First observation of the ROT-effect of LCP emission asymmetry in the ^{239}Pu ternary fission induced by the cold polarized neutrons

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Abstract

According to the Program of T-odd asymmetry effects investigations in ternary fission of heavy nuclei induced by polarized neutrons the TRI and ROT- effects of charged particle emission asymmetry in 239-Pu fission have been observed and investigated for the first time. Investigations of these effects precisely in ternary fission of 239-Pu are of special interest because in contrast to 233, 235-U fission investigated before only one polarized transition state takes place in this process after the cold polarized neutron capture. The new experimental results obtained in 239-Pu fission are analyzed together with the 233, 235-U fission ones in the framework of semi-classical model proposed.

1. Introduction

In 2005 at the ILL High Flux Reactor in studies of T-odd asymmetry effect of light charged particle (LCP) emission in the 235-U ternary fission induced by the cold polarized neutrons the new physical effect had been observed for the first time. This effect has been named ROT-effect of LCP emission as it consists in the shift of the LCP angular distribution as a result of the polarized fissioning system rotation about the polarization direction [1].

According to the proper hypothesis pushed by the authors such a rotation is appeared at the top of fission barrier and can be estimated with the following expressions [2, 3]:

$$E_{rot} = \hbar/2\,\Im_{\perp}^{2} \cdot [J(J+1) - K^{2}] \quad \text{and} \quad R^{2} = \omega^{2}\Im_{\perp}^{2} = \hbar^{2} \cdot (J(J+1) - K^{2}) \qquad (1)$$

As one can see the value of rotation energy E_{rot} and angular rotation velocity ω depend on the transition states parameters (J, K) and inertia momentum $\Im_{\perp}^{2}$. In this case rotation momentum R about polarization axis stays constant but inertia momentum $\Im_{\perp}^{2}$ (t) is raising very fast with the time. As a result rotation is stopped very soon after the rupture point.

The specially performed trajectory calculations of the charged fission products movement in the Coulomb field taking into account the fissioning system rotation had shown that in addition to (J, K, $\Im_{\perp}^{2}$) values the shift of the LCP's angular distributions appeared as a direct result of such a rotation depends on the start linear velocities of ternary fission products [2].

Thus, in the frameworks of this hypothesis measureable shift of the LCP angular distribution puts at our disposal absolutely new possibilities for studies not only transition states properties but the start parameters of LCP's and fission fragments as well. But for successful realization of all these possibilities ones needs to study and understand in detail the mechanism of TRI and ROT-effect appearance.

From this point of view the 239-Pu ternary fission is of special interest because the fissioning system 240-Pu* appeared after the cold polarized neutron capture has only one polarized transition state with the spin $\boldsymbol{J} = \boldsymbol{I} + \frac{1}{2} = \boldsymbol{1}^{+}$. While, as it was well known from the preliminary measurements [4] and from detailed analysis of the existing experimental data for the 233, 235-U ternary fission [5], possible values of TRI and ROT-effects may be sufficiently smaller compared with ones in these two investigated nuclei.
All these things govern all difficulties and peculiarities of our new experiment with the 239-Pu target.

2. Experiment

To perform search measurements with the 239-Pu target we used practically the same experimental set-up constructed in Tuebingen University for the first investigations of TRI-effect in the 233, 235-U ternary fission [6].

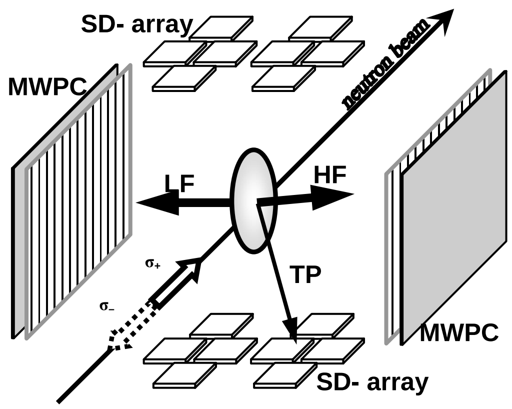

Fig.1. Schematic view of experimental set up in the measurements of TRI and ROT-effects in 239-Pu. MWPC – multi-wires proportional counters, LF and HF - light and heavy fragments.

The main difference consisted in the necessity to use as much fissile material as possible (in our case net weight of Pu isotope may be about 1.5 mg). For the radiation safety reasons we were forced to use two layers target on the thick Al foil. As a result we register direction and time of flight of only one of the two fission fragments in coincidence with LCPs, flight direction and energy of which are measured as well. Some changes have been performed also in the number and parameters of semiconductor detectors for the LCP registration. It is evident that all these things led to some changes in electronics and in the data evaluation procedures. The general results of twenty days measurements are presented in the Fig.2.

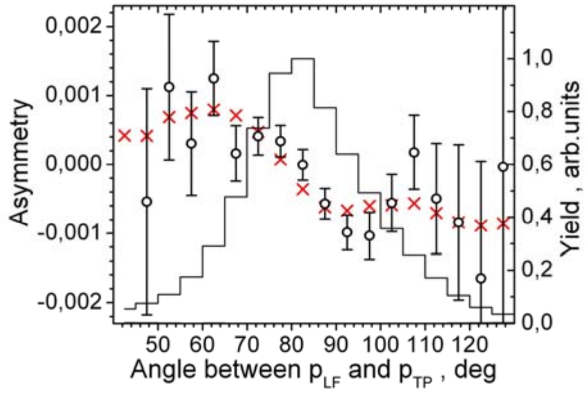

Fig.2 . Angular dependence of the T-odd asymmetry coefficient of LCP emission in the 239-Pu ternary fission induced by the cold polarized neutrons (circles). The crosses show the results of model calculations of asymmetry.

