THE ESTIMATION OF ROT-EFFECT FOR NEUTRONS EVAPORATED FROM FULLY ACCELERATED FRAGMENTS IN BINARY FISSION

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Abstract

Following the recent observation of ROT-effect for ternary particles accompanying the reaction $^{235}U(n,f)$ induced by cold polarized neutrons [1] the analogical effect for gammas in binary fission was measured [2]. The last effect analysis was based on the conservation of primary fission fragment spin orientation and on the anisotropy (in fragment centre-of-mass) of γ-quanta evaporation generated by this spin. As a result of this analysis the angle δ of fission axis rotation in binary fission was found. Using this angle δ it is possible to estimate ROT-effect also for neutrons evaporated from fully accelerated fragments. It was shown that the angular distribution of neutron ROT-asymmetry has 4 extremuma in the region 0˚-180˚ what is two times as much as for gammas. It is necessary to mention the peculiarities in the regions about 26˚and 154˚ can be easier measured than near 72˚ and 108˚ for the reason of statistic (neutron count rate).

At the high flux reactor of ILL in the summer of 2005 new and unexpected phenomenon was revealed during a detailed investigation of the triple angular correlation in ternary fission of ^{235}U induced by cold polarized neutrons [1]. This phenomenon was the shift of angular distribution for ternary particles. The sign of the shift depends on the neutron beam polarization and consequently on effective polarization of compound nucleus. The explanation of this phenomenon was connected with a rotation of nuclear system before scission [1, 3].

It was established tree years after by the group of Danilyan [4] and then in PNPI [2] that oriented rotation of fissioning system causes an analogical effect in gamma-quanta emission, too. The figure 1 demonstrates both results for gamma count rate asymmetry.

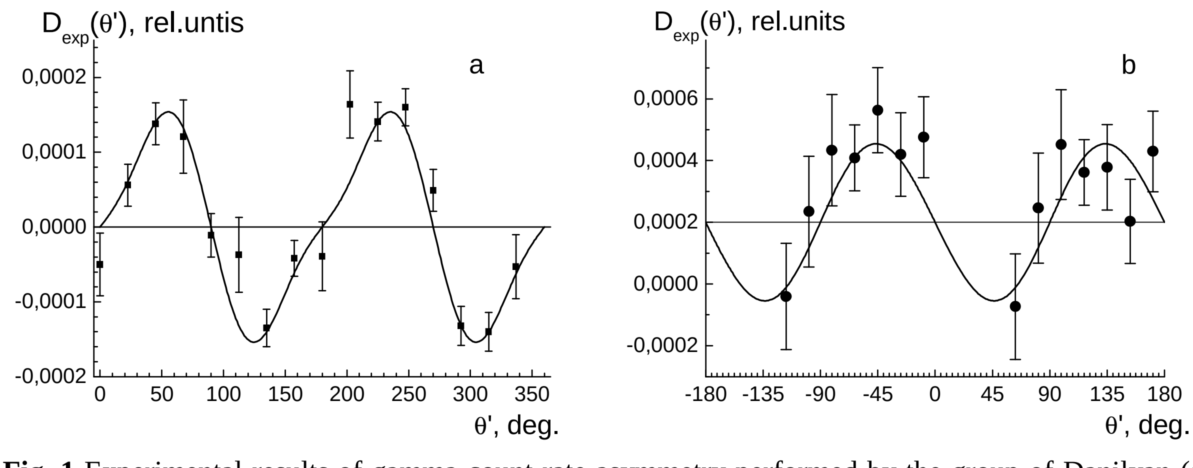

Fig. 1 Experimental results of gamma count rate asymmetry performed by the group of Danilyan (a) and in PNPI (b) with corresponding theoretical descriptions (lines).

If one takes into account a systematical shift in experimental data of PNPI group, which is equal 0.0002, it is possible to deduce that absolute values are in a good agreement but their signs are opposite. Such discrepancy may be connected with a different order of vectors in the triple correlation. The above-mentioned order determines the frame of reference. Our vector combination was: neutron spin polarization, fission fragment and then gamma-quantum directions of motion.

