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Simulation of the ROT-effect using GEANT4

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Introduction. ROT-effect.

The effect of nuclear rotation, the so-called ROT-effect, was discovered in the angular distributions of α-particles from the ternary fission of the ^{235}U nucleus by cold polarized neutrons.

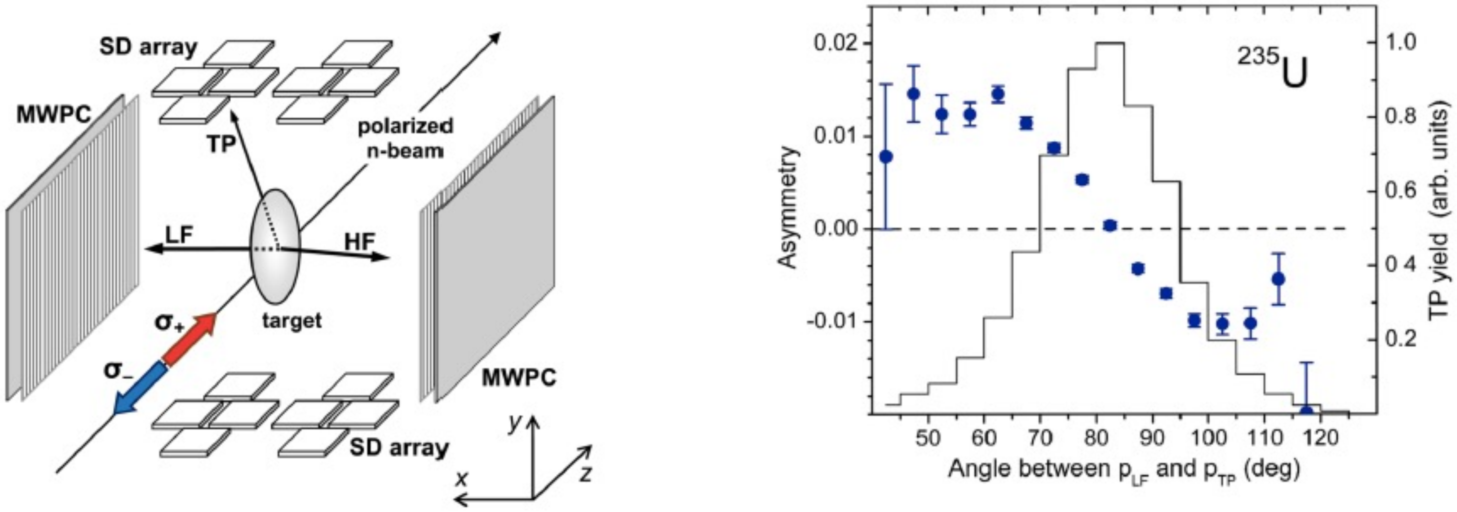


Fig. 1. Left: Layout of the experimental setup from [1]; right: measured experimental asymmetry.

Asymmetry:

$$D = \frac{N^+ - N^-}{N^+ + N^-}$$

The ROT effect manifests itself in the asymmetry of the counting of detectors of α-particles when the polarization of incident neutrons changes. It is explained by a shift in the angular distributions of the α-particles relative to the axis of emission of fission fragments.

1. A. Gagarski et al, Phys.Rev.C 93, 054619 (2016).

Introduction. ROT-effect.

Subsequently, a similar effect was observed in the angular distributions of γ-quanta and neutrons [2] in the binary fission of ^{235}U and ^{233}U.

