TRI- and ROT-effects in ternary fission as a new way of investigating fission dynamics at low excitation energies

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1.Introduction

It is common knowledge that angular distributions of fission products may be used effectively for investigating the so-called transition states at the barrier of the fission process induced by energetic light and/or heavy ions and γ-rays /1,2/. These investigations demonstrated for several different fission reactions not only the existence of transition states of the fissioning compound system near the barrier top, but some more general characteristics were obtained as well. Based on the analysis of experimental data it was suggested that the fissioning system in these transition states is axially symmetric with quantum numbers for total spin ***J*** and its projection on the nuclear symmetry axis ***K***. It was further argued that these numbers are conserved from the transition shape onwards. Fission probability was assumed to be proportional to the number of open (J, K) channels of the fissioning nucleus in its movement from the top of the barrier to the rupture point along the different valleys of the potential energy surface /3/. As a result, the configuration of the system at the rupture point, its excitation energy, and the resulting mass–energy distributions of the fission fragments may be very different for different nuclei. In addition to this, the barrier heights at the entrance to potential energy valleys may in principle be different as well /3/. Of course this overall picture of the fission dynamics in the passage of a deformed system through fission barriers and in its subsequent descent from the barrier top to the rupture point requires the investigation of further more fine details. The main still open questions are the fraction of the energy liberated in the descent process being dissipated into internal excitation, and the collective kinetic energy of the scissioning system near the rupture point. The available information on these important questions is rather contradictory and, as a rule, has been obtained rather indirectly.

Near the end of the last century, in addition to conventional measurements of fission fragment angular distributions for reactions induced by energetic particles /1/ and in continuation of experiments with oriented nuclei and polarized neutrons P-even and P-odd angular correlations in binary fission (see e,g. /4/), T-odd angular correlations in ternary fission induced by polarized low energy neutrons were discovered and contributed to the transition state investigations /5,6.7/. The angular distribution of fission fragments is described by

$$W(\Omega)\sim 1+\alpha_{PNC}(\boldsymbol{\sigma_n}\cdot\mathbf{P_f}) + \alpha_{PC}\cdot\boldsymbol{\sigma_n}\cdot[\mathbf{P_f}\ \mathbf{x}\ \mathbf{P_n}] + D_{TRI}\cdot\boldsymbol{\sigma_n}\cdot[\mathbf{P_f}\ \mathbf{x}\ \mathbf{P_\alpha}] + D_{ROT}\cdot\boldsymbol{\sigma_n}\cdot[\mathbf{P_f}\ \mathbf{x}\ \mathbf{P_\alpha}]\cdot(\mathbf{P_f}\cdot\mathbf{P_\alpha}). \qquad (1)$$

Here σ_n, P_f , and P_α are unit vectors directed along neutron polarization and linear momenta of fission fragment and ternary particle, respectively. The coefficients α_{PNC}, α_{PC}, D_{TRI}, and· D_{ROT} are the asymmetry coefficients for Parity-Non-Conservation, parity conserving Left-Right asymmetry and the two T-odd TRI- and ROT-effects, respectively. The latter two asymmetries were discovered in ternary fission with the additional emission of a light charged particle.

It could be shown in /8, 9/ that the coefficients α_{PNC} and α_{PC} are expected to be very small (10^{-3} – 10^{-4}) yet closely connected with the transition states' properties, in particular, with the J and K values. It should be pointed out that non-vanishing coefficients D do not imply time reversal invariance to be violated. Instead both, statistical and quantum-mechanical dynamical models were proposed emphasizing the role played by the interplay of fragment spin and the orbital momentum of ternary particles and, most important, collective rotations of the scissioning compound steering the emission probabilities of the light charged particles in ternary fission /6,10/. The coefficients D_{TRI} are determined in the framework of a statistical model by level densities and moments of inertia of spherical fission fragments, and by the split between fragments of the excitation energy and polarization of the scissioning system /6/. On the other hand, the values of D_{ROT} are determined mainly by the ***J*** and ***K*** values and the relationship between ternary fission fragment and light charged particle velocities near the rupture point of the fissioning system /11/.

