SFBE “PETERSBURG NUCLEAR PHYSICS INSTITUTE NAMED B.P. KONSTANTINOV”

MAIN RESULTS AND FUTURE TRENDS OF THE T-ODD ASYMMETRY EFFECTS INVESTIGATIONS IN NUCLEAR FISSION

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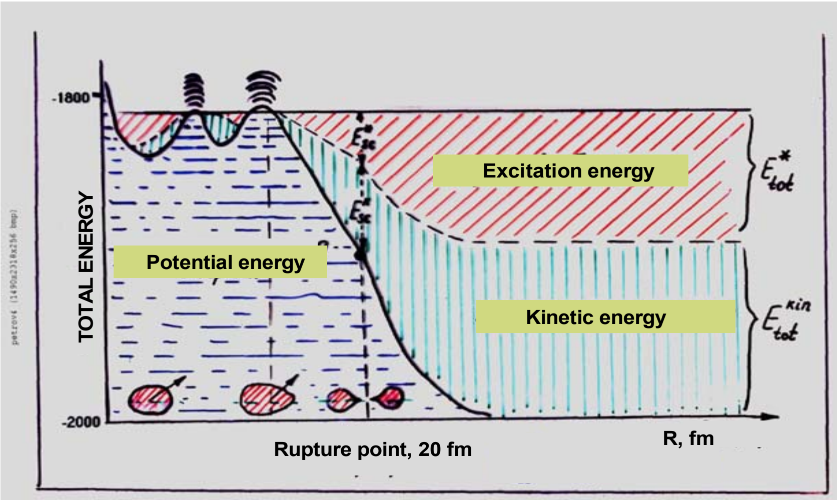
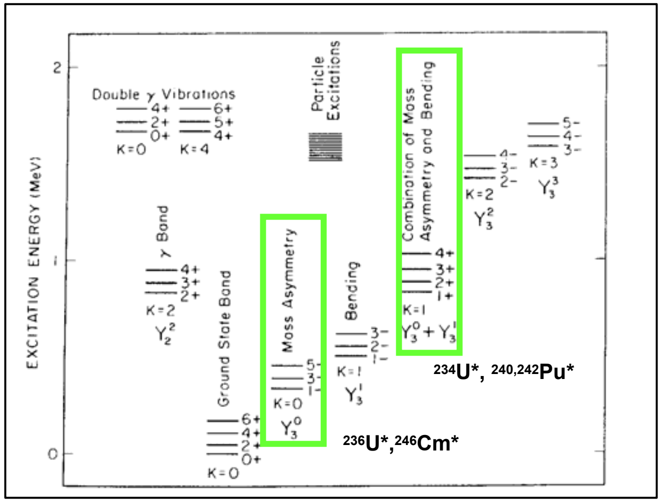
Heavy nucleus fission at the low excitation energies

Qualitative pictures of the low excitation energy fission



Transition states of the fissioning system



Estimates of the descend and rupture parameters:

No dissipation (Halpern, 1971): $\tau \approx 10^{-21}$ s. $E_\alpha \approx 20$ MeV, $E_f^{\,kin} \approx 50$ MeV

No dissipation (Carjan, 1975, Nix, 1987): $\tau \approx (2\text{-}3)\cdot 10^{-21}$ s, $E_f^{\,kin} \approx 50$ MeV

Surface-widows dissipation (Nix, 1987): $\tau \approx (2\text{-}3)\cdot 10^{-21}$ s, $E_f^{kin} \approx 50$ MeV

Surface-widows dissipation+pair breaking dissipation: $\tau \approx 10^{-20}$ s.

Thermodynamics equelibrium (Fong, 1971): $E_\alpha \approx 20$ MeV, $E_f^{\,kin} \approx 0.5$ MeV

TDHF calculations (Flocard, 1995): $\tau \approx 3.5\cdot 10^{-21}$ s.

At the fission by low energy neutrons:

^{233}U (I = 5/2): Compound spins J = 2 and 3.

^{235}U (I = - 7/2): Compound spins J = -3 and - 4.

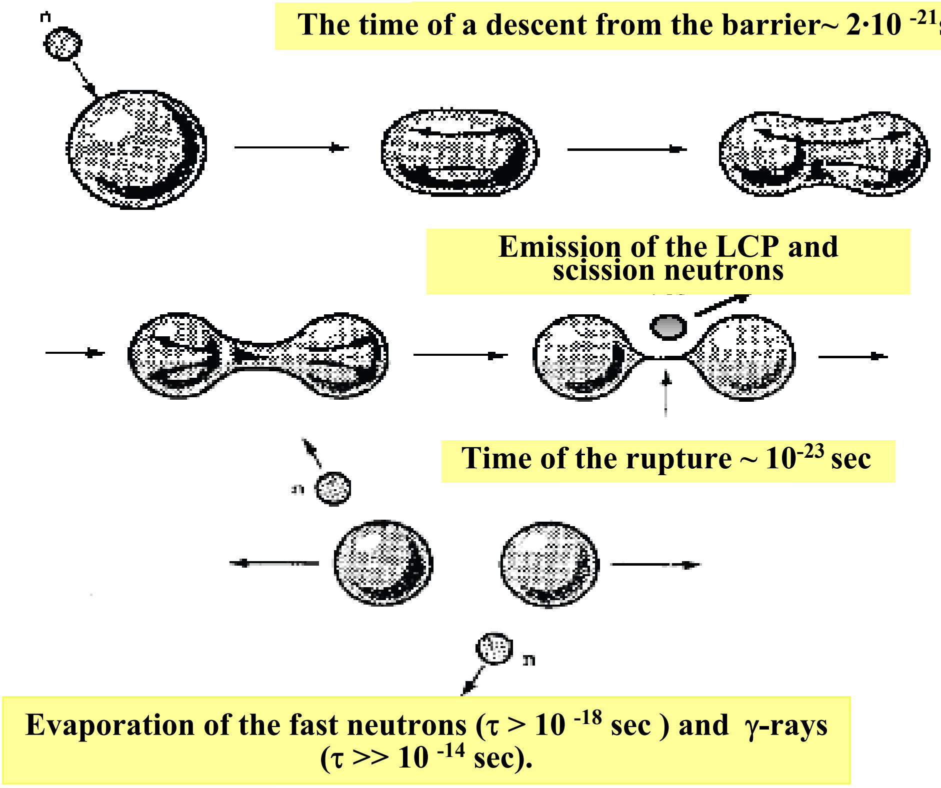
^{239}Pu(I = 1/2): Compound spins J = 0 and 1.

^{241}Pu(I = 1/2): Compound spins J = 2 and 3.

^{245}Cm(I = 7/2): Compound spins J = 3 and 4.

At the saddle point of even-even fissioning system only collective states are accessible. Compound spins are conserved down to scission and in particular they control the angular distributions of fission fragments.