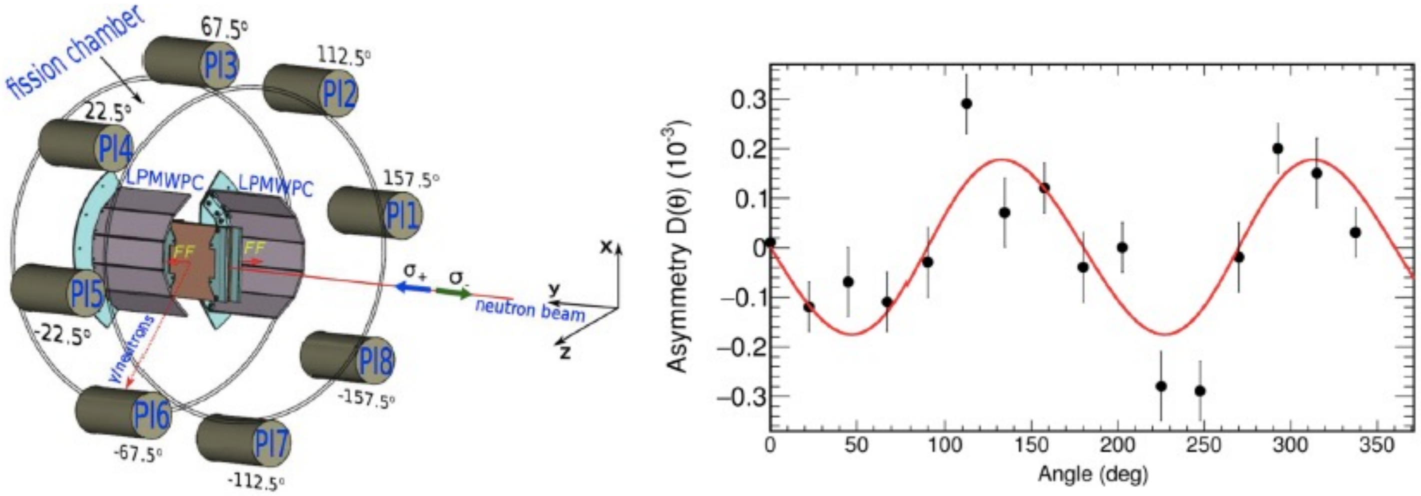
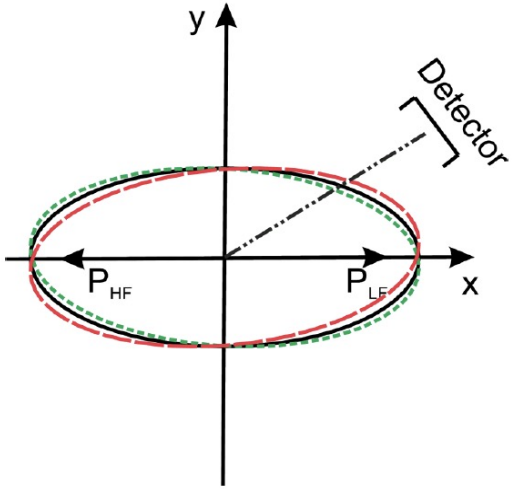


Fig. 2. Left: Layout of the experimental setup from [3]; right: measured experimental asymmetry.



The observed value of the asymmetry coefficient is about 10^{-2} for α-particles in ternary fission and 10^{-4} for γ-quanta in binary fission of ^{235}U. Currently, the effect has been measured for cold neutrons, for neutrons with energies of 0.06 eV and 0.3 eV in ^{235}U. Of great interest is the measurement of this effect in the resonance region, as well as for other fissile nuclei.

2. G. V. Danilyan et al., Phys. At. Nucl. 74, 671 (2011).
3. D. Berikov et al, Phys.Rev.C 104, 024607 (2021).

Virtual setup.

The main goal of the simulation is to determine the possible accuracy of the measured effect for an installation consisting only of detectors of γ-rays and prompt neutrons without the use of fragment detectors. That fact that fission neutrons are kinematically focused in the direction of emission of fission fragments allow us use them as the fission axis.

