based on CoFe single crystal; 2 — spin flipper; 3 - leading magnetic field; 4—^{235}U target; 5 - plastic scintillation detectors.

distinguish between neutron and gamma ray signals. This discrimination will be achieved using the time-of-flight (TOF) method, which relies on the start signal from the pulsed IBR-2M reactor.

Similar to the previous experiment, the asymmetry of the coincidence count will be measured using the formula presented in Eq. (1). In this case, $N^+(\theta)$ and $N^-(\theta)$ are the number of coincidences between prompt gamma quanta and neutrons in two coordinate systems corresponding to two opposite polarization directions of induced neutrons. While the resulting asymmetry is expected to be lower compared to measurements using fission fragment coincidences (about 3—4 times less), the use of a thicker target significantly improves the data collection rate, which is crucial for a successful experiment.

The proposed technique offers the potential to observe the rotation of the fragment emission axis relative to the deformation axis, occurring within a plane perpendicular to the polarization axis of the fissile nucleus. This prediction is based on previously obtained experimental data, which will be discussed in detail in the next chapter.
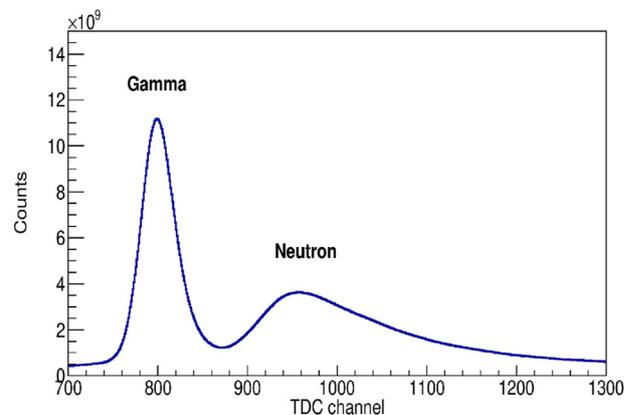

Fig. 3. Time-of-flight spectrum from a plastic scintillation detector.

3. Experimental

3.1. Neutron/gamma discrimination using plastic scintillator

Fig. 3 shows the time-of-flight spectrum measured using a plastic scintillation detector. The spectrum was obtained using fission events of ^{235}U induced by monochromatic neutrons with an energy of 60 meV. The distance from the uranium target to the center of the detector was 30 cm. In the experiment, a time-to-digital converter (TDC) with a timing resolution of 75 ps was used.

In these spectra, two peaks are distinguished: a narrow peak of prompt fission γ-quanta and a broad peak of prompt fission neutrons. The first of them corresponds to shorter time intervals between the start and stop pulses. Both peaks are located on an approximately horizontal substrate formed by random coincidences of the start and stop pulses.

3.2. Anisotropy of prompt neutrons

Eight plastic scintillation detectors were used to measure the angular distribution of prompt γ-rays and neutrons emitted in the fission of ^{235}U induced by monochromatic neutrons with an energy of 60 meV. These detectors provided subsequent coincidence measurement between prompt γ-rays/neutrons and fission fragments. By recording coincidences between pulses from the eight plastic detectors and each segment of the ten stop detectors, data for 16 different angles between the fission fragment and gamma ray/neutron axes were collected (see Fig. 4). Fig. 4 shows that the angular distribution of fission neutrons relative to the fission axis is highly anisotropic.

Unlike the emission of γ-quanta, the primary contribution to the anisotropy of the angular distribution of prompt neutrons comes from the kinematic effect of adding the nonrelativistic velocities of the neutron and the fission fragment. Since the speed of the
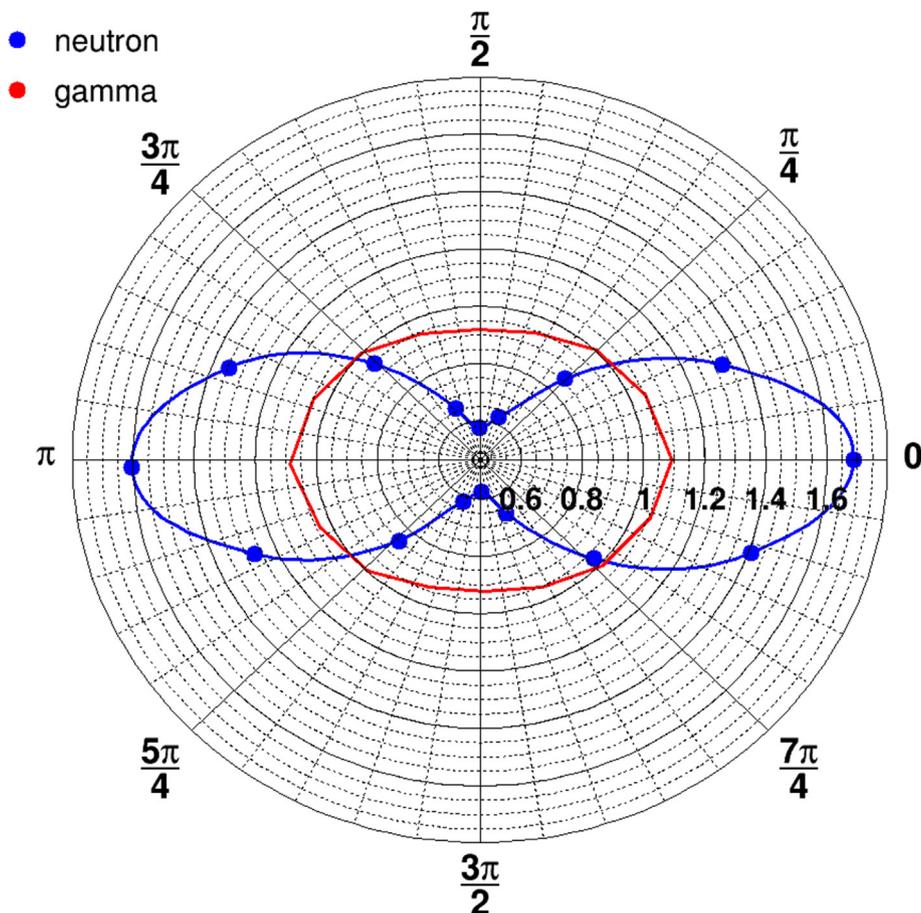

