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ANGULAR DISTRIBUTION OF PROMPT FISSION γ-RAYS

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Abstract. The angular distributions of prompt-fission γ-rays with respect to the direction of fission fragments in the monochromatic “warm” neutron induced fission of ^{235}U have been studied. The fragments were detected with low-pressure position sensitive multi-wire proportional counter and the gamma-rays with a plastic scintillators. The time-of-flight method is used to discriminate prompt neutrons and prompt γ-rays of fission. From the measured angular distributions with respect to the direction of the selected fragments, the value of the laboratory anisotropy has been found to be 15 % in comparison to the value obtained in the perpendicular direction. The measurements indicate the existence of a significant anisotropy of emission of the γ-rays in the emitting-fragment system, suggesting the presence of significant angular momenta of the fragments correlated with the fission axis, which also lead to an enhanced emission of the γ-rays. Moreover, the article includes a new technique for measuring and correcting the obtained angular distribution, in the case of when plastic scintillators have different threshold levels for detection of γ-rays.

Key words: Neutron induced fission of ^{235}U; angular distributions of the prompt γ-rays of fission; angular anisotropy.

1. INTRODUCTION

Despite intensive past studies in nuclear fission processes, there are still many that are not fully understood and just partially studied. The problem of de-excitation of fission fragments in the nuclear fission processes is nowadays in focus of many studies. The de-excitation of fission fragments takes place through the emission of prompt neutrons and γ-rays [1]. Emission of the prompt γ-rays removes some amount of energy and a small amount of angular momentum. In other words, this excitation energy and angular momentum is released *via* the emission of prompt γ-rays [2]. The properties of prompt γ-rays depend on the angular momentum of the emitting system and are also very useful for studying the initial value of fission-fragment spins [2].

The angular distribution of prompt γ-rays of fission is anisotropic and elongated along the trajectory of the fragments emitting them due to the fact that the spins of the fragments are aligned perpendicular to the fission axis [3–5]. According to the model [6], the alignment of the fragments is formed at the moment of fragments separation in a time of $\sim 10^{-21}$ seconds and its direction does not change during the deviation of the fragments from the fission axis. That is, due to the angular momentum conservation law, the orientation of the fragment angular momenta (spins) remains the same with respect to the initial direction of the deformation axis of the fissioning nucleus, while the fission axis rotates by the certain angle δ_{ff}. Experimentally, this rotation can be observed as a shift in the angular distribution of the γ-rays with respect to the fragment emission direction, depending on the neutron polarization, since gamma quanta are emitted after a time of $\sim 10^{-11}$ seconds. Thus, the alignment of the fragments serves as a kind of undistorted memory of the fission axis direction, while the anisotropy of gamma radiation provides information about the mechanism and dynamics of the fission process.

An experimental study of the nuclear rotation effect, the so-called ROT effect in the angular distributions of prompt fission γ-rays, was carried out by our group. The results of the experiments are published in [7–9], where has been given a more detailed description of the ROT effect. This paper presents a new technique and the results of measuring the angular distribution of prompt γ-rays in the fission of ^{235}U induced by monochromatic neutrons with an energy of 60 meV. From the measured angular distributions, the value of the laboratory anisotropy A for gamma quanta was found, and the obtained values of A were then used to study the ROT effect.

1.1. EXPERIMENTAL SETUP

The detailed description and performance evaluation of the setup and data acquisition electronics have been discussed previously [9, 10] and therefore only some specific features of the setup will be briefly described.

The two-sided fissile target, containing about 82 mg of $^{235}U_3O_8$ (99.99 %) oxide-protoxide, deposited on the ≈ 30 μm thick 50×110 mm^2 aluminum backing is mounted on the axis of the fission chamber along neutron beam direction. The size of the uranium layer was 40×100 mm^2 and the thickness of each uranium layer was about 1 mg/cm^2.

Two low pressure position sensitive multiwire proportional counters (LPMWPC) facing each other to the left and right of the target at a distance 2.5 cm (start detector) and 12.5 cm (stop detector) recorded the fission fragments (see Fig. 1). Each stop counter consists of five independent segments at the angles of 0, $\pm$ 22.5, $\pm$ 45 degrees in the left side and $\pm$ 135, $\pm$ 157.5, 180 degrees in the right side of the target to increase the angular sensitivity of the detector. Each segment of the stop detector is connected in a chain separated by delay lines and fed into one TDC channel. The time of arrival of the signal relative to the start detector indicated which segment was hit by the fission fragment.