Some attempts were produced to explain the angular dependence of gamma count rate asymmetry using the similar way as for ternary particles. All members of Danilyan group except V. Novitsky have an opinion that gamma-quanta concerned with ROT-asymmetry are emitted near the rupture point. But in contradiction to light charge particles accompanied a process of scission, most of the gamma-quanta radiates from the fission fragments essentially later than the moment of scission. In this case all gammas emitted by fully accelerated fragments are associated with background radiation and must reduce this effect appreciably.

This effect explanation in PNPI group was based on the idea of a conservation of primary fission fragment spin orientation and on gamma radiation anisotropy generated by this spin in the reference frame of fragment centre-of-mass. The figure 2 shows the scheme of calculations. Initial orientation of fission axis, it means, at the moment of scission, is marked by the letter *f*, while f' corresponds to the final direction of fission fragment motion. The last arises due to compound system rotation. We determine δ as the angle between f and f' directions in case of positive neutron spin projection. If neutron polarization has negative value, rotation of scissioning nucleus goes in the opposite direction. In this case the angle of rotation equals $-\delta$.

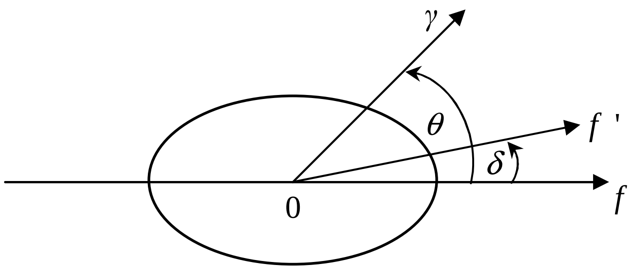

Fig. 2. The scheme of calculations: *f*-initial orientation of fission axis (at the moment of scission); θ – the angle of γ-quantum emission with respect to initial direction of fission axis; δ – the angle of fission axis rotation; f' – the final direction of fission fragment motion due to compound system rotation.

Theta is the angle of gamma-quantum emission with respect to initial direction of fission axis. This angle must be used to determine the influence of anisotropy on gamma radiation and to calculate gamma count rate connected with it. Due to the system rotation θ is not the angle of γ-quantum registration versus fission fragment direction of motion. In experiment we should detect it at the new angle θ'. This angle equals θ minus or plus δ depending on the neutron spin polarization:

$$\begin{aligned} \theta' &= \theta - \delta \quad if\ \sigma > 0 \\ \theta' &= \theta + \delta \quad if\ \sigma > 0. \end{aligned} \tag{1}$$

If following Strutinsky the gamma count rate without nuclear system rotation can be written this way

$$N(\theta) = N(90°)\cdot(1 + A\cdot\cos^2\theta), \tag{2}$$

were A is the coefficient of anisotropy, the count rates corresponding to different neutron spin polarizations are $N^+(\theta')$ and $N^-(\theta')$:

$$N^{+}(\theta') = N(90°)\cdot(1 + A\cdot\cos^{2}(\theta'+\delta)) \quad if\ \sigma > 0$$
$$N^{-}(\theta') = N(90°)\cdot(1 + A\cdot\cos^{2}(\theta'-\delta)) \quad if\ \sigma < 0. \tag{3}$$

In experiment the angular dependence of asymmetry coefficient $D_{\exp}(\theta')$ was measured:

$$D_{\exp}(\theta') \equiv \frac{N^{+}(\theta') - N^{-}(\theta')}{N^{+}(\theta') + N^{-}(\theta')}. \tag{4}$$

Taking into consideration a smallness of the angle δ for fission axis rotation this coefficient can be written by this equation:

$$D_{\exp}(\theta') \approx \frac{A\cdot\left[\cos^{2}(\theta'+\delta) - \cos^{2}(\theta'-\delta)\right]}{2\cdot\left[1 + A\cdot\cos^{2}(\theta')\right]} \approx \frac{-A\cdot\delta\cdot\sin 2\theta'}{1 + A\cdot\cos^{2}\theta'}. \tag{5}$$

It is necessary to mention that anisotropy for gamma emission in the reference frame of fission fragment centre-of-mass does not differ essentially from this one in laboratory system. The coefficient of anisotropy *A* (see Fig. 3) was measured in the same experiment [2] and corresponds to the same energy interval, which was used for gamma ROT-effect observation.

