Effect of Rotation of Heavy Nucleus in the Fission by the Cold Polarized Neutrons

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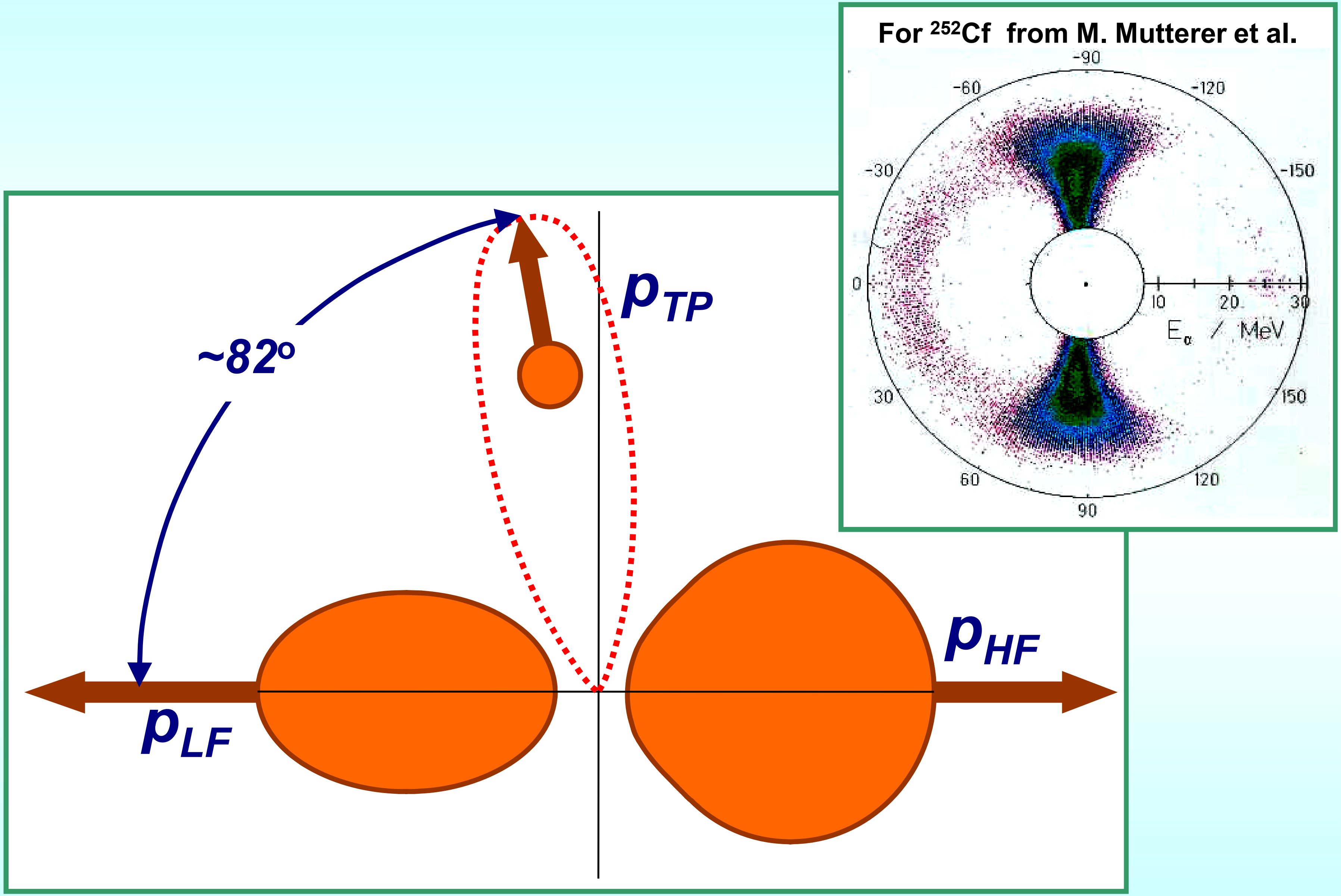
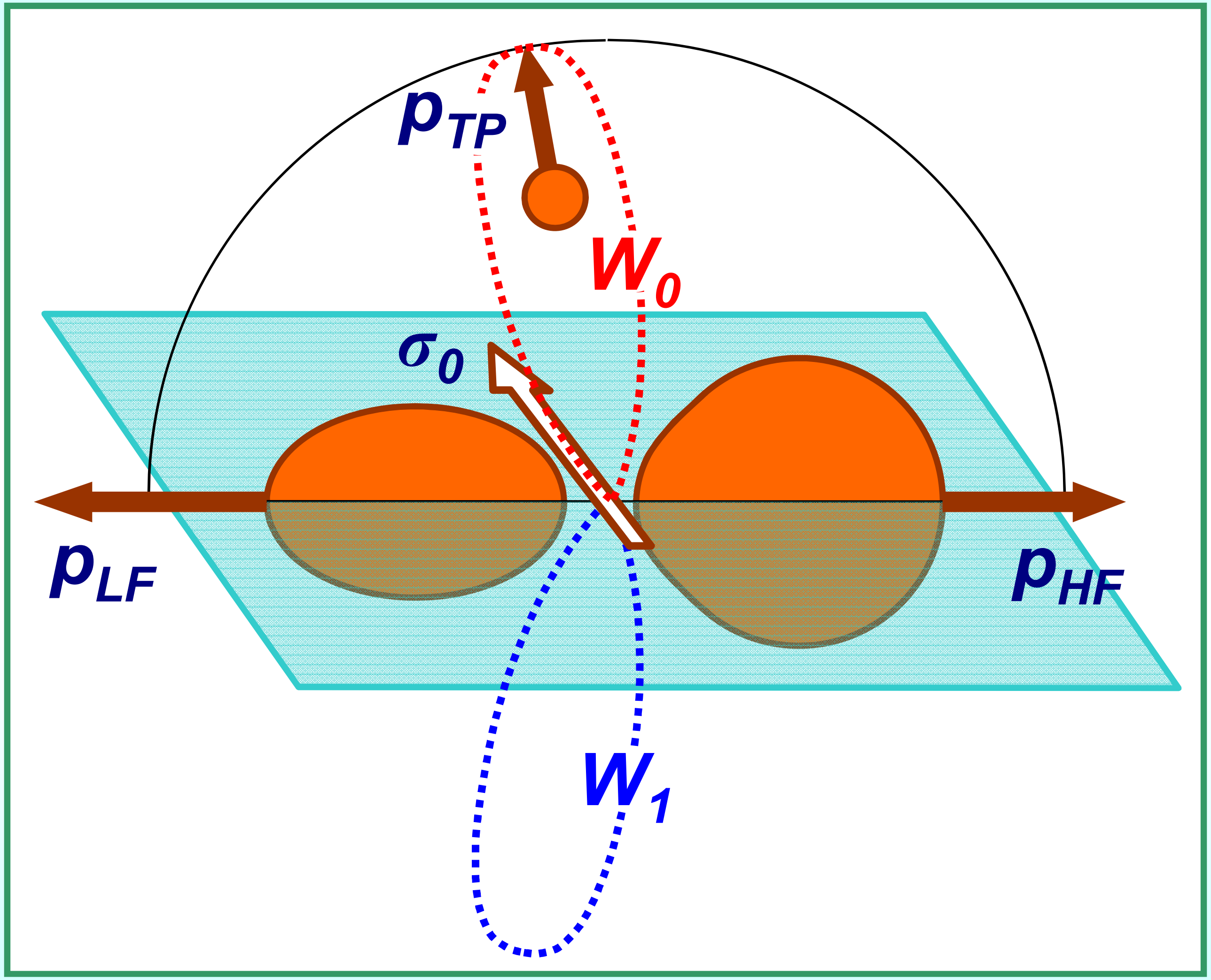
Introduction



