ANGULAR CORRELATIONS OF LIGHT CHARGED PARTICLES IN TERNARY FISSION OF ^{241}Pu BY POLARIZED COLD NEUTRONS

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Since several years our collaboration has studied angular distributions of light charged particles (LCP) in ternary fission induced by polarized cold neutrons. For the fissile isotopes ^{233}U, ^{235}U and ^{239}Pu novel features of ternary fission termed ROT and TRI effects were discovered. It is well known that most LCP`s are coming from the neck region between the fission fragments (FF), and hence their angular distribution is focused by the Coulomb force into a narrow angular region close to the median plane. Around the fission axis the distribution is expected to be symmetrical. The ROT effect is a small shift of the LCPs angular distribution relative to the fission axis in a plane perpendicular to the spin of the neutron inducing fission (shift angle ~10^{-1} – 10^{-2} degrees). The TRI effect describes a small difference in probabilities for the LCP to be emitted into the two hemispheres relative to the plane defined by the directions of light fission fragment (LF) and neutron spin (σ) (asymmetry ~10^{-3} – 10^{-4}) [1-8, 10]. These effects are illustrated schematically in Fig. 1.

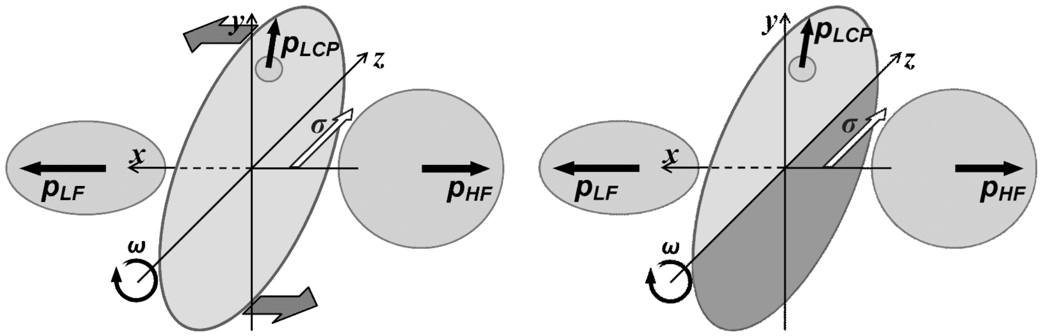

Figure 1. Illustration of ROT and TRI effects. ROT (left) is a small turn of the LCP angular distribution around the polarization axis (z); TRI (right) is a difference in total probabilities for LCPs to be emitted up and down relative to (xz) plane.

Such small effects can only be detected in relative measurements, where the angular distributions of LCPs are compared with the same detectors arrangement for two opposite neutron spin directions in the [$\sigma \times p_{LF}$] plane. The setup is shown in Fig. 2. Details of the experiment can be found in our former publications [1-8]. The experimental asymmetry is defined as follows:

$$A(\varphi) = \frac{Y^0(\varphi) - Y^1(\varphi)}{Y^0(\varphi) + Y^1(\varphi)} , \qquad (1)$$

where $Y^{0(1)}(\varphi)$ are yields of LCPs as a function of angle between LF and LCP in the (xy) plane around the z axis (azimuth angle) for two opposite spin directions (see Fig. 1). By considering the effect of neutron spin flipping as a superposition of ROT shift and TRI scaling, the experimental asymmetry can be described as follows:

$$A(\varphi) = S \cdot \left(\frac{Y'(\varphi)}{2 \cdot Y(\varphi)} \right) + D \ , \tag{2}$$

where $Y'(\varphi)$ is the derivative of the angular distribution, S characterizes the size of the ROT effect (the angular shift between LCPs distributions for the two neutron spin polarizations), and the parameter D describes the TRI effect (one half of the relative difference in probabilities for LCPs to be emitted towards the upper (lower) hemisphere for the two neutron spin directions).

The angular dependence of the experimental asymmetry $A(\varphi)$ measured in the present experiment for ^{241}Pu(n,f) is shown in Fig. 3 together with its fit according to Eq. 2. All necessary experimental corrections: for solid angles of registrations, non-perfect separation between light and heavy fragments, accidental coincidences and finite neutron polarization have been

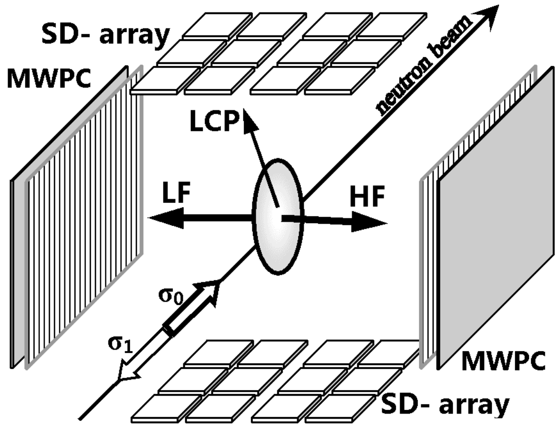

Figure 2. The experimental setup. MWPCs are multiwire gas detectors for FFs, SDs are arrays of silicon PIN diodes for LCPs. $\sigma_{0(1)}$ are two neutron spin polarizations.

