Dependence of ROT-effect on light charged particle energy in ternary fission of ^{235}U induced by polarized neutrons

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Abstract

The shift of the light charged particles angular distribution arising in neutron induced fission of ^{235}U due to spin-flip of polarized neutron beam was obtained with the help of trajectory calculations for rotating nucleus. For the first time the influence of ^{3}H nuclei was considered. It was shown that the inclusion in the calculation of tritons besides of alpha-particles significantly improves the agreement of the experimental ROT-effect dependence on the light charged particle energy and the results of calculation.

In the process of ternary fission besides of two fragments with large masses also light charged particles are observed. There is a wide variety of such particles in neutron induced ternary fission of ^{235}U [1]. They can be separated by a charge, mass, energy and angular distributions. Light charged particles (LCPs) are also different in their outputs. In ternary fission of ^{235}U alpha-particles are emitted most often. In the Table 1 their yield is considered equal to 10000. The alpha-particles are followed by tritons. The yield of such particles is 7.2% of the alpha-particles yield.

Table 1

light charged particle	the most probable energy, MeV	full width at half maximum, MeV	extrapolated yield, relative units
^{2}H	8.6±0.15	7.1±0.2	50.0±2.0
^{3}H	8.2±0.1	6.5±0.2	720.0±30.0
^{4}He	15.9±0.1	9.8±0.1	10000
^{6}He	11.1±0.2	11.2±0.2	196.0±8.0
^{8}He	10.2±0.2	6.8±0.4	6.0±0.4
^{7}Li	14.8±0.9	13.0±1.0	4.4±0.6
^{8}Li	13.2±0.9	12.1±1.3	2.6±0.3
^{9}Be	18.0±1.3	13.0±1.8	3.2±0.5
^{10}Be	17.5±0.6	15.2±0.9	37.0±3.0

The nuclear fission is a very complex process and represents a big problem for its description. However, when the nucleus rupture has already happened and nuclear forces have stopped to influence, two fragments and ternary particle (TP) move only due to their mutual Coulomb interaction. Their motion can be reproduced using Monte Carlo simulations [2÷7]. The result of computer simulation for this final fission phase is a complex of calculated trajectories for all described objects, which can give information about angular and energy distributions for ternary particles at the moment of their registration. The energy distributions for several light charge particles one can see as example in Fig.1. Points correspond to experimental data [1] and lines are calculated distributions. They are very close to the Gaussian shape.

