

Dependence of the ROT effect on the energy of different light charged particles and on the incident neutron energy

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Abstract. The shift of the angular distribution of different light charged particles in ternary fission of ^{235}U induced by polarized neutrons, the so-called ROT effect, was estimated by modified trajectory calculations, which take into account the rotation of the compound nucleus. In previous publications only α -particles were considered. It is shown here that inclusion of tritons significantly improves the agreement of the energy dependence of the ROT effect with experiment while the inclusion of ^5He particles practically does not influence this dependence. In particular, the change in the magnitude of the ROT effect depending on the energy of incident neutrons is correctly predicted. Also, the ROT effect for gamma quanta and neutrons in binary fission is discussed along the same lines, because all mentioned effects are proportional to the effective angular velocity of the compound nucleus at the moment of scission.

1 Introduction

The ROT effect was discovered in 2005. It corresponds to a shift of the angular distribution of light charged particles (LCP), mainly alphas, which was observed in ternary fission of ^{235}U induced by cold polarized neutrons [1, 2]. It was assumed that this experimentally detected shift of the angular distribution is associated with the presence of rotational states in the level structure of the deformed compound nucleus. The validity of this hypothesis was confirmed by Monte-Carlo calculations [3, 4]. The rotational structure of the nucleus was known for a long time [5] but in case of unpolarized compound nuclei their rotations are arbitrarily oriented in space and can not to shift the angular distributions of ternary particles. In the present experiments the angular shift can arise only due to the spin polarization of the compound nucleus following capture of polarized neutrons. Flipping the spin of the polarized neutron beam inducing fission leads to opposite shifts Δ and $-\Delta$ of the LCP angular distribution, which allows to detect the ROT effect. The difference in angular distributions of LCP for the two spin orientations then is 2Δ .

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2 Experimental technique and data analysis

In Fig. 1 is shown the scheme of the experimental setup for the measurements to be discussed. The longitudinally polarized neutron beam was hitting the fissile target ^{235}U mounted at the center of a reaction chamber. Detectors for fission fragments (FFs) and LCP were installed in a plane perpendicular to the neutron beam.

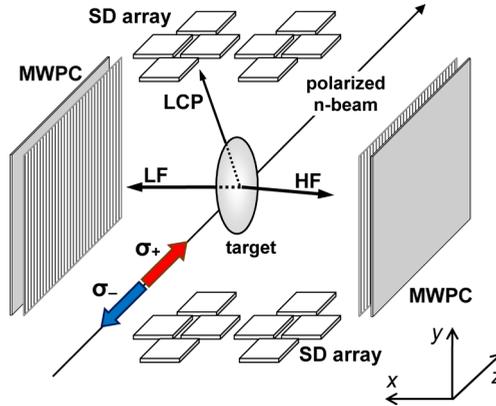


Figure 1. Scheme of the experimental setup: two multiwire proportional counters (MWPC) facing each other to the left and right of the target intercept fission fragments. LCPs are measured by two arrays of up to twelve Si detectors on the top and bottom of the target.

We assume that the ROT effect mostly develops after the nucleus rupture and when nuclear forces have already ceased to influence the trajectories of FFs and LCPs flying apart. This phenomenon then arises due to the motion of charged objects in the rotating field of Coulomb forces.

The time dependence of the motion for two fission fragments and a ternary particle due to their mutual Coulomb interaction can be reproduced using Monte-Carlo simulations [3, 4]. Initially it is necessary to perform calculations without considering the rotation of the fissile system [6]. Since this motion cannot be calculated in closed analytical form, it is necessary to replace the differential equations of motion

$$\frac{dX_{ij}}{dt} = V_{ij}, \quad m_i \frac{dV_{ij}}{dt} = F_{ij} \quad (1)$$

by a set of difference equations

$$X_{ij}^{n+1} = X_{ij}^n + \tilde{V}_{ij}^n \Delta t, \quad V_{ij}^{n+1} = \tilde{V}_{ij}^n + \frac{1}{2m_i} F_{ij}^n \Delta t, \quad (2)$$

where

$$\tilde{V}_{ij}^n = V_{ij}^n + \frac{1}{2m_i} F_{ij}^n \Delta t. \quad (3)$$

Here the subscript i denotes a particle with the masse m_i , while j corresponds to its component index for the coordinate X_{ij} , the velocity V_{ij} and the force F_{ij} acting on this particle. The superscript n refers to the value of the parameter after the n -th time interval. By iterations the time dependence of the coordinates for FFs and LCPs is found step by step.