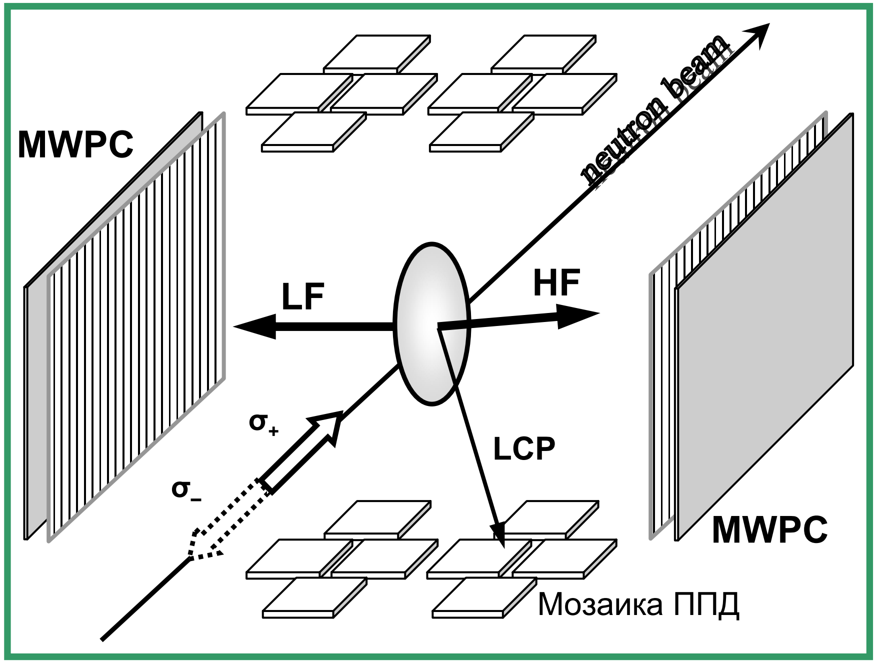
Schematic view of the neutron induced fission process: (excitation, decent from the barrier, rupture and radiation emission.



The main radiation characteristics:

1. **Fission fragments acquire in the rupture process the angular momenta about (6÷8)ħ oriented perpendicularly to the fission axis.**
2. **Light charged particles (mainly ^{4}He) are emitted near the rupture time with the yields ~ $2 \cdot 10^{-3}$ par fission event.**
3. **Excited fission fragments are emitted about 2.5 neutrons/ ^{235}U fission with the average energies ~ 1.5 Mev**
4. **Average number of γ-quanta per fission is about 8 with the average energy ~ 0.8 MeV.**
5. **As a result of the big oriented angular momenta existence and kinematic effect of the flying away fragments the neutrons and γ-quanta are emitted unisotropically relative to the fission axes.**

The method for the first observation and subsequent comprehensive investigations of so called T-odd asymmetry TRI and ROT-effects



- Measurements of the angular distributions:
  - The diode dimensions ~ 30x30 мм^2
  - Resolution of the position sensitive MWPCs (~ 2 mm)
- Spectroscopy of the fission products:
  - Light particle energies
  - Masses and energies of fission fragments)
- Spin–flip technique for the neutron polarization: (frequency ~ 1 hertz)
- Relative measurements
- Control and suppressing of the falce effects:
  - measurements with depolarized beam
  - comparison 0f the A(θ) for the symmetric detector positions

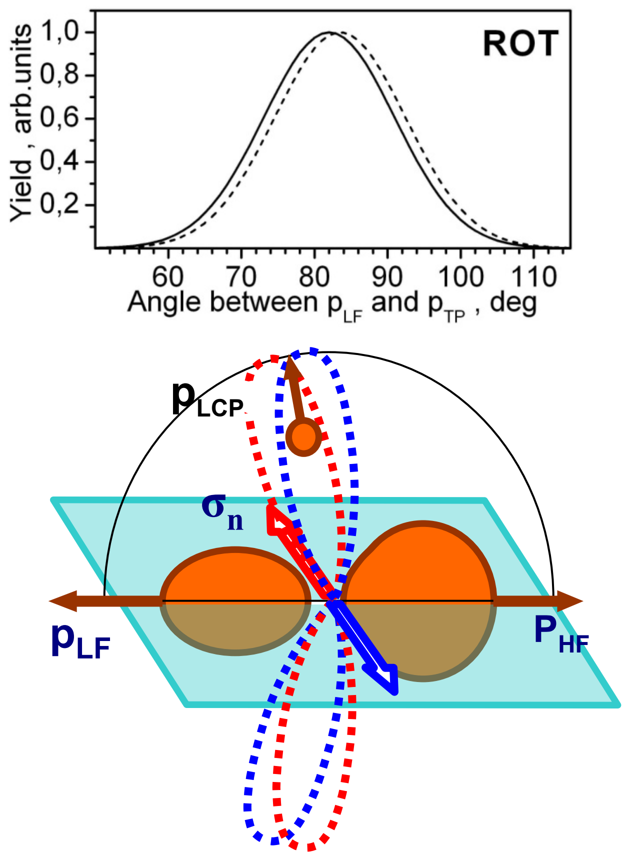
$$A(\theta) = \frac{N^0(\theta) - N^1(\theta)}{N^0(\theta) + N^1(\theta)}$$

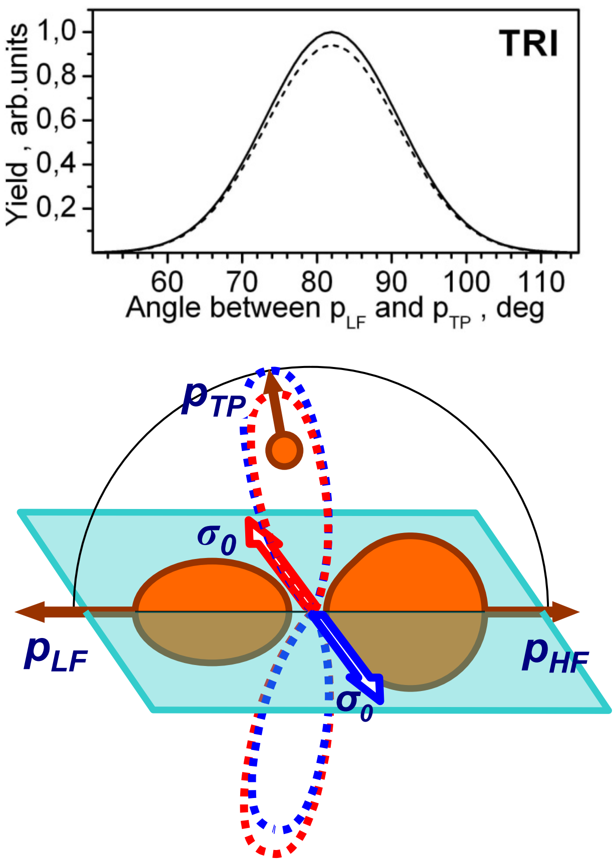
$$A(\theta) = D_{ROT} \cdot \left(\frac{Y'(\theta)}{2 \cdot Y(\theta)} \right) + D_{TRI}$$

Demonstrative pictures of the TRI and ROT-effects appearance in the ternary fission of the heavy nucleus induced by the cold polarized neutrons.

$W(\theta) = 1 + D_{ROT}\cdot\boldsymbol{\sigma}_{\mathbf{n}}\cdot[\mathbf{p_f x p_{tp}}]\cdot(\mathbf{p_f}\cdot\mathbf{p_{tp}})$

$W(\theta) = 1 + D_{TRI}\cdot\boldsymbol{\sigma}_{n}\cdot[\mathbf{p_f x p_{tp}}]$





The main model preposition consists in the following: TRI and ROT-effects of the T-odd asymmetry are result of the polarized fissioning nucleus rotation around polarization axes under its decent from the barrier to the rupture.

