MEASUREMENT OF T-ODD EFFECTS IN THE NEUTRON INDUCED FISSION OF ^{235}U AT A HOT SOURCE OF POLARIZED RESONANCE NEUTRONS

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Abstract. The TRI and ROT asymmetries in fission of heavy nuclei have been extensively studied during more than a decade. The effects were first discovered in the ternary fission in a series of experiments performed at the ILL reactor (Grenoble) by a collaboration of Russian and European institutes, and were carefully measured for a number of fissioning nuclei. Later on, the ROT effect has been observed in the emission of prompt gamma 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. All experiments performed so far are done with cold polarized neutrons, what assumes a mixture of several spin states, the weights of these states being not well known. The present paper describes the first attempt to get "clean" data by performing the measurement of gamma and neutron asymmetries in an isolated resonance of ^{235}U at the POLI instrument of the FRM2 reactor in Garching.

1. Introduction

The T-odd effects in fission of heavy nuclei have been known since more than a decade. The first effect of this type, the so called TRI-effect was discovered at the ILL reactor (Grenoble) by a collaboration of Russian and European institutes [1,2] in an experiment aimed at the search for violation of time reversal invariance (TRI) following the idea, proposed in [3]. It was found that the probability of emission of an alpha-particle in ternary fission in the direction perpendicular to the plane formed by the neutron spin and the fragment momentum shows a pronounced anisotropy. The magnitude of the effect turned out to be surprisingly large, and the current explanation doesn’t imply the existence of such a violation, but is based on the final state interaction of the reaction products. In other words, the effect is not connected with the violation of the time reversal invariance, but with the mechanism of the fission process. Nevertheless, the effect is still called the “TRI-effect” in literature.

Furthermore, it was noticed that when reversing the direction of polarization of the neutron beam, the angular distribution of α- particles is shifted by a small angle relative to the axis of fragment emission, the offset direction being determined by the direction of polarization of the neutron beam. The authors called this effect the ROT - effect [4]. Both, TRI and ROT effects are formally T-odd, but have no direct connection with the violation of the time reversal invariance.

From the semiclassical description of the ROT effect, which assumes the rotation of a polarized nucleus before it splits into two (or three) fragments it follows that a similar phenomenon can also be discovered in the angular distribution of some other particles accompanying the fission of a nucleus into two fragments. The effect can be observed only if this 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 gamma 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 [5-7].

At present, there are several theoretical models which can describe both effects [8-13]. According to the model, proposed in [13], both effects depend on the quantum numbers J and K (the total angular momentum and its projection on the deformation axis), which characterize the fission channel. For the thermal (or cold) neutron induced fission (where all previous data are obtained), there is a mixture of several spin states, and the weights of these states are not known. The only way to get "clean" data is to perform measurements in isolated resonances. Such an experiment was performed at the POLI instrument of the FRM2 reactor in Garching, which provides the necessary polarized neutron beam with an energy of 0.27 eV, corresponding to the lowest resonance of ^{235}U. Preliminary results of this experiment are presented in this paper.

2. Experiment

We used the polarized hot neutron beam provided by the POLI instrument [14] at the FRM-II reactor in Garching. The schematic view of the experimental setup is shown in Fig. 1.