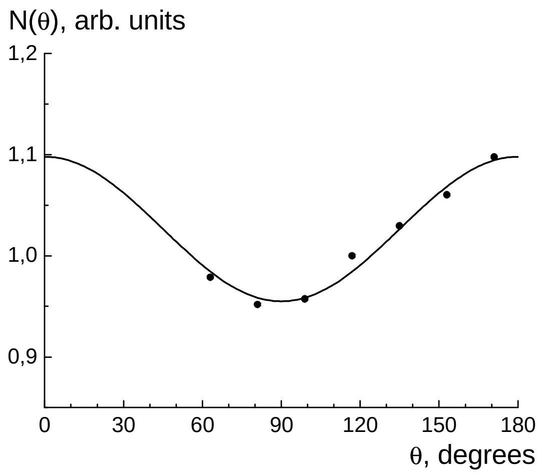

Fig. 3. Experimental dependence of γ-quantum yields versus the angle of their emission (points) measured in PNPI [2]. Using the analytical description (1) the fitted coefficient *A*=0.146(2) of γ-quantum emission anisotropy was obtained.

So, only the value δ in the equation (5) is not known. This angle characterizes rotation of fission axis in binary fission and corresponding angular shift for gamma distribution. We can get it by least squares estimation of experimental data for gamma ROT-asymmetry using required hypothesis (5) which has one parameter only. In such a way obtained angle $\delta = 0.0018(5)\ rad$ has the same sign as the angle of axis rotation for ternary fission. Its absolute value is not very different from analogical angular shift in ternary fission, too.

Having the angle δ of fission axis rotation in binary fission one can try to obtain the angular dependence of ROT-asymmetry for prompt neutrons. It is well established that most of the neutrons evaporates during the fission process from fully accelerated fragments. One can calculate the neutron yield $N_{L(H)}$ in any direction θ_{lab} of laboratory system on the base of neutron angular φ and energy $\Phi_{L(H)}$ dependences in the reference frame of each fragment using Jackobian of transformation *B*:

$$N_{L(H)}(E_{lab},\mu_{lab}) = \varphi(\mu_{cm}) \cdot \Phi_{L(H)}(E_{cm}) \cdot B\,. \qquad (6)$$

In case of fully accelerated fragments this coefficient is very simple

$$B = \begin{vmatrix} \dfrac{\partial E_{cm}}{\partial E_{lab}} & \dfrac{\partial E_{cm}}{\partial \mu_{lab}} \\ \dfrac{\partial \mu_{cm}}{\partial E_{lab}} & \dfrac{\partial \mu_{cm}}{\partial \mu_{lab}} \end{vmatrix} = \sqrt{\frac{E_{lab}}{E_{cm}}}\,. \qquad (7)$$

Hear $\mu_{lab} = \cos(\theta_{lab})$, where θ_{lab} is the angle of neutron registration in laboratory system versus light fragment direction of motion; the analogical value in the fragment centre-of-mass system determines as $\mu_{cm} = \cos(\theta_{cm})$. It is known the form of neutron spectrum $\Phi_{L(H)}(E_{cm})$ in the fragment system is very close to Maxwellian distribution.

The neutron emission in the reference frame of fission fragment is not isotropic. This angular distribution can be written by

$$\varphi(\mu_{cm}) = 1 + b \cdot P_2(\mu_{cm})\,. \qquad (8)$$

The coefficient of anisotropy b cannot be obtained by direct measurements because in laboratory system the own neutron anisotropy exists which is a consequent of fragment velocities. In the figure 4(a) you can see experimental data [5] of neutron count rates measured on condition that direction of light fragment motion corresponds to zero degree and 180˚ for heavy fragment.