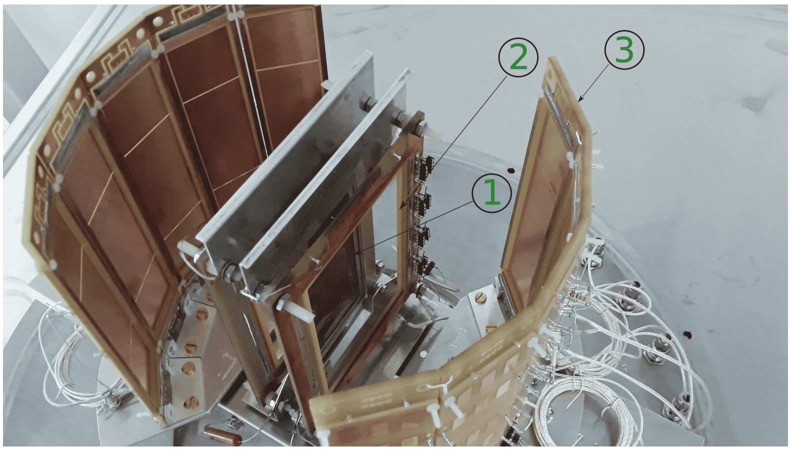

Fig. 1 – Picture of the low-pressure position sensitive multiwire proportional counters. 1 – fissile target; 2 – start detector; 3 – segmented stop detector.

The gamma detectors were plastic scintillators, 70 mm long and 120 mm in diameter, viewed by a EMI 9839A photomultiplier tube. The plastic detectors were placed outside the fission chamber, about 30 cm from the center of the target and in a direction perpendicular to the direction of the detected fission fragments. Plastic detectors, located at the angles of $\pm$ 22.5, $\pm$ 67.5, $\pm$ 112.5, and $\pm$ 157.5 degrees ensure subsequent measurements of coincidences of prompt fission γ-rays and fission fragments with respect to the mean axis of the detection of fragments. The schematic view of the used detector array inside/outside the fission chamber is shown in Fig. 2.

The prompt neutrons that are also released during the fission events cause a background in the gamma detector. The time-of-flight technique was used for discrimination between the prompt neutrons and the fission γ-rays.

2. RESULTS AND DISCUSSION

The angular distribution of prompt γ-rays was measured using eight plastic scintillation detectors (see Fig. 3). The angular distribution of γ-rays from the binary fission of a compound nucleus can be described by the following function [11]:

$$N(\theta) \sim 1 + A \cdot \cos^2\theta \tag{1}$$

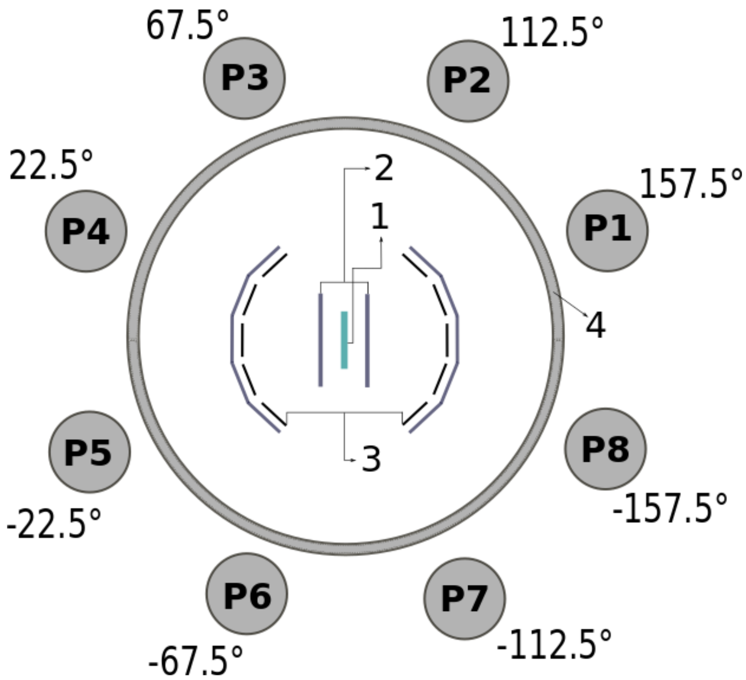

Fig. 2 – The layout of the detector positioning around the target inside/outside the fission chamber. View from the beam direction. 1 – fissile target, 2 – start detectors; 3 – segmented stop detectors; 4 – fission chamber; P1-P8 are plastic scintilators.

where A is the coefficient of the angular anisotropy, and θ is the angle of gamma quantum emission.

The obtained angular distribution was approximated by the function (1), which is also shown in Fig. 3. As shown in the figure, the approximation curve deviates from some experimental points. This is mainly due to setting different threshold levels of gamma detectors. Different threshold levels resulted in different counting efficiency of gamma detectors, which were corrected by the found coefficients for every detector.