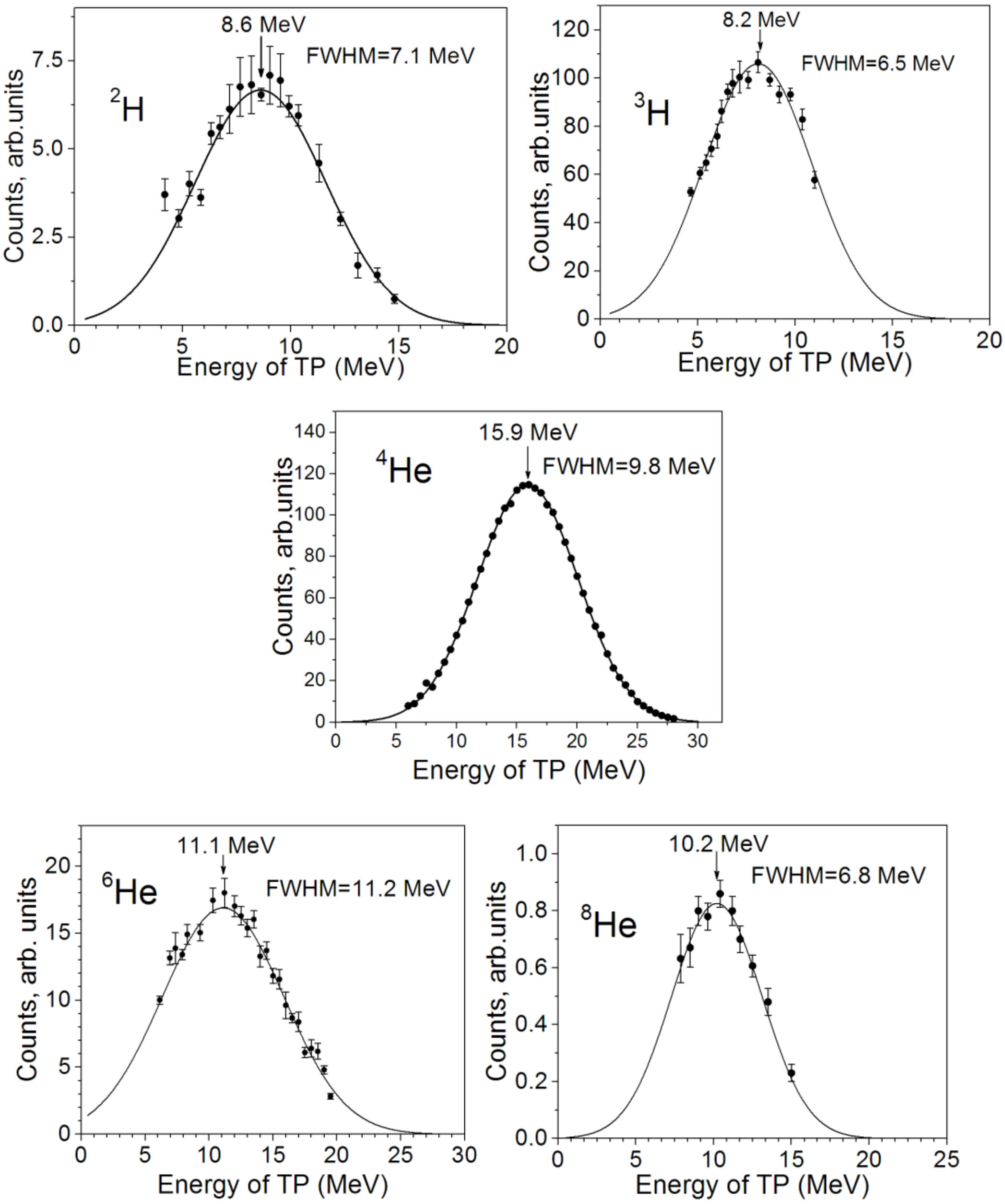

Fig.1. *The energy distributions for some ternary particles in neutron induced fission of* ^{235}U. *Points correspond to experimental data, lines are calculated distributions.*

All calculated distributions were fitted to experimental data using a variation of initial calculation parameters such as: a distance between fragments, initial velocities of fragments, starting position of ternary particle just after the moment of scission and their starting energy and angular distributions. This set of initial parameters allows us to find characteristics of fissile system acceptable soon after the rupture point.

The trajectory calculations cannot be performed 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

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

Then iterative way is used to find step by step time dependence of coordinates for fission fragments (FFs) and TP. It is necessary to have small time intervals in the calculation process, what means that every partner has to move during each period approximately along the straight line with fixed velocity.

At the first steps of iterative process all partners are still close together and their directions of motion and velocities change rapidly. When described objects are already widely separated and their characteristics of motion change slowly we do not need the same small size of the time interval. To make calculations more quickly an exponential function of n for total time t_n after n time intervals is commonly used:

$$t_n = t_0(e^{na} - 1). \tag{3}$$

and hence the size of the n-th time interval is given by

$$\Delta t_n = t_n - t_{n-1} = t_{n-1}(e^{a} - 1). \tag{4}$$

The calculated individual trajectory patterns for FFs and α-particle are shown in Fig.2. As one can see the final direction of α-particle motion with respect to the light fragment is about 80° independently from initial angle of its emission. To get the angular and energy distributions of ternary particles several millions of similar trajectories were calculated.

