ROT – effect in Binary Fission Induced by Polarized Neutrons

G.V. Danilyan [1], P. Granz [2], V.A. Krakhotin [1], F. Mezei [2], V.V. Novitsky [1,3], V.S. Pavlov [1], M. Russina [2], P.B. Shatalov [1], T. Wilpert [2].

1. Alikhanov Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
2. Hahn-Meitner Institut (BENSC, HMI), Berlin, Germany
3. Frank Laboratory of Neutron Physics, (FLNP, JINR), Dubna, Russia

Introduction

Recently a small shift has been observed in the angular distribution (AD) of light charged particles (LCP) emission relative to the fission axis in ternary fission of ^{235}U nuclei induced by cold polarized neutrons at ILL HFR [1]. The authors explained this effect as a result of the rotation of the fissile nuclei around the nuclear spin and called it the "ROT-effect". The shift of AD of LCP is an apparent effect, which appears due to the summation of radial and tangential velocities of fission fragments; the trajectories of the fragments become hyperbolae instead of straight lines and direction of deviation of the trajectory from a straight line depends on the direction of fissile nucleus rotation. In experiment, AD is measured relative to so called fission axis defined by the trajectory of fragment while in reality it is formed relative to the deformation axis.

ROT-effect should become apparent also in binary fission accompanied by other particles. From this reason we performed an experiment at the BENSC HMI BER-II reactor to search for the ROT-effect in ^{235}U(n,γf) - reaction induced by cold polarized neutrons. It's well known that the fission process is accompanied by the emission of gamma-quanta. The main part of these gamma's is irradiated by excited fragments, while another part can be emitted by the fissile nuclei at the scission moment or before the scission (rupture of the neck). In the last case the shift angle should include the additional small angle defined by the turning of the deformation axis during the time interval τ. Of course, τ must be much less than the fissile nucleus period of revolution, otherwise the ROT-effect will be washed out. This part of gamma's will be referred to as pre-scission gamma's (PscG).

The experiment has been arranged similarly to experiment [1]. The difference was in the particles detected in coincidence with the fission fragment. It was LCP of ternary fission in the experiment [1], and it was PscG from binary fission in our experiment. The asymmetry of the coincidence count rates between pulses from gamma-quanta and from fission fragments detectors with respect to the direction of the fissile nuclei polarization,

$$R = \{N_1(\theta) - N_2(\theta)\}/\{N_1(\theta) + N_2(\theta)\} \qquad (1)$$

is proportional to the angle of shift. Here $N_1(\theta)$ and $N_2(\theta)$ are count rates at opposite directions of the neutron beam polarization, and θ is the angle between gamma-quantum and fission fragment detectors.

Experiment

The cold polarized neutron beam passes through a thin Al window into the cylindrical fission chamber filled with isobutane at pressure of 8 mbar (Fig.1). The two sided target of ^{235}U (40 mg in total) evaporated on a thick Zr substrate with dimensions 4x10 cm is mounted on the axis of the chamber along the longitudinally polarized neutron beam direction. Two multi-wire low pressure proportional counters (MWPC) to detect fission fragments were disposed on both sides of the target at of 7.5 cm distance. Both detectors are connected in parallel and they don't distinguish between light and heavy fragments. The gamma-ray detectors are arranged outside the fission chamber at 25 cm distance from the center of the target. They consist of plastic scintillator and photomultiplier (PMT). We used plastic scintillators with the aim to search for the ROT effect not only for PscG, but also for the so called scission neutrons (ScN). They also can be used as a trigger to see the shift of their angular distribution relative to the fission axis if this distribution is not the isotropic. To distinguish between the gamma pulses and the prompt fission neutron (PFN) pulses from PMT we used the time-of-flight technique. We used the pulses from the fragment detectors (FD) as start pulses, while pulses from gamma/neutron detector (GND) were used as stop. The GND are mounted at the angles 0, ±π/8, ±π/4, ±3π/8, ±π/2, ±5π/8, ±3π/4,