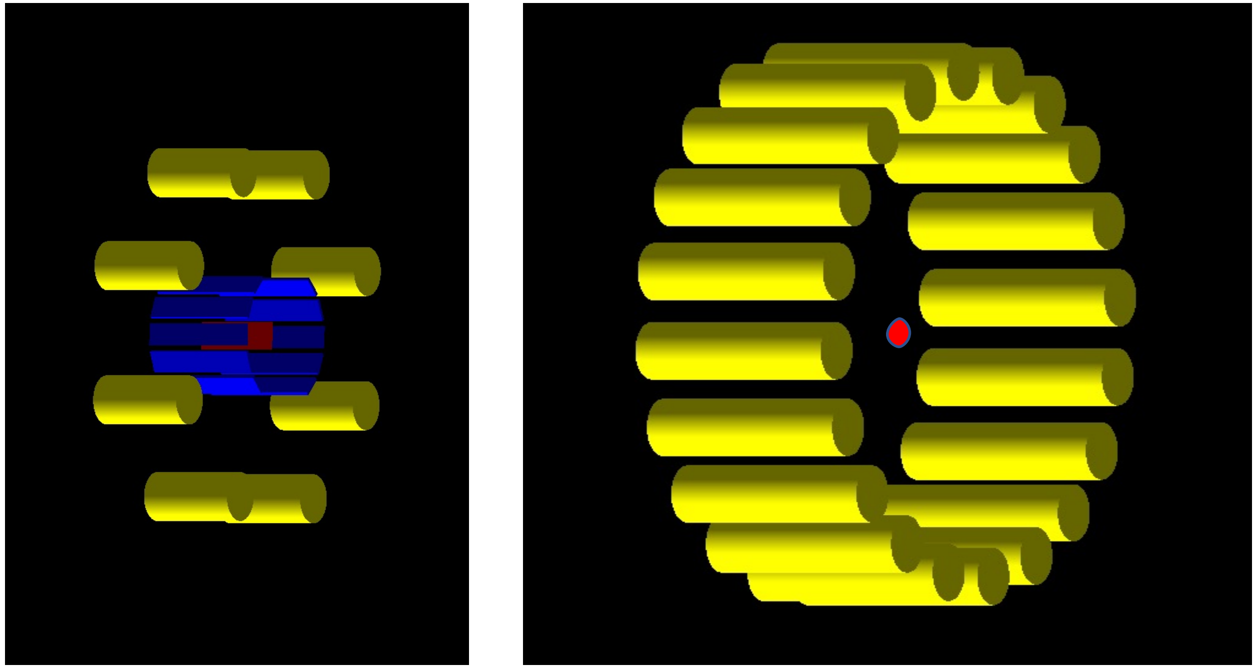


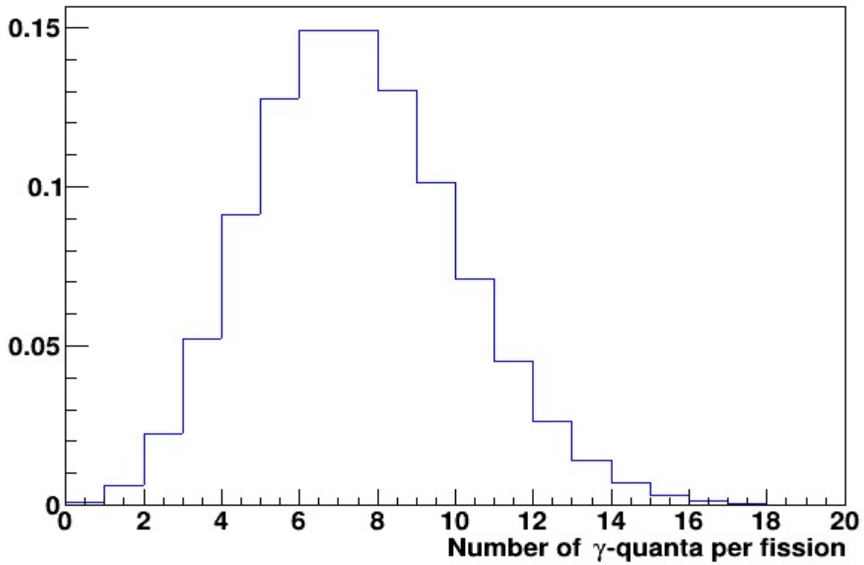
Fig. 3. Left: virtual setup of a real experiment with fragment detectors and 8 γ-ray detectors; right: virtual setup with 20 detectors of γ-rays and neutrons.

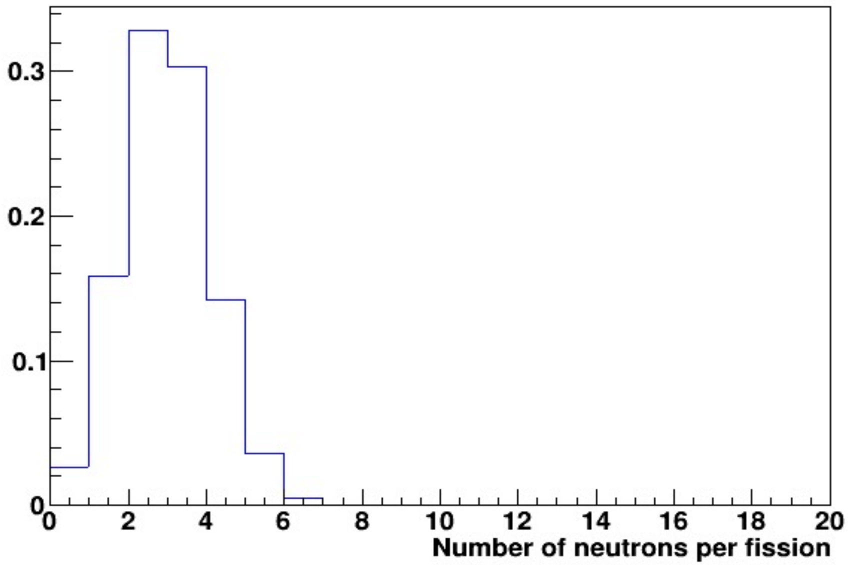
Detectors/ setup	**8-det FF-γ**	**20-det n-γ**
Fission fragment detectors	10 detectors 32x100mm around target with R=100mm with same azimuthal pitch of 22.5^0	------
Neutron and γ-ray detectors	8 plastic scintillators Ø70x120 mm are located at angles $\pm22.5^0$, $\pm67.5^0$, $\pm112.5^0$, $\pm157.5^0$	20 plastic scintillators Ø90x300 mm around a target with R=400 mm
Target	Double-sided ^{235}U target 40x100 mm	Point-like ^{235}U target

Simulation parameters.