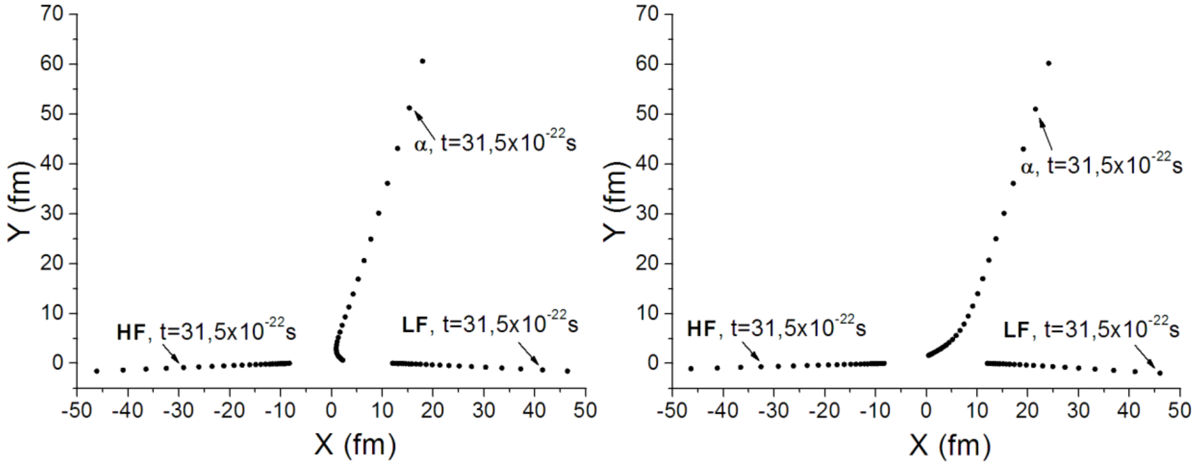

Fig.2. *The calculated trajectory patterns. The coordinates of the object centers are labelled by circles. Their positions are in iterative step order. The arrows point at the simultaneous object placements.*

It is necessary to mention that such standard trajectory calculations are commonly used to describe spontaneous ternary fission or ternary fission induced by unpolarized neutrons. The study of nuclear fission in (n,f) reactions with polarized neutrons as projectiles has revealed particular features of the process, that cannot be described by standard method.

Let us remind you about experiments related to ternary fission of some actinides induced by cold polarized neutrons [8]. In Fig.3 you can see the schema of experimental setup for such measurements. The polarized neutron beam was hitting the fissile targets mounted at the center of a reaction chamber. Detectors for fission fragments and ternary particles were installed in a plane perpendicular to the neutron beam.

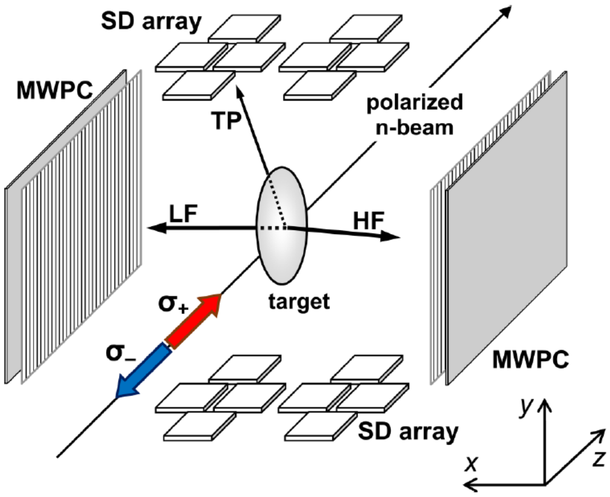

Fig.3. *Layout of the experimental setup: fissile target locating at the center; polarized neutron beam running horizontally; two MWPC detecting complementary fission fragments to the left and right of the target, two arrays of Si detectors on top and bottom of the target intercepting ternary particles. All centers of particle detector assemblies lie in a plane perpendicular to the beam.*

In the process of these experiments some modification of the light charged particles angular distribution was observed due to spin-flip of a polarized neutron beam. Such transformation (see Fig.4, a) of the angular distribution can be divided into two components: the relative change in the amount of recorded particles in the lower and upper hemispheres (Fig.4 b) and the shift of the angular distribution (Fig.4 c). These phenomena were named TRI and ROT-effects, respectively. Now it is shown that both effects are present simultaneously, but with different weights for the four studied actinides [8].

The asymmetry corresponding to TRI-effect is attributed to the Coriolis force present in the nucleus while it is rotating up to scission. The size of the asymmetry is typically 10^{-3}. This phenomenon should be described with the help of quantum mechanics. The ROT-effect, in contrast to this, mostly develops during the next time interval, namely after the nucleus rupture and when nuclear forces have already stopped to action. This phenomenon arises due to the motion of charged objects (two fragments and light particle) in the rotating field of Coulomb forces. To describe this effect we can apply classical estimation using trajectory calculations, but they must be modified taking into account rotation of fissile system.