Such standard trajectory calculations are commonly applied to describe spontaneous ternary fission or ternary fission induced by unpolarized neutrons [7, 8]. Our goal at this

first stage of calculations is to find parameters of the nuclear system at a moment close to its rupture. It is necessary to determine mass distributions of FFs, positions of all partners with respect to the center of mass and initial velocity distributions of FFs and LCP. In the case of correctly fitted initial parameters of the considered system, the calculated final distributions for fission fragments and light charge particles should coincide with those that were experimentally recorded for a non-rotating fission system, in our case for ternary fission induced by unpolarized neutrons.

Found in this way, the initial configuration of the nuclear system allowed us to calculate its moment of inertia \mathfrak{I} immediately after the nucleus rupture.

Then the initial angular velocity $\omega(J, K)$ can be obtained as the ratio of the mean value of the compound nucleus spin projection $\langle J_z(K) \rangle$ onto the axis z of neutron beam polarization to the moment of inertia \mathfrak{I} :

$$\omega(J, K) = \langle J_z(K) \rangle / \mathfrak{I}. \quad (4)$$

In the process of nuclear fission induced by slow polarized neutrons two spins of the compound nucleus may appear. They are equal to $J_+ = I + 1/2$ and $J_- = I - 1/2$, where I is the spin of the target nucleus.

The partial angular velocities $\omega_{+/-}(J, K)$ depend on the spins $J_{+/-}$, the projections $K_{+/-}$ on the fission axis, the moment of inertia \mathfrak{I} and neutron beam polarization p_n [9]:

$$\begin{aligned} \omega_+(J, K) &= + \frac{p_n \hbar}{2\mathfrak{I}} \cdot \frac{J_+(J_+ + 1) - K_+^2}{J_+} \\ \omega_-(J, K) &= - \frac{p_n \hbar}{2\mathfrak{I}} \cdot \frac{J_-(J_- + 1) - K_-^2}{J_- + 1}. \end{aligned} \quad (5)$$

The different signs of the angular velocities for J_+ and J_- indicate opposite directions of the fissile system rotation.

The ROT effect 2Δ in the angular distributions of ternary particles is proportional to the initial effective angular velocity ω_{eff} . This velocity is the sum of the two partial angular velocities ω_+ and ω_- for the two spins J_+ and J_- with coefficients depending on the partial fission cross sections:

$$\omega_{\text{eff}}(J, K) = \omega_+(J_+, K_+) \frac{\sigma_f(J_+)}{\sigma_f(J_+) + \sigma_f(J_-)} + \omega_-(J_-, K_-) \frac{\sigma_f(J_-)}{\sigma_f(J_+) + \sigma_f(J_-)}. \quad (6)$$

Based on the obtained effective angular velocity ω_{eff} , one can proceed to the second stage of trajectory calculations. In the present case the fissile system is rotating around the z -axis of neutron beam polarization in Fig. 1, and it is only necessary to modify the initial velocities of the objects described by taking into account their additional components tangential to this rotation. Considering spin-flip of the polarized neutron beam, this must be performed twice. The following iterative steps of the calculations are no different from the standard method. Using modified trajectory calculations one should recalculate all distributions.

As follows from the calculations (see Fig. 2), the rotational speed of the nuclear system after rupture is variable. It depends on the moment of inertia of the fissile system at any given time. This rotation starts with a huge angular velocity. It reaches about 10^{18} turns per second immediately after scission and tends to zero after about 5 zs.

As a result of the rapid decrease in the angular velocity, the fission fragments and the ternary particle can change their directions of motion only during a very short time, and then they move along straight lines. Already after a short time the angle of rotation of each reaction partner reaches its final value. In other words, each partner has got its final direction

of motion leading possibly to a detector for registration. In the experiment, the angle of α -particle is measured from the final direction of motion of the light fragment.

Figure 2 shows a typical example of time dependencies of deflection angles for LF and LCP. It is observed that already in a few zs the LCP trajectory lags behind the LF in turning angle. The final lag angle Δ is reached in only ≈ 5 zs. The angular LCP distribution, which is the result of many fission events, is hence shifted compared to a non-rotating composite system by a similar angle Δ , but which is averaged over all fission events.