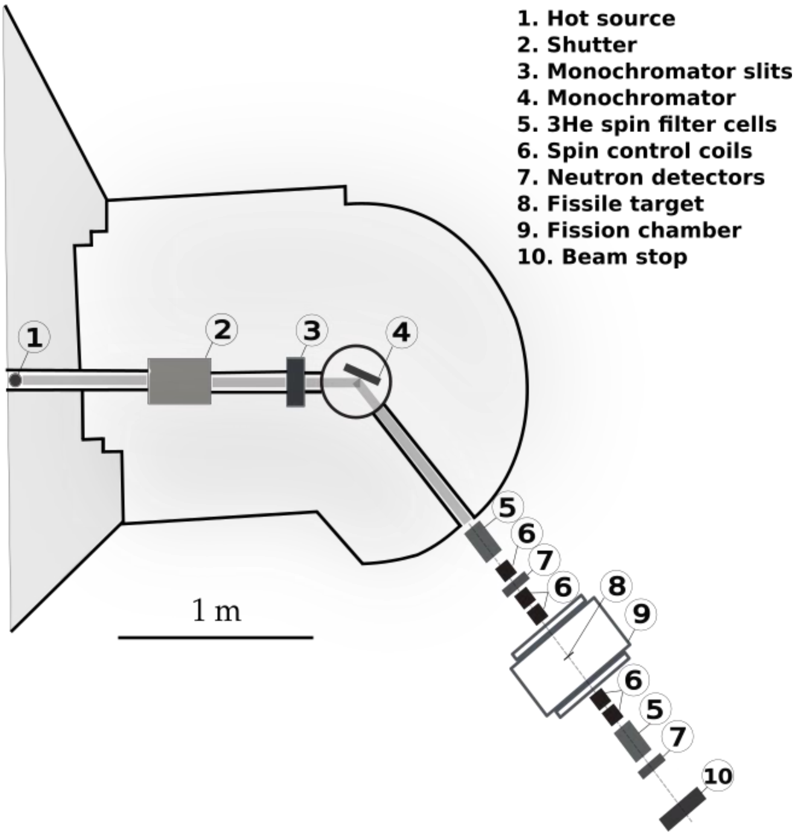

Fig. 1. Schematic view of the experimental setup at the POLI facility of FRM-II.

A monochromator made of a mosaic of Cu crystals was used to select a narrow neutron beam with the mean energy of 270 meV (λ=0.55 Å). This energy exactly coincides with the position of the lowest resonance of ^{235}U [15]. The monochromator also allows simultaneous focusing of the neutron beam on the target position providing the maximum intensity of unpolarized neutrons of about $4\cdot10^6$ n/cm^2/sec.

The neutrons were polarized using specially designed ^{3}He gas cells [16]. The same type of cell was also used as analyzer for measuring beam polarization. Since polarized nuclei of ^{3}He possess very high spin-dependent neutron absorption efficiency over a wide range of energies, the ^{3}He cell can be used as a broadband neutron polariser or analyser, with the possibility to optimise its efficiency for nearly all neutron wavelengths. In our experiment, the size of the cells was Ø60×130 mm and the gas pressure 2.5 bar (0.25 MPa), which provided the maximal neutron polarization of about 70%. The polarizer and analyzer cells were polarized in an external lab and placed into a special magnetic housing with highly homogeneous constant magnetic field. The polarization of ^{3}He in the cell exponentially decreased with the time constant of about 40 hours, therefore both cells were replaced every 24 hours.

Both, polarizer and analyzer provided vertical polarization of the neutron beam while the searched effect requires horizontal (longitudinal) polarization. For changing the polarization direction from vertical to horizontal, a specially designed spin control system was used, consisting of several μ-metal shielded magnetic coils, which allowed also flipping the spin at the target position by 180 degrees every 1.3 seconds.

The schematic view of the fission chamber surrounded by a set of gamma-ray detectors is shown in Fig. 2.