The rotational structure should be expected in the spectrum of fission channels at energies not much higher than the fission threshold. After slow neutron capture by the target nucleus with the angular momentum $\boldsymbol{I}$ it is possible to obtain compound states with $J = I + 1/2$ and

$J = I - 1/2$. In this case the fission process comes through a few transitional states (fission channels) with fixed K values, where K is the projection of spin $\boldsymbol{J}$ on the symmetry axis. Any rotation of axial nucleus comes around a perpendicular to a line of nuclear symmetry and angular velocity ω can be obtained from this expression [9]:

$$\omega^2 \Im^2 = \hbar^2 (J(J+1) - K^2), \tag{5}$$

where $\Im$ is the moment of inertia of the fissile system.

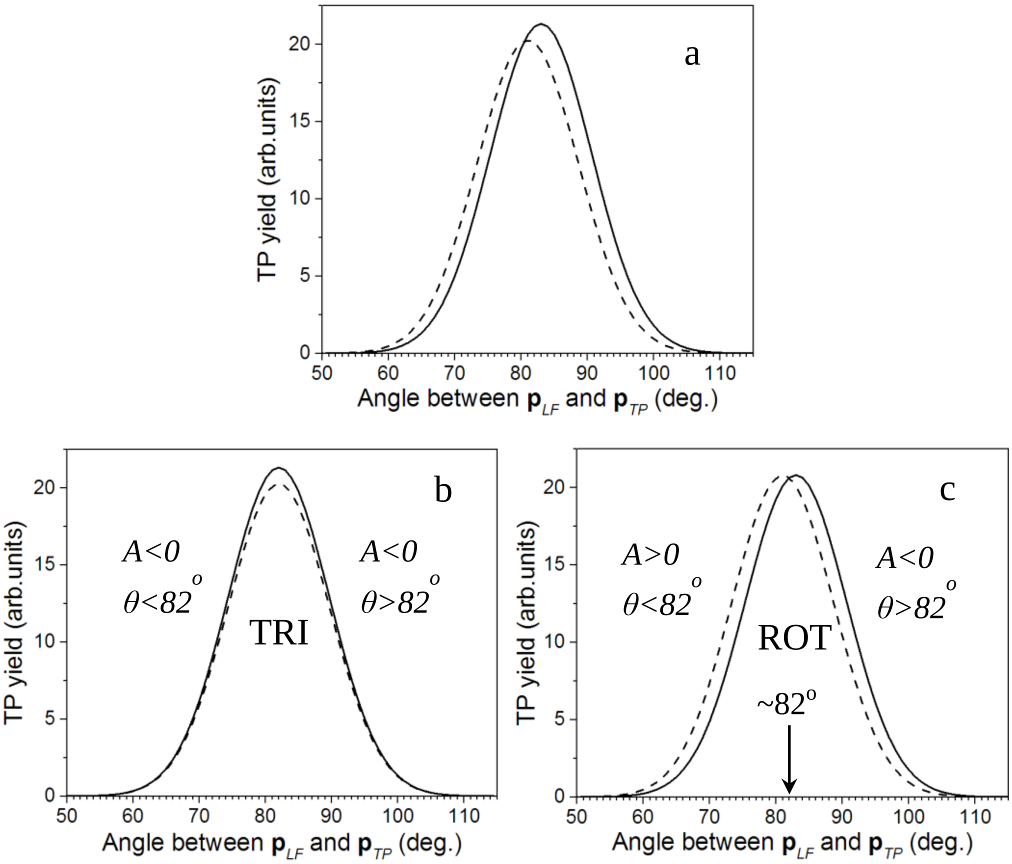

Fig.4. *a) The modification of the angular distribution for light charged particles, which was observed due to spin-flip of a polarized neutron beam; b) the relative change in the number of recorded particles in the lower and upper hemispheres (TRI-effect); c) the shift in the angular distribution (ROT-effect).*

Note that even with a fixed fission axis, we have many directions of fissile nucleus rotation. It is possible to say only about an alignment of rotational axis in a plane perpendicular to the fission axis. Randomly oriented rotation of compound nucleus does not form any regular shift of TP angular distribution, because averaged angular velocity for all nuclei equals zero. Such phenomenon can be observed in ternary fission experiments with unpolarized neutrons and targets. In contrast to this, in case of polarized neutrons it is possible to obtain a non-zero effective angular velocity for the fissile system rotation around the line of neutron beam polarization. The angular velocity for fixed J and K one can get using quantum-mechanical expression:

$$\omega(J,K) = \langle J_Z(K) \rangle / \Im. \tag{6}$$

As it was shown by Kadmenski and Bunakov [10] this expression can be written in the form:

$$\omega_{+/-}(J,K) = \begin{cases} \dfrac{J(J+1)-K^2}{J}\cdot\dfrac{\hbar}{2\Im}\cdot p_n & for \quad J = I+1/2 \\ -\dfrac{J(J+1)-K^2}{(J+1)}\cdot\dfrac{\hbar}{2\Im}\cdot p_n & for \quad J = I-1/2 \end{cases} \tag{7}$$

