MEASUREMENT OF GAMMA AND NEUTRON ROT-EFFECTS IN 0.3 eV RESONANCE OF ^{235}U AT A HOT SOURCE OF POLARIZED NEUTRONS

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

[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]Petersburg Nuclear Physics Institute of National Research Centre "Kurchatov Institute", 188300 Gatchina, Russia
[4]Institut für Kristallographie, RWTH Aachen and Jülich Centre for Neutron Science at Heinz Maier-Leibnitz Zentrum (MLZ), Lichtenbergstr, 1, 85748 Garching, Germany
[5]Forschungs-Neutronenquelle Heinz Maier-Leibnitz, D-85747 Garching, Germany
[6]National Nuclear Research Centre, Baku, Azerbaijan
[7]L.N. Gumilyov Eurasian National University, 010000 Astana, Kazakhstan

Abstract. The present paper describes the first attempt to get "clean" data by performing the measurement of gamma and neutron ROT-asymmetries in an isolated resonance of ^{235}U at the POLI instrument of the FRM2 reactor in Garching. The measurement was performed in 0.3 eV resonance of ^{235}U at a hot source of polarized neutrons. Thin low-pressure multiwire proportional counters (LPMWPC) were used as fission fragment detectors, being placed on two sides of ^{235}U target at a distance of ~3 cm (start detector) and ~11 cm (stop detector). In order to register gamma rays and neutron, the fission chamber was surrounded by 8 plastic (for both gamma rays and neutron) and 4 NaI scintillation detectors (for gamma rays) placed at different angles with respect to the fission detector. The statistic was accumulated during 30 days. The analysis of collected events showed that gamma and neutron asymmetries in 0.3 eV resonance energy of ^{235}U were definitely smaller than that in the cold neutron induced fission.

1. Introduction

The search for the T-odd asymmetries in the angular distributions of the products in ternary fission of heavy nuclei induced by cold polarized neutrons began in the last years of the 20th century. The aim was that to discover the effects of T-invariance violation in nuclear fission processes (following the idea, proposed in [1]), by analyzing 3-fold angular correlation between fission fragments, neutron spin (polarization) and ternary particle in ternary fission. Although the effect was discovered, the observed asymmetry could not be an indisputable evidence of time-invariance violation. The reason is related to the significant influence of the interaction between fission products in final states and the interference of reaction amplitudes related to neighboring compound states. The result of these investigations by now has been the discovery of T-odd asymmetries of the TRI and ROT types in the ternary fission of a number of actinide nuclei with the emission as a third particles of both charged particles, α particles and tritons, and neutral particles, neutrons and γ-quanta. Both, TRI and ROT effects are formally T-odd, but have no direct connection with the violation of the time reversal invariance.

At present, there are several theoretical models, which can describe both effects [2–7]. According to the model, proposed in [7], 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 the 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 [8] at the FRM-II reactor in Garching. In the POLI instruments, 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 [9]. The monochromator also allows simultaneous focusing of the neutron beam on the target position providing the maximum intensity of unpolarized neutrons of about $4 \cdot 10^6$ n/cm^2/sec. Detailed description of the POLI instruments was given [10].

The neutrons were polarized using specially designed ^{3}He gas cells [11]. 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% (fig. 1). 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.

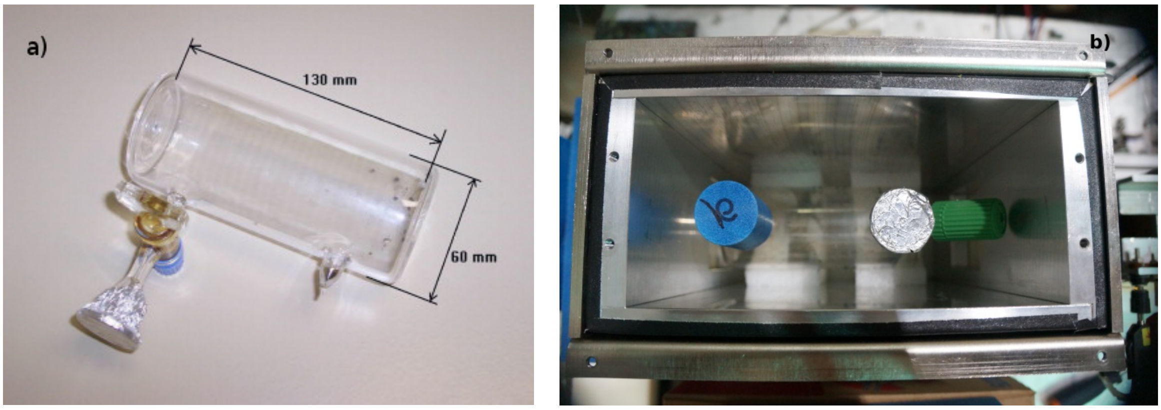

Fig. 1. Spin filter cell, made of fused silica. a) General view of the cell; b) inside of magnetic housing.