Schematic diagram of the ROT-effect appearance in ternary fission

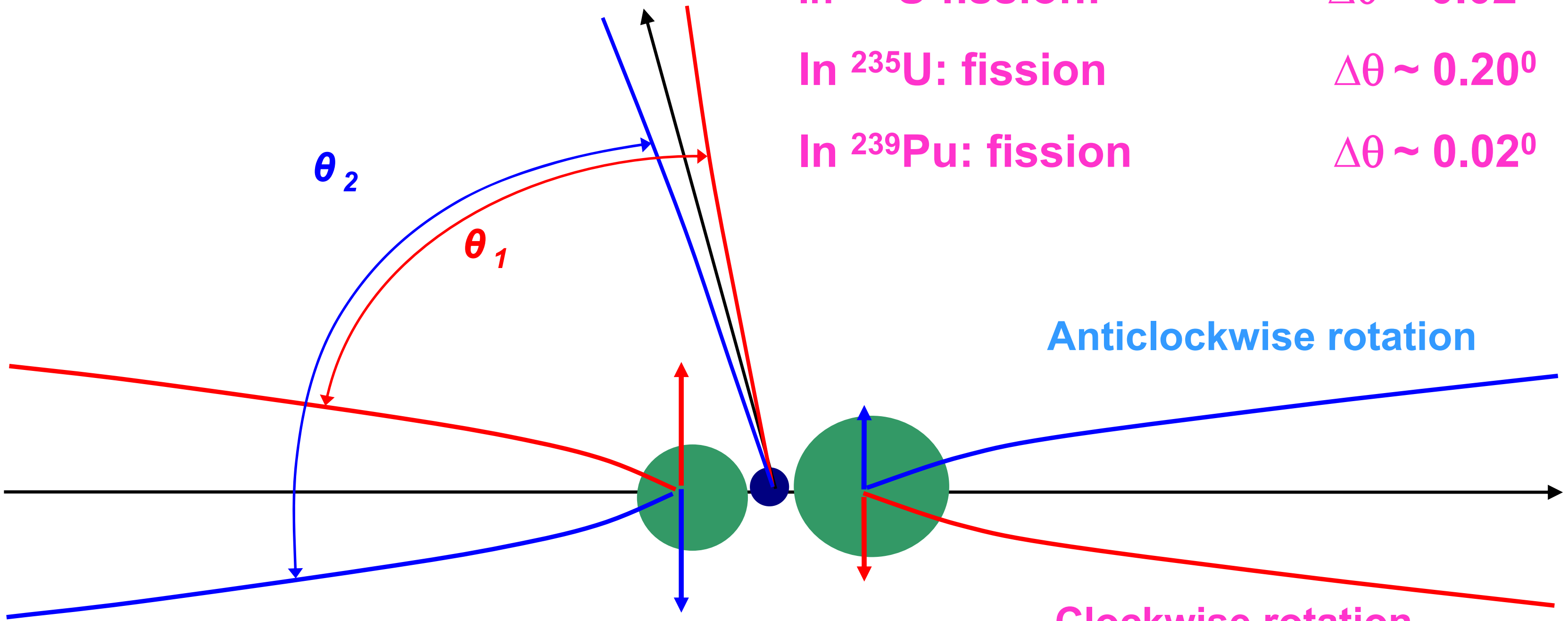
(Shift of the LCP angular distributions)

Observed shift of LCP angular distribution:

In ^{233}U fission: $\Delta\theta \sim 0.02^0$

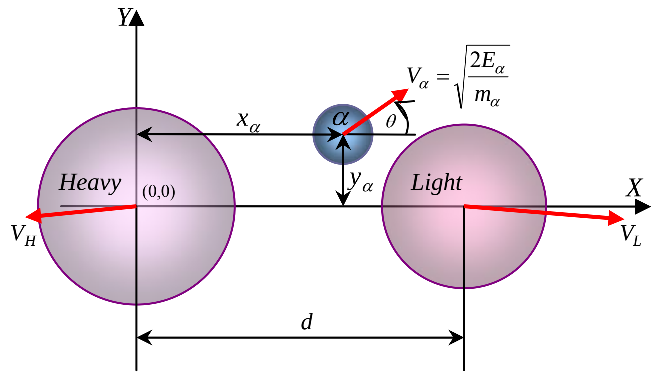
In ^{235}U: fission $\Delta\theta \sim 0.20^0$

In ^{239}Pu: fission $\Delta\theta \sim 0.02^0$



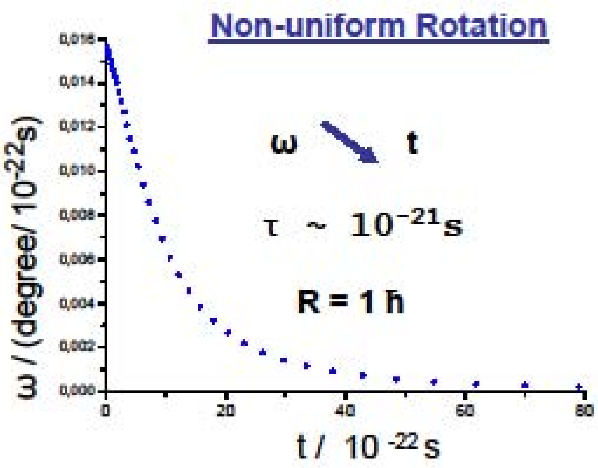
After rupture LCP is rotating together with fragments but with some lag behind

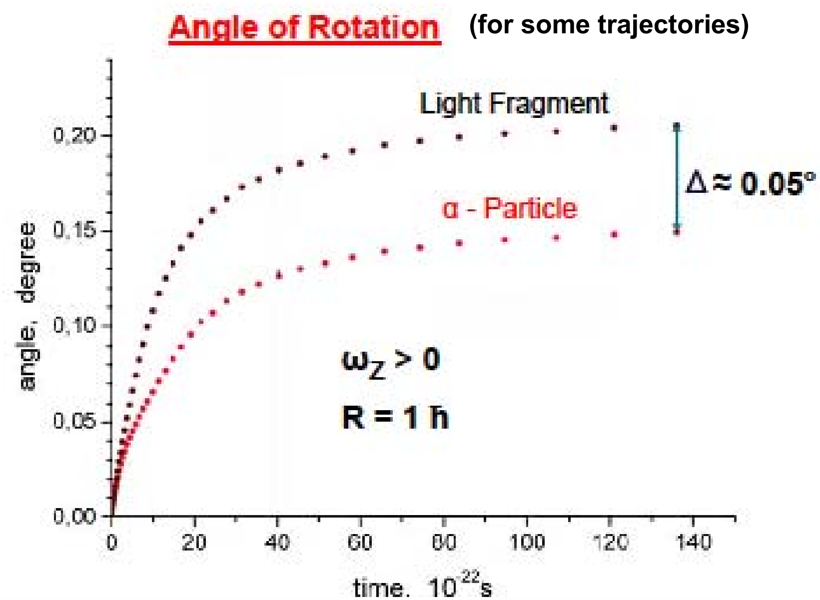
Ranges of the main parameters used in trajectory calculations of LCP emission by rotating nucleus