The different signs of angular velocities for $J = I+1/2$ and $J = I-1/2$ in these expressions indicate the opposite directions of fissile system rotation.

If several transition states contribute to the fission, it is necessary to perform summation over all possible K values:

$$\omega(J) = \sum_K \left|a_K^J\right|^2 \omega(J,K), \tag{8}$$

where $\left|a_K^J\right|^2$ is the probability to find the component with corresponding value K in the resonance wave-function. To obtain the final effective angular velocity ω it is necessary to take into account the relative contribution of resonance components with different *J* to the total fission cross-sections:

$$\omega_{eff} = \frac{\omega_+(J)\cdot\sigma_{I+1/2} + \omega_-(J)\cdot\sigma_{I-1/2}}{\sigma_{I+1/2} + \sigma_{I-1/2}}. \tag{9}$$

Here $\sigma_{I+1/2}$ and $\sigma_{I-1/2}$ are the partial fission cross-sections for $J = I+1/2$ and $J = J-1/2$, respectively.

Using such effective angular velocity we can modify trajectory calculations. In case of nuclear system rotation this requires only a change of all initial velocities for described objects [11, 12], namely, additional tangential components for FFs and TP should be taken into account. They can be obtained as a product of the angular velocity on the object distance, on which this object is located soon after the nucleus rupture, from the rotational axis. For the angular velocity calculation it is necessary to find inertia moment of the fissile system, which mostly depends on the fragment masses ratio and on the initial distance between fragments.

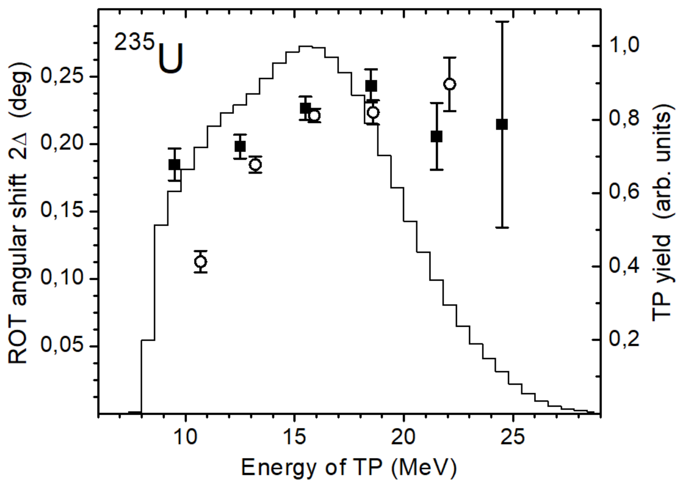

Fig.5. *Angular ROT shift as a function of TP energy for reaction $^{235}U(n,f)$. Experimental data (squares). Theoretical calculation with TPs assumed to be α-particles (open points). The experimental TP energy spectrum is given as histogram with scale to the right.*

The modified trajectory calculations give us the possibility to evaluate the ROT angular shift for light charge particles. Before now these calculations have been performed only with alphas as 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 α-particles deviated from the experimental data (see Fig.5). The experimental angular shift [8] was larger than the calculated result in the energy range (8÷13) MeV of the third particle.

It was assumed that this discrepancy can be explained by the presence of other light charged particles in addition to the alphas, because corresponding measurements in this experiment were performed without identification of light charged particles. It was therefore supposed, that taking into account the presence of tritium, which contributes about 7% to the ternary particles yield, it may be possible to bring closer together calculated and experimental results.