The simulation was performed for two setups with the same number of events. To speed up calculations, virtual geantino particles that do not interact with matter were used instead of decay products. The efficiency of fragment and γ-ray detectors was taken as 100%; The efficiency for detecting neutrons was 30%, and the scattering of particles from detector to detector was not taken into account.

The multiplicity of γ-quanta was generated in accordance with the Poisson distribution with a mean value of 7, the multiplicity of neutrons had the form of a two-dimensional normal distribution with mean values of 1.4 and 1 for light and heavy fragments, respectively.

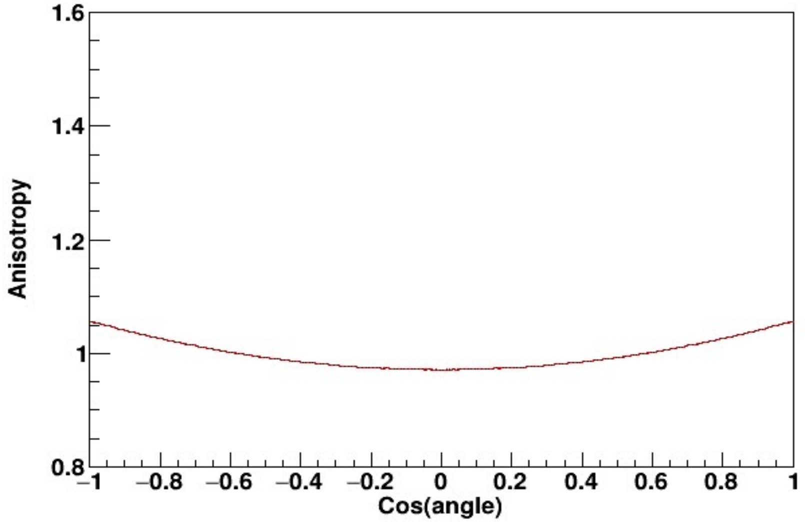

γ-ray multiplicity

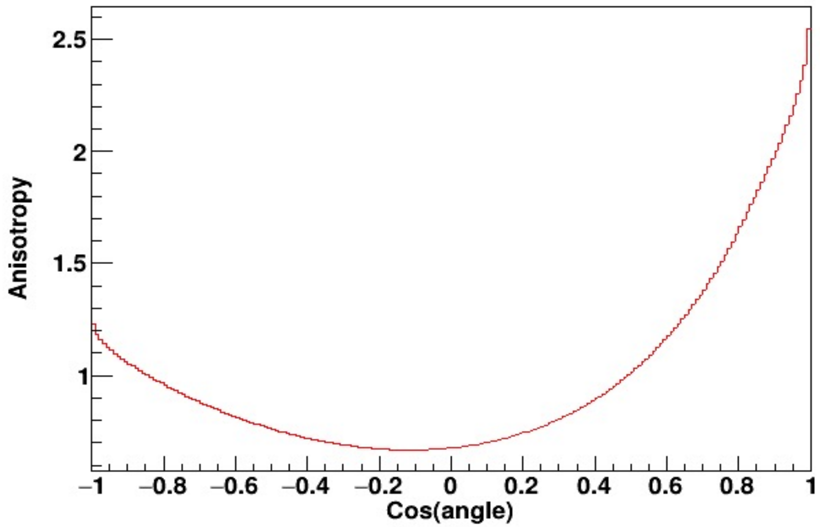

Neutron multiplicity

	Efficiency
n	30%
γ-rays	100%
FF	100%

Simulation parameters.

The neutron energy distribution had the form of a Maxwell distribution with temperatures of 0.91 MeV and 0.93 MeV for light and heavy fragments, respectively. Neutrons were emitted isotropically in the center of mass system of each fragment. In the laboratory system, their velocities were added up with the fission fragment ones. γ-rays were emitted anisotropically relative to the fission axis with an anisotropy coefficient of 10%.