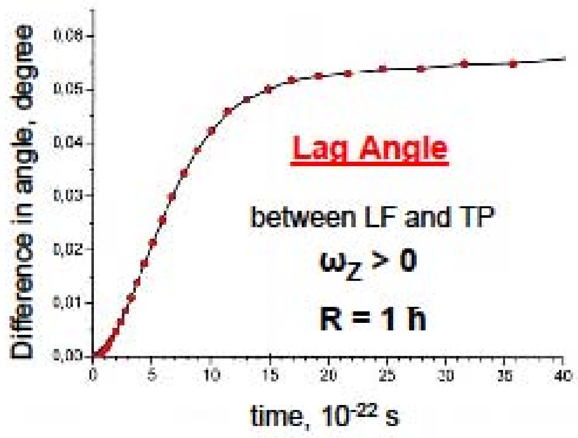


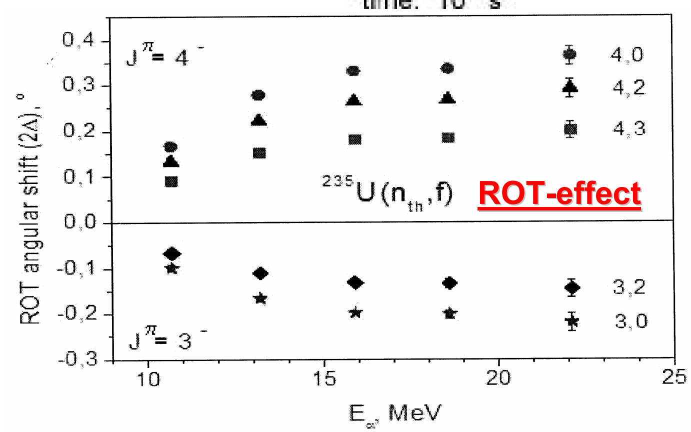
Input parameter	Symbol	Value (^{235}U)	Units
Compound system spins	$J = I \pm 1/2$	- 3 and -4	$\hbar$
Distance between fragments just after rupture	d	20.2 (18 ÷ 22)	10^{-13} cm
Initial velocity of heavy fragment	V_H	0.26	10^9 cm/s
Initial position of the LCP between fragments	x_α	any possible	10^{-13} cm
Initial distance of the LCP from the fission axis	y_α	0 ÷ 1.83	10^{-13}cm
Initial energy of the LCP	E_α	0.1 ÷ 1.3	MeV
Initial angle of the LCP with respect to the fission axis	θ_α	0 ÷ 180	degrees

Some results of trajectory calculations in the ^{235}U fission induced by the cold polarized neutrons





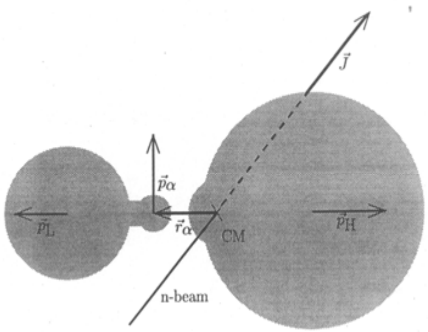




J = I +1/2

J = I - 1/2

TRI-asymmetry effect in statistical model
(PNPI. V. Bunakov et al.)



$P(J^+) = (2I+3) / [3\cdot(2I+1)]\cdot Pn$ for $J^+ = (I+½)$
$P(J^-) = -1/3\cdot Pn$ for $J^- = (I-½)$

Probability of fission reaction proportional to the level density of the final system.

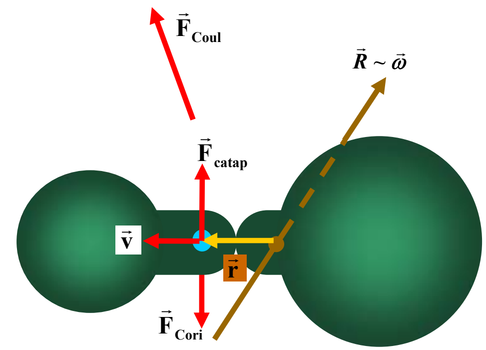
$$D_i \approx \frac{\hbar^2 J l_\alpha \sqrt{a_i}}{2\Im_i \sqrt{E_{xi}^{sc}}} \cdot \mu_{11} P(J)$$

- *Spin of compound nucleus*
- *LCP momentum*
- *Level density parameter*
- *Compound nucleus polarization*
- *Polarization sharing between FF*
- *Internal fragment excitation*
- *Moment of inertia*

$D_i \sim 1/(6 - 0.2\, E_\alpha)^{1/2}$

Semi-classical model of the TRI-effect
(PNPI. A. Gagarsi and I. Guseva)

$$F_{Cori} = -2m\,[v \times \omega]$$
$$F_{catap} = m\,[r \times d\omega/dt]$$
$$F_{centr} = m\omega \times [r \times \omega]$$

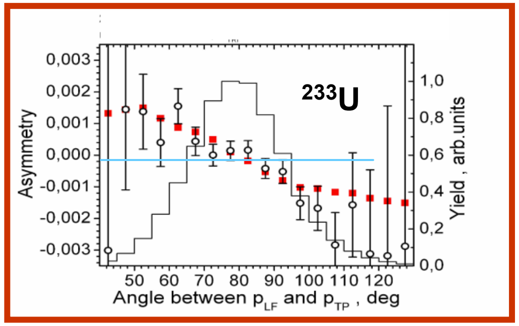


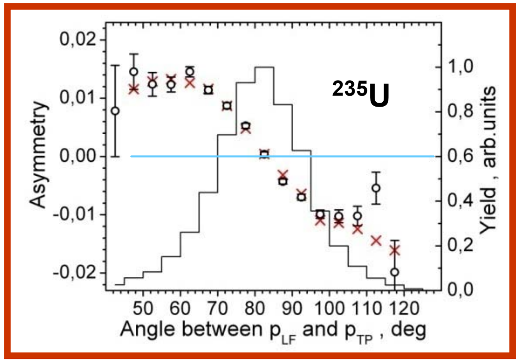
$$\omega^2 \Im_\perp^2 = \hbar^2 \cdot (J(J+1) - K^2)$$

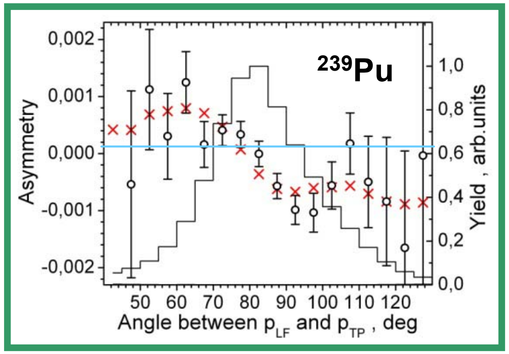
$$D_{ROT} + D_{TRI} = A\cdot[\omega^+/(1+s) + \omega^- \cdot s/(1+s)]$$
$$+ B[K^+\omega^+/(1+s) + K^- \omega^- \cdot s/(1+s)]$$

TRI and ROT-effects in ^{233,235}U and ^{239}Pu ternary fission

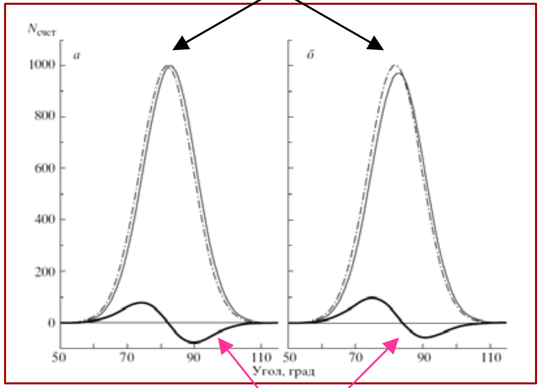
Experimental ROT-effects







$W(\theta) = 1 + D_{TRI}\cdot\sigma_n\cdot[p_f x p_{TP}]$



$W(\theta) = 1 + D_{ROT}\cdot\sigma_n\cdot[p_f x p_{TP}]\cdot(p_f\cdot p_{TP})$

TRI and ROT experimental results

nuclei	spin	ROT ^{0}	TRI x 10^3
^{233}U	2+, 3+	0.03(1)	-3.9(1)
^{235}U	3-, 4-	0.215(5)	1.7(2)
^{239}Pu	0^+, 1^+	0.020(3)	0.23(9)
^{245}Cm	-	-	1.2(1)*