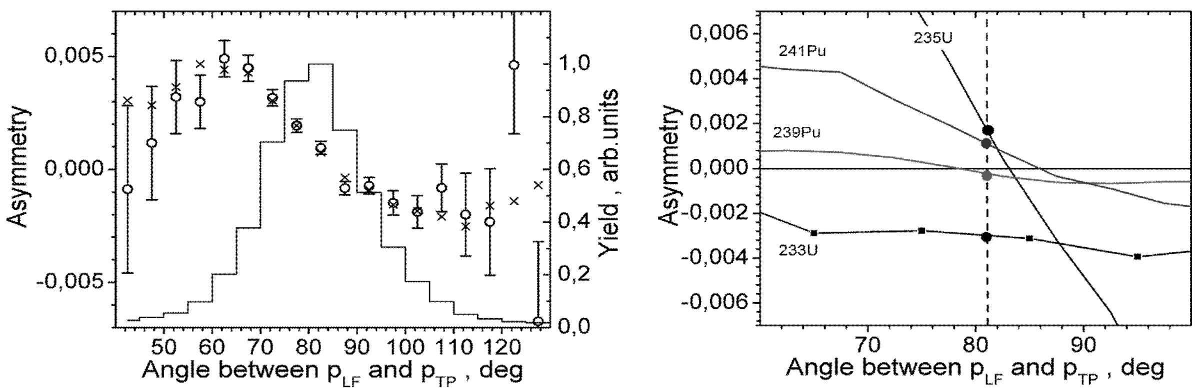

Figure 3. Left panel: Angular dependence of experimental asymmetry– $A(\varphi)$ for ^{241}Pu(n,f) (open circles); fit of $A(\varphi)$ by Eq. 2 (crosses); experimental angular distribution (solid line). Right panel: The angular dependences $A(\varphi)$ for the 4 studied isotopes in zoomed scale. The line slopes characterize ROT effect, and the asymmetry value at 81° gives the TRI effect.

applied. The values obtained for S (ROT) and D (TRI) are: $+(0.047\pm0.004)^{o}$ and $+(0.0013\pm0.00015)$, respectively. On the right panel of Fig. 3 the asymmetry $A(\varphi)$ for the 4 isotopes ^{233,235}U and ^{239,241}Pu studied so far are shown in zoomed scale. One can notice huge variations of the ROT effect (characterized by the slope $A(\varphi)$ as a function of the angle φ between LF and LCP) and the TRI effect (the asymmetry value $A(\varphi)$ at $\varphi = 81^{o}$) for these rather close-by isotopes.

In Fig. 4 the dependence of S and D on the LCP energy in ^{241}Pu(n,f) are shown. The same dependences for ^{235}U(n,f) studied earlier are presented for comparison.