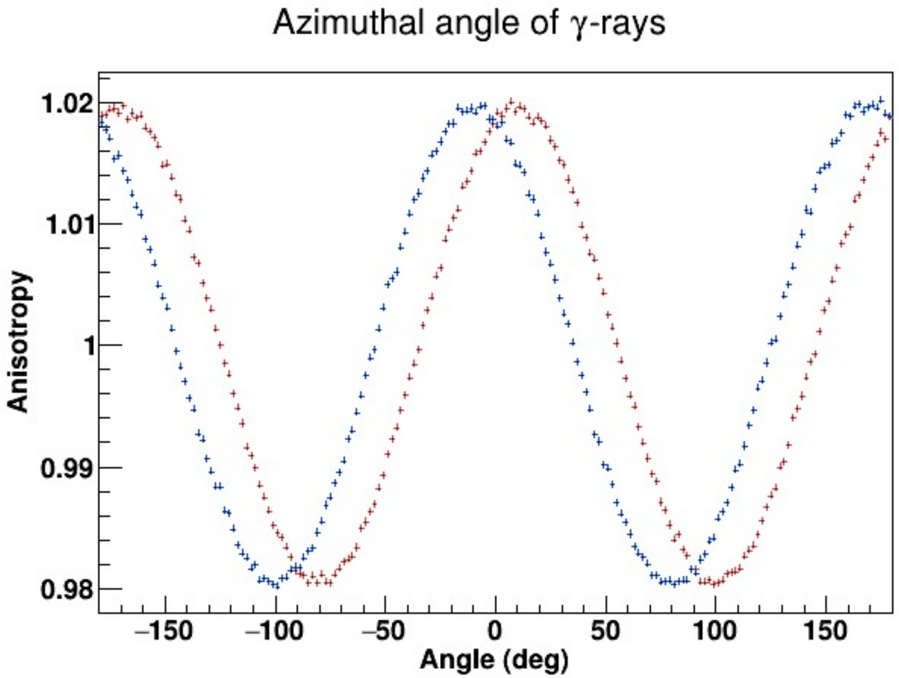

Anisotropy of γ-quanta

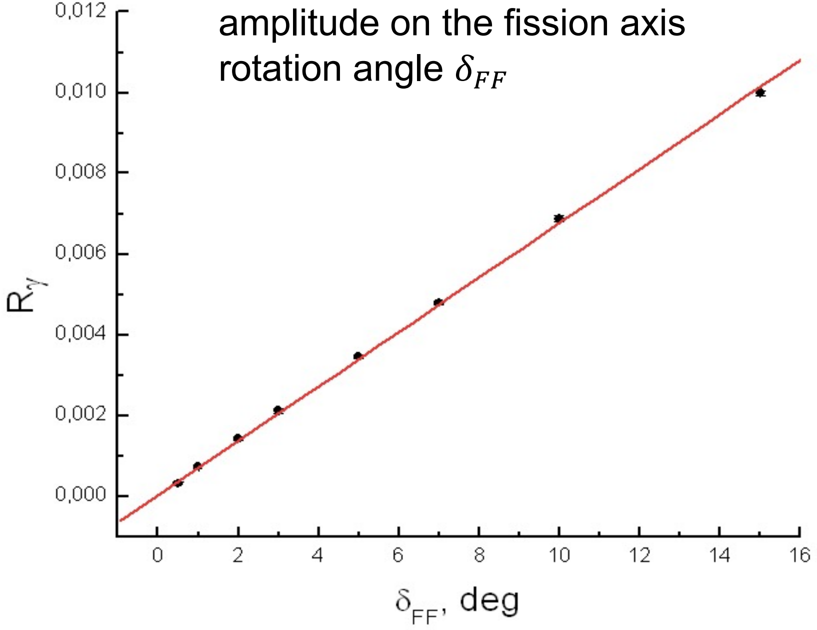

Anisotropy of neutrons

To simulate the ROT-effect, emission axis of the fission fragment was rotated by an angle δ around the neutron polarization axis. The sign of the rotation angle was positive for half of the events and negative for the other half. Because prompt fission neutrons are emitted from fully accelerated fragments, the direction of neutron emission was calculated relative to the rotated fission axis.

Results.

The shift in the angular distribution of γ-rays with positive and negative rotation of the fission axis is essentially the observed ROT-effect.

