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THE COMPARISON OF BINARY- AND TERNARY-FISSION CONFIGURATIONS CLOSE TO THE INSTANT OF SCISSION

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A new way to bring into comparison the binary- and ternary-fission configurations is proposed. The method is founded on recently discovered ROT effect. The angle of fission axis deflection from its initial orientation at the moment of scission comes into existence as a result of dividing system rotation and carries information about fissioning nucleus deformation. The comparison of proper angles for binary and ternary fission can be used to estimate the difference in the rupture configurations.

Предложен новый способ сравнения конфигураций двойного и тройного деления. Метод основан на недавно открытом ROT-эффекте. Отклонение оси деления от ее первоначальной ориентации в момент разрыва является следствием вращения делящейся системы. Величина угла отклонения зависит от деформации делящегося ядра. Сравнение соответствующих углов в бинарном и тройном процессах деления может быть использовано для оценки различия разрывных конфигураций.

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The shift of angular distribution for light charge particles was discovered in 2005 during a detailed investigation of T-odd correlation in ternary fission of ^{235}U induced by slow polarized neutrons [1]. Figure 1 shows the scheme of experimental setup which was used for this purpose. In the process of these measurements, coincidences between fission fragment and light charge particle (LCP) were recorded. Multiwire proportional counters (MWPCs) were used for fission fragments registration. Light charge particles (mostly α particles) were intercepted by silicon detectors. Neutron beam was polarized longitudinally.

The solid curve in Fig. 2 demonstrates the angular dependence of α-particle distribution, which was obtained for positive neutron spin projection, while the dashed line corresponds to negative neutron beam polarization. Asymmetry in coincidence count rates discovered for different detector combinations at the neutron spin flip was connected with a rotation of dividing system before rupture and named ROT effect [1, 2]. The quantitative estimation of this effect was done by modified trajectory calculation [3].

During this calculation it was shown that all objects of dividing system, as fission fragments or alpha particle, deviate from their primary ways due to compound system rotation. But alpha particle deviates less than fission fragments. Since experimentally the angle of alpha

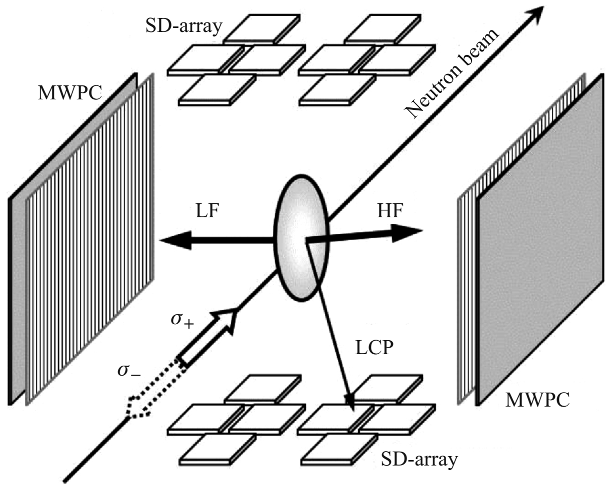

Fig. 1. The scheme of the experimental set-up for the searching of T-odd asymmetry in ternary fission of ^{235}U induced by cold polarized neutrons

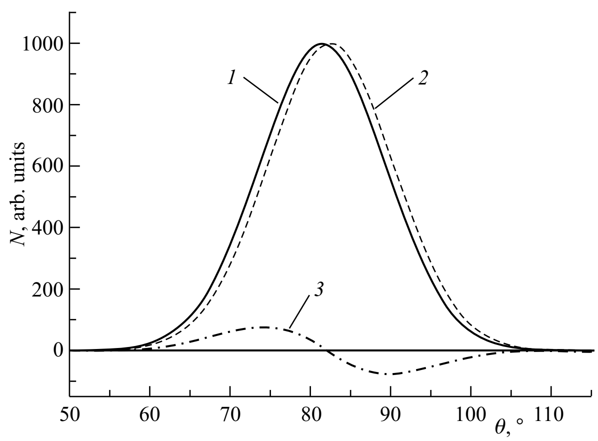

Fig. 2. Angular distributions of α particles for two opposite neutron spin projections (*1, 2*) and difference between them (*3*) in case of nuclear system rotation before scission. The curve (*1*) corresponds to the positive neutron beam polarization, while (*2*) complies with the negative spin projection