The figure 4(b) shows calculated neutron yields in case if we are not interested in what kind of fission fragment is registered. These curves for angular distributions are symmetric relative to 90˚ but neutron yields at different angles can vary significantly, too.

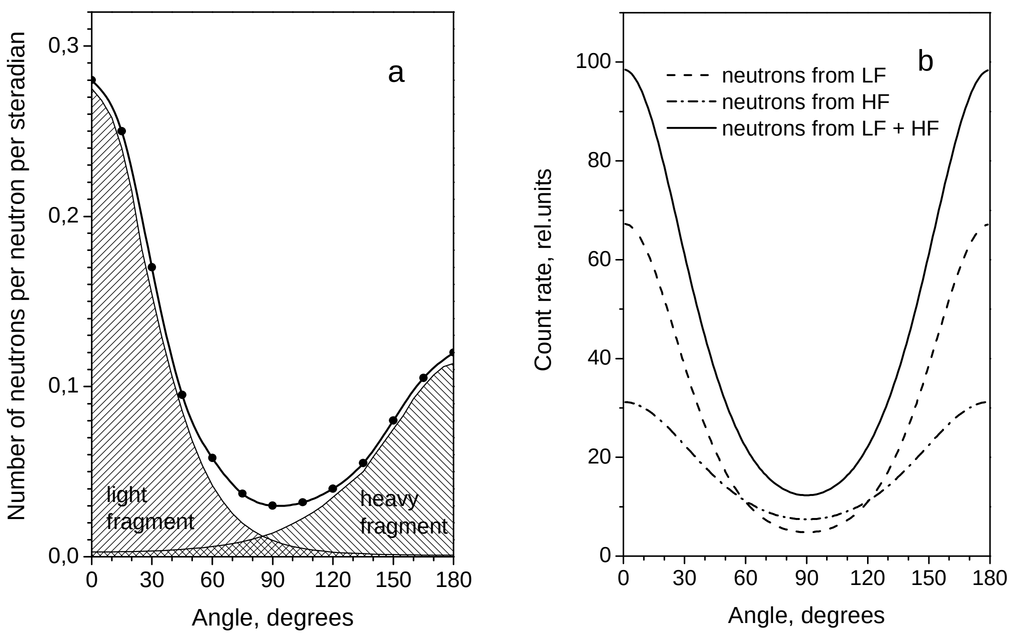

Fig 4. The angular distribution of neutron yields measured on condition that direction of light fragment motion corresponds to zero degree and 180˚ for heavy fragment (a); the figure (b) shows calculated neutron yields in case if we are not interested in what kind of fission fragment is registered.

Although the anisotropy of neutron emission in the reference frame of fragment centre-of-mass can not be obtained by direct measurements we can evaluate it taking into consideration the existence of initial angular momentum for each fragment. The base of such estimation was published in [6]. The soled curves in the figure 5 demonstrate the results of Monte-Carlo calculations of energy dependence of neutron emission anisotropy $A(E_n)$ for both fragments. Here E_n is the neutron energy in the fragment system. The relation between coefficients A and b from (8) can be approximately written by $A \approx 3/2b$. In process of calculation the most probable masses for light and heavy fission fragments were used. These estimations were performed with the averaged initial angular momentum 7 for light and 8 for heavy fragment. The dashed curves show corresponding neutron spectra, which shapes determine the value of averaged anisotropy for each fragment. They were estimated as 6.3% for light and as 9.5% for heavy fragment, respectively.