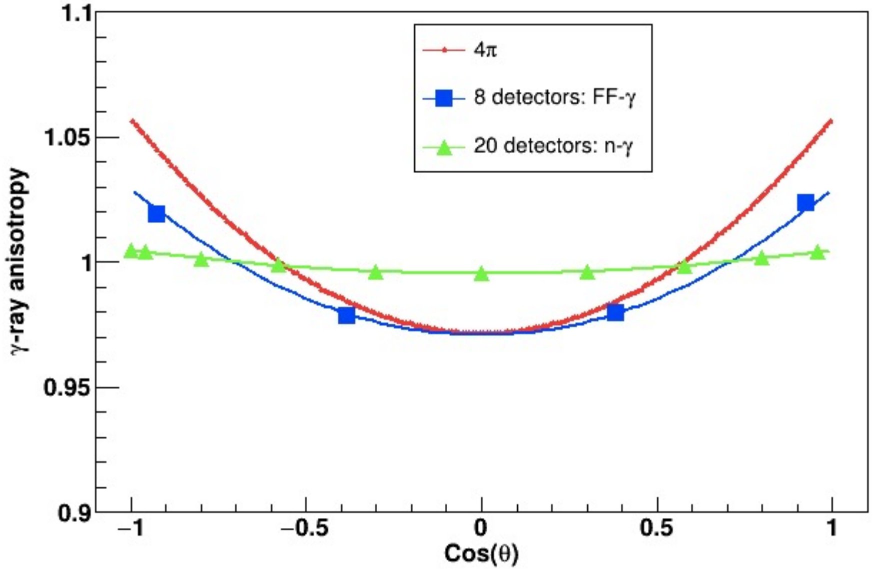


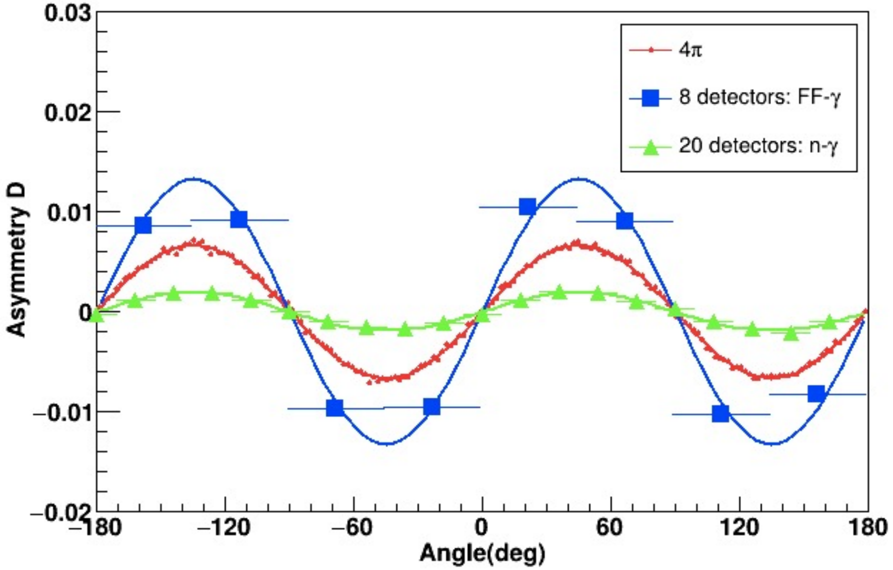


The dependence of the effect amplitude on the fission axis rotation angle δ_{FF}

The dependence of the effect amplitude on the fission axis rotation angle δ was observed. It has a linear appearance. This allowed all calculations to be carried out for a rotation angle of 10^0, which is two orders of magnitude larger than the actually observed angles. So, the results can be easily recalculated for more realistic and smaller rotation angles.

Results.





Graphics show the angular distributions of γ-rays (left) and the angular dependence of the asymmetry of the ROT-effect (right), generated using GEANT4 for three cases:

a) the initial distribution of γ-rays in 4π relative to the fission axis;

b) setup with 8 γ-ray detectors and fragment detectors;

c) setup with 20 detectors of γ-rays and neutrons which “replace” the fission axis.

Virtual setup	4π	8 detectors: FF-γ	20 detectors: n-γ
Asymmetry coefficient	6.68 ± 0.02	13.5 ± 0.5	1.91 ± 0.09

Conclusions.

Virtual setup	4π	8 detectors: FF-γ	20 detectors: n-γ
Asymmetry coefficient	6.68 ± 0.02	13.5 ± 0.5	1.91 ± 0.09
Relative error	0.3%	3.7%	4.7%

For a planned installation with 20 detectors, the effect has decreased by 7 times compared to the virtual setup of work [3], while the relative accuracy decreased by only ~20% for the same number of fission events. In the new setup the fission fragments are not detected, therefore it is possible to carry out measurements with a thicker target, which will increase the statistics by several orders of magnitude compared to work [3].