particle registration is measured from the final direction of light fragment motion, the angular shift, which was observed through the polarization of compound nucleus, is the lag angle Δ of alpha particle in comparison with the angle of fission axis deflection. In experiment the double lag $S_{\rm exp} = 2\Delta$ was observed, because we did not stop rotation of compound system, but we changed only its direction using the neutron spin-flip procedure. Spin polarization of compound nuclei, which was obtained after polarized neutron capture, determines the direction of dividing system rotation and influences its average velocity. The absolute value of the effect depends also on the inertia moment of fissioning system at the instant of rupture, which means the dependence on compound system deformation.

The estimation of effective angular velocity ω for the dividing system rotation with fixed spin J and its projection K on fission axis around the line Z of neutron beam polarization p_n can be performed using the quantum-mechanical expression: $\omega(J,K) = \langle J_Z(K)\rangle/\Im$, where $\Im$ corresponds to the moment of inertia for the above-mentioned system. As was shown by V. Bunakov and S. Kadmenski [4], this expression can be written in the form

$$\omega\,(J,K) = \begin{cases} \dfrac{J(J+1)-K^2}{J}\,\dfrac{\hbar}{2\Im}\,p_n & \text{for}\quad J = I + 1/2, \\ -\dfrac{J(J+1)-K^2}{(J+1)}\,\dfrac{\hbar}{2\Im}\,p_n & \text{for}\quad J = I - 1/2. \end{cases} \tag{1}$$

The different signs of angular velocity for two values of J in this expression indicate the opposite directions of the fissioning system rotation. If several transition states contribute to the fission process, it is necessary to perform summation over all possible K values, where factors of summation are probabilities to find the component with corresponding value K in the resonance wave function. To obtain the total effective angular velocity, one should take into account the relative contribution of resonance components with different J to the total fission cross sections.

Table 1 contains the information about our angular shift estimation, performed on the basis of modified trajectory calculations [3] for several targets. In the process of evaluation we used the ratios of partial fission cross sections σ with different J, which were obtained by V. Maslov and A. Popov in multilevel approach on the basis of evaluated data from ENDF and JENDL files. The positive signs of the shift allow us to conclude that rotation in the positive direction predominates for these three isotopes, when we consider the set of K values normally used in low-energy fission. We have obtained experimental results for these three targets and can compare them with calculated values of the ROT effect. One can see that the predicted sign coincides with the sign of each experimentally measured shift. Although the sign of effect for each nucleus does not depend on the choice of K value, the dominant K can be selected through the best fitting to the experimental shift.

We have not yet obtained experimental results of the ROT effect for the targets of ^{241}Pu and ^{245}Cm, but expected results for the ROT effect for these cases could be evaluated in the

Table 1

^{235}U, $S_{\text{exp}} = 0.215^\circ$; $\dfrac{\sigma(J=3)}{\sigma(J=4)} = 0.57$ (from A. Popov)	(J,K)	$(3,0)$	$(3,1)$	$(3,2)$
	$(4,0)$	0.183°	0.191°	0.215°
	$(4,1)$	0.169°	0.177°	0.201°
	$(4,2)$	0.128°	0.135°	0.159°
	$(4,3)$	0.058°	0.066°	0.090°
^{233}U, $S_{\text{exp}} \sim 0.02{-}0.04^\circ$; $\dfrac{\sigma(J=2)}{\sigma(J=3)} = 0.79$ (from V. Maslov)	(J,K)	$(2,0)$	$(2,1)$	$(2,2)$
	$(3,0)$	0.118°	0.131°	0.170°
	$(3,1)$	0.102°	0.115°	0.153°
	$(3,2)$	0.053°	0.066°	0.105°
^{239}Pu, $S_{\text{exp}} = (0.020 \pm 0.003)^\circ$; $\dfrac{\sigma(J=0)}{\sigma(J=1)} = 2.09$ (from V. Maslov)	(J,K)	$(0,0)$		
	$(1,0)$	0.057°		
	$(1,1)$	0.028°		