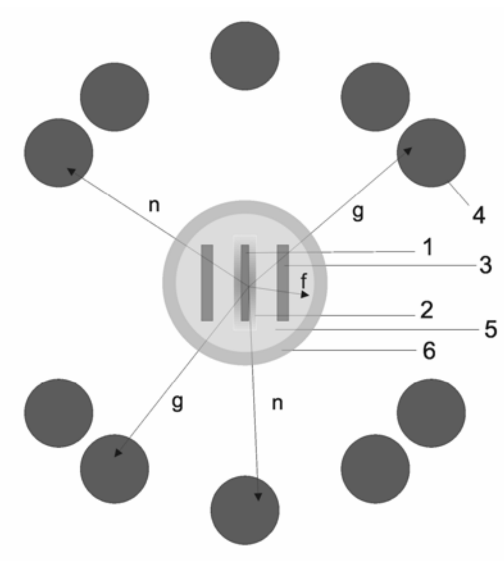

Fig. 1. The cross-section of the experimental setup, with the GND's placed at ±35°, ±57° and ±90°. 1 – ^{235}U double-sided target; 2 – longitudinally polarized neutron beam; 3 – fission fragments' detectors (multiwire proportional counters); 4 – gamma-quanta and neutrons detectors (plastic scintillator and photomultiplier); 5 – isobutane C_4H_{10} at pressure 8 mbar; 6 – fission chamber (stainless steel)

±7π/8, and π, relative to the average fission axis defined by fission fragment detectors. The plane formed by the vectors of the gamma/neutron momentum and the momentum of the fragment is orthogonal to the longitudinally polarized neutron beam direction. The polarization of the neutron beam is reversed every 0.5 second. We have measured counts rate under the gamma-peak and under the peak of PFN for both directions of neutron beam polarization (Fig. 2). The asymmetry R of the counts rate (eq. 1) is calculated on-line.

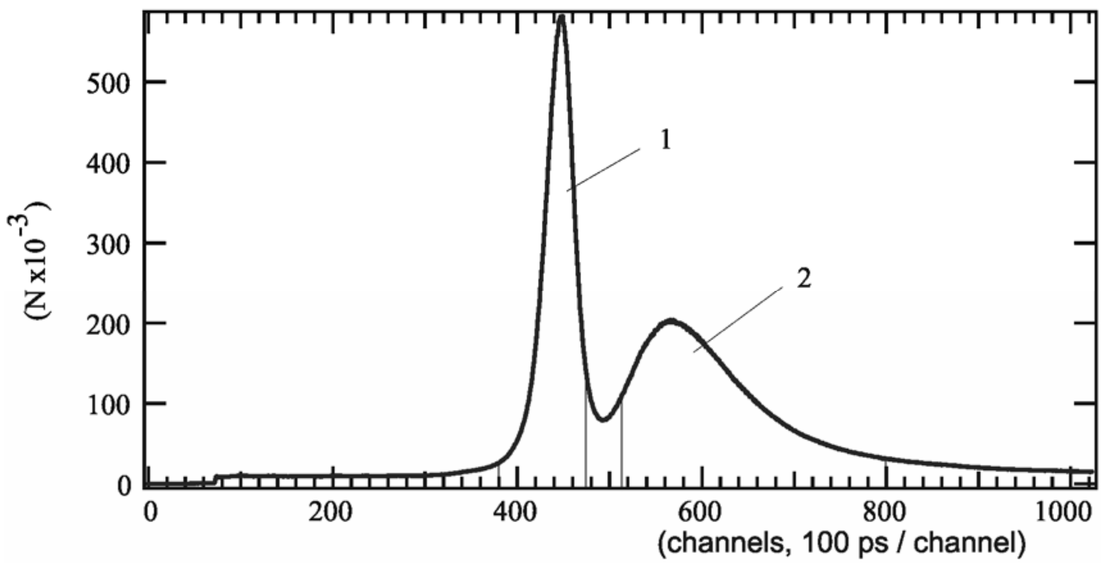

Fig. 2. Time-of-flight spectrum of the coincidence between pulses from gamma/neutron and fission fragment detectors.

1 – The prompt fission gamma-ray events
2 – The prompt fission neutrons events.

Results

The first results of the ROT-asymmetry measurements performed on the instrument V-13 BER-II reactor of BENSC HMI were presented in [2]. Averaging the ROT-asymmetry results for PscG for symmetric combinations of the detectors, we obtained for 3 angles between GND and fission axis the next values:

$$R_\gamma(35°) = (+ 1.5 \pm 0.4) \cdot 10^{-4}$$

$$R_\gamma(57°) = (+ 2.3 \pm 0.4) \cdot 10^{-4}$$

$$R_\gamma(90°) = (- 0.2 \pm 0.6) \cdot 10^{-4}$$

For the ScN there was no significant asymmetry, although the statistical error is larger compared to the results for PscG.