3. D. Berikov et al, Phys.Rev.C 104, 024607 (2021).

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Abstract

This work represents the results of modeling the ROT effect using the Monte Carlo method and the GEANT4 toolkit [1]. The influence of the geometry of the experimental setup, target parameters, and other factors on the magnitude of the observed asymmetry was studied. Particular attention is paid to assessing the possibility of measuring the ROT-effect by determining the fission axis using the detection of prompt fission neutrons.

1. Introduction. Experimental observation of the ROT effect and its explanation.

The effect of nuclear rotation, the so-called ROT effect, was first discovered in the angular distributions of α-particles from the ternary fission of the ^{235}U nucleus by cold polarized neutrons [2]. Subsequently, a similar effect was observed in the angular distributions of γ-quanta and neutrons [3] in the binary fission of ^{235}U and ^{233}U. The ROT effect manifests itself in the asymmetry of the counting of detectors of α-particles, γ-quanta or neutrons when the polarization of incident neutrons changes to the opposite and is explained by a shift in the angular distributions of the corresponding fission products relative to the axis of emission of fission fragments. The observed value of the asymmetry coefficient

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

– is about 10^{-2} for α-particles in ternary fission and 10^{-4} for γ-quanta in binary fission of ^{235}U. Currently, the effect has been measured for cold neutrons, as well as for neutrons with energies of 0.06 eV and 0.3 eV in ^{235}U. Of great interest is the measurement of this effect in the resonance region, as well as for other fissile nuclei.

Figures 1 and 2 show layouts of experimental setups for measuring the ROT effect for α-particles in [4] and for γ-quanta in [5], as well as the effects observed in these experiments.

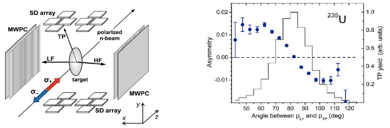

Fig. 1. Left: Layout of the experimental setup from [1]; right: measured experimental asymmetry.

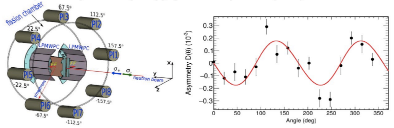

Fig. 2. Left: Layout of the experimental setup from [3]; right: measured experimental asymmetry.

2. Virtual setup and its features

In this work, computer simulation of the ROT effect for γ-rays was carried out using the GEANT4 software package. The geometry of the experimental setup from [5] was taken as a basis. Fig. 3 (left) shows a diagram of the virtual setup for which the simulation was carried out. A double-sided ^{235}U target (marked in red) with the dimensions of 40x100 mm is surrounded by 8 plastic γ-ray detectors (marked in yellow). Their size is Ø70x120 mm, and they are located at angles 22.5°, 67.5°, 112.5°, 157.5°. 10 fission fragment detectors are shown in blue, located with the same azimuthal pitch of 22.5° and a distance to the target center of 100 mm.

The main goal of the simulation is to determine the magnitude of the effect and the possible gain in statistics for an installation consisting of detectors of prompt γ-rays and fission neutrons without the use of fragment detectors. Since prompt fission neutrons are kinematically focused in the direction of emission of fission fragments, they can be used as an indicator of the direction of the fission axis, with a certain uncertainty. The use of such a method will reduce the magnitude of the observed effect, but may allow the thickness of the target used to be increased by several orders of magnitude. The layout of the virtual setup for the new method is shown in Fig. 3 in the center. It consists of 20 detectors measuring Ø90x300 mm, located evenly around a circle with a radius of 400 mm. Detectors are used to register both γ-rays and neutrons simultaneously. In the experiment they will be separated by time of flight. In the center of the installation there is an almost point-like target.

The simulation was carried out for two layouts shown in Fig. 3 with the same number of events. To speed up calculations, virtual geantino particles that do not interact with matter were used instead of fission fragments, γ-rays and neutrons. The efficiency of fragment and γ-ray detectors was taken as 100%; The efficiency of plastic detectors for detecting neutrons was 30%, and the scattering of particles from detector to detector was not taken into account.

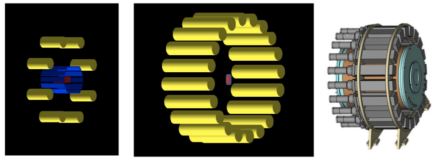

Fig. 3. Left: virtual setup with fragment detectors and 8 γ-ray detectors; center: a virtual setup with 20 detectors of γ-rays and neutrons; right: a mock-up of an installation with 20 detectors of γ-rays and neutrons.