Experimental values of D_{TRI} and·D_{ROT} coefficients reveal a marked dependence on fragment masses and kinetic energies, and on the energies of the light charged particles. Such peculiarities in the behavior of the coefficients open new possibilities to answer some interesting questions of fission dynamics. The main results of investigations on P-odd and P-even interference effects were published earlier in the works /12-15/. Here we are presenting and shortly discussing the first results obtained in the studies of T-odd angular distributions of light charged particle emission in ternary fission and some conclusions about fission dynamics obtained from the data analysis in the framework of a rotational model of the fissioning system /11/.

2. Current status of experimental investigations of TRI- and ROT- effects in ternary fission induced by cold polarized neutrons

The average values of T-odd asymmetry coefficients D_{TRI} for the α-particles and tritons in ternary fission of $^{233, 235}U$, ^{239}Pu, and ^{245}Cm induced by cold polarized neutrons are presented in Table I /16,17/. In all cases the average T-odd asymmetry coefficients are calculated as normalized differences of the two LCP angular distributions for mutually opposite directions of neutron polarization (spin flip technique). It should be noted that in the first experiments the existence of two distinct T-odd effects was not known.

Table I. Average asymmetry coefficients for different fissioning nuclei with the spins J

Target / D> coefficient	^{233}U J = 2, 3	^{235}U J = 3, 4	^{239}Pu J = 1, 0	^{245}Cm J = 2, 3
$\langle D_\alpha \rangle \cdot 10^{-3}$	- (3.9 ± 0.1)	+ (1.7 ± 0.2)	- (0.15 ± 0.23)	+ (1.30 ± 0.48)
$\langle D_t \rangle \cdot 10^{-3}$	- (2.9 ± 0.5)	+ (0.90 ± 0.6)	-	-

The polarization of compound states after capture of polarized cold neutrons ($P_n \sim 95\%$) by fissile targets with spin I may be estimated by the following simplified expressions:

$$P(J^+) = (2I+3)/([3(2I+1)] \cdot P_n \qquad \text{for } J^+ = I + 1/2 \qquad (2)$$
$$P(J^-) = -1/3 \cdot P_n \qquad \text{for } J^- = I - 1/2$$

The complicated structure of compound nuclei at excitation energies of about 6 MeV makes it difficult to get experimental values of T-odd asymmetry coefficients for individual compound states. Therefore the values <D> in Table 1 contain the contributions to the effect from all the nearby resonances with different compound-states spins $J^{(\pm)} = (I \pm 1/2)$.

This seems to be a possible reason for the scattering of experimental data in Table I both as to magnitudes and signs. Another interesting result presented in Table I lies in the fact that the T-odd asymmetry values for the α-particles and tritons are equal at the limit of accuracy in spite of the difference in particle spins and, probably, also orbital momentum. This fact was successfully explained by theory /18/.

First explanations of experimental results were given in a statistical model of V. Bunakov et al. /6/. In this model the probability of ternary fission is proportional to the density of final states of the system after LCP emission. Assuming that the fragments being deformed at scission have their spins oriented perpendicular to the deformation (fission) axis the level density is

$$\rho_i(A_i, E_{xi}^{sc}, M) \sim \exp[2\sqrt{a_i(E_{xi}^{sc} - \hbar^2 M_i^2/2Z_i)} \approx \exp[2\sqrt{a_i E_{xi}^{sc}} \cdot (1 - \hbar^2 M_i^2 / 4Z_i E_{xi}^{sc})], \qquad (3)$$