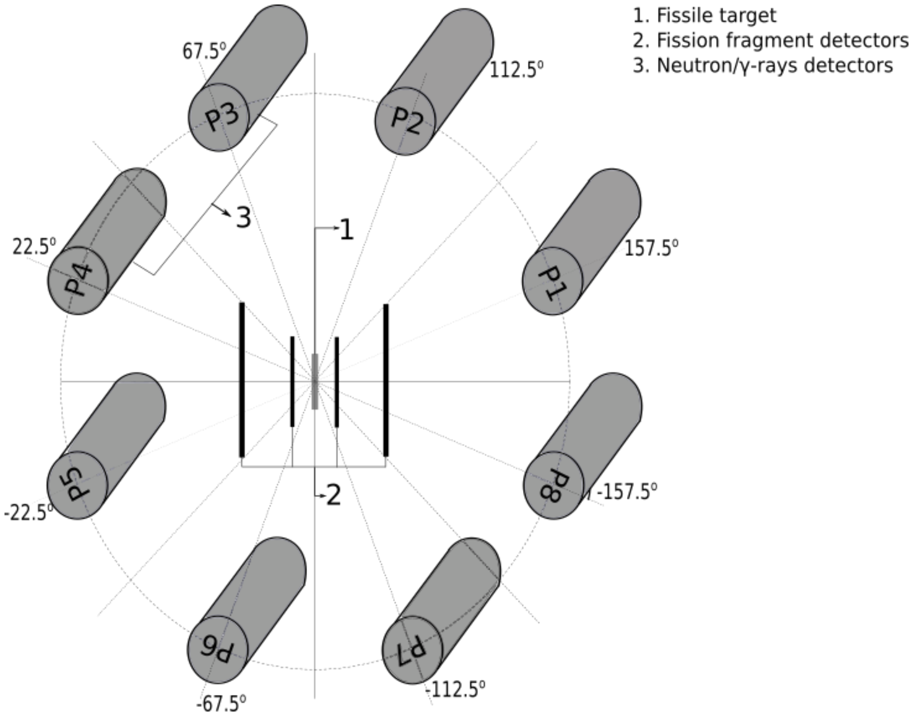

Fig. 2. Layout of the experimental facility. View from the beam direction.

The chamber was filled with CF_4 gas at a pressure of about 10 mbar. A uranium target containing about 82 mg of ^{235}U (99.99%) oxide-protoxide deposited on the two sides of a thick 40×100 mm^2 aluminium backing was arranged along the chamber axis. Thin low-pressure multiwire proportional counters (MWPC) were used as fission fragment detectors, being placed on two sides of the target at a distance of ~3 cm (start detector) and ~11 cm (stop detector). Start and stop detectors are supposed to be used for measuring the fragment velocities (momenta). Eight cylindrical plastic scintillators were inserted in a rotatable holder at a distance of about 30 cm from the target center that ensures subsequent measurements of coincidences of prompt fission gamma rays and neutrons with fission fragments at angles of ±22.5, ±67.5, ±112.5 and ±157.5 degrees with respect to the mean axis of the detection of fragments. The detectors of gamma rays and fission fragments were arranged in the plane orthogonal to the neutron beam direction, which also coincides with the axis of the polarization of ^{236}U nuclei.

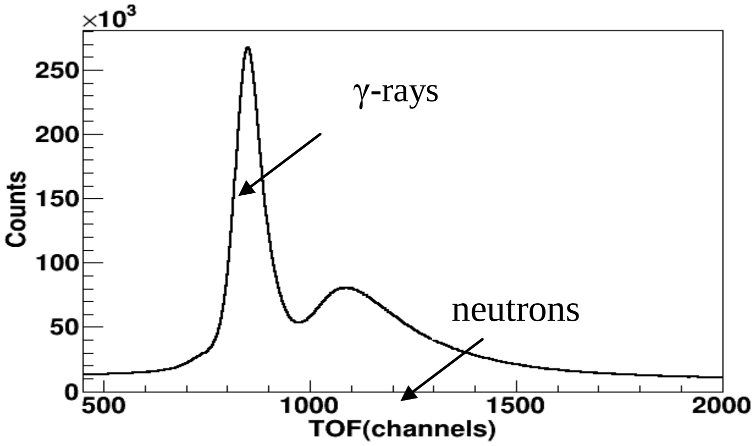

Fig. 3. Time-of-flight spectrum from one of the plastic detectors.

Prompt neutrons could be rather well separated from the prompt gamma-rays using the time-of-flight method (see Fig.3). Every event matching coincidence of the signals from the gamma/neutron and fragment detectors is digitized by a multichannel TDC CAEN V775N and stored together with the information about the direction of polarization of the neutron beam. A reversal of the polarization occurs at a frequency of 1.3 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 fission fragments were recorded by counters, which were read out every 5 min for each detector. The values of the asymmetries, calculated by the formula:

$$R = \frac{(N^+ - N^-)}{(N^+ + N^-)}, \tag{1}$$

were constantly monitored. Here N^+ and N^- are the coincidence count rates for opposite directions of the neutron polarization. Simultaneously, the asymmetry of the fragment count rates was measured and controlled.

The total time allocated for the experiment at the POLI facility was 11 days. Four days were spent for the installation of the setup, calibration of the detectors, alignment of the spin control system etc. The statistic was accumulated during 7 days. Because of the rather short measurement time, to increase the coincidence rate only “start“ fission fragment detectors were used in the analysis, which made the determination of the fragment mass (separation of light and heavy fragment groups) impossible and increased the angular spread of the fission fragments. For the ROT-effect the light-heavy fragment separation is not necessary, as the effect is mass-symmetric. The use of only the “start” detector increased the solid angle of the fission fragment detection which could lead to a decrease of the potentially observed effect, but significantly increased the accumulated statistics, which was more important considering that the main aim of this pioneering experiment was to observe the effect, but not to measure its absolute value.