*** Without correction for possible ROT-effect**

Model evaluation of ROT-effects

^{233}U(n_{th},f): σ(J=3) / σ(J=2) = 1,27

Exp: 2Δ ≈ 0,03(1)°

Calculations for (J,K) combinations

3^+\ 2^+	(2,0)	(2,1)	(2,2)
(3,0)	0,118	0,131	0,170
(3,1)	0,102	0,115	0,153
(3,2)	0,053	0,066	0,105

^{235}U(n_{th},f): σ(J=4) / σ(J=3) = 1.75

Exp: 2Δ = 0,215(5)°

Calculations for (J,K) combinations

4^-\ 3^-	(3,0)	(3,1)	(3,2)
(4,0)	0,183	0,191	0,215
(4,1)	0,169	0,177	0,201
(4,2)	0,128	0,135	0,159

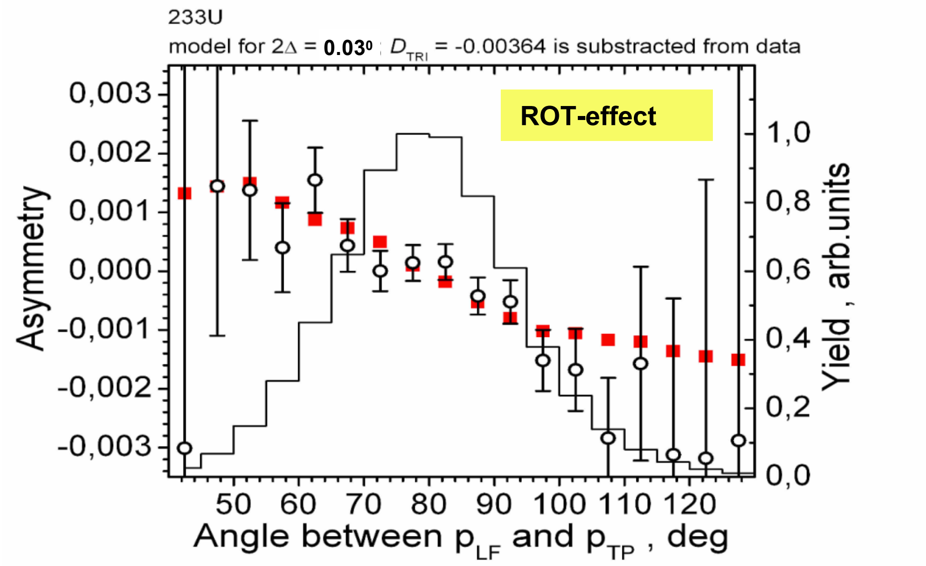
^{239}Pu(n_{th},f): σ(J=1) / σ(J=0) = 0.48