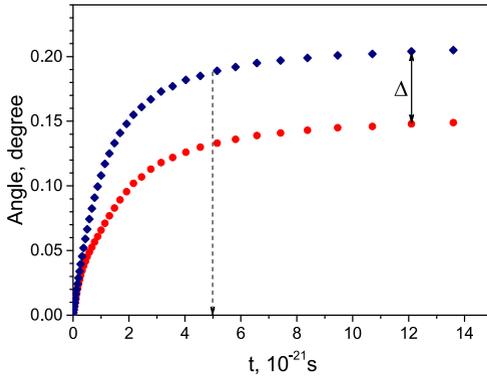


Figure 2. Time dependencies of deflection angles θ_α for α -particle (full dots) and θ_{LF} for LF (rhombs). $\Delta = \theta_{LF} - \theta_\alpha$. Calculations were performed with $\langle J_z \rangle = 1 \hbar$.

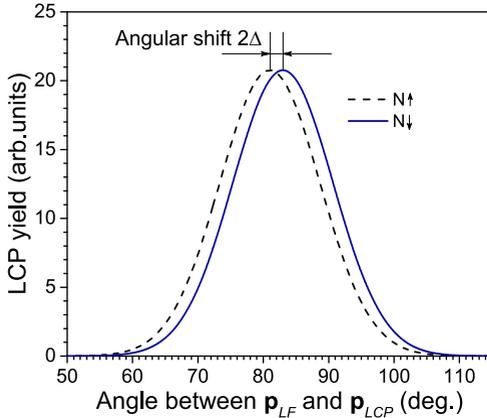


Figure 3. Double shift 2Δ of the angular distribution of ternary particles in (n,f) reactions depending on the orientation of neutron spin inducing fission. N_\uparrow and N_\downarrow are emission rates for neutron spin parallel and antiparallel to $(\mathbf{p}_{LF} \times \mathbf{p}_{LCP})$, respectively. Here the angular shift is about 10 times greater than the experimental one for better visualization.

Taking into account the spin-flip technique, we need to repeat the last version of trajectory calculation, in which the directions of the additional velocities should be reversed. The difference in the angular distributions of ternary particles corresponding to different signs of the neutron beam polarization gives us the sought-for double shift 2Δ of this angular distribution (Fig. 3).

To get the best fit between experimental shift and the result obtained by modified trajectory calculations, which take into account rotation of the compound nucleus, we can change only the spin projections $K_{+/-}$ of the compound nucleus, while the other initial parameters of the fissile system were determined on the first standard stage of trajectory calculations. It was concluded that for the reaction $^{235}\text{U}(n, f)$ induced by cold neutrons combinations of the nuclear spin and its projection $(J_+, K_+) = (4, 0)$ and $(J_-, K_-) = (3, 2)$ are dominant.

3 Results of calculations

As already pointed out, originally these calculations have been performed only with alphas as the third particle, since they dominate in ternary fission. The evaluated angular shift averaged over the energy of α -particles was in good agreement with the experimental result, but the detailed distribution of the calculated ROT-effect values depending on the energy of ternary particles deviated from the experimental data. The experimental angular shift was larger than the calculated result in the energy range (8 ÷ 13) MeV of the third particle (Fig. 15 in [2]).

This discrepancy can be explained by the presence of other ternary particles besides alphas, since the corresponding measurements in this experiment were performed without precise identification of the ternary particle type. Accounting for the presence of tritons, which contribute about 7% to the LCP yields, it was possible to bring the calculated results in better agreement to experimental data. The results of such calculations were presented in [10].

However, besides α -particles and tritons, there are ternary particles of ^5He with a sizable contribution to ternary fission. Therefore, it was decided to start a new version of trajectory calculations including this isotope. We rely on ref [11], where the LCP yields in spontaneous fission of ^{252}Cf were studied. It was observed that in addition to “true” α -particles, which are formed during the nucleus separation, about 20% of the α -spectrum can be produced due to disintegration of ^5He into α -particle and a neutron. This is assumed to be true also in neutron induced fission of ^{235}U . Further, the fraction of emitted ^5He particles and their energy distribution for ternary fission of ^{235}U were taken to be identical to those for ^{252}Cf (see Table 1).

Evidently, it was necessary to take into account the very short lifetime of ^5He , which is approximately $1 \times 10^{-21}\text{s}$. This ternary particle rapidly decays into ^4He and a neutron. In addition, the smaller energy from ^5He decay should be considered when estimating the dependence of ROT effect on the energy of LCPs.

Table 1. Experimentally obtained energy distributions of LCP for spontaneous fission of ^{252}Cf [11].

LCP	$\langle E \rangle$	TWHM
^4He	15.7(2)	10.9(2)
True ^4He	16.4(3)	10.3(3)
Residues from ^5He	12.4(3)	8.9(5)

Figure 4 shows the energy distributions for tritons, true α -particles and for isotope of ^5He , which were obtained by standard trajectory calculations. The initial parameters of the fissile system required for this task were chosen suitable to reproduce the energy distributions of ternary particles in the spontaneous fission of ^{252}Cf . The yields of emitted particles were taken in agreement with experimental data for neutron induced fission of ^{235}U and evaluations in ref. [11].