The polarization of the incoming beam is determined by the transmission measurement of the ^{3}He cells using two beam monitors. The general formulas that describe the transmittance T of a spin-filter for an incident unpolarized monochromatic neutron beam and neutron polarization P after passing through the cell with a polarized ^{3}He gas can be written as:

$$T = T_0 \cdot e^{-\eta} \cdot \cosh(\eta P_{He}), \quad (1)$$

$$P = \tanh(\eta P_{He}). \quad (2)$$

Here T_0 is a neutron beam transmission measured for an evacuated ^{3}He cell and P_{He} the polarization of the ^{3}He gas used. The parameter η defines a filter opacity related directly to the σ_0, σ_p, N and d, where N is the number of atoms per unit volume, d is the filter thickness, σ_0 is the spin-independent part of the total cross-section and σ_p is the so-called polarization cross-section. For practical purposes the value of the opacity of the ^{3}He gas at room temperature can be estimated using the relation

$$\eta = 7.32 \cdot 10^{-2} \cdot p(\text{bar}) \cdot d(\text{cm}) \cdot \lambda(\text{Å}), \quad (3)$$

where p is the gas pressure, d is the neutron path length in the gas and λ is the neutron wavelength. For clarity, the dependence of the transmission and the degree of polarization of neutrons on the degree of polarization of the ^{3}He from equations (1–2) are plotted in fig. 2.

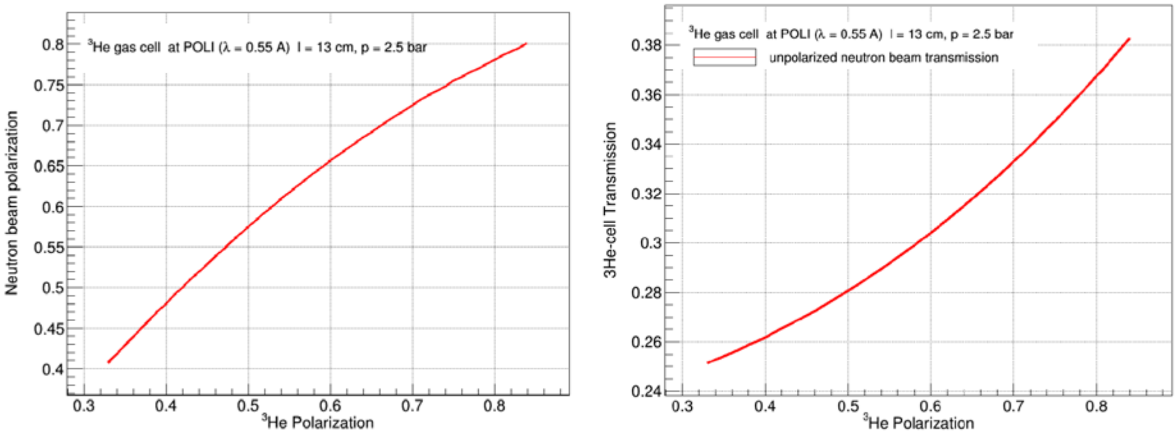

Fig. 2. Dependence of the transmission and the degree of polarization of neutrons on the degree of polarization of the ^{3}He.

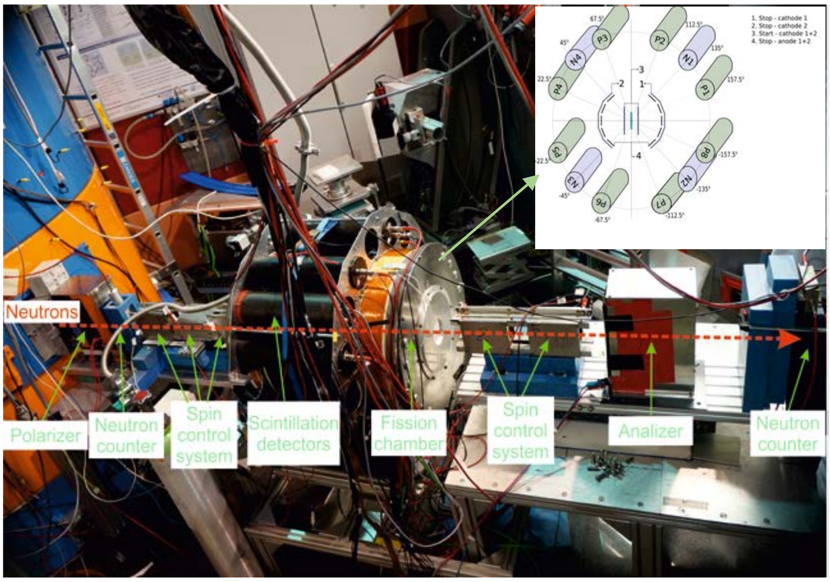

Fig. 3. The photograph of the experimental setup and the schematic drawing of fission chamber (upper right and view from the beam direction).