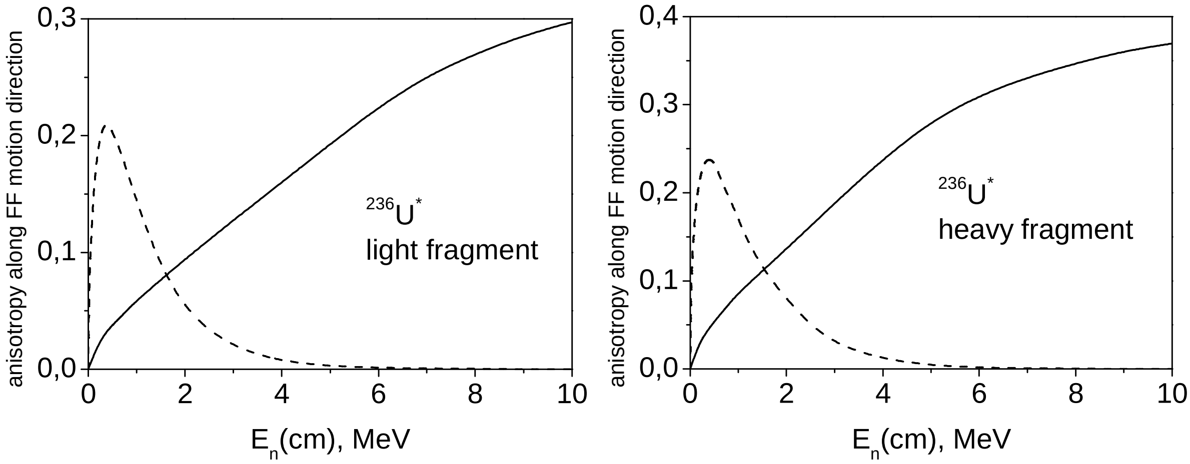

Fig 5. The energy dependence for coefficient of anisotropy in case of neutron emission for light and heavy fission fragments (solid lines). The dashed curves show corresponding neutron spectra in fragment centre-of-mass.

So, using all these parameters and Jackobian of transformation we can calculate the neutron yield (6) in any direction of laboratory system without rotation of fissioning system. But for prompt neutrons ROT-effect evaluation it is necessary to modify this equation taking into account two variants of nuclear system rotation before scission depending on neutron beam polarization. The way of modification is similar to the performance of analogical task for gamma radiation but with a small difference. Following an obligate course of calculations one needs to obtain the neutron yields corresponding to different neutron spin polarizations: $N^{+}_{L(H)}(\theta')$ and $N^{-}_{L(H)}(\theta')$. Here θ' is the angle of neutron registration in laboratory system. Taken into account the interrelation (1) and the existence of the conservation of primary fission fragment spin orientation the neutron angular dependences $\varphi(\mu'_{cm})$ in the reference frame of each fragment (8) in case of nuclear system rotation should be written as:

$$\begin{aligned} \varphi(\mu'_{cm}) &\approx 1 + A \cdot \cos^2(\theta'_{cm} + \delta) \quad if\ \sigma > 0 \\ \varphi(\mu'_{cm}) &\approx 1 + A \cdot \cos^2(\theta'_{cm} - \delta) \quad if\ \sigma < 0. \end{aligned} \tag{9}$$

Unlike of experiment with gamma radiation, where we used experimental averaged value of angular anisotropy $A = 0.146$, in case of neutron emission the anisotropy A dependent on neutron energy was employed. These values were different for light and heavy fragments (see Fig. 5). The form of neutron spectrum $\Phi_{L(H)}(E_{cm})$ was approximated by Maxwellian distribution with temperature parameters T=0.78 MeV and T=0.81 MeV for light and for heavy fragments respectively [5].

In the figure 6 you can see the result of such calculations for neutron count rate asymmetry with respect to the angle of neutron registration in laboratory system. It was suggested here that direction of light fragment motion corresponds to zero degree and 180º for heavy fragment. The solid curve shows the angular dependence of asymmetry for neutrons evaporated from the light fragment, the dashed curve is connected with heavy fragment asymmetry. The dashed-dot line is plotted for gamma radiation.