where A_i, and E_{xi}^{sc} are atomic number and fragment excitation energy, M_i is the projection of total momentum J_i on a given axis, and Z_i is the moment of inertia of spherical fragments. As seen from expression (1) the magnitude of the T-odd asymmetry effect peaks at mutually orthogonal vectors $\boldsymbol{\sigma_n}$, $\mathbf{P_f}$, and $\mathbf{P_\alpha}$. In such a configuration the orbital momentum of the light particle may be directed alternatively along or against the polarized compound nucleus spin. As a result $M_{final} = (M \pm l_\alpha)$, so the LCP emission probability increases or decreases depending on the mutual direction of the momenta $\boldsymbol{l_\alpha}$ and $\boldsymbol{J}$:

$$D_i(J^\pm) \approx \frac{\hbar^2 M_i l_\alpha \sqrt{a_i}}{Z_i \sqrt{E_{xi}^{sc}}} \mu_i P(J^\pm) \text{ and } D \sim 1/\sqrt{6 - 0.2E_\alpha^{kin}} \qquad (4)$$

Here a_i and μ are level density parameters and factors characterizing the transfer of compound nucleus polarization to the fragments, respectively, while Z_i, E^{sc}_{xi}, and E^{kin}_{α} are the fragment inertia parameter, excitation energy of the fragments at the rupture point and ternary particle kinetic energy.

The observed dependences of the modulus of T-odd asymmetry coefficients on different parameters of the ternary ^{233}U fission process are presented in Fig.1. The histograms show experimental angular, mass and

