# Dependence of the ROT effect on the energy of 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 cold polarized neutrons 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 was shown here that the inclusion of tritons significantly improves the agreement of the energy dependence of the ROT effect with experiment while the involvement of $^{5}$He particles practically did not influence this dependence. The change in the magnitude of the ROT effect depending on the energy of the incident neutrons is predicted. 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 (LCPs), 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 such hypothesis was confirmed by Monte Carlo calculations [3, 4]. The rotational structure was known for a long time [5] but usually the rotations of different compound nuclei are randomly oriented in space and cannot influence on the angular distribution of ternary particles, namely on their shift. Without a general orientation of rotation in space the mentioned shift cannot be seen in ternary fission experiments. The required result can arise only due to the spin polarization of the compound nucleus. Using spin-flip of a polarized neutron beam it is possible to observe the shift of the LCPs angular distribution doubled. This is the ROT effect phenomenon which is evaluated and reported.

## 2 Experimental technique and data analysis

In Figure 1 is shown the scheme of the experimental setup for the measurements being 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 LCPs were installed in a plane perpendicular to the neutron beam.

We presume that the ROT effect mostly develops after the rupture of the nucleus when nuclear forces have ceased to be of importance and cannot significantly affect trajectories of FFs and LCPs flying apart. The ROT phenomenon then emerges due to the motion of charged objects in the rotating field of Coulomb forces between fission fragments and LCPs.

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]. To start, it is necessary to perform calculations without any rotation of the fissile system [6].

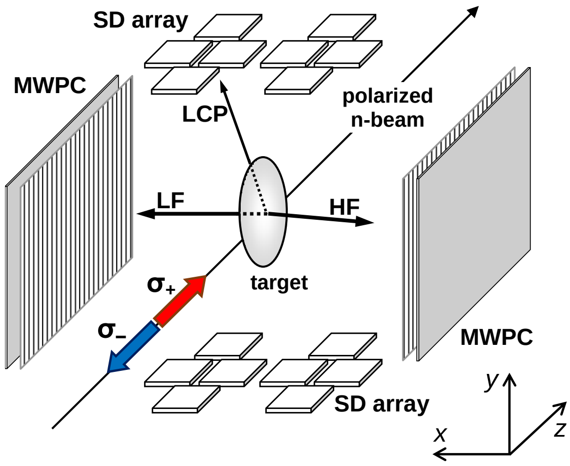


**Fig.1:** *Scheme of experimental setup: two multiwire proportional counters (MWPC) facing each other to the left and right of the target intercept fission fragments. Light charged particles are measured by two arrays of up to twelve Si detectors on the top and bottom of the target.*

Since the particle trajectories cannot be calculated in closed analytical form, it is necessary to replace the differential equations of motion

$$\frac{dX_{ij}}{dt} = V_{ij}, \qquad m_i \frac{dV_{ij}}{dt} = F_{ij} \tag{1}$$

by a set of difference equations

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

where

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

Here $n$ is the number of iterative step, the subscript $i$ denotes the particle with masse $m_i$, while $j$ corresponds to the component index for the coordinates $X_{ij}$, velocity $V_{ij}$ and force $F_{ij}$ acting on this particle.

By iterations, the time dependence of coordinates for fission fragments and LCP are 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.

Determining the initial configuration of a nuclear system allows us to evaluate its moment of inertia right at the time of the nucleus scission.

Then the initial angular velocity is calculated as the ratio of the mean value of the compound nucleus spin projection onto the axis of neutron beam polarization to the moment of inertia $\Im$:

$$\omega(J,K) = \langle J_Z(K) \rangle / \Im . \tag{4}$$

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, in addition to the moment of inertia, depend on these spins, their projection $K_{+/-}$ onto the fission axis, and on neutron beam polarization $p_n$ [9]:

$$\omega_{+/-}(J,K)=\begin{cases}+\dfrac{J_{+}(J_{+}+1)-K_{+}^{2}}{J_{+}}\cdot\dfrac{\hbar}{2\Im}\cdot p_n \\ -\dfrac{J_{-}(J_{-}+1)-K_{-}^{2}}{(J_{-}+1)}\cdot\dfrac{\hbar}{2\Im}\cdot p_n\end{cases} \quad (5)$$

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

The ROT effect, observed as the double shift 2Δ in the angular distribution of ternary particles, is proportional to the initial effective angular velocity. This velocity is the sum of the two partial angular velocities with coefficients depending on the partial fission cross sections associated with two possible spins of the compound nucleus.