3. Simulation parameters

For each fission event, one fission fragment was generated (the second fragment is absorbed in the substrate), emitted in a random direction and a certain number of γ-rays and neutrons in accordance with the multiplicity distribution for these particles (see Fig. 4). The multiplicity of γ-quanta was generated in accordance with the Poisson distribution with a mean value of 7, the multiplicity of neutrons had the form of a two-dimensional normal distribution with mean values of 1.4 and 1 for light and heavy fragments, respectively. The neutron energy distribution had the form of a Maxwell distribution with temperatures of 0.91 and 0.93 for light and heavy fragments, respectively. Neutrons were emitted isotropically in the center of mass system of each fragment; in the laboratory system, their velocities were added up with the fission fragment ones. Gamma rays were emitted anisotropically relative to the fission axis with an anisotropy coefficient of 10%. The angular distributions of neutrons and γ-rays relative to the fission axis in the laboratory system are shown in Fig. 5.

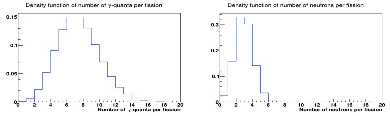

Fig. 4. Multiplicity distribution for γ-rays (left) and neutrons (right).

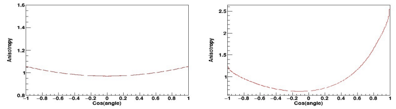

Fig. 5. Angular anisotropy of the emission of prompt γ -rays (left) and neutrons (right) relative to the fission axis.

To simulate the ROT effect, the direction of polarization of the neutron beam along the symmetry axis of the setup was introduced. The emission axis of the fission fragment was rotated by an angle δ around the neutron polarization axis. The sign of the rotation angle was positive for half of the events and negative for the other half. Because prompt fission neutrons are emitted from fully accelerated fragments, the direction of neutron emission was calculated relative to the rotated fission axis. And the angular anisotropy of γ-rays is due to the alignment of the spins of fission fragments. It is assumed that the direction of the spins of the fragments is invariant with respect to the rotation of the fission axis due to the angular momentum conservation law, therefore the angular distribution of γ-rays was generated relative to the fission axis before the rotation. The shift in the angular distribution of γ-rays with positive and negative rotation of the fission axis is essentially the observed ROT effect, see Fig. 6, left.

The dependence of the effect amplitude on the fission axis rotation angle δ was studied. It has a linear appearance (see Fig. 6, right). This allowed all calculations to be carried out for a rotation angle of 10°, which is two orders of magnitude larger than the actually observed angles. Thanks to the linear dependence of the amplitude of the effect, the results obtained can be easily recalculated for more realistic and smaller rotation angles.

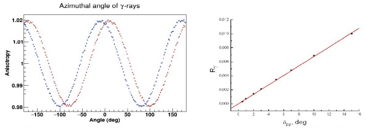

Fig. 6. Left: Displacement of the angular distribution of γ-rays with positive and negative rotation of the fission axis. Right: dependence of the amplitude of the effect on the angle of rotation.

4. Results

Figure 7 shows the angular distributions of γ-rays (left) and the angular dependence of the asymmetry of the ROT effect (right), calculated using formula (1), generated using GEANT4 for three cases: a) the initial distribution of γ-rays in 4π relative to the fission axis; b) setup with 8 γ-ray detectors and fragment detectors (see Fig. 3, left); c) setup with 20 detectors of γ-rays and neutrons.

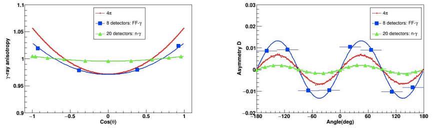

Fig. 7. Angular distributions of γ-rays (left) and angular dependence of asymmetry (right) for three calculation options.

Virtual setup	4π	8 detectors: FF-γ	20 detectors: n-γ
Asymmetry coefficient	6.68 ±0.02	13.2± 0.5	1.91± 0.09

The table shows the asymmetry parameters of the ROT effect for γ-ray for these three cases. It can be seen that in the geometry of the experiment from [5] the ROT-effect asymmetry increases compared to the full distribution in 4π due to the choice of the optimal location of the detectors in the plane perpendicular to the direction of neutron polarization. However, in this case the error increases significantly. For a planned installation with 20 detectors, the effect is reduced by a factor of 7, while the relative accuracy deteriorates by only 20% for the same number of fission events. In the new setup, it is possible to carry out measurements with a thicker target, which will increase the statistics by several orders of magnitude compared to work [5].

References

1. Geant4 Simulation toolkit, https://geant4.web.cern.ch/
2. F. Goennenwein et al., Phys. Lett. B 652, 13 (2007).
3. G. V. Danilyan et al., Phys. At. Nucl. 74, 671 (2011).
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