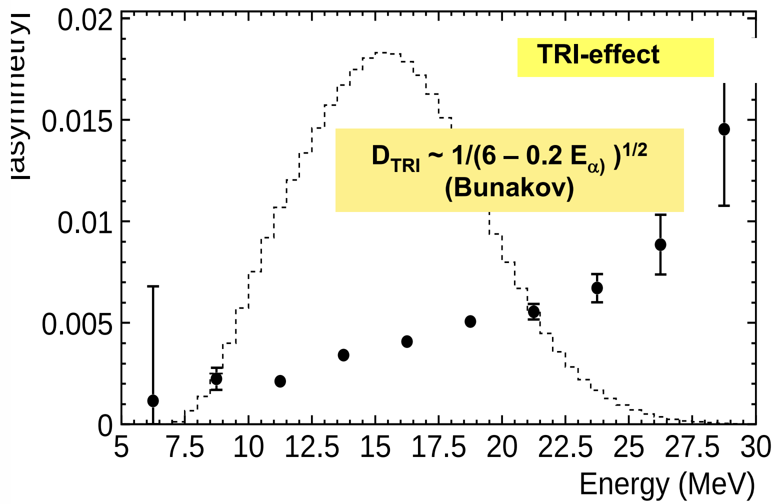
Exp: 2Δ = 0,020(3)°

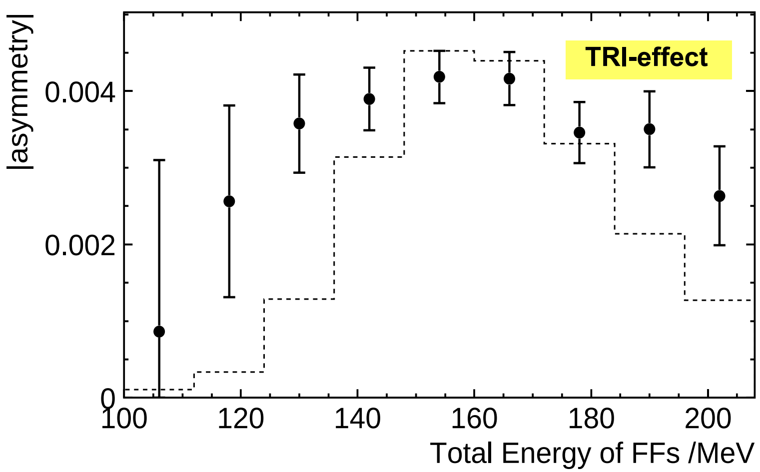
Calculations for (J,K) combinations

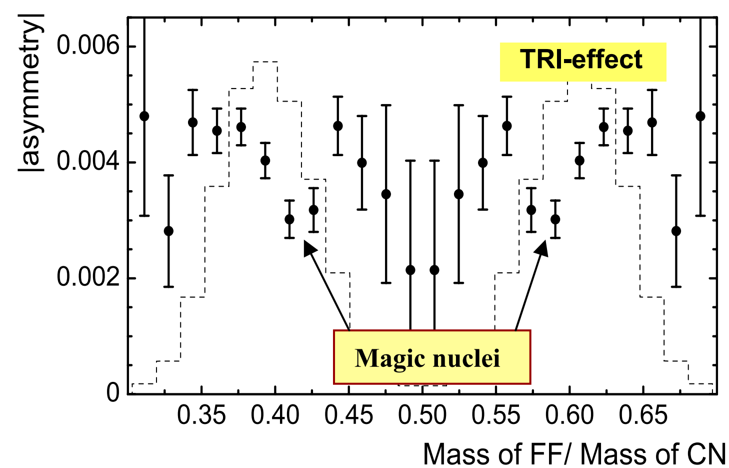
1^+\ 0^+	(0,0)
(1,0)	0,057
(1,1)	0,028

Some properties of the TRI-effect in ^{233}U ternary fission

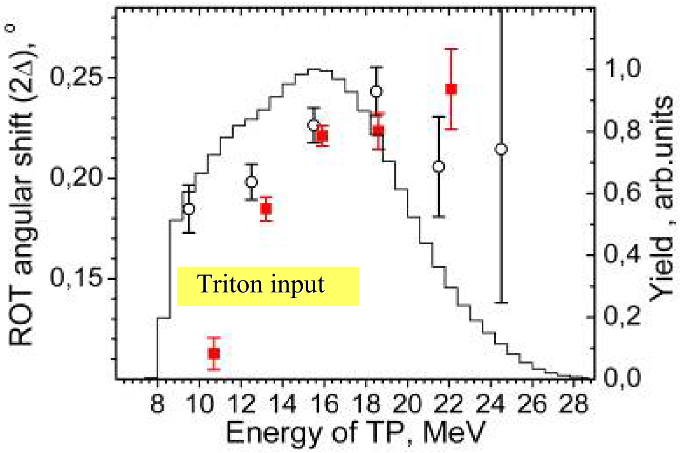


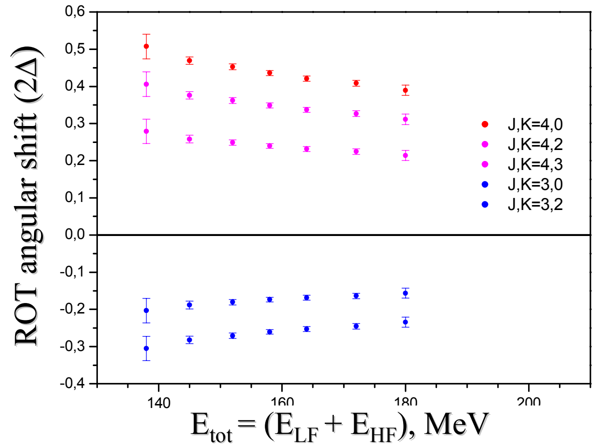


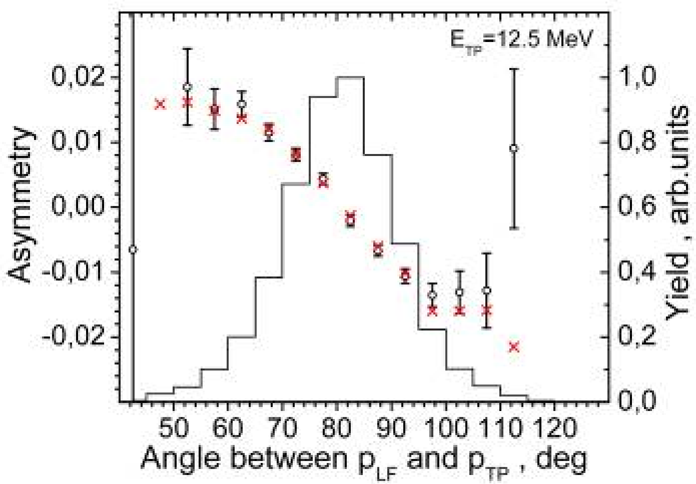


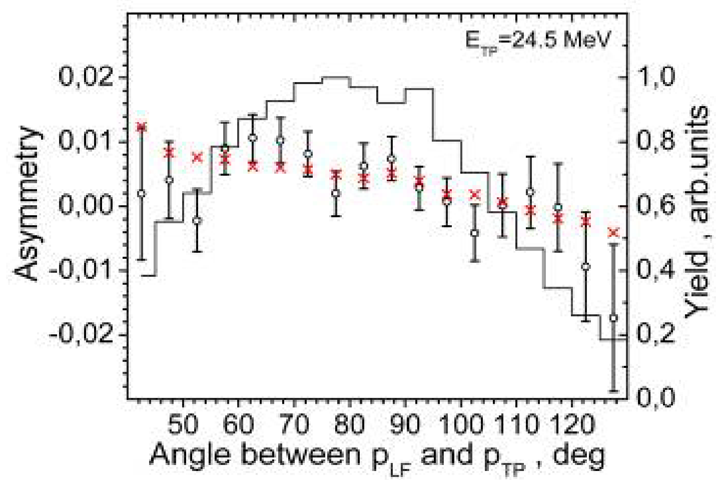


ROT-effect in ^{235}U ternary fission as a function of E_{TP} and $(E_{LF} + E_{HF})$
(Experiment and Model calculations)









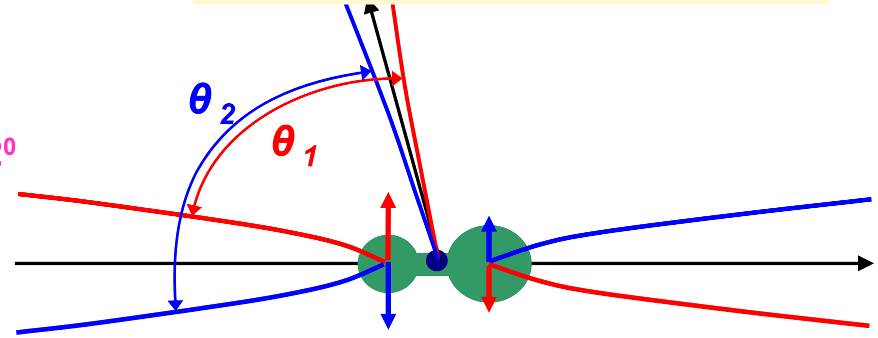
Comparative mechanisms of ROT-effect appearance in ternary and binary fission

Observed shift of LCP angular distribution:

In ^{235}U: $\theta_2 - \theta_1 \sim 0.2^0$

in ^{239}Pu: $\theta_2 - \theta_1 \sim 0.02^0$

Shift of LCP angular distribution in ternary fission



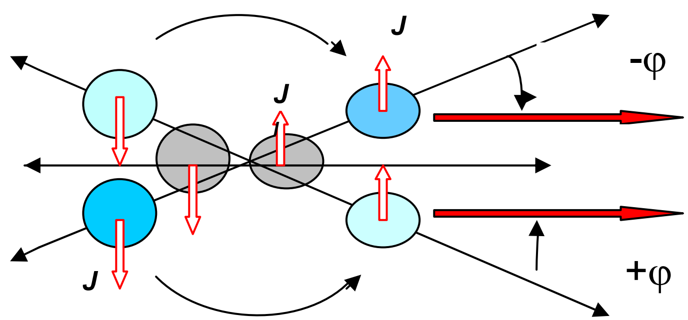
Anticlockwise rotation

Clockwise rotation

LCP and fission fragments are rotating together up to the stop but with some lags behind

Shift of γ-quanta angular distribution in binary fission

Expected shift of the γ-quanta angular distribution may markedly differs from the LCP one as a result of different start configurations in ternary and binary fission and preceding emission of neutrons!