Experimental data were fitted as a superposition of TRI and ROT-effects. In doing so it was considered that ROT-effect is characterized by the shift of LCP angular distribution (Gaussian, Y(θ)) equal to 2Δ and TRI-effect has no clear angular dependence. As a result the following expression has been used for the fit of experimental data:

$$A(\theta) = (2\Delta)[Y'(\theta)/2Y(\theta)] + D_{TRI} \qquad (2)$$

In the Table I the parameters 2Δ and D_{TRI} are presented for the ternary fission of 239-Pu in comparison with the values obtained after the similar procedure for the 233,235-U ternary fission.

Table I. TRI and ROT-effects values for the 233, 235-U and 239-Pu ternary fission

Targets	Compound spin J	Shift $(2\Delta)^0$	$D_{TRI}\cdot 10^3$
233-U	$2^+, 3^+$	0.03(1)	-3.90(12)
235-U	$3^-, 4^-$	0.215(5)	+ 1.7(2)
239-Pu	$0^+, 1^+$	0.020(3)	- 0.23(9)

Using known ratios [7, 8] of cross sections *S* for different transition states in the 233, 235-U and 239-Pu fission expected shifts of LCP angular distributions had been calculated in the frameworks of our model to be compared with experiment (see Tables II –IV).

An effort was made to describe experimental values and signs of TRI effects presented in the Table I. To do this it seemed to be reasonable to suppose that Coriolis interaction, which is essential point for TRI-effect [9] may be proportional to $\boldsymbol{K}_\pm$ number and angular velocity $\boldsymbol{\omega}_\pm$. Here $\boldsymbol{K}_\pm$ and $\boldsymbol{\omega}_\pm$ are the values for transition states with $J = I \pm ½$.

Then averaging over transition states one can write:

$$D_{TRI} = Const \cdot \left[K_+\omega_+ \frac{1}{1+S} + K_-\omega_- \frac{S}{1+S} \right] \qquad (\ )$$

If the constant in this formula will be taken in accordance with D_{TRI} value for 235-U then one can try to estimate D_{TRI} values for 233-U and 239-Pu fissile targets. These estimates are presented in Tables (V-VII).

Table II. ROT-effect in 235-U

J= 3 / J=4	K = 0	K = 1	**K = 2**	K = 3
K = 0	0.184	0.192	**0.215**	0.253
K = 1	0.171	0.178	0.201	0.240
K = 2	0.129	0.140	0.160	0.198
K = 3	0.060	0.068	0.091	0.129
K = 4	-0.037	-0.029	0.006	0.032

$S = \sigma(J=3/\sigma(J=4)=0.57$

Table III. ROT-effect in 233-U

J = 2 / J = 3	**K = 0**	K = 1	K = 2
K = 0	0.032	0.050	0.102
K = 1	**0.021**	0.038	0.090
K = 2	-0.013	0.004	0.056
K = 3	-0.070	-0.053	0.0006

$S = \sigma(J=2/\sigma(J=3)=1.52$

Table IV. ROT-effect in 239-Pu

J = 0 / J = 1	**K = 0**
K = 0	**0.0184**
K = 1	0.0092

$S = \sigma(J=0/\sigma(J=1)=2.16$

Table V. Calculated D_{TRI} values and signs in ternary 235-U fission ($D_{exp} = + 1.7\cdot10^{-3}$)

	$K_-=0$	$K_-=1$	$\mathbf{K_-=2}$	$K_-=3$
$\mathbf{K_+=0}$	*0*	1,2	**1,7**	0,96
$K_+=1$	*-3,5*	*-2,4*	*-1,8*	*-2,6*
$K_+=2$	*-6,0*	*-4,8*	*-4,3*	*-5,0*
$K_+=3$	*-6,1*	*-5,0*	*-4,4*	*-5,2*
$K_+=4$	*-3,0*	*-1,8*	*-1,3*	*-2,0*

Table VI. D_{TRI} values and signs in ternary 233-U fission (D_{exp} = - 3.9·10^{-3})

	K_-=0	K_-=1	K_-=2
K_+=0	*0*	*1,2*	*0,94*
K_+=1	-1,7	*-0,53*	*-0,76*
K_+=2	**-2,5**	-1,3	-1,5
K_+=3	-1,4	*-0,22*	*-0,45*

Table VII. Calculated D_{TRI} in 239-Pu
(D_{exp} = – 0.23·10^{-3})

	K_-=0
K_+=0	*0*
K_+=1	**-0,37**

In regard to ROT-effect (Tables II-IV) one can see unexpected good agreement between experimental and calculated shift values for definite pointed out **(J.K)** combinations.
Less definite conclusions may be inferred from the Tables (V-VII) analysis specifically because of inadequate statistical accuracy especially in the cases 233-U and 239-Pu. The most acceptable values in all Tables are marked in bold. The other acceptable values are shown in normal font. The values in italic have to be rejected. One needs to point out that the signs of TRI-effects are correctly predicted for all fissile targets. But it is clear from the other side that accepted suppositions have no well-founded reasons. Nevertheless it is improbable that such agreement, although not perfect, could appear by chance. However, more careful theoretical analysis has to be done in order to find proper explanations of all these facts.

In continuation of our investigations Program of TRI and ROT-asymmetry effects we plan in the nearest future to study ternary fission of 245-Cm an 241-Pu with transition state spins similar to 233-U and 235-U, respectively.

The authors express their thanks to the staff of the High Flux Reactor ILL for the ensuring all conditions necessary for successful fulfillment of scientific measurements.
This work had been performed under support of RFBR Grant 02-08-00277 and RFBR 09-02-91346-ННИО_a.

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