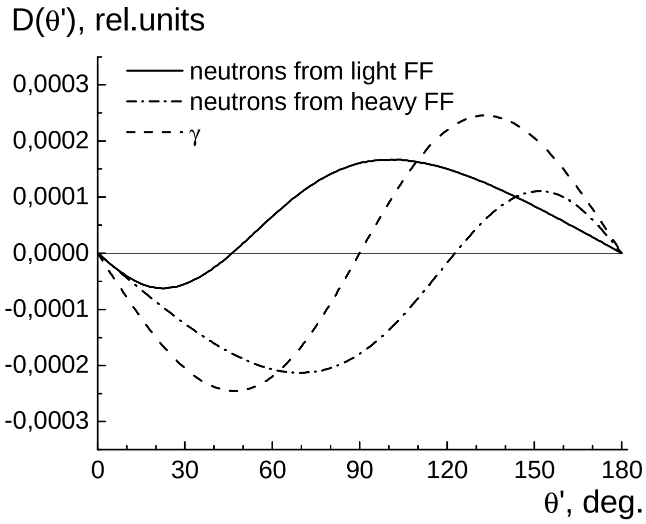

Fig. 6. The partial neutron (separately for light and heavy fragments) and aggregate gamma count rate asymmetries versus their angles of registration (0º – corresponds to light fragment motion direction, 180º - for heavy fragment).

The figure 7 allows us to compare the aggregate result of neutron count rate asymmetry (solid line) with corresponding result for gamma radiation which is plotted by the dashed curve. As we can see the curve for neutron count rate asymmetry has twice more turning-points than the curve for gamma emission.

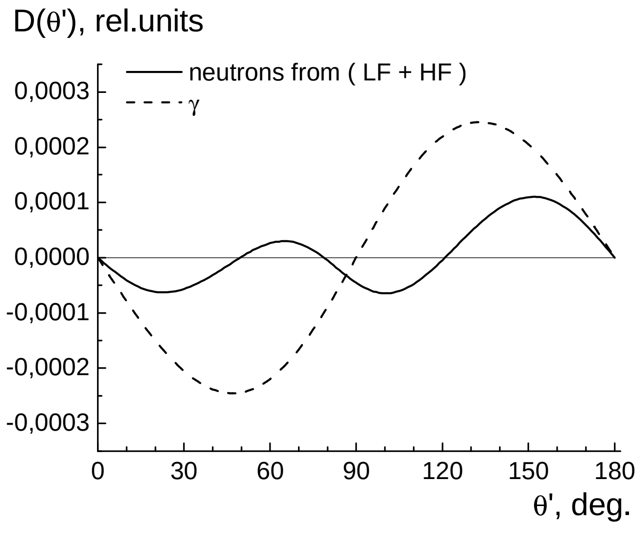

Fig. 7. The total neutron and total gamma count rate asymmetries versus their angles of registration (0˚ – corresponds to light fragment motion direction, 180˚ – to heavy fragment).

If experimental conditions do not imply the type of fragment fixation, the total neutron count rate asymmetry is somewhat different from previous result. The result calculated on this condition is antisymmetric relative to 90˚ (Fig. 8).

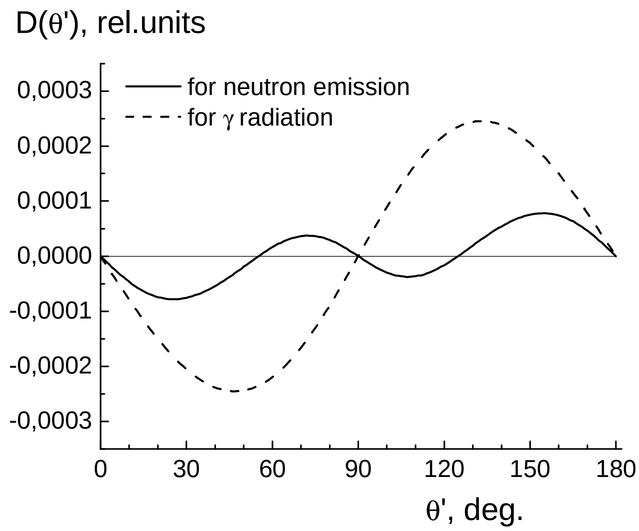

Fig. 8. The total neutron and total gamma count rate asymmetries versus their angles of registration in case if we are not interested in what kind of fission fragments was registered.