The new measurements in the geometry described above resulted in more accurate values:

$$R_\gamma(0) = (-0.1 \pm 0.3) \cdot 10^{-4}$$
$$R_\gamma(\pi/8) = (+0.8 \pm 0.2) \cdot 10^{-4}$$
$$R_\gamma(\pi/4) = (+1.5 \pm 0.2) \cdot 10^{-4}$$
$$R_\gamma(3\pi/8) = (+0.7 \pm 0.3) \cdot 10^{-4}$$
$$R_\gamma(\pi/2) = (-0.3 \pm 0.3) \cdot 10^{-4}$$

The main result of this experiment is, of course, the observation of pre-scission, scission or post-scission gamma-rays which are “time markers” for the scission moment. The origin of this radiation is not known yet. To get some information relating to the mechanism of the radiation we performed measurements the dependence of the ROT-asymmetry on gamma-rays energy using NaI(Tl)-detectors as well as the angular dependence of the ROT-asymmetry. The preliminary results are shown in Fig. 3 and 4. Angular dependence of the ROT-asymmetry does not contradict with the assumption that radiation is the dipole irradiation. As to the energy of gamma-rays, it’s evident that it differs from the spectrum of gamma-rays emitted by excited fragments.

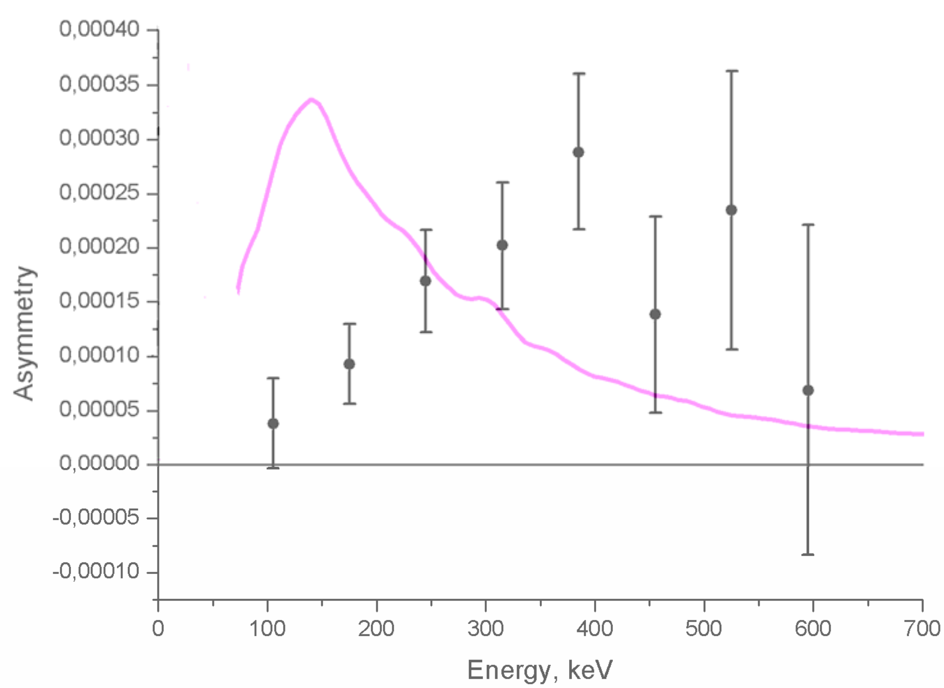

Fig. 3. Energy dependence of ROT-effect.
Dots – energy dependence of ROT-asymmetry (angle 45°)
Curve – corresponding experimental γ-ray energy spectrum