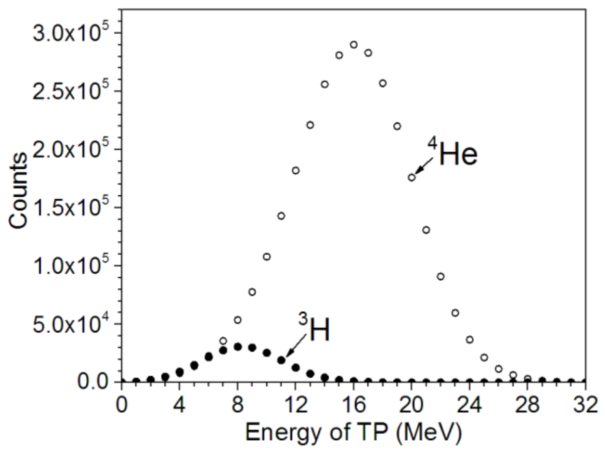

Fig.6 *Calculated energy distributions of light charge particles in neutron induced ternary fission of ^{235}U.*

Fig.6 shows the energy distributions of α-particles and tritons, which were obtained with the help of standard trajectory calculations. The initial calculation parameters for tritons were similar to those of α-particles. The most probable energies and widths of these distributions completely coincide with experimental data [1]. In addition, the calculated angular distributions of the LCPs and fragment's kinetic energies were also in a good agreement with experimental values. This confirms that initial parameters were well selected. The amounts of emitted particles were taken proportional to the corresponding particles yields in neutron induced ternary fission of ^{235}U. They were established in agreement with the experiment.

Using obtained by such a way initial parameters and calculated effective angular velocity (9) it was possible to get energy dependences of the angular shift for both α-particles and tritons with the help of the modified trajectory calculations (Fig.7 a). In order to get the final result, we need to sum two calculated ROT-effects with their weights.

In Fig.7 b one can see the result of ROT-effect estimation, where the influence of tritium was considered using the modified trajectory calculations. It is demonstrated that alphas and tritons taken together improve the agreement between calculated and experimental values of the ROT-effect depending on the energy of light charged particles.

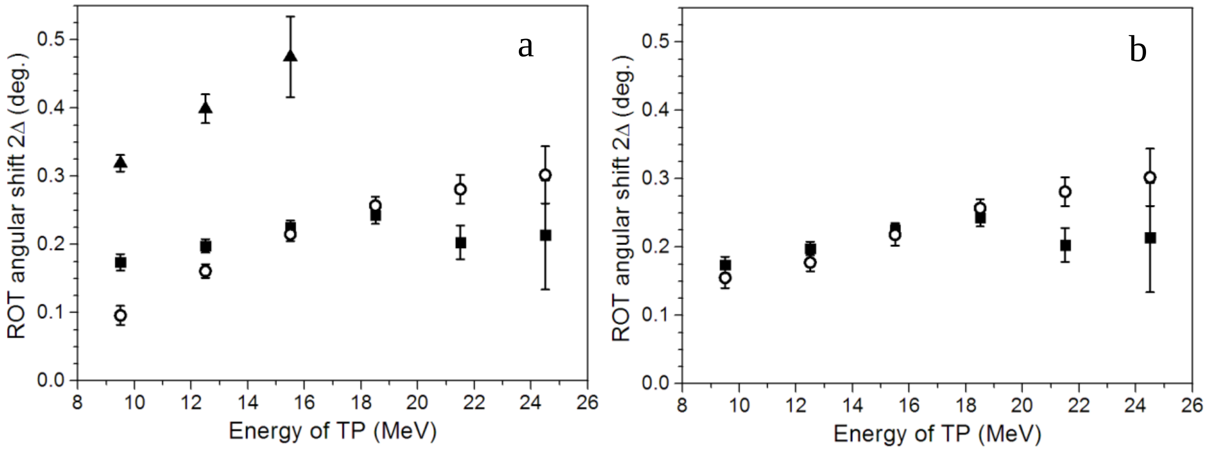

Fig.7. *Angular ROT shift 2Δ as a function of TP energy for the reaction $^{235}U(n,f)$:*
a) squares are experimental data, triangles – calculated result for tritons, open dots show the result of calculation for α-particles; b) squares are experimental data, open dots show the weighted sum of calculated results for tritons and α-particles.

Conclusion

The ROT-effect dependence on light charged particle energy was calculated using modified trajectory calculations. The influence of ^{3}H nuclei is considered for the first time. It was shown that the inclusion in the calculation of tritons, in addition to α-particles, significantly improves the agreement between experimentally obtained data and calculation results.

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