Table 2

<table>
<tr><td rowspan="4">^{241}Pu, $S_{\rm exp}=?$
$\dfrac{\sigma(J=2)}{\sigma(J=3)}=0.15$ (from V. Maslov)</td><td>(J,K)</td><td>$(2,0)$</td><td>$(2,1)$</td><td>$(2,2)$</td></tr>
<tr><td>$(3,0)$</td><td>0.282°</td><td>0.285°</td><td>0.297°</td></tr>
<tr><td>$(3,1)$</td><td>0.256°</td><td>0.260°</td><td>0.271°</td></tr>
<tr><td>$(3,2)$</td><td>0.180°</td><td>0.184°</td><td>0.195°</td></tr>
<tr><td rowspan="4">^{245}Cm, $S_{\rm exp}=?$
$\dfrac{\sigma(J=3)}{\sigma(J=4)}=5.73$ (from V. Maslov)</td><td>(J,K)</td><td>$(3,0)$</td><td>$(3,1)$</td><td>$(3,2)$</td></tr>
<tr><td>$(4,0)$</td><td>-0.159°</td><td>-0.140°</td><td>-0.084°</td></tr>
<tr><td>$(4,1)$</td><td>-0.162°</td><td>-0.143°</td><td>-0.087°</td></tr>
<tr><td>$(4,2)$</td><td>-0.172°</td><td>-0.153°</td><td>-0.097°</td></tr>
</table>

framework of our rotation model (see Table 2). The measurements with the isotope of ^{241}Pu are planned for the autumn of 2012. In this case we expect a rather big ROT effect with positive sign as well. The absolute value of the effect can be the same order as for the target of ^{235}U. The target of ^{245}Cm deserves special attention. This is the only element we have estimated with a sizable ROT effect and negative sign.

It was established two or three years after the discovery of the ROT effect in ternary fission, first by the group of Danilyan [5] and then in PNPI [6], that oriented rotation of fissioning system causes an analogical effect in gamma-quanta emission. Figure 3 demonstrates our result of measurements for gamma count rate asymmetry. If one takes into account a systematic shift in experimental data of the PNPI group, which is equal to 0.0002, it is possible to deduce that the absolute value of this asymmetry is in good agreement with the asymmetry obtained in the work [5], but their signs are opposite. Such a discrepancy is connected with a different order of vectors in the formula for the triple correlation. This order determines the frame of reference.

Some attempts were made to explain the angular dependence of gamma count rate asymmetry in a way similar to that for ternary particles. Thus, for example, the authors of the article [5] had an opinion that gamma quanta concerned with ROT asymmetry are emitted

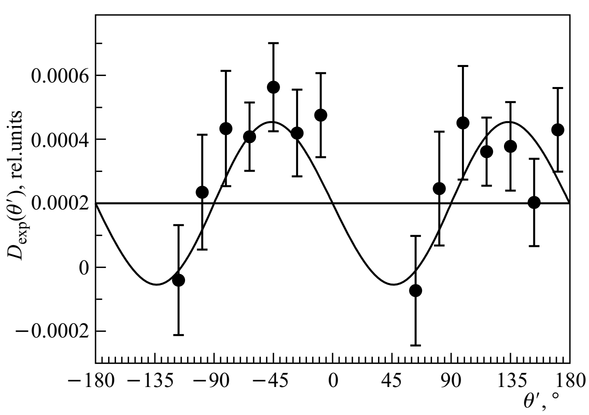

Fig. 3. Experimental angular dependence of the T-odd asymmetry coefficient $D(\theta')$ for γ-ray emission in ^{236}U* fission obtained at the WWR_M reactor. The solid line is the result of theoretical approximation of this dependence

near the rupture point. But in contradiction to light charge particles accompanying a process of scission, most of the gamma quanta radiate from the fission fragments essentially later than the moment of scission. As is well known, most gammas in low-energy fission are emitted by fully accelerated fragments.

In contrast to the approach [5], the PNPI group's explanation is 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, although the co-author of [5] V. Novitsky was the first to draw attention to the ability to describe the effect of T-odd asymmetry in the emission of gamma rays in such a way. Figure 4 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 latter 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 should have inverse sign.