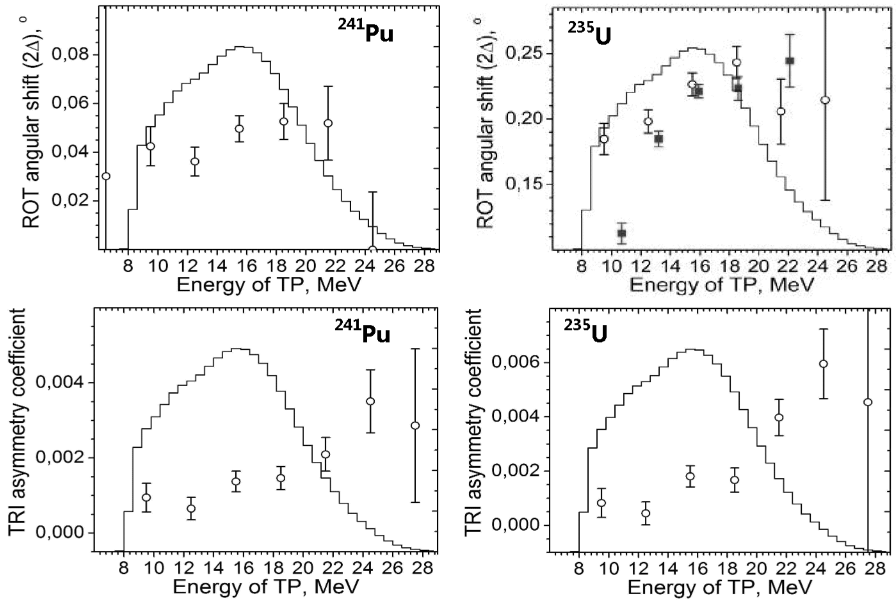

Figure 4. Left graphs: dependence of S_{ROT} shift and D_{TRI} coefficient on LCPs energy (open dots), experimental energy distributions of LCPs (solid line) for ^{241}Pu(n,f); on the right graphs the same plots for earlier studied ^{235}U(n,f) are given for comparison. Squares on the ROT plot for ^{235}U show result of the trajectory calculations based on our model for ROT effect.

In semi-classical phenomenological models being proposed [7, 8, 10] both effects are considered to be the result of the oriented rotation of the fissioning compound nucleus before rupture. The asymmetries appear to be very sensitive to the parameters of transition states on top of the fission barrier and to the characteristics of the nuclear configuration at scission [1-8, 10].

In our model the ROT effect is discussed in terms of the classical motion of the LCP and the FFs. The LCP`s are emitted from a rotating pre-scission system and are accelerated after scission by their mutual Coulomb interactions with FFs. The parameter S of the ROT shift is proportional to the effective collective angular momentum R of the fissioning nucleus around the neutron polarization axis at the top of the fission barrier:

$$S = s \cdot \left[R_{+} \frac{1}{1+k} + R_{-} \frac{k}{1+k} \right]. \qquad (3)$$

In this formula the 2 terms correspond to the $J = I \pm 1/2$ s-wave capture states of neutrons (J and I are the spins of the mother and compound nuclei respectively). The coefficient k is the relative contribution of the capture states to the fission cross-section. The parameter s is settled by the scission configuration (distances between particles and their velocities at the moment of scission). The expression for $R_{+/-}$ was given in [9]:

$$R_{+/-}(J,K) = \frac{J(J+1)-K^2}{J}\cdot\frac{\hbar}{2} \ for\ J = I + 1/2 \text{ and } -\frac{J(J+1)-K^2}{(J+1)}\cdot\frac{\hbar}{2} \ for\ J = I - 1/2, \quad (4)$$

where K is the projection of the compound nuclear spin onto the fission axis.

For the TRI effect a semi-classical explanation is proposed. It is suggested that the TRI effect arises due to the Coriolis interaction of the collective rotation defined by R and transversal bending vibrations of the deformed compound nucleus before scission. As follows from the quantum mechanical description of the perpendicular vibrations, just these vibrations carry the projection of the angular momentum K onto the fission axis. The Coriolis interaction will violate the symmetry of LCP emission relative to the plane $[\sigma \times p_{LF}]$ and gives rise to a TRI asymmetry which is proportional to $K{\cdot}R$ (σ is the neutron spin). Finally one can finds:

$$D = d\cdot\left[K_+R_+\frac{1}{1+k} + K_-R_-\frac{k}{1+k}\right]. \quad (5)$$

In this formula d is a coefficient related to the scission mechanism and pre-scission dynamics. The 2 terms correspond to the contributions of $J = I \pm 1/2$ capture states in the cross-section.

In the models proposed for ROT and TRI we can explain the strong variation of both effects for rather close-by isotopes by different combinations of fission channels involved in these 4 reactions. Using Eq. 3, 4 and 5 and taking available data about spin partial contributions in the cross-section from [11, 12] we can describe experimental data for ROT and TRI effects in ^{235}U, ^{233}U, ^{239}Pu. (Table 1). We took into account only one (dominant) K value for each compound system spin J. It is gratifying that not only the signs of the effects are described, but also the absolute values are reproduced with reasonable accuracy. The coefficient s (scission configuration) in Eq. 3 and d (scission mechanism, pre-scission dynamics) in Eq. 5 were taken to be identical for all these compound systems. The s coefficient was obtained from the scission configuration in ^{235}U ternary fission, which was found in trajectory calculations [4] to yield the best fit of all conventional experimental data about energy and angle distributions of LCPs and FFs in ^{235}U(n,f). The d coefficient in Eq. 5 was determined by requiring that for the (J,K) combinations (J_-=3, K_-=2) and (J_+=4, K_+=0) best fitting the ROT effect in ^{235}U(n,f), also the experimental value for D in this reaction was reproduced.