The modified trajectory calculations based on the adopted initial parameters and the calculated effective angular velocity allowed to find the angular shifts for tritons, true α -particles, and ^5He isotope decaying into an alpha and a neutron. The resulting ROT effect as a function of the kinetic energy of the LCPs is visualized in Fig. 5a.

By summing ROT angles 2Δ for the contributing LCPs with their respective weights, we obtain the result to be compared with the experimentally observed effect shown in Fig.5b. Evidently, the inclusion of tritons in the calculations gives a significant contribution to the energy dependence of the ROT effect at low LCP energies and convincingly improves agreement with experiment. On the other hand, the ROT effects for the ^4He and ^5He isotopes are virtually identical and the inclusion of the ^5He isotope cannot bring a noticeable change compared with the previous description of its energy dependence [10].

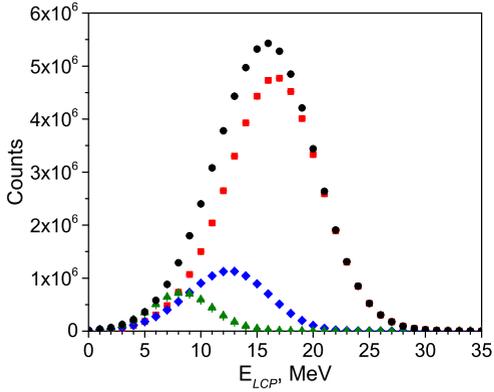


Figure 4. The calculated LCPs energy distributions: for ${}^3\text{H}$ (triangles), for true α -particles (squares), for ${}^5\text{He}$, which turns into α -particle plus a neutron (rhombs), and for the sum of true and residual α -particles (full dots).

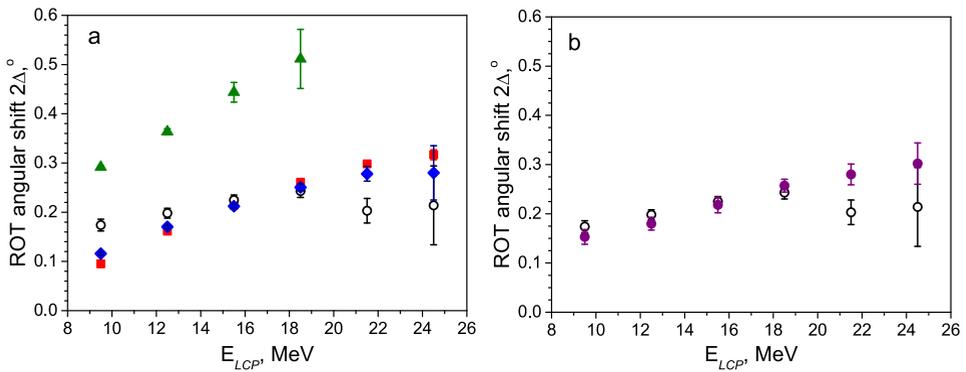


Figure 5. a) Calculated ROT effect for ${}^3\text{H}$ (triangles), true ${}^4\text{He}$ (squares), ${}^5\text{He}$ which turns into an α -particle plus a neutron (rhombs) and experimental data (opened dots); b) the calculated ROT for the sum of all LCP components considered (full dots) in comparison with experimental data (open dots).

4 Dependence of the ROT effect on the incident neutron energy

As discussed in connection with eq. (5), the rotational speeds for the two possible spins of the ${}^{236}\text{U}^*$ compound nucleus, $J_+ = 4$ and $J_- = 3$ have different signs. Both contribute to the effective angular velocity ω_{eff} in Eq. (6) as the start velocity for trajectory calculations and ensuing ROT effects. But the sign and size of the effective angular velocity and, therefore, the sign and magnitude of the ROT effect also depends on the partial fission cross-sections, more precisely, on their ratio. This ratio varies with the energy of the incident neutron.

The energy dependence of the spin-separated fission cross sections for neutron induced fission of ${}^{235}\text{U}$ were calculated by the computer code SAMMY (see Fig. 6). This figure shows two curves for the partial fission cross sections and their sum for the target of ${}^{235}\text{U}$. In these calculations the data of resonance parameters were taken from ENDF/B-VIII.0 (USA, 2018) [12].