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

Based on this effective angular velocity, one can proceed to the second stage of trajectory calculations. In the case of a rotating nuclear system it is only necessary to modify the initial velocities of the described objects, namely, to take into account their additional components due to the rotation of the fissioning system around the z-axis in Figure 1. With spin-flip of the polarized neutron beam, these calculations must be performed twice. The following iterative steps of the calculations are no different from the standard method. Finally, one has to recalculate all distributions depending on ($J$, $K$) on the basis of these modified trajectory calculations.

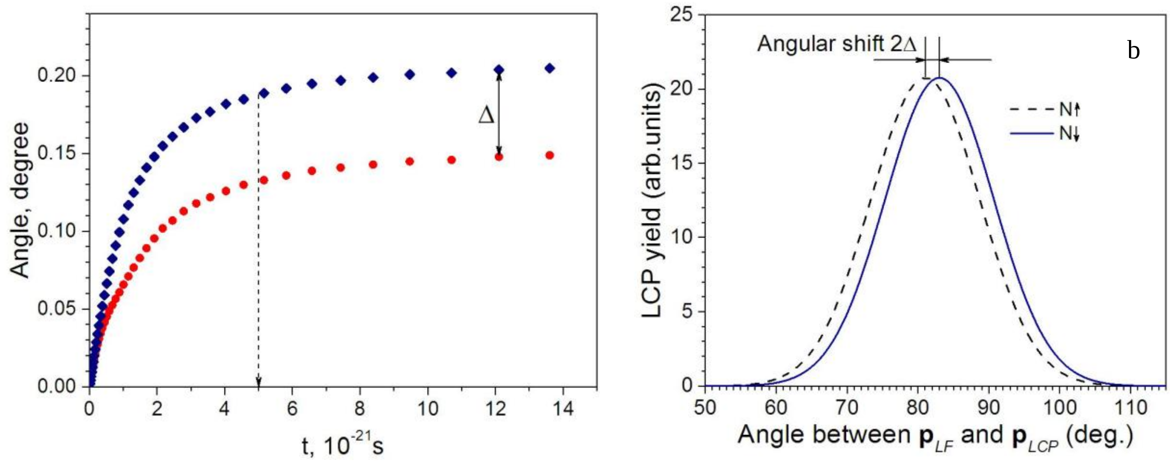


**Fig.2.** *a) Time dependencies of deflection angles* $\theta_\alpha$ *for* $\alpha$*-particle (full dots) and* $\theta_{LF}$ *for LF (rhombs).* $\Delta=\theta_{LF}-\theta_\alpha$. *Calculations were performed with* $\langle J_z\rangle=1\hbar$,

*b) Double shift* $2\Delta$ *of the angular distribution of ternary particles in (n,f) reactions depending on the orientation of neutron spin inducing fission. N↑ and N↓ are emission rates for neutron spin parallel and antiparallel to (*$\mathbf{p}_{LF}\times\mathbf{p}_{LCP}$*), respectively.*

As follows from the calculations (see Fig.2a), the rotational speed of the nuclear system after scission 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. Then they move along straight lines. Already after a short time the angle of rotation of each object gets its final value. In other words, each object gets its final direction of motion leading to a detector for registration.

In experiment the angle of the α-particle is measured relative to the final direction of motion of the light fragment. With the trajectory calculations it is shown that the α-particle rotates somewhat slower than the fission fragments. This lag leads to the observed shift Δ in the angular distribution of α-particles. On account of the spin-flip technique, it is necessary to repeat the trajectory calculations where the sign of rotation of the fissile system is inversed.

The difference in the angular distributions of ternary particles corresponding to different signs of the neutron beam polarization gives the sought-for double shift 2Δ of the angular distributions, called the ROT effect (see Fig.2b).

To get the best fit for the experimental shift one can in the trajectory calculations only play with the spin projections $K$ of the compound nucleus on the fission axis. These variations can be implemented in the small range from $K = 0$ to $K = J$.

**3 Results of calculations**

For the reaction $^{235}$U(n,f) induced by cold neutrons it was concluded that combinations $(J, K)$ of the nucleus spin and its projection $(J_+, K_+) = (4, 0)$ and $(J_-, K_-) = (3, 2)$ dominate. Originally these calculations were 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 experiment, 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 low energy range from 8 to13 MeV of the α-particle (see Fig.15 in [2]).

Experiments were performed without precise identification of the ternary particle type. The above deviations can be explained by the presence of other ternary particles besides alphas. The second most important LCP yield is for tritons contributing about 7% to the total LCP yield. Including tritons in the calculations gave a much better approach to experiment. Results were presented in [10].