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 photograph of the experimental setup is shown in fig. 3. The schematic view (upper right) of the fission chamber surrounded by a set of gamma-ray detectors is illustrated in fig. 3 (upper right) too.

The chamber was filled with the 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 (LPMWPC) 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) (fig. 4).

The chamber was filled with the 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 (LPMWPC) 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) (fig. 4).

Basic advantages of LPMWPCs which make them very suitable for registration of heavy ions such as fission fragments (FFs) are the following: excellent timing characteristics, high efficiency, high transparency and low energy losses inside the detector, large surface area, high counting rate capability, good position resolution with proper signal readout, long term stability. The table below contains typical parameters of LPMWPCs:

Table 1: Typical parameters of LPMWPC

Working pressure	~ 0.1–10 mbar
Counting gases	isobutane, heptane, ethylene
Anode–cathode gap	~ 1.6–3.2 mm
Anode wire spacing	~ 1 mm
Anode wire diameter	~ 10–25 μm
Reduced electric field in the constant field region	$\sim 10^2$–10^3 V/(cm· mb)
Reduced electric field on the wire surface	$\sim 10^4$–10^5 V/(cm· mb)
Total gas amplification	$\sim 10^4$–10^6
Amplification on the wires	$\sim 10^1$–10^3
Signal current pulses rise time	~2–5 ns
Timing resolution	~ 0.1–1 ns

The fission fragment detector consisted of two start detectors placed on both sized of the target and 10 stop detectors, 5 on each side of the target. They were used for measuring the fragment velocities (momenta). The start detectors were also used for measuring the time-of-flight of the gamma-rays and neutrons, which were detected by eight cylindrical plastic scintillators and four NaI(Tl) scintillators. They 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.

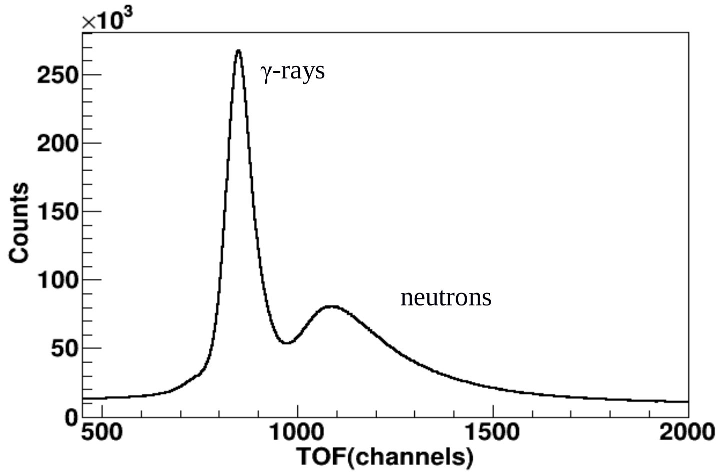

Fig. 5. Time-of-flight spectrum from one of the plastic detectors.

Prompt neutrons could be rather well separated from the prompt gamma-rays using the time-of-flight method (see fig. 5). 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:

$$R=(N^{+} - N^{-})/(N^{+} + N^{-}) \quad (4)$$

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.

3. Results and discussion

Fig. 6 shows the anisotropy ratio R determined from the experimental data according to formula (4), for prompt gamma-rays (top) and neutrons (below), detected in coincidence with one of the fission fragments. The 16 points in the figure are 16 possible combinations of angles between the scintillators and the fragment detectors. At each point, events from different scintillators and fragment detectors, but having the same angles, are summed up. The angular dependence at first approximation can be fitted by the function F=A·sin(2θ), which is shown on the plots. The anisotropy parameter A could be determined from the fit and equals to $A_{\gamma}=(-3.8\pm2.8)\cdot10^{-5}$ for the γ-rays and $A_{n}=(2.6\pm3.1)\cdot10^{-5}$ for the neutrons, χ^{2}/N being 0.87 and 0.96, respectively. These results can be compared to the corresponding values for ^{235}U

obtained with cold neutrons: $A_\gamma=(-16.6\pm1.6)\cdot10^{-5}$ (at 45 degrees) and $A_n=(-21.2\pm2.5)\cdot10^{-5}$ (at 22.5 degrees). It follows that the effect is definitely smaller than that in the induced fission.