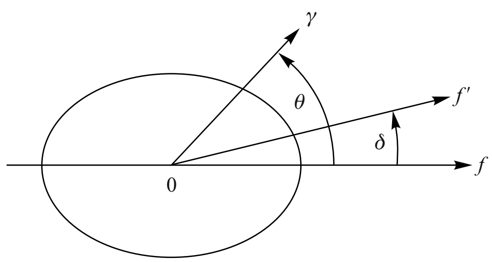

Fig. 4. The scheme of the shift formation in the angular distribution of quadrupole γ rays from fission fragments with respect to their measurement detection

The oval in Fig. 4 shows a preferential emission of gamma rays along the axis of fission. A location of an axis is assumed at the time of compound system rupture. The angle θ defines the direction of gamma-quantum emission with respect to this initial orientation of fission axis. This angle must be used to determine the influence of anisotropy on gamma radiation and to calculate gamma-quanta count rate connected with it. Due to the system rotation, θ is not the angle of gamma-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 beam polarization.

Following Strutinskii [7], the gamma count rate without nuclear system rotation can be written as $N = N(90°)(1 + A\cos^2\theta)$, where A is the coefficient of anisotropy, the count rates corresponding to different neutron spin polarizations σ are $N^+(\theta')$ and $N^-(\theta')$:

$$\begin{aligned} N^+(\theta') &= N(90°)\,(1 + A\cos^2(\theta' + \delta)) \quad \text{if } \sigma > 0, \\ N^-(\theta') &= N(90°)\,(1 + A\cos^2(\theta' - \delta)) \quad \text{if } \sigma < 0. \end{aligned} \tag{2}$$

In experiment the angular dependence of asymmetry coefficient $D(\theta')$ was measured:

$$D_{\exp}(\theta') \equiv \frac{N^+(\theta') - N^-(\theta')}{N^+(\theta') + N^-(\theta')}. \tag{3}$$

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

$$D(\theta') \approx \frac{-A\delta\sin 2\theta'}{1 + A\cos^2\theta'}. \tag{4}$$

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 was measured in the same experiment and corresponds to the same energy interval, which was used for gamma ROT-effect observation.

So, only the value δ in the last equation is not known. This angle characterizes the 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 (4) which has one parameter only. In such a way the obtained angle of fission axis rotation in binary fission equals

$$\delta_B \equiv \delta = 0.0018\,(5)\ \mathrm{rad} = 0.10\,(3)^{\circ}. \tag{5}$$

If we want to compare the ROT effect in binary and ternary processes, we have to obtain the angle of fission axis rotation in ternary fission as well. The scheme of ROT-effect origin in ternary fission is presented in Fig. 5. Here you can see initial directions of fragments (P_{LF}, P_{HF}) and light charge particle motion (P_α) at the moment of scission. The final object directions, which were obtained due to nuclear system rotation, are labeled by primes. It is necessary to mention that in experiment we can see directly only the double lag of ternary particle relative to the fission axis deflection: $2\Delta = 2(\theta - \theta') = 2(\delta_T - \delta_\alpha)$. But for both binary and ternary ROT-effect comparison we have to use the angle of fission axis deflection δ_T. In ternary fission we can get it by trajectory calculations on the basis of experimental result for the angular shift. In such a way the obtained angle for ternary fission is $\delta_T = 0.0032\,(3)\ \mathrm{rad} = 0.18\,(2)^{\circ}$.

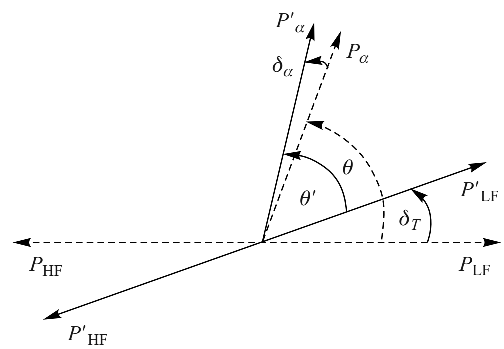

Fig. 5. The scheme of the ROT-effect origin in ternary fission

As one can see, both angles of axis deflection in ternary and binary fission have the same sign which corresponds to the mechanism presented above. Although their absolute values do not differ very much, it is necessary to point out that the angle of fission axis deflection obtained for binary fission process is about 1.8 times smaller than for ternary fission. This result may be the consequence of different moments of inertia. It can serve as an evidence that close to the instant of scission, the compound system has more elongated configuration in binary fission than in ternary case. This result agrees with the conclusion of Mutterer [8] that fragment deformation in ternary fission is considerably less than in binary fission.