Table 1:

	^{235}U (I = 7/2)	**^{233}U (I = 5/2)**	**^{239}Pu (I = 1/2)**
Spin capture states ratio	$\sigma(J=3)/\sigma(J=4) = 0{,}57$ (from [12])	$\sigma(J=2)/\sigma(J=3) = 0{,}79$ (from ENDF/B-VII [11])	$\sigma(J=0)/\sigma(J=1) = 2{,}09$ (from ENDF/B-VII [11])
(J, K) of dominant fission channels	(J_-=3, K_-=2) and (J_+=4, K_+=0)	(J_-=2, K_-= 0) and (J_+=3, K_+=2)	(J_-=0, K_-= 0) and (J_+=1, K_+=1)
S (experiment)	0,215 ± 0,005	0,021 ± 0,004	0,020 ± 0,003
S (model)	0,215	0,053	0,028
D (experiment)	(1,7 ± 0,2) × 10^{-3}	(-3,9 ± 0,12) × 10^{-3}	(-0,23 ± 0,09) × 10^{-3}
D (model)	1,7 × 10^{-3}	-3,5 × 10^{-3}	-0,38 × 10^{-3}

With these common calibration coefficients s and d, and using data about spin contributions k in the cross-section as evaluated in ENDF files [11], we applied Eq. 3, 4 and 5 for to calculate ROT and TRI effects in ^{241}Pu for different (J_-, K_-) + (J_+, K_+) combinations (see Table 2a). Evidently there is no (J,K) combination in Table 2a which can explain simultaneously the experimental ROT and TRI data for ^{241}Pu.

For a fit of the experimental results we have to change the ratio of spin contributions to the fission cross section $\sigma(J=2)/\sigma(J=3)$ from 0.15 to 1.56. This allows to obtain a simultaneous description of ROT and TRI for the (J_-=2, K_-=1) and (J_+=3, K_+=0) channel combination as shown in Table 2b. It is interesting to note that the positive value of the experimental TRI asymmetry excludes from consideration all combinations with (J_+, $K_+ > 0$) (only first line in the table can be considered). The similar situation was observed in ^{235}U(n,f).

Table 2:

ROT shift, angular degrees — **TRI asymmetry, × 10^{-3}**

a) ^{241}Pu $\sigma(J=2)/\sigma(J=3) = 0{,}15$ (from ENDF/B-VII [11])

S (experiment) = +0,047 ± 0,004

(J,K)	*(2,0)*	*(2,1)*	*(2,2)*
(3,0)	0,282	0,285	0,297
(3,1)	0,256	0,260	0,271
(3,2)	0,180	0,184	0,195
(3,3)	0,053	0,057	0,068

D (experiment) = (+1,30 ± 0,15) × 10^{-3}

(J,K)	*(2,0)*	*(2,1)*	*(2,2)*
(3,0)	0,0	0,25	0,20
(3,1)	-3,7	-3,5	-3,5
(3,2)	-5,4	-5,2	-5,2
(3,3)	-3,1	-2,8	-2,9

b) ^{241}Pu $\sigma(J=2)/\sigma(J=3) = 1{,}56$ (our fit to ROT-TRI experiment)

S (experiment) = + 0,047 ± 0,004

(J,K)	*(2,0)*	*(2,1)*	*(2,2)*
(3,0)	0,030	**0,048**	0,101
(3,1)	0,019	0,036	0,090
(3,2)	-0,015	0,002	0,056
(3,3)	-0,072	-0,055	-0,001

D (experiment) = (+1,30 ± 0,15) × 10^{-3}

(J,K)	*(2,0)*	*(2,1)*	*(2,2)*
(3,0)	0,0	**1,19**	0,95
(3,1)	-1,7	-0,49	-0,73
(3,2)	-2,4	-1,2	-1,5
(3,3)	-1,4	-0,18	-0,42

The failure to describe experimental data for ^{241}Pu with spin contributions to the fission cross section as evaluated by ENDF [11] is not too surprising. There are no direct measurements available and the required spin assignments for low-lying and negative resonances in ^{241}Pu(n,f) reported by ENDF are not very reliable.

The sensitivity of ROT and TRI effects on the characteristics of transition states above the fission barrier and to the nuclear configurations at scission makes their study very promising for obtaining new information on the fission process. For further tests and elaboration of models the following experiments are of great importance:

- Study of ROT and TRI in ^{245}Cm(n,f) (I = 7/2)
- Measurement of the TRI and ROT effects in resonances of ^{235}U thereby varying the weight of spin contributions to the cross-section
- More detailed experiment in ^{235}U(n,f). Study of the ROT and TRI dependence on the type of LCP (alphas, hydrogen isotopes, ...) and on fission fragment masses and energies.

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