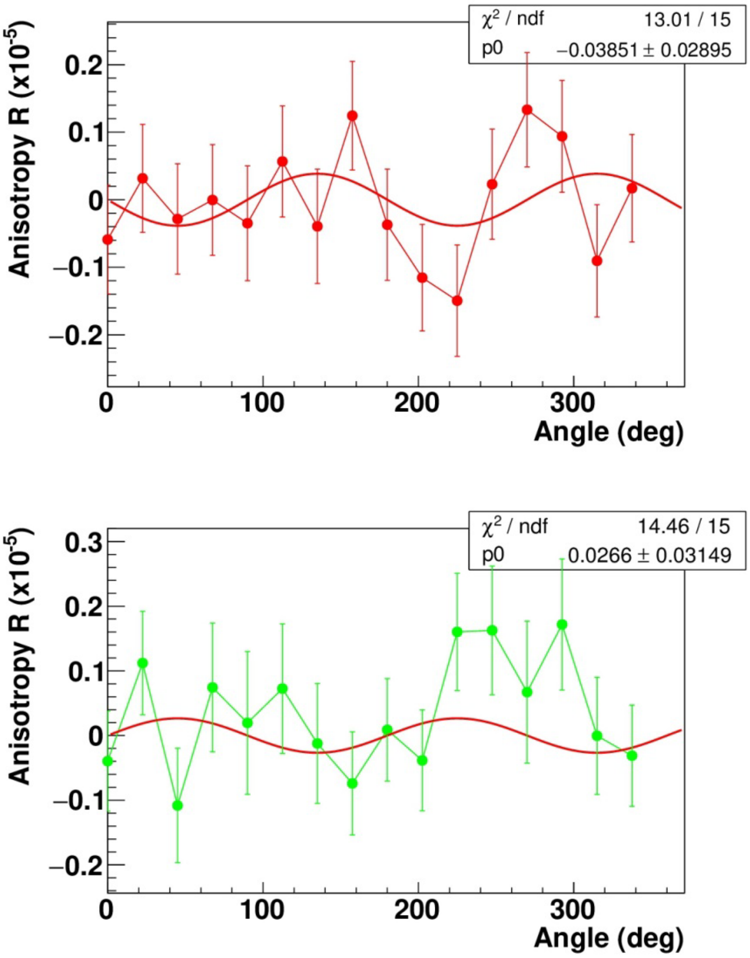

Fig. 6. Anisotropy ratio R as a function of angle for the gamma-rays (top) and neutrons (below).

It should be mentioned that the authors of [12], 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 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.

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're grateful to A. Sazonov, W. Luberstetter, and P. Stein for their help in setting up and conducting the experiment.

References

1. K. Schreckenbach, J. van Klinken, and J. Last, Proceedings of the 2nd International Workshop on Time Reversal Invariance and Parity Violation in Neutron Reactions, Dubna, Russia, May 4–7, 1993, (World Scientific Publishing Company, Singapore, 1994), p. 187.
2. V.E. Bunakov and S.G. Kadmensky, Phys. At. Nucl. **66**, 1846 (2003).
3. V.E. Bunakov, S.G. Kadmensky, and S. S. Kadmensky, Phys. At. Nucl. **71**, 1887 (2008).
4. V.E. Bunakov and S.G. Kadmensky, Phys. At. Nucl. **74**, 1655 (2011).
5. A.L. Barabanov, in Proceedings of the IX International Seminar on Interaction of Neutrons with Nuclei, Dubna, May 23–26, 2001 (Dubna, Russia, 2001), p. 93.
6. A.L. Barabanov, Phys. Part. Nucl. Lett. **10**, 336 (2013).
7. A. Gagarski F. Goennenwein, I.Guseva et al., Phys. Rev. C **93**, 054619 (2016).
8. V. Hutanu, J. Large-Scale Res. Facil. 1, A**16** (2015).
9. L.C. Leal, G. de Saussure & R. B. Perez, Nuclear Science and Engineering Vol. **109**, Iss. 1,1991.
10. https://www.mlz-garching.de/poli
11. V. Hutanu, M. Meven, S. Masalovich, G. Heger, and G. Roth, J. Phys.: Conf. Ser. 294, 012012 (2011).