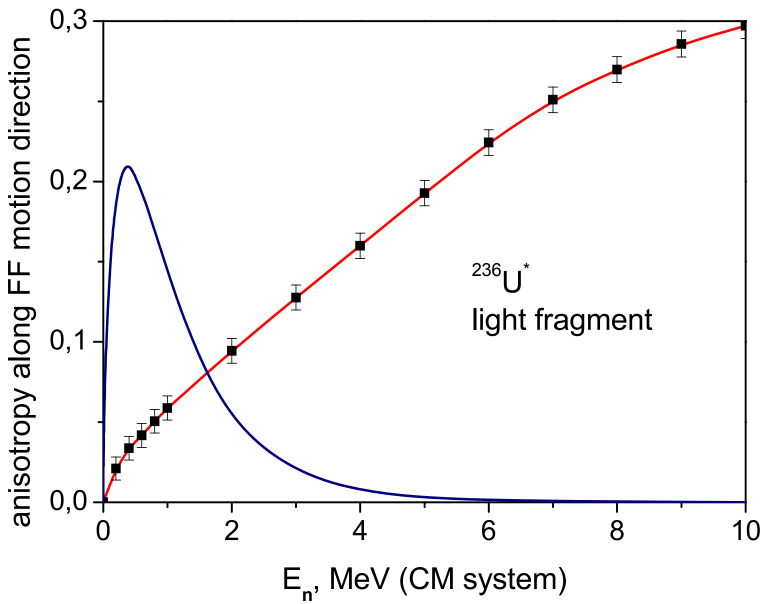
Anticlockwise rotation

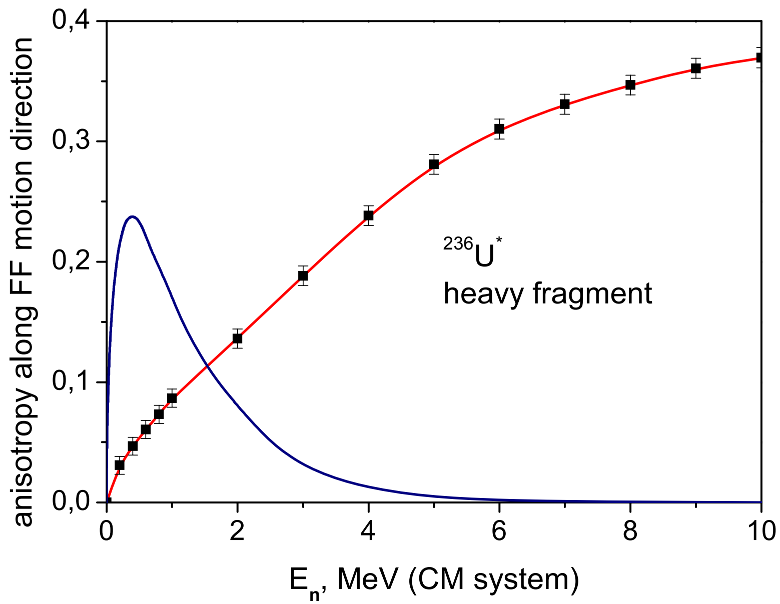
Clockwise rotation

Angular distribution of γ-quanta is specified by the fragment angular momentum orientation appeared much later the rupture and LCP emission!

Anisotropy of neutron emission in the C.M.S. of fission fragments

(I.S. Guseva)



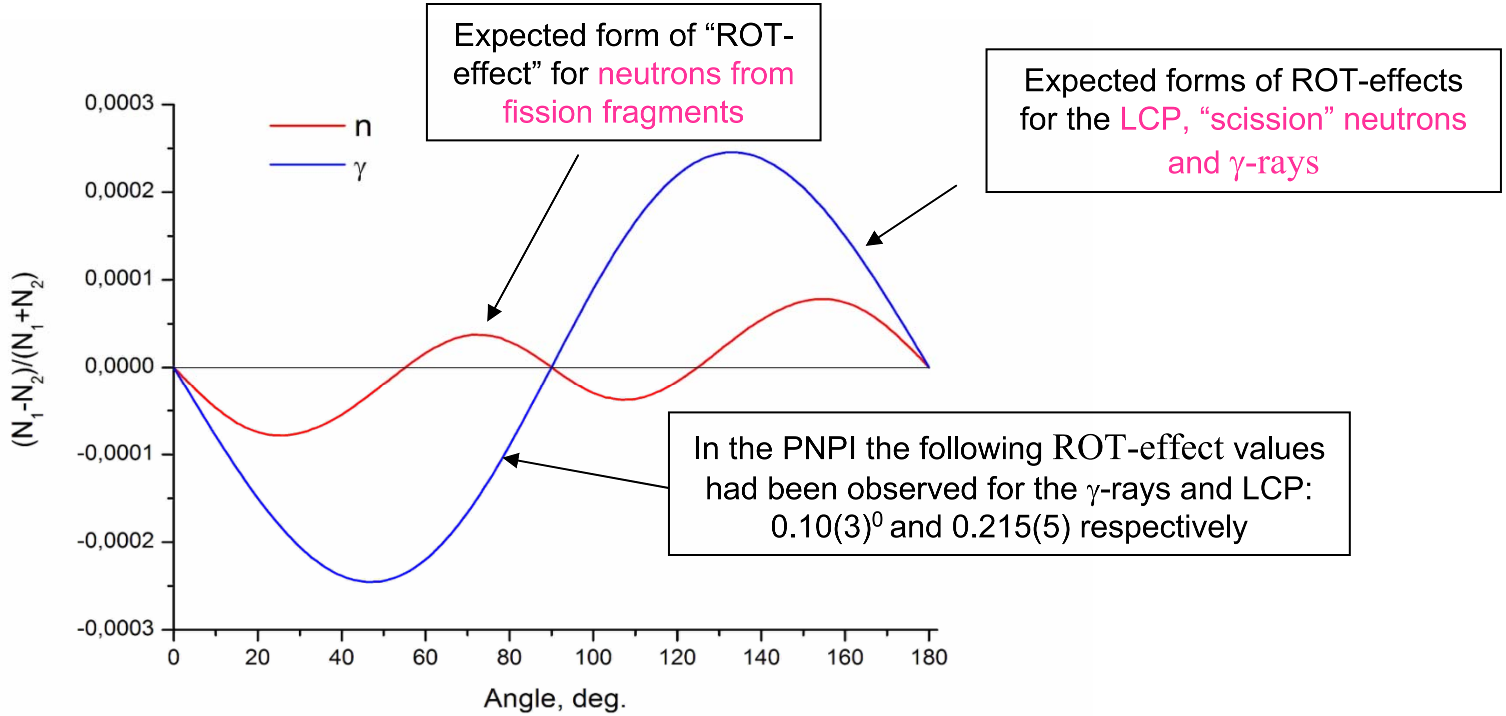


The red lines are the results of Monte-Carlo calculations of neutron emission anisotropy.
The blue lines are the neutron energy spectra in the center-of- mass system.

For the average values $\langle J_{LF}\rangle = 6\hbar$ and $\langle J_{HF}\rangle = 8\hbar$ the angular anisotropy values were found to be equal: 6.3% - for light fragments and 9.5% for the heavy fission fragments.

Expectations for the ROT-effect angular dependence of neutrons and γ-rays emitted by excited fragments in $^{236}U^*$ fission

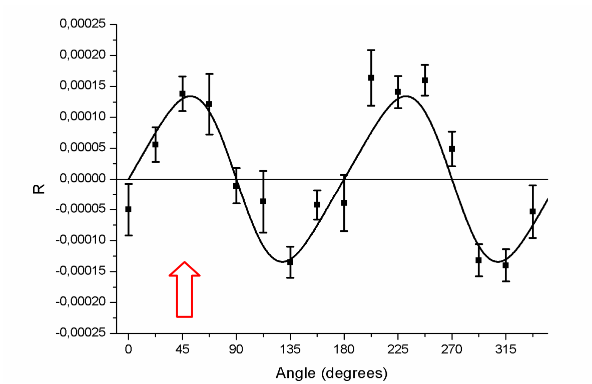
(I.S. Guseva)



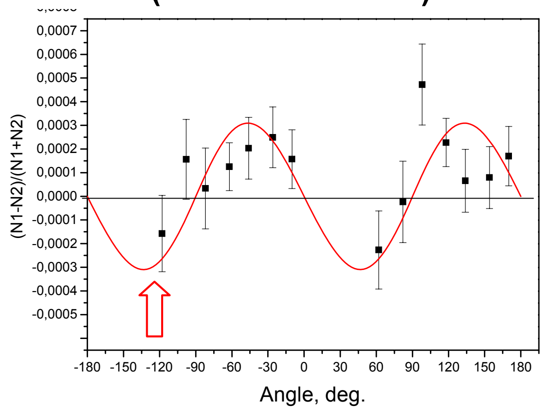
ROT-effect form for <u>"scission neutrons"</u> has to be similar to the LCP ones!