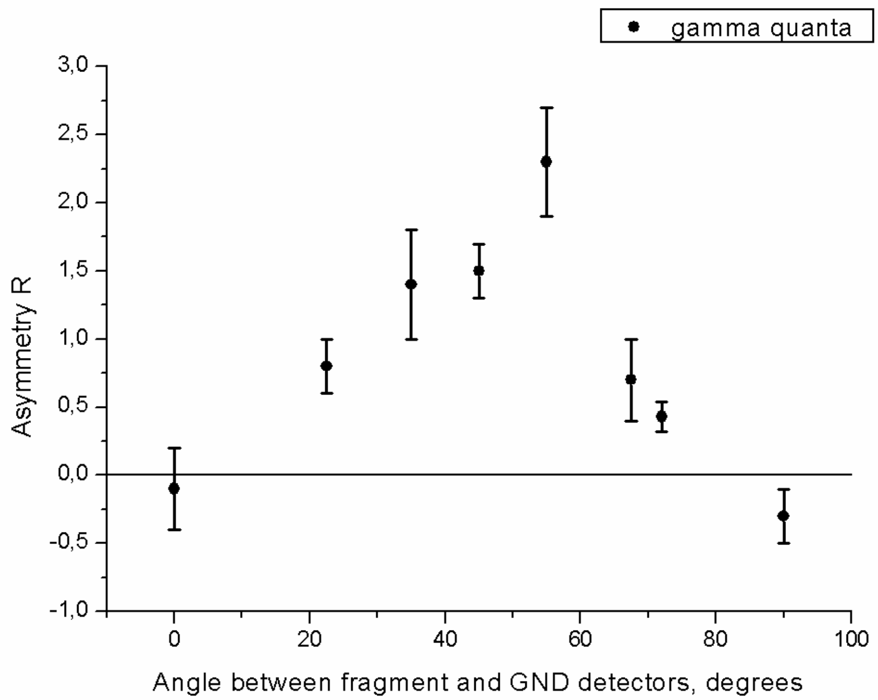

Fig. 4. Angular dependence of ROT-effect.

Discussion

In the reaction ^{235}U(n,γf), soft gamma-rays can be emitted by the transitions between excited states in the first wall of the compound nucleus. The life time of the compound nucleus measured from the gamma-quanta transition is of the order of 10^{-14} s. In this case the time interval between gamma-quantum radiation and the scission is much larger then the characteristic rotational time of the nucleus, so the fissile nucleus can make about 10^5 revolutions before scission. Therefore the average ROT-effect in this process will be washed out. The transitions between the states of the second wall of the potential barrier can produce the very fast soft radiation. The time of the descent from saddle point to scission is of the order of 10^{-21} – 10^{-20} s. So, at this stage of the fission the trigger gamma's can be also generated. It’s impossible to exclude the possibility to generate the radiation during the fragments acceleration time like the bremsstrahlung. It can be the E1-irradiation of highly deformed light fragment very soon after neck rupture (giant resonance) as well as the radiation accompanied the transition of highly deformational state of light fragments to the normal deformational state.

Conclusion

This experimental work revealed the existence of asymmetry in the angular distribution of pre-scission gamma radiation (so called ROT-effect) in the binary nuclear fission process. Our observation implies the discovery of a new kind of electromagnetic radiation accompanying the fission. This is very important for theoretical considerations of the fission dynamics. From the practical point of view it opens new perspectives. The magnitude of the ROT-effect depends on the projection of the fissile nucleus spin on the deformation axis, i.e., on the ***K*** value. According to the O.Bohr's theory of nuclear fission ***K*** is one of main quantum numbers of quasi-stationary state at the saddle point, which defines the fission channel. For a fission channel with ***K*** = 0 the ROT-effect should be maximal, while for a channel with ***K*** = ***I*** the ROT-effect does not exist at all. Therefore, the measurement of the dependence ROT-effect on the neutron energy in the wide resonance region can give information about effective ***K***-value in different neutron resonances. The observation of ROT-effect in (1) as well as in this work is the definite indication that the fission of ^{235}U by slow neutrons take place from the rotational state. And finally it should be taken into account that AD relative the "fission axis" of LCP or gamma-rays in fission of ^{235}U by unpolarized slow neutrons is wider than true AD respect to deformation axis.

Acknowledgements

We should like to thank to the aid of HMI and ITEP staff, in particular to Werner Graf and to Yuri Belov. Our thanks to RFBR (grant 07-02-01095) and FANI for financial support of this work. We also are indebted to K. Diederichsen for linguistic work on this paper.

References

1. A.Gagarski, I.Guseva, F.Gönnenwein, et al. XIV International Seminar on Interaction of Neutrons with Nuclei, Dubna (2006), Abstracts volume, p. 33.
2. G.V. Danilyan, P. Granz, V.A. Krakhotin, F. Mezei, V.V. Novitsky, V.S. Pavlov, M. Russina, P.B. Shatalov, T. Wilpert. Physics Letters B, 2009, to be published.