However, at closer inspection α-particles observed have two different sources. There are first “true” α′s ejected right at scission and second there are α′s from the decay of $^5$He providing a sizable contribution to ternary fission. Therefore, it was decided to start a new version of trajectory calculations taking into account also the $^5$He isotope. We relied on reference [11]. The authors of this paper studied the LCP yields in the spontaneous fission of $^{252}$Cf. They found that in addition to “true” ternary α-particles about 20% of α′s in the spectrum are due to disintegrations of $^5$He into an α-particle and a neutron. The contribution of α′s from $^5$He decay should also be present in neutron induced fission. Due to the lack of experimental data it was assumed that the fraction of emitted $^5$He particles and their energy distribution in ternary fission of $^{235}$U(n,f) are close to the corresponding data for $^{252}$Cf(sf) in Table 1.

Evidently it was necessary to take into account that the lifetime of $^5$He is very short. It equals approximately $1 \times 10^{-21}$s. This isotope rapidly decays into $^4$He and a neutron. In addition, the smaller energies of residual $^4$He from $^5$He decay could affect the energy dependence of the ROT effect. The energy dependent ROT effect was studied separately for the 3 isotopes at issue.

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

| LCP | $\langle E \rangle$ | FWHM |
|---|---|---|
| $^{4}$He | 15.7(2) | 10.9(2) |
| true $^{4}$He | 16.4(3) | 10.3(3) |
| residues from $^{5}$He | 12.4(3) | 8.9(5) |

Figure 3 shows the energy distributions for tritons, true α-particles and $^{5}$He, which were obtained using standard trajectory calculations reproducing the known average energies. The initial parameters of the system undergoing fission 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 from experimental data for neutron induced fission of $^{235}$U and evaluations in the paper [11].

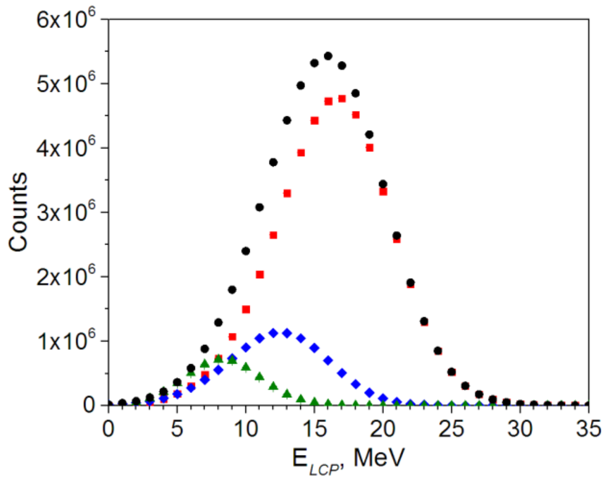


**Fig.3.** *The calculated LCPs energy distributions: for $^{3}$H (triangles), for true α-particles (squares), for $^{5}$He, which turns into α-particle plus a neutron (rhombs), and for the sum of true and residual α -particles (full dots).*

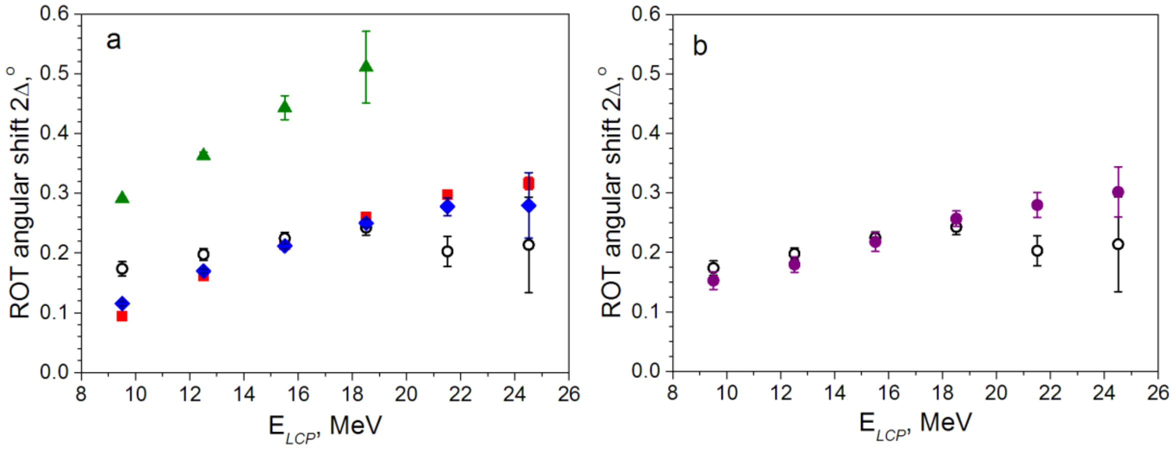


**Fig.4.** *a) The calculated ROT effect for $^{3}$H (triangles), true $^{4}$He (squares), $^{5}$He, which decays into an α-particle and a neutron (rhombs) and experimental data (open dots); b) the calculated ROT effect for the sum of all LCP components added with their corresponding weights (full dots) in comparison with experimental data (open dots).*