Experiments in ternary fission were performed in the energy region of cold neutrons. Here, the partial fission cross section for $J = 4$ is approximately 2 times larger than the corresponding value for $J = 3$. Furthermore, as follows from Eq. (5), the positive partial angular velocity of the state $(J_+, K_+) = (4, 0)$ exceeds in absolute value the negative rotational speed of the compound state $(J_-, K_-) = (3, 2)$. As a result, we get in this region a positive and sizable value of the ROT effect.

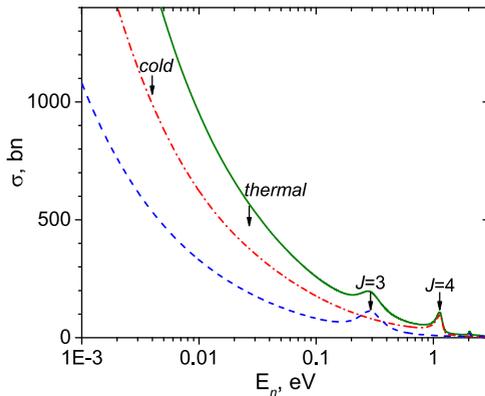


Figure 6. Spin-separated fission cross-sections for the target of ^{235}U as a function of the energy of the incident neutron: dashed line for $J = 3$, dash-dotted line for $J = 4$, solid line for the sum of both.

Practically the same results should be expected for thermal neutrons. Closer to the resonance at $E_n = 0.3$ eV the situation is different. The spin of this resonance is defined as $J = 3$. Although at its top the partial fission cross section is slightly larger than the value corresponding to spin $J = 4$, the rotation in the positive direction continues to dominate due to the significant larger absolute value of the positive partial angular velocity compared to the negative velocity. As a result, the sign of the ROT effect remains also here positive, but its size becomes two times less than for thermal or cold neutrons. For the resonance region near 1 eV, on the contrary, we can expect an increase in the ROT effect compared to the cold or thermal region by a factor 2.3.

5 Summary and outlook

In the present semi-classical interpretation of the ROT effect, the main cause of the shift in the angular distribution of light charged particles observed in the ternary fission induced by polarized neutrons is the interaction of charged objects when they move in a rotating Coulomb field. It is especially important to take into account the development of this phenomenon in time, namely, that the angular velocity very quickly tends to zero. If case the angular velocity would remain constant for a long period of time, no experiments of this type could have predictable results, since this would lead to a dependence of the magnitude of the effect on the distance between the detectors and the target.

The evolution in time of the motion of three charged objects in a Coulomb field can well be described classically. The quantum-mechanical aspect of the ROT effect phenomenon is represented by the initial angular velocity ω_{eff} . Moreover, using the values of partial fission cross sections calculated by the computer code SAMMY based on the most recent Nuclear Data Files, the interference of s -resonances with the same spins is duly described.

The need to take into account the interference of s -resonances with different spins, on which the authors [13] insist to describe the ROT effect, cannot be considered proven. Justifying the correctness of their approach, they do not perform real calculations in accordance with their formulas, but simply fitted the corresponding coefficients to the experimental ones. In these calculations, the resonance parameters are not used at all, not to mention the interference between them.

In contrast to the authors of [13], we obtained real parameters of s -resonances from the Evaluated Nuclear Data File in a fairly wide energy range and used them to correctly calculate spin-separated fission cross sections. We need them in order to determine the ratio of rotations of compound-nuclei in two opposite directions. In addition, we can quite adequately estimate the moment of inertia of the fissile system from the point of its rupture to the end of rotation,

which the authors [13] do not have. They do not at all follow the change in time of the size of the rotating system, which is characterized by the distances between interacting charged objects and determines the moment of inertia of interest to us, as well as the change in their kinematic parameters.

Our evaluation of the magnitude of the ROT effect occurs independently of the experimental results and only after performance of calculations are these values compared.

As was shown, the result of our calculations for the magnitude and sign of the ROT effect are in good agreement with experimental data, both averaged over the energy of LCPs as well as their detailed LCP energy dependence.

At present, all measurements of the ROT effect in ternary fission are carried out only at incident neutrons from the cold energy region. To test our predictions about the dependence of the ROT effect on the neutron energy, it should be of great interest to measure this effect at neighboring *s*-resonances.

It should finally be noted that this predicted energy dependence is also valid for the ROT effect for neutrons and gammas in binary fission [14], because these effects are likewise proportional to the effective angular velocity of the compound nucleus at the moment of scission. These conclusions can be tested in experiment by comparing the ROT effect values in the resonance energy region [15] with those obtained for cold or thermal neutrons.

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