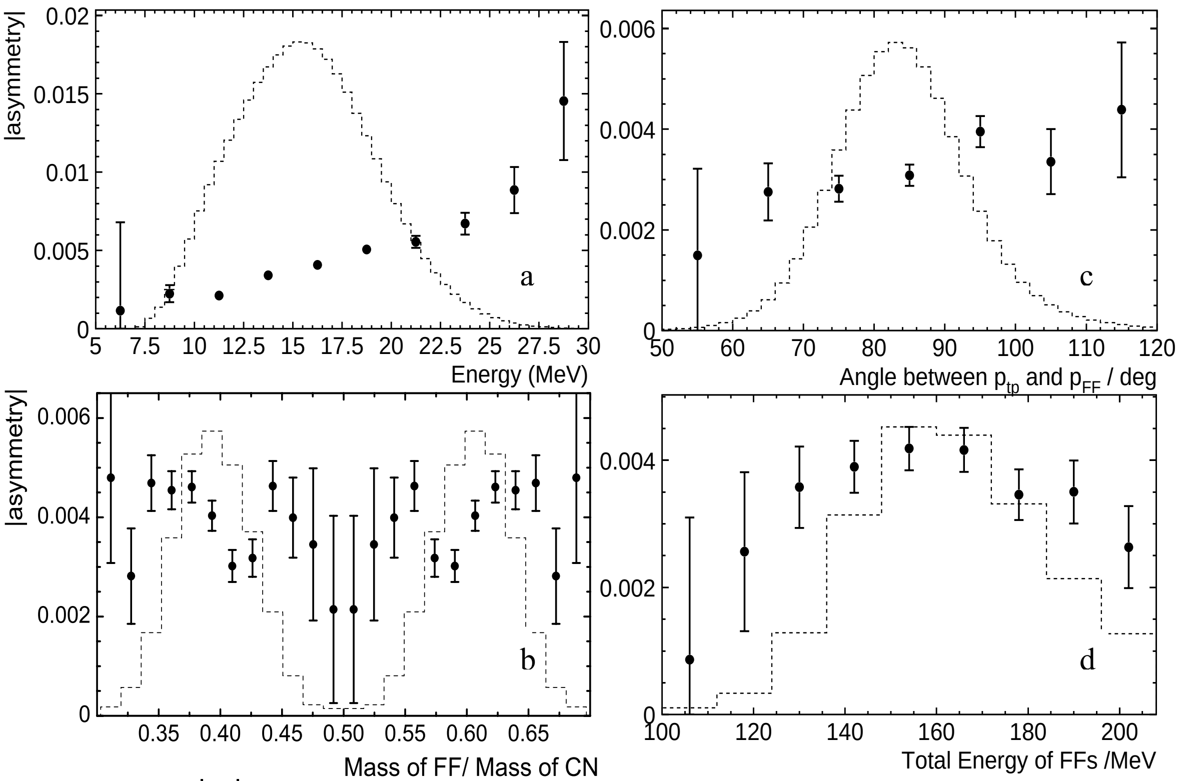

Fig.1. The modulus │D│of the correlation coefficient as a function of: ternary particle (TP) energy (a), mass of the fission fragment (FF) normalized to the mass of the compound nucleus (CN) (b), angle of TP's emission relative to the light FF (c), total kinetic energy of the FFs (d).

energy distributions of fission products. Quite evidently there is a dip in the fragment mass dependence of the asymmetry coefficient │D│in the region of doubly magic masses where the level density is low (see eq. 4). Likewise the dependence of the asymmetry │D│ on the kinetic energies of light particles and fission fragments is in qualitative agreement with eq. (4). In addition, a slight increase of │D│ for increasing emission angles of the ternary particles relative to the fission axis is observed.

In 2005 further investigations of T-odd asymmetries in ternary fission ^{235}U revealed a pronounced dependence of the T-odd asymmetry on the emission angle of the light particle. To explain this new and unexpected effect, called ROT-effect in contrast to the TRI-effect discussed above, the hypothesis was proposed that the fissioning compound is rotating around its direction of polarization /5/. It is relatively easy to understand that such a rotation can induce a shift of the angular distributions of ternary particles. The shift is wobbling back and forth when the direction of polarization is changed by flipping the neutron spin inducing fission. For angular distributions assumed having Gaussian shapes centered around 90° relative to the fission axis, the difference between two shifted distributions varies with the cosine of the angle. It is important to point out that the ROT-effect (shift of Gaussians) can exist together and independently of the TRI-effect which corresponds to differences of yields (areas of Gaussians) under reversal of polarization.

A comparison of experimental results on the angular dependence of the ROT-effect in $^{233,\,235}$U ternary fission is presented in Fig.2. In the case of ^{235}U ternary fission, experimental data are compared with the results of an evaluation where a small TRI-effect (assumed to be independent of angle (dashed line)) and a pronounced ROT-effect (crosses) are superimposed. The size of the ROT-effect is calculated as the difference in yield (normalized to the sum) for two shifted angular distributions depicted as histogram. The fit is excellent indicating that the angular shift $2\Delta = 0.215(5)°$ between two distributions is very small. By contrast, for the $^{233}U(n,f)$ reaction the TRI-effect is large and the ROT-effect is still smaller than for the companion reaction $^{235}U(n,f)$.

To support the experimental findings trajectory calculations for fission fragments and ternary particles were performed for a rotating nucleus undergoing ternary fission. The initial conditions for the trajectory calculations of reaction products flying apart after scission of the rotating compound nucleus were chosen under the condition to describe properly the particles' angular and energy distributions observed in experiments. This means that the third particle was born in between the two fission fragments ($d \approx 20$ fm for