Fig. 4. Angular distributions of prompt gamma rays and neutrons in the fission of ^{235}U induced by "warm" neutrons By approximating the obtained angular distributions with the function $N(\theta) \approx 1 + A \cdot cos^2\theta$, the anisotropy coefficients $A = 0.157 \pm 0.0053$ for prompt gamma rays [21] and $A = 1.0256 \pm 0.0638$ for prompt fission neutrons were determined.
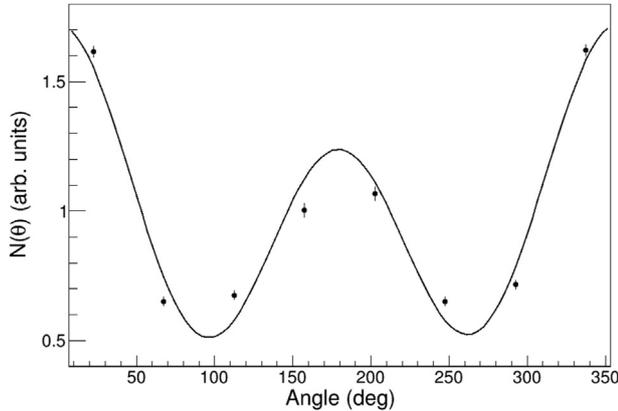
Fig. 5. The dependence of fission neutrons on the angle between the directions of neutron pulses and the light fragment.

neutron emitted by the fragment is comparable to the speed of the fission fragment, the anisotropy of the angular distribution of neutrons highly depends on the angle between the momenta of the light fragment and the prompt neutrons. Fig. 5 presents the angular distribution curve of prompt neutrons from the fission of ^{235}U induced by cold neutrons, where only a light fragment is released.

Error bars depicted by vertical lines represent statistical uncertainties due to the number of event counted. The ratio of events at $0°$ (aligned with the light fragment) to those detected at $180°$ (aligned with the heavy fragment) is equal to N $(0°)$/N $(180°)$ = 1.69. This indicates that the probability of neutron emission in the direction of light fission fragment emission is ~1.7 times higher than in the direction of a heavy fragment.

4. Summary and conclusions

This paper discusses the possibility of using the anisotropic angular distribution of fission neutrons (instead of fragments) to study the ROT effect for prompt gamma rays in binary fission. It also presents the measurement results of the angular distribution of prompt neutrons in the fission of ^{235}U induced by cold and "warm" neutrons. According to the quasi-classical model [8], it is necessary to note two important points o explain the mechanism of the ROT effect in the angular distribution of prompt γ-quanta:

1) the existence of anisotropic emission of fission γ-quanta in the fragment rest system;
2) the absence of axial symmetry of the corresponding angular distribution (in the rest system of the fragment) relative to the axis of the fragment emission.

The model proposes that the ROT effect arises from the following sequence:

a) Immediately after the rupture of the fissile nucleus neck, the excited fission fragments align relative to the axis, connecting the centers of mass of the two fragments (the deformation axis) at that moment. This alignment influence the spins of the fragments, leading to the observed anisotropy in the emission of γ-quanta by the fission fragments.
b) The orbital angular momentum of fission fragments is not zero and correlates with the direction of polarization of the fissioning nucleus. In this case, the emitting fragments have a velocity component perpendicular to the deformation and the polarization axis of the fissile nucleus. This component causes the fragment emission axis to rotate in a plane perpendicular to the polarization axis of the fissile nucleus.
c) The angular distribution of fission γ-quanta is anisotropic, with the axial symmetry axis being the alignment axis of the spins of fission fragments, i.e., deformation axis. Since this axis does not coincide with the axis of fragment emission, there is no axial symmetry in the angular distribution of fission γ-quanta relative to the fragment emission axis.
d) Traditionally, the ROT effect is measured by coincidence counting signals from γ-ray and fragment detectors located at an angle θ relative to each other. This measurement is performed with the neutron beam polarization flipped between two opposite directions.

It is shown that the angular distribution of prompt fission neutrons exhibits strong anisotropy relative to the fragment emission axis due to the addition of velocities. This allows us to effectively reconstruct the emission direction of fragments using the angular distribution of prompt fission neutrons, enabling the use of thicker targets in future experiments. While the ROT effect magnitude will likely be lower using neutron coincidences compared to fragment coincidences, the improved statistical accuracy will enhance the measurement reliability.

Conflict of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Acknowledgments

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