At the same time, this ratio of angle deflections for fission axis in ternary and binary processes may give an answer to the question of how quickly formation of the primary fragment spin occurs. From ternary fission experiment, it is possible to obtain the information about such an angle deflection just from the rupture point. The situation is different in the experiment with gamma rays. In fact, our fixation of the space configuration in binary fission is not directly related to the time of nucleus scission, but it is connected with the moment when the fragment spin was already formed. And this may be the cause of the seeming lengthening of fission configuration in binary fission.

Although experimental results [5] and [6] are in agreement, it is necessary to mention that PNPI data have appreciable systematic error. This reason and the deficiency of experimental points in down half-plane (see Fig. 3) can be a cause of inaccuracy in gamma ROT-effect estimation. If we take into account the later measurements of Danilyan's group [9], it is possible to conclude that the angle of fission axis rotation in binary fission can be somewhat larger than our value (5). As follows from Eq. (4), the angular dependence of asymmetry reaches its maximum at $45°$. So far as the magnitude of asymmetry coefficient obtained in [9] equals $(20.9 \pm 2.4) \cdot 10^{-5}$ and was measured at the angle $67.5°$, the maximal value of this asymmetry can be about $3 \cdot 10^{-4}$. Such an estimation is one and a half times larger than our result for gamma-quantum ROT asymmetry [6] and the difference between both angles of axis rotation (in binary and ternary fission) will be not as significant. Their ratio will be $\delta_T/\delta_B = 1.27$ instead of 1.8. Therefore, the moment of inertia for binary dividing system will be greater than in ternary process only by the same factor: $\Im_B/\Im_T = 1.27$. Consequently, the deformation of the nuclear system, corresponding to binary fission, will approach the elongation of ternary fission, though the first one will remain more extended.

If we admit that the angle of axis deflection in binary fission can be larger than the result obtained in PNPI [6], then the ROT-effect evaluation, which was performed in [10] for fission accompanied by neutron emission, should also be modified. Figure 6 shows the curve for gamma count rate asymmetry in accordance with PNPI data. Here one can also see the prediction for angular dependence of neutron ROT asymmetry with respect to the angle of neutron registration in laboratory system. In the process of calculations it was suggested that the direction of light fragment motion corresponds to zero degree and $180°$ for heavy fragment. The above-mentioned increase of the angle of axis rotation in binary fission should lead to proportional rise of asymmetry values for both effects.

Thus, precise measurements of these two types of asymmetry (for gammas and for neutrons) will contribute to the determination of the angle δ_B of axis deflection in binary fission.

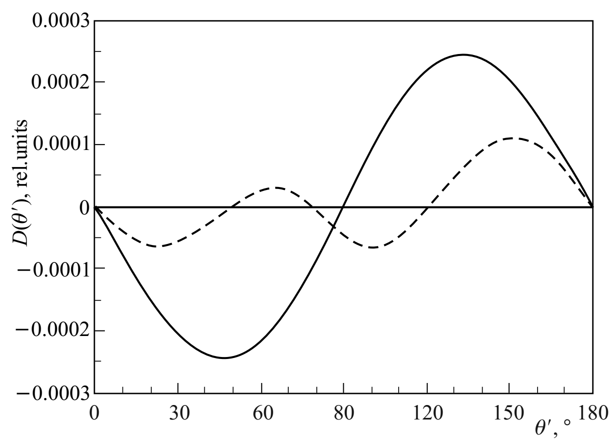

Fig. 6. The angular dependence for gamma T-odd asymmetry in accordance with PNPI data (solid line) and the Monte Carlo prediction for neutron count rate asymmetry versus their angles of registration (dashed line). Direction $0°$ corresponds to light fragment motion, $180°$ — to heavy fragment

Understanding the exact correlation between both angles δ_B and δ_T of fission axis rotation can help us to specify the configurations in binary and ternary fission processes. However, at present, the accuracy of asymmetry measurements in binary fission is not sufficient and research should be continued.

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