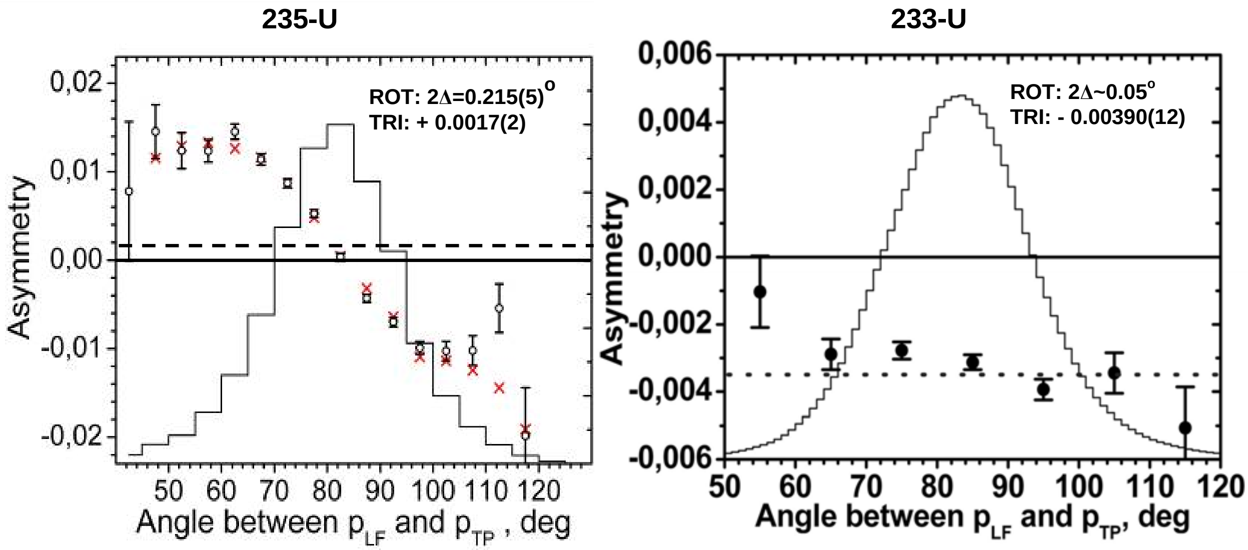

Fig. 2. T-odd asymmetry effects in $^{233,\,235}U$ ternary fission as a function of emission angle of the third particle. Histograms show the angular distributions of the third particle. Dotted lines show the absolute values of the TRI-effects in $^{233,\,235}U$ ternary fission.

for $M_H/M_L \sim 1.44$) and with the initial energy inside the interval (0.1 - 1.3) MeV. It is important to point out that in estimating the rotation velocity of the fissioning system we used the ensemble averaged value $\langle J(K) \rangle$ of the total spin projection on the polarization axis which depends on K and was obtained in ref. /20-21/ .

In the trajectory calculations the (J,K) spin values of the transition states enter as free parameters. In case of the $^{235}U(n,f)$ reaction, for example, the compound spin J takes on the values J = 3 or J = 4 and the K-values are running from K = 0 to K = J. Calculational results are given in Fig. 3 for this reaction. In view of the convincing fit of the ROT asymmetry in terms of a shift angle 2Δ, the dependence of the ROT asymmetry on ternary particle and fragment mass and energy is not described by a D_{ROT} coefficient following eq. (1) but as a shift angle 2Δ. As seen in Fig. 3 the ROT angle depends indeed on the above parameters.

A striking feature in Fig. 3 is the strong dependence of the calculated angular shifts on the (J,K) values adopted. In the Figures 3a through 3c it is obvious that a combination of (J,K) = (3,2) with (J,K) = (4,0) gives a much better description of angular shifts as a function of ternary particle and fragment energy and fragment mass than the combinations (J,K) = (3,0) with (4,2). It demonstrates the sensitivity of the ROT effect on transition state properties. This is even more clearly evident in Fig. 3d where the transition states (J,K) = (4,0) and (J,K) = (3,0) yield completely different predictions even differing in sign for the ROT angle. But the comparison of Figs 3b and Fig. 3d also reveals ambiguities in the spectroscopy of transition states since the combinations (J,K) = (3,2) with (J,K) = (4,0) and the set with J = 3 and 4, and K = 0, 1 and 2 taken from ref. /19/ reproduce the experimental data equally well. Nevertheless, it is surprising that a variety of experimental data may be successfully explained with a simple semi-classical hypothesis of a rotating fissioning compound that continues to rotate beyond scission. It should be noted, however, that after scission the rotation comes very quickly to a virtual stop within a few 10^{-21} s because the moment of inertia of the rotation explodes when the fragments are flying apart.