Based on the starting parameters the effective angular velocities were calculated independently for the 3 isotopes. From trajectory calculations the angular shifts for tritons, true alpha particles, and the $^{5}He$ isotope were evaluated as a function of LCP energy.

It should be stressed that, in particular at small LCP energies, the inclusion of tritons as LCP`s gives a significant contribution to the energy dependence of the ROT effect and improves agreement with experiment. In contrast, the inclusion of $^{5}He$ has virtually no influence on the model prediction of the energy-dependent ROT effect. But is should be pointed out that, in the high energy tail of the LCP distribution, the present model of the ROT effect does not perfectly match the experimental findings, though experimental errors in this energy region are large. Averaged over LCP energies the ROT effect amounts to $2\Delta = 0.215°$ for neutron induced fission of $^{235}U$. It is a tiny effect which is safely assessed by the spin flip technique.

**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 $^{236}U^*$ compound nucleus, $J_+$=4 and $J_-$=3 have different signs. Both contribute to the effective angular velocity $\omega_{eff}$ 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 depend 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 $^{235}U$ were calculated by the computer code SAMMY. The figure 5 shows two curves for the partial fission cross sections and their sum for the target of $^{235}U$ as a function of incoming neutron energy. In these calculations the data of resonance parameters were taken from ENDF/B-VIII.0 (USA, 2018) [12].

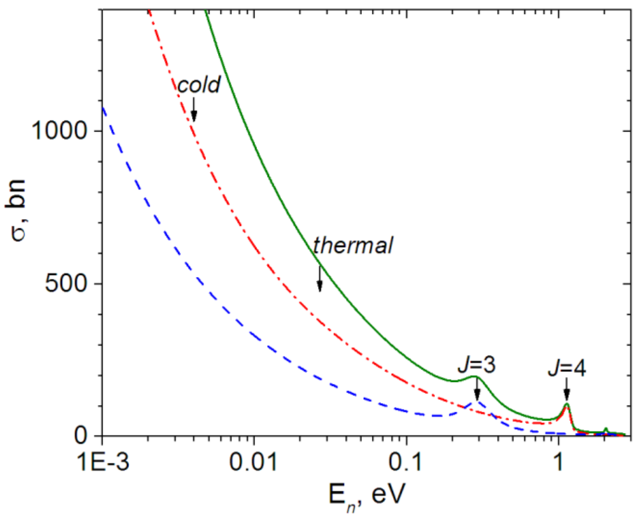


**Fig.5.** *Spin-separated fission cross sections for the target of $^{235}U$ depending on the energy of the incident neutron: dashed line for J=3, dash-dotted line for J=4, solid line corresponds to the sum of both.*

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 $\omega_+$ of the state $(J_+, K_+) = (4,0)$ exceeds in absolute value the negative rotational speed $\omega_-$ 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.

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 $\omega_+$ compared to the negative velocity $\omega_-$. 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.

Experiments for ROT effect in ternary fission beyond thermal neutron energies have not yet been staged. It should be interesting to see whether the above predictions are confirmed.

## 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 $\omega_{eff}$. 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, 14] 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, 14], 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, 14] 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.

Finally, it should be noted that this predicted energy dependence is also valid for the ROT effect for neutrons and gammas in binary fission, 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 by comparing the ROT effect values obtained experimentally in the resonance region [15] with corresponding results for nuclear fission induced by thermal neutrons [16, 17]. Although the accuracy of determining the magnitude of the ROT effect for γ-rays $(6.5 \pm 3.9) \cdot 10^{-5}$ in the resonance region with neutron energy about $E_n$=0.3 eV is not very high, nevertheless, it can be argued that this value of the angular asymmetry in comparison with the corresponding result $(16.6 \pm 1.6) \cdot 10^{-5}$, which was obtained in the thermal region, is approximately 2.5 times less, i.e. consistent with the energy dependence of the ROT effect predicted here.

We did not use the ROT asymmetry data for neutrons from [15] because the angular dependence used in this paper to fit the corresponding experimental results was incorrect. The correct form of the angular behavior of ROT asymmetry for neutrons is presented in [18].

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