It is necessary to remind the neutron yields measured at different angles can vary significantly. This is the reason that in my opinion extremuma at 26˚ and at 154˚ can be easily measured than both extremuma around 90˚. The angular distributions here represent the situation when only the fission axis is fixed and we are not interested in what kind of fission fragment (light or heavy) is registered.

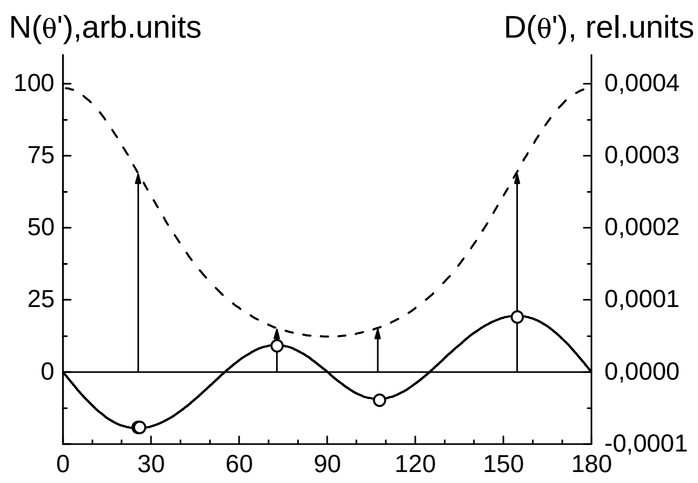

Fig.9. The angular dependence of neutron count rate asymmetry D(θ’) and corresponding neutron yields N(θ’).

It is known the part of prompt neutrons evaporated by fully accelerated fragments is not less than 90% [7, 8]. During the evaluation just this component was taking into account. It means the calculations were performed without including of isotropic (or non-isotropic) scission component.

At the moment only one experimental result [9] on search for T-odd correlations in angular distribution of prompt fission neutrons in ^{235}U induced by cold polarized neutrons is known. In this experiment the value of ROT-effect for prompt neutrons at 67.5° was measured: $(-5.0 \pm 3.4) \cdot 10^{-5}$. Although in [9] no significant effect was found with achieved accuracy it is possible to deduce that experimental value is not in contradiction with the result of calculations presented here in order of amplitude (see fig.8). The opposite signs of prompt neutron ROT-effect in this calculation and obtained by the authors [9] can be explained in the same way as for gamma radiation, namely they may be conditional on different order of the vectors (different coordinate systems).

One should provide new measurements to examine the angular dependence of neutron count rate asymmetry $D(\theta')$. It is necessary to take into consideration that the peculiarities in the regions about 26°and 154° can be easier measured than at 72°and 108° for the reason of statistic (neutron count rate). As far as the main part of prompt neutrons is evaporated by fully accelerated fragments, experimental confirmation of calculated T-odd correlations in angular distribution of prompt fission neutrons (see Fig. 9) can discern real causes of gamma ROT-asymmetry measured in [2, 4] and resolve a dispute about time and point of gamma-quanta radiation which produced this effect.

The value δ of fission axis rotation in binary fission is of significant importance for neutron ROT-effect evaluation. This angle was obtained from experiment for gamma emission [2]. It will be advisable to repeat these measurements because geometry of experimental setup in PNPI (positions of detectors) was not optimal.

Finally I would like to point out that in ternary fission the difference between the angle of fission axis rotation and experimentally observed angle [1, 10], which characterises ROT-effect, exists. The last angle equals the double-lag of α-particle from fission axis rotation [3]. In gamma ROT experiment (in binary fission) we have not third charge particle deflection and consequently we can register only the fission axis rotation. The exact correlation between two angles of fission axis rotation (in binary and ternary fission) can help to specificate these fission configurations.

Author is very grateful to G.A. Petrov who was initiator of these calculations.

This work was financially supported by RFBR grant 02-08-00277-a and RFBR grant 09-02-91346-ННИО_а.

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