Comparison of the shift angles obtained from the ROT-effects for the LCP and γ-rays *(ternary and binary fission of ^{235}U)*

ROT-effect obtained by ITEP group, FRM-II (Garching, Germany)



ROT-effect obtained by PNPI group, WWR-M (Gatchina. Russia)



The ROT-effect existence for γ-rays is fully confirmed in both works but not the signes

$$D_{\exp}(\theta') \cong -A\cdot\delta\cdot\sin(2\theta')/[1+A\cdot\cos^2(\theta')]$$

The shift "δ_γ" of the γ-rays angular distribution is equal to (0,0018 ± 0,0005) rad

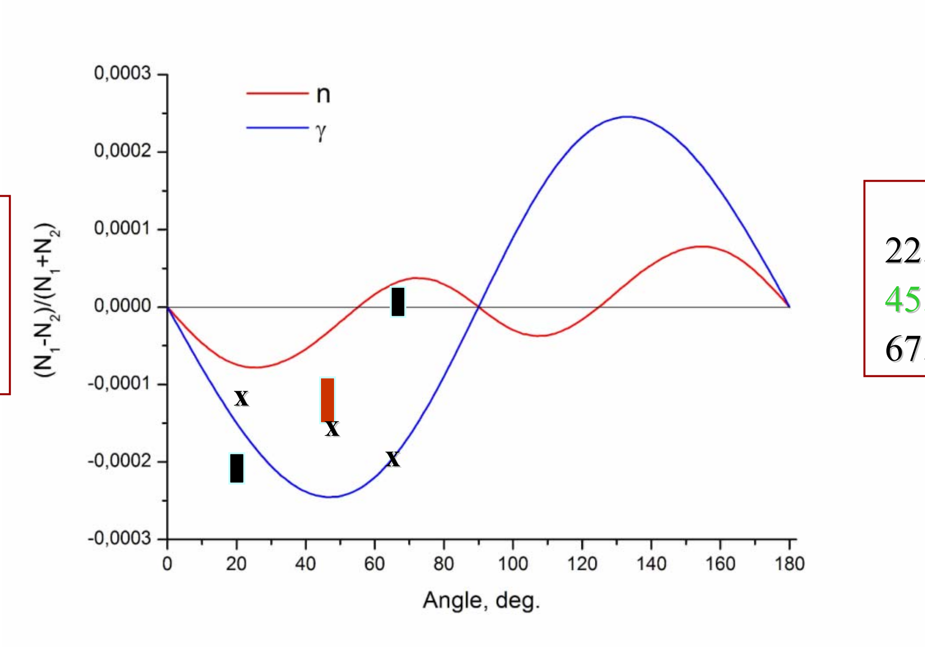
Full turn angle of the ^{235}U ternary fission axis around polarization direction, obtained from the data evaluation for LCP, had been equal to (0,0032 ± 0,0003) rad.

The reason for such essential difference in the angular distribution shifts δ_γ and δ_{LCP} may be connected with difference in the fissioning system configurations in the times of LCP and γ-ray emission and with violation of angular momentum orientation in the preceding neutron emission.

ROT-effect for the fast neutrons in the ^{235}U fission (FRM-II reactor, ITEP, 2011)

γ-rays data (x)

22.5°	**- (1.29 ± 0,24)·10⁻⁴**
45°	**- (1.50 ± 0.25)·10⁻⁴**
67.5°	**- (2.00 ± 0. 18)·10⁻⁴**



Fast neutron data (I)

22.5°	**- (2.12 ± 0,25)·10⁻⁴**
45.0°	**- (1.13 ± 0.20)·10⁻⁴**
67.5°	**+ (0.03 ± 0.22)·10⁻⁴**

Mechanism of ROT-effects appearance for neutrons and γ-rays in binary fission seems to be more understandable then T-odd asymmetry effects for the LCP. That is why it would be very important now to investigate all these effects with the greatest possible accuracy. One can hope that the results of such joint investigations for the LCP, fission neutrons and γ-rays will allow to get new and important information about fission dynamics.

Expected T-odd asymmetry effects for tritons

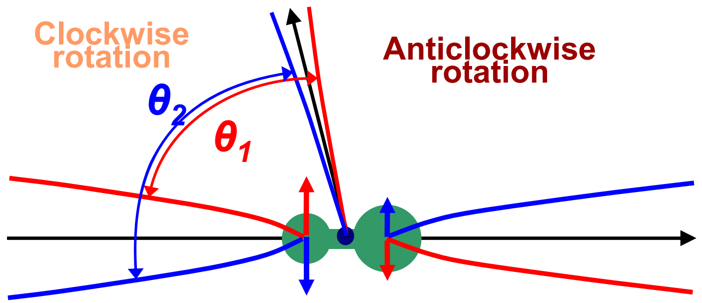
MOTIVATION

<u>**In the contrast to the α-particles:**</u>

- **tritons have about ten times less yield: only about 7%,**
- **for some reasons appearance mechanism of the tritons may be different,**
- **triton kinetic energies are two times less then α-particle ones: ~ 7.8 MeV,**
  (It means that the triton velocity has to be about 20% less then α-particle one)
- **nevertheless, average triton emission angle is as α-particle one: ~ 82^0,**

- **but under the fission axis rotation: $\theta_{1,2}^{t} > \theta_{1,2}^{\alpha}$**

At the first sight one can expect that the T-odd asymmetry effects for alfas and tritons may vary in signs and values.



But simple estimates show that these effects values may be very close!

Existing first experimental estimates for t: $D_{TRI} = -(2.8 \pm 0.5)\cdot 10^{-3}$ and $D_{ROT} = ?$

Existing first experimental results for α: $D_{TRI} = -(3.9 \pm 0.1)\cdot 10^{-3}$ and $D_{ROT} = (0.03 \pm 0.01)^0$

Some conclusions and possible predictions

Within the framework of the statistical model (*Bunakov et al*): -----
One can expect the same values of the TRI-effects for the fission of nuclei with the same transition states (*possible candidates $^{234}U^*$ and $^{242}Pu^*$ ($J = 2^+$ and 3^+), and may be $^{236}U^*$ and $^{246}Cm^*$$_*$ ($J = 3^{\pm}$ and $4^{\pm}$).*

- TRI-effect for the $^{240}Pu^*$ transition state with $J = 1^+$ may be two-three times smaller then ones for the $^{234,236}U^*$ with the average spins $\langle J \rangle = 2, 3$: $D_{TRI} = + 0.23(9) \cdot 10^{-3}$

-Possible average values of the TRI-effects for two U isotopes have to be of the same order of magnitudes (*it is just the case in experiment*): **D_{TRI} ($^{234}U^*$) = -3.9(1)·10^{-3} and D_{TRI} ($^{236}U^*$) = 1,7(2)·10^{-3}.**
Proposed model estimates: $D_{TRI}(^{242}Pu^*) = 0.205 \cdot 10^{-3}$. $D_{ROT}(^{242}Pu^*) = 0.18^0$.

-- For the fissile nuclei $^{236}U^*$ and $^{246}Cm^*$ with the same spins of transition states the TRI effects have to have the same value and the sign (*It is just the case*): **$D_{TRI} = + 1.7(2)$)·10^{-3} and +1.2(1))·10^{-3}(!) respectively). Proposed model estimates: $D_{TRI}(^{246}Cm^*) = 4.0 \cdot 10^{-3}$. $D_{ROT}(^{246}Cm^*) = - 0.083^0$.**

- **Phenomenon of ROT-effect is much more easy to understand in the frameworks of semi classical model of rotation as in value so in the sign** *(rotation direction around polarization axis).*

- **It seems to be interesting to analyze more carefully ROT-effect in $^{240}Pu^*$ fission where only one polarized transition state takes part** (*$J_{1,2} = 1^+, 0^+$. Admixture of the 1^+ state is about 33% . Average distances between 1^+ and 0^+ levels are about 3 eV and 14 eV respectively).*

- **At the same time, the main statement of the quantum-mechanical consideration** *(V. Bunakov and S. Kadmensky)* **consists in the conclusion that ROT-effect came into existence only as a result of the neighbouring transition states interference !**

THANK YOU FOR ATTENTION