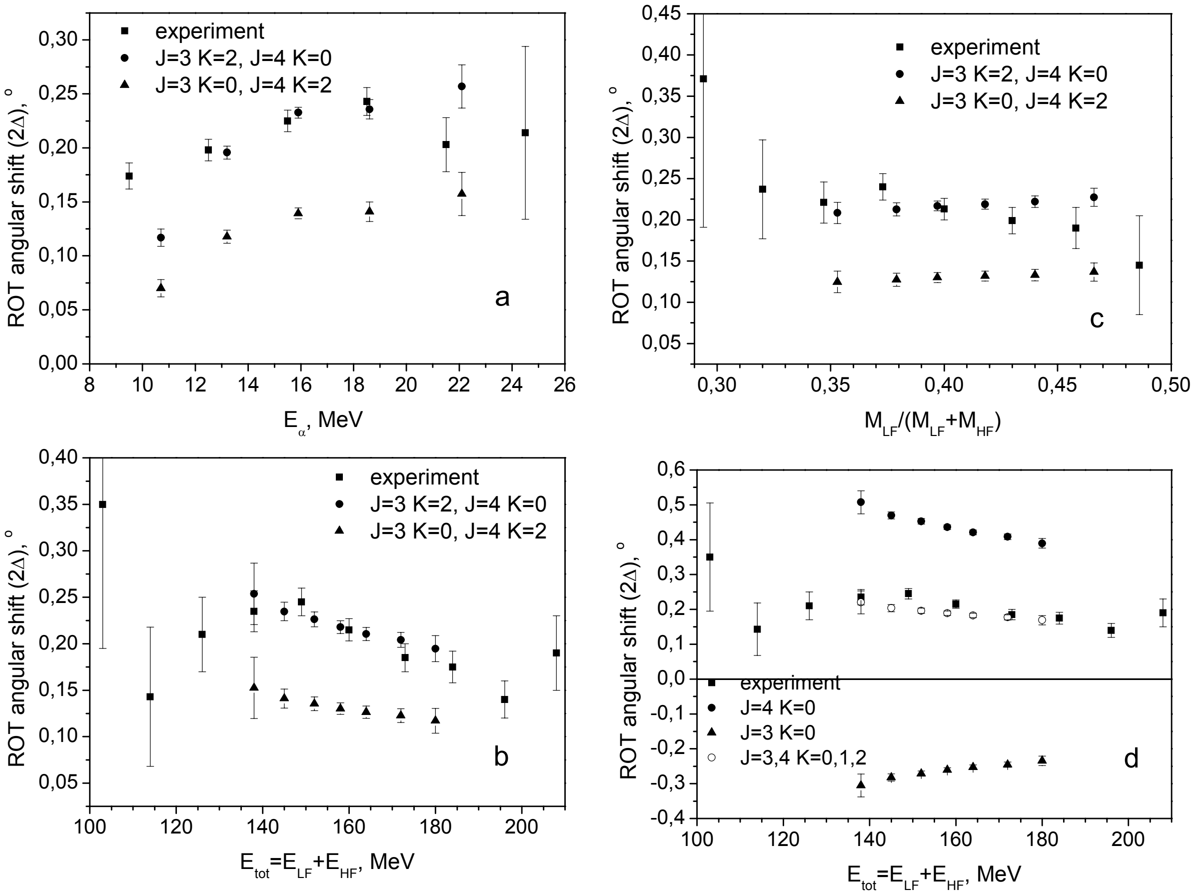

Fig.3. ROT angular shift in the reaction $^{235}U(n,f)$ as a function of the ternary particle kinetic energy (a), total fragment kinetic energy (b), and normalized masses of light fragment (c) in comparison with results of trajectory calculations performed for two possible sets of J =3, 4 and different K values. In Fig.3 (d) the ROT angular shift is presented as a function of total fragment kinetic energy in comparison with the results of trajectory calculations performed separately for J =3 and J = 4 values and with combination J and K obtained in the work /19/ where the fission cross section was investigated with an oriented target of ^{235}U and a polarized resonance neutron beam.