3. METHODOLOGY OF COEFFICIENTS DETERMINATION

For an illustrative example, let us draw the function (1) (see Fig. 4). Figure 4 shows that detectors located in certain positions (indicated in different colors in the figure) should register approximately the same number of γ-rays from the binary fission. Hereof, the counting efficiency of each detector could be predicted.

But in our case, each angle does not correspond to a specific detector, for example, angle 0 is given by four, and the angle 22.5 by six combinations of detectors

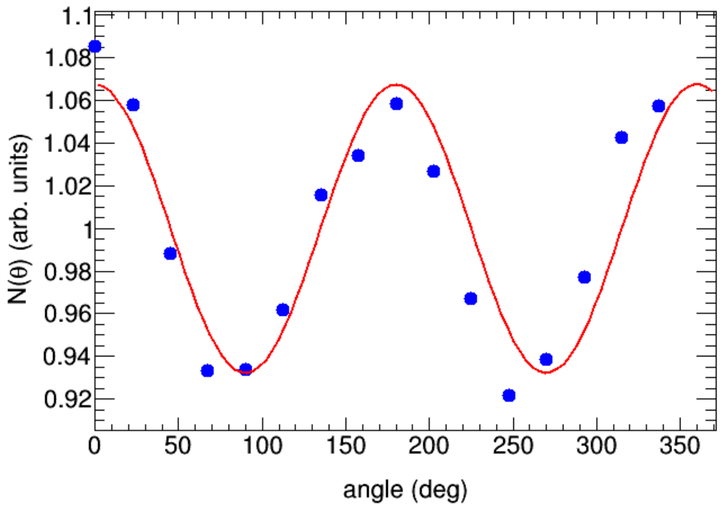

Fig. 3 – The angular distribution of prompt γ-rays in binary fission of ^{235}U induced by monochromatic "warm" neutrons. The red line shows the approximation of this distribution by the function (1).

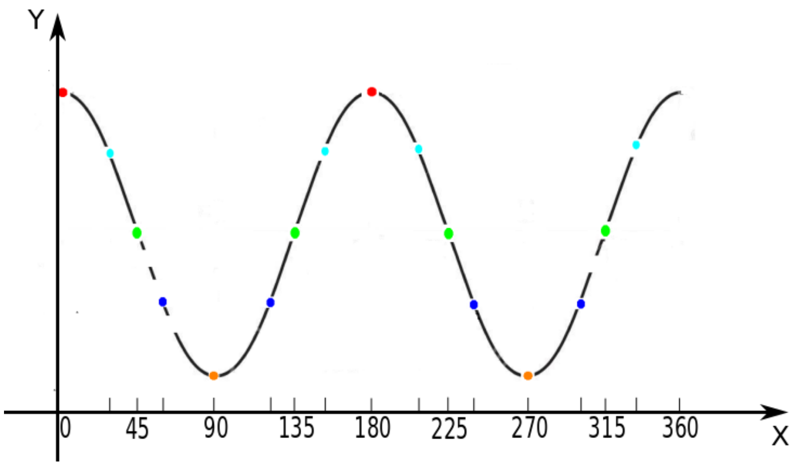

Fig. 4 – Plotting the function $1 + A \cdot \cos^2\theta$.

of γ-rays and fission fragments. In experiment coincidence pulses from eight independent plastic detectors with each pulse from ten segments of the stop detector form sixteen different angles between the axes of fission fragments and gamma detectors:

$$\theta = Pl_{ang} - FF_{ang}, \tag{2}$$

where FF_{ang} and Pl_{ang} are the angular positions of the segments of the fission fragment stop detector and γ-ray plastic detectors, respectively.

The counting efficiency of gamma detectors was corrected by analyzing all possible combinations of angles between each segment of the stop detector with all gamma detectors (ten iterations in total). Such an operation is similar to that one rotates an array of eight detectors and measures the counts of each detector at the same angle per unit time. Consequently, a specially written computer program (in C++) was used [10]. The program sets time intervals in the time-of-flight spectra to discriminate prompt γ-rays from prompt neutrons and separate the segments of the stop detector. Some typical time-of-flight spectra are shown in Fig. 5.