Ternary fission by polarized neutrons



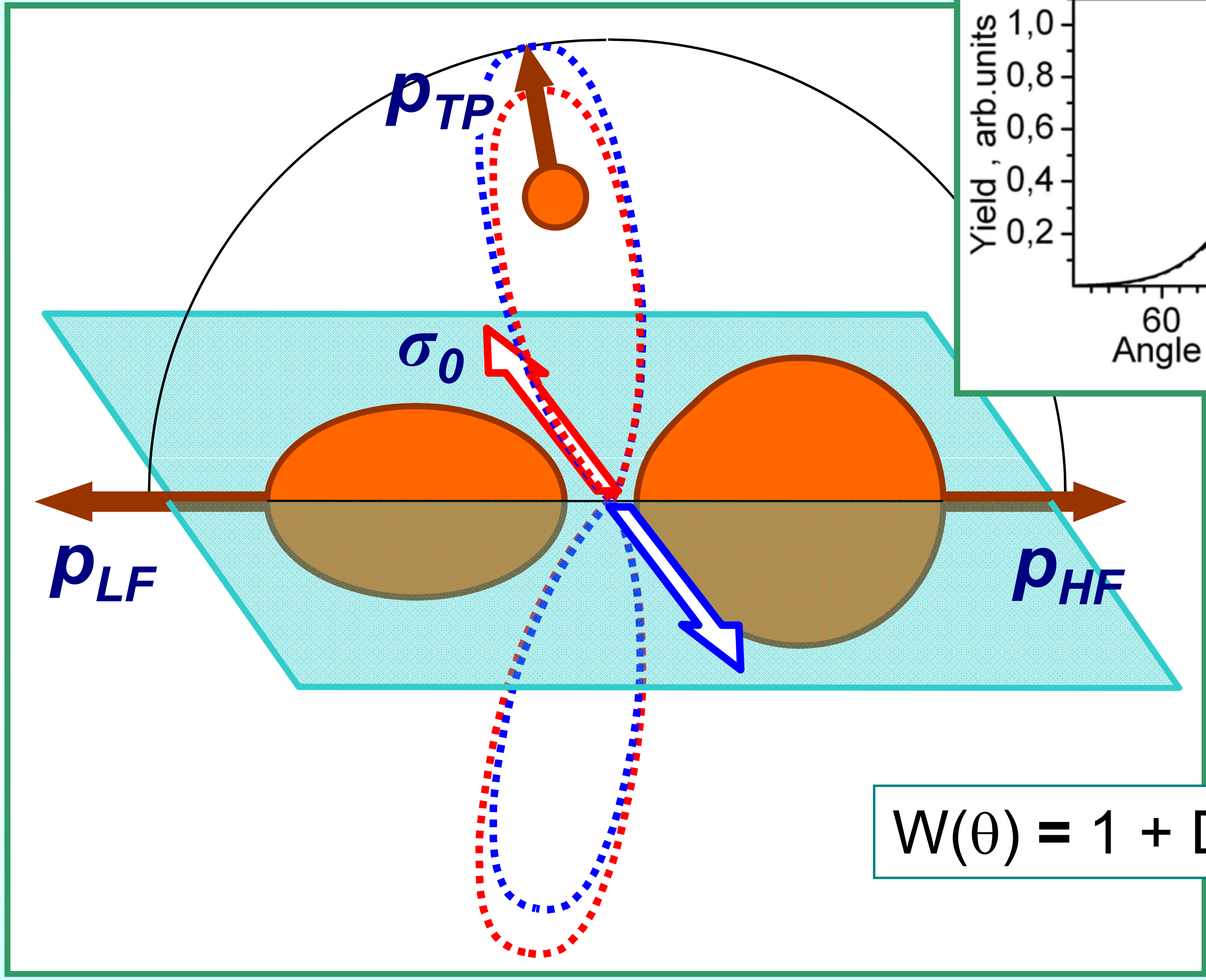
What happens if we reverse the spin?