A quantum theory of this phenomenon /20/ has shown that the above quasi classical approach is not based on too crude assumptions and, anyhow, today is the only possibility to get quantitative estimations. It was pointed out, however, that for a more detailed analysis, in future work it will be necessary to take into account the possibly strong influence of interference effects from neighboring resonances.

Summarizing all the aforesaid one can state that the discovery and the first detailed investigations of relatively small P-odd and P-even interference effects as well as TRI- and ROT-effects of T-odd asymmetry in ternary fission open the way to quite new and interesting investigations of low energy fission dynamics. Of course both, the statistical accuracy and the resolution for mass, energy and angles of fragments and ternary particles should be improved. As to the trajectory calculations they should be refined by taking into account more parameters of low energy fission. In particular the calculated trend of the dependence of the ROT effect on fragment mass is for the moment opposite to experiment. Very probably this is simply due to a not appropriate choice of scission configurations as a function of mass split. In the following chapter some possible ways of immediate investigations of T-odd asymmetry effects are briefly recalled /21/.

3. Puzzles of T-odd asymmetry effects and tasks for investigations

One of the main questions is to understand why two very similar uranium isotopes $^{233,235}U$ exhibit a quite different behavior as to T-odd asymmetry effects in ternary fission. As seen from inspecting Fig.2 and Table I the magnitudes of TRI- and ROT-effects are very different in these isotopes. The authors of /20/ pointed out that the reason for this difference is due to different phase factors of the interfering neighboring neutron resonances. In any case it seems to be important to clarify this question. It is evident that the most direct way to answer this question would be T-odd effect measurements for isolated resonances with well-known spins. However, for the time being due to the low intensity of polarized neutrons in the resonance energy region such studies are not feasible. But, in principle, one can also perform comparative measurements of TRI- and ROT-effects for two energy intervals with different but well-known mixtures of resonances with different spins. In this case one can at any rate check the validity of the semi-classical trajectory calculations. In those calculations the "averaged" value <J> of the polarized spin of the system, which defines the angular rotation velocity, might for interfering (I + 1/2) and (I - 1/2) states be roughly estimated as

$$\langle J \rangle = [(\sigma_{J+} \cdot P_{J+} \cdot J_+ + \sigma_{J-} \cdot P_{J-} \cdot J_-)]/(\sigma_{J+} + \sigma_{J-}), \qquad (5)$$

where σ_J and $\cdot P_J$ are partial cross-sections and polarizations. An example for the ^{235}U target is shown in Fig.4:

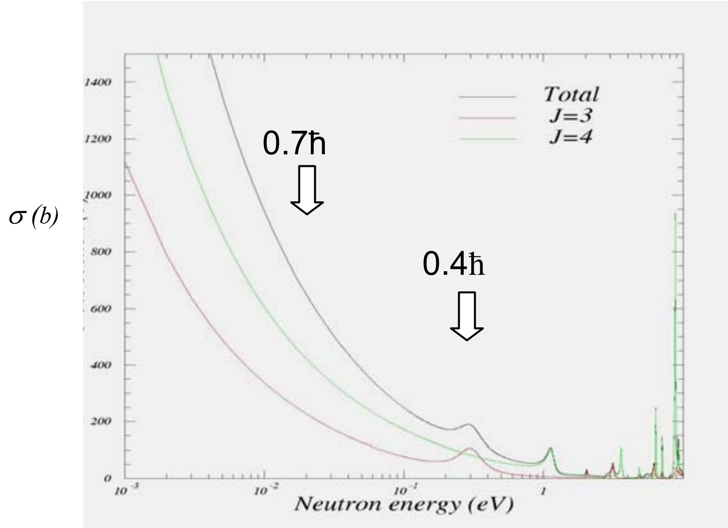

Fig.4. Partial fission cross-sections: total (upper curve), for spin J = 3 (lower curve) and J = 4 (middle). Arrows show the estimates of "averaged" spin values at the energy of cold neutrons (0.7ħ) and the 0.3 eV resonance $^{236}U^*$ (0.4 ħ). The estimates have been obtained with formula (5).