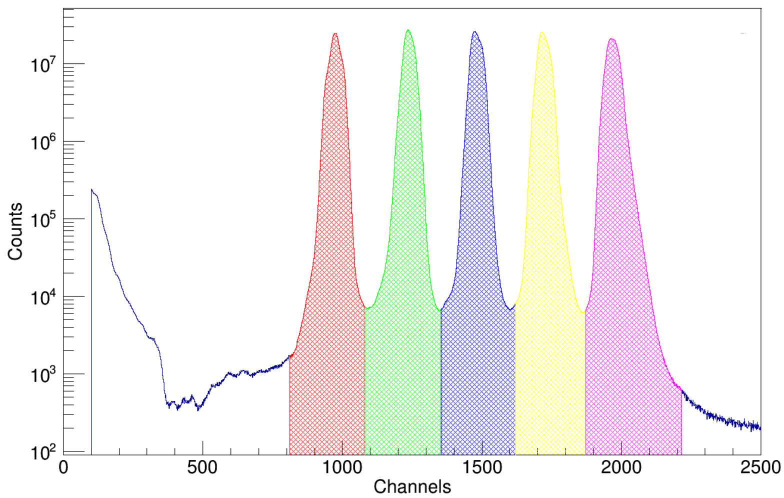

Fig. 5 – Time-of-flight spectrum from one of the stop detectors.

From all the data analyzed, it is found that the two plastic scintillators counted less, while the others had approximately the same counting efficiency. The corresponding coefficients for each detector were found by comparing the count rates of different detectors at the same angles. Figure 6 shows the angular distribution of prompt γ-rays in binary fission of ^{235}U, obtained after slightly correcting (taking into account the correction for counting efficiency) of the same distribution (Fig. 3).

As shown in Fig. 6, a small, but definite, γ-ray fission fragment directional correlation exists. The data obtained uniquely indicate the existence of an anisotropy of γ-ray emission in the center-of-mass system. The experimental data indicate that a relationship exists between the nuclear spin axis and the direction of fragment motion, subsequently referred to as the fission axis. This can be explained due to that the probability of emission of γ-rays by an excited nucleus generally depends on the angle between the nuclear spin axis and the direction of emission. Assuming that the fission fragments, after the emission of neutrons, decay toward the ground state

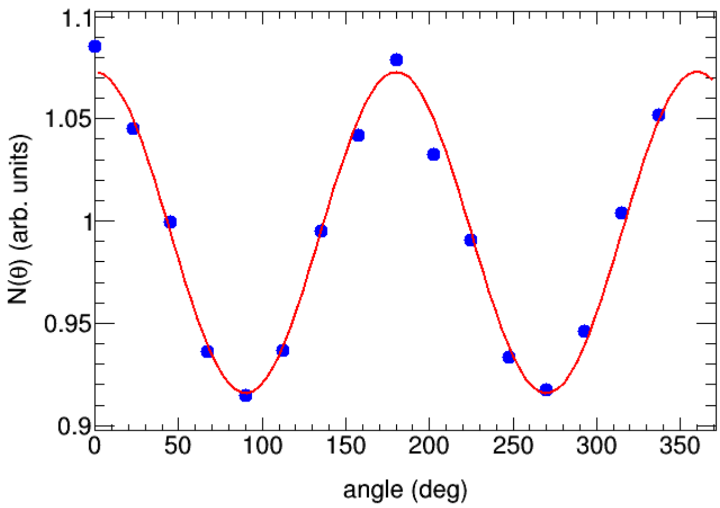

Fig. 6 – The angular distribution of prompt γ-rays in binary fission of ^{235}U after correcting of all gamma detectors for efficiency.

by dipole radiations, the observed γ-ray correlation indicates a net polarization of the fragment angular momentum along the fission axis. For dipole gamma radiation, the data indicate an orientation of the momentum along the fission axis, and for quadrupole radiation the data show an orientation perpendicular to the axis [5].

The coefficient of the angular anisotropy was found by fitting the angular distribution of the prompt γ-rays emitted in binary fission by function (1).

4. CONCLUSION

The angular distribution of prompt γ-rays from the fission of ^{235}U was measured using a beam of monochromatic neutrons with an energy of 60 meV provided by a POLI instrument at the Heinz Mayer-Leibniz research neutron source (FRM II reactor) at the Technical University of Munich in Garching (Germany). In the measurement procedure, unlike others, we did not change places of scintillation and fission fragment detectors. All plastic detectors were placed at the fixed angle of $\pm$ 22.5, $\pm$ 67.5, $\pm$ 112.5, and $\pm$ 157.5 degrees. Sixteen different angles between the axes of the fission fragments and gamma detectors were obtained using coincidences between the stop detector (fission fragment detector) and eight independent plastic detectors. The resulting angular distribution was corrected for the thresholds of the detectors. The coefficients associated with the threshold of each detector were found by analyzing data from all possible combinations of stop and gamma detectors separately. The average coefficient of angular anisotropy was found by fitting the corrected angular distribution by function (1). This result is in good agreement with the results of other authors. The value of the anisotropy was found A = 0.1570 $\pm$ 0.0053. The error of this value was estimated from the statistical error of the measured data. The probability of γ-ray emission in the direction of fission was higher than in the perpendicular direction.

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