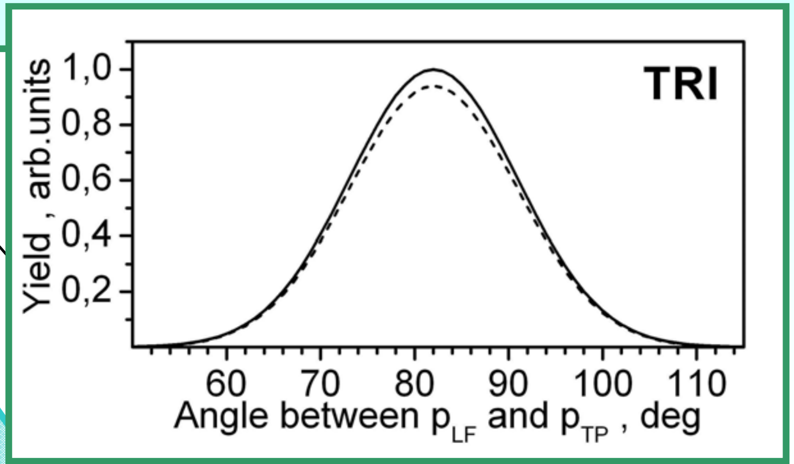
The angular distribution of the LCP may be changed!

$W(\Omega) \sim \boldsymbol{\sigma_n} \cdot [\mathbf{p_f x p_{TP}}]$

(K. Schreckenbach, 1988)

TRI-effect

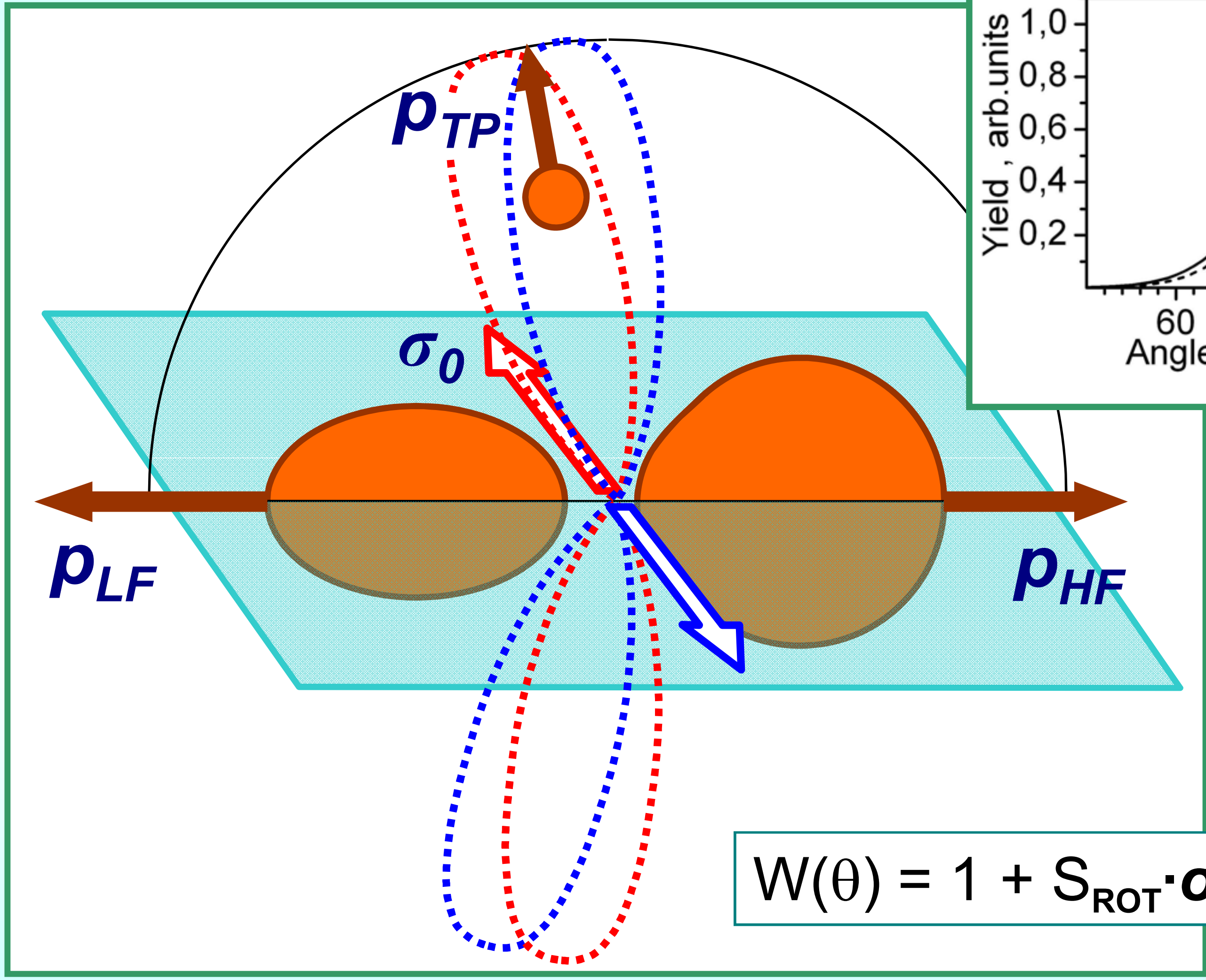


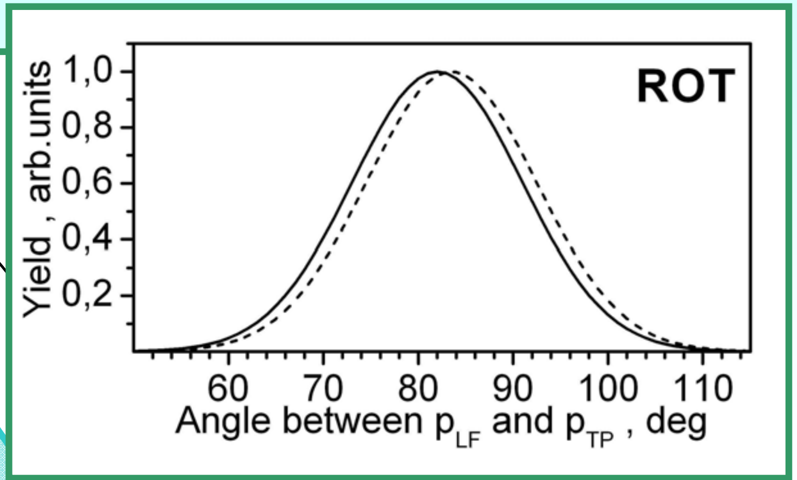


Bla-bla-bla

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

ROT- effect





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

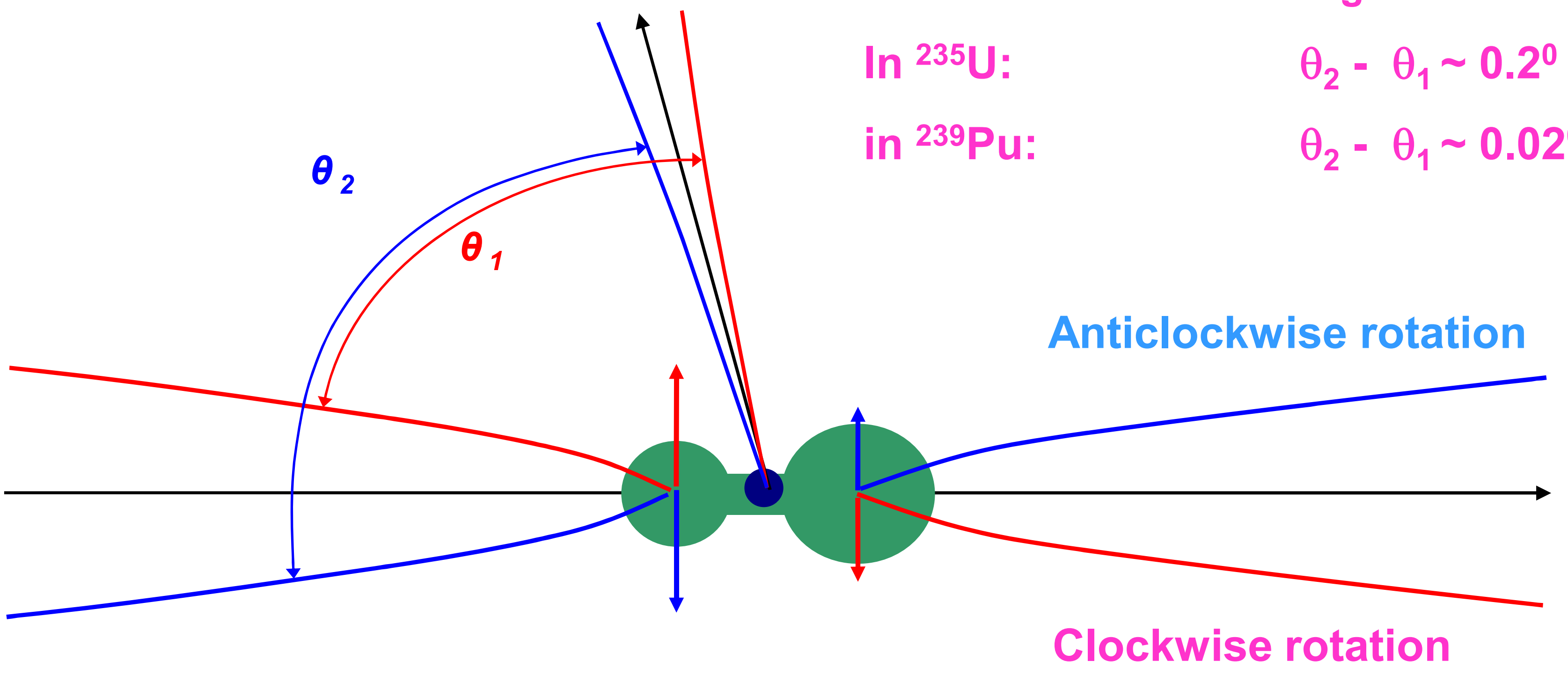
Schematic diagram of ROT effect appearance in ternary fission

(Shift of LCP angular distributions)

Observed shift of LCP angular distribution

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

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

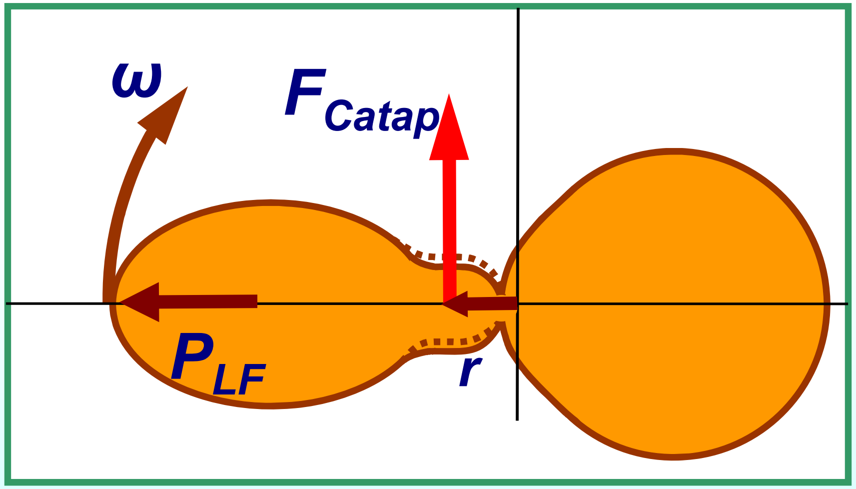