Another possibility for studies of T-odd asymmetries with definite spins of transition states of the fissioning nucleus without having to apply the approximate expression (5) consists in the use of a polarized fissile ^{235}U target and a high intensity polarized cold neutron beam. The main difficulties of such a method are connected with the necessity to use rather complicated cryogenic equipments.

Investigations may also be performed with specially selected fissile nuclei such as presented in Table II.

Table II. Main parameters of fissile targets with similar transition state properties of compound systems, formed after cold neutron capture. E_0 – energy of the nearest low-lying resonances.

Parameter Target	**E_0 (eV)**	**J**	**$2g\Gamma_n$ (meV)**	**Γ (meV)**	**Γ_f (meV)**
^{233}U ($I=5/2^+$)	- 3.92	-	-	-	557
	1.35	(+2)	0.165	60	553
^{241}Pu ($I=5/2^+$)	-0.16	-	-	-	103.4
	0.258	+3	0.055	-	75
^{235}U ($I=7/2^-$)	-1.4	-4	-	-	200
	0.29	-3	0.0032	-	98
^{245}Cm ($I=7/2^-$)	-0.25	-	-	-	220
	0.85	-	0.102	-	800
^{239}Pu ($I=1/2^+$)	-0.576	+0	-	-	290
	0.296	+1	0.108	102	60

The majority of resonance spin values **J** given in the table are either unknown or not reliable. But interestingly there are two pairs of target nuclei with the same spin and parity. One may therefore anticipate that the ratios of TRI to ROT effect could be similar for both nuclei of a pair. Thus one might expect to obtain for the pair (^{233}U - ^{241}Pu) relatively large TRI- but small ROT-effects because this is observed in ^{233}U. An opposite situation might obtains for the pair (^{235}U - ^{245}Cm) with a small TRI- but large ROT-effect. Besides, in the compound system ^{246}Cm* the excitation energy following neutron capture is much higher above the barrier top than in its partner ^{236}U*. By contrast, in the pair (^{233}U - ^{241}Pu) these heights are close to each other.

The fissile target ^{239}Pu is interesting because only one type of polarized transition states with spin J = 1 can be formed after the capture of polarized slow neutrons. The capture probabilities for J = 0 and J = 1 states are close to each other. As one can see from Table I, the TRI-effect in ^{239}Pu ternary fission was not observed, but it does not mean that the ROT-effect is absent as well! If this effect should be observed in ternary fission of ^{239}Pu there will be a unique chance to pin down the (J,K) values for the J = 1state. It means that one can learn much more about the mechanism of T-odd asymmetry effects.

4. Conclusion

The modern methods of fission investigations are characterized by multi-parameter measurements of angular, mass, and energy distributions of all or at least of the most interesting reaction products. Among them, the distinguishing feature of T-odd asymmetry effects is the relative smallness of the magnitude to be measured as a function of fission parameters. But at the same time, the quantities measured (in our case asymmetry coefficients) turn out to be highly sensitive to most important characteristics of fission dynamics, such as fission fragment velocities just near the rupture point, configuration of the scissioning system and properties of transition states.

Of course, for the full and successful realization of all possibilities presented by the T-odd asymmetry effects it is necessary to have available high fluxes of resonance polarized neutrons and to make use of modern methods of registration and spectrometry of fission fragments, neutrons and γ-radiation at counting rates of up to 10^6 sec^{-1}.

In conclusion, the authors are grateful to the ILL staff for running the High Flux Reactor with the Cold Polarized neutron beams PF1 and especially PF1B, to the staff of JINR for running the IBR-30/LUE-40 with Resonance polarized neutron beams, and to all colleagues for fruitful discussions. The work has been supported by numerous grants of RFBR, grants from ISF, and INTAS grants (99-0229 and 03-51-6417).

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