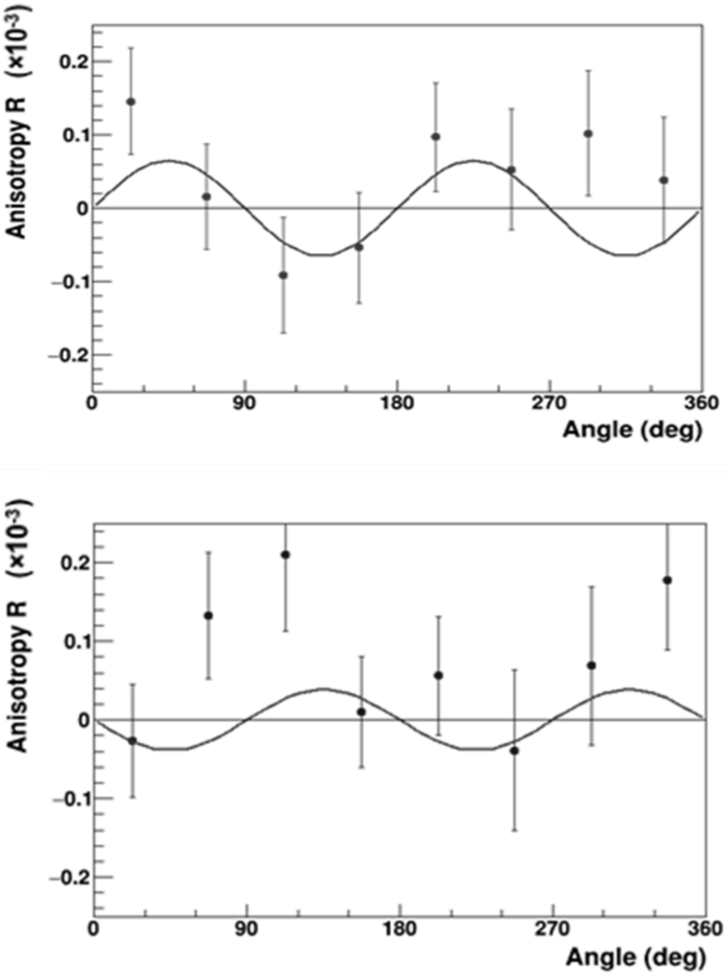

Fig. 4. Anisotropy ratio R as a function of angle for the gamma-rays (top) and neutrons (bottom).

3. Results and discussion

Figure 4 shows the anisotropy ratio R determined from the experimental data according to formula (1), for prompt gamma-rays (top) and neutrons (bottom), detected in coincidence with one of the fission fragments. Each point corresponds to the angular detector position with respect to the average direction of emission of the detected fission fragments. The angular dependence at first approximation can be fitted by the function $F = A\cdot sin(2\theta)$, which is shown on the plots. The anisotropy parameter A could be determined from the fit and equals to $A_\gamma = (-6.5\pm3.9)\times10^{-5}$ for the gamma-rays and $A_n = (+3.8\pm4.1)\times10^{-5}$ for the neutrons, χ^2/N being 0.98 and 1.70, respectively. These results can be compared to the corresponding values for ^{235}U, obtained with cold neutrons: $A_\gamma = (-16.6\pm1.6)\times10^{-5}$ (at 45 degrees) and $A_n = (-21.2\pm2.5)\times10^{-5}$ (at 22.5 degrees). Although the statistical accuracy is not sufficient to claim that the ROT effect has been observed in the lowest resonance of ^{235}U, one can conclude that the effect is definitely smaller than that in the cold neutron induced fission.

It should be mentioned that the authors of [13], who developed one of the most comprehensive models of the TRI- and ROT-effects, predicted such a decrease of the anisotropy coefficient for the 0.27 eV resonance of ^{235}U, based on the known contributions of the J=3 and J=4 partial cross sections for this nucleus and on the value of the most probable K-channel for these spins, derived from their work. Thus, the results of our experiment are in agreement with the most modern theoretical model prediction.

We believe that it is important to continue this type of experiments in order to gain better statistical accuracy for the 0.27 eV resonance and extend the measurements to higher energies, e.g. to the 1.14 eV resonance where the effect should be larger than for cold neutrons and where practically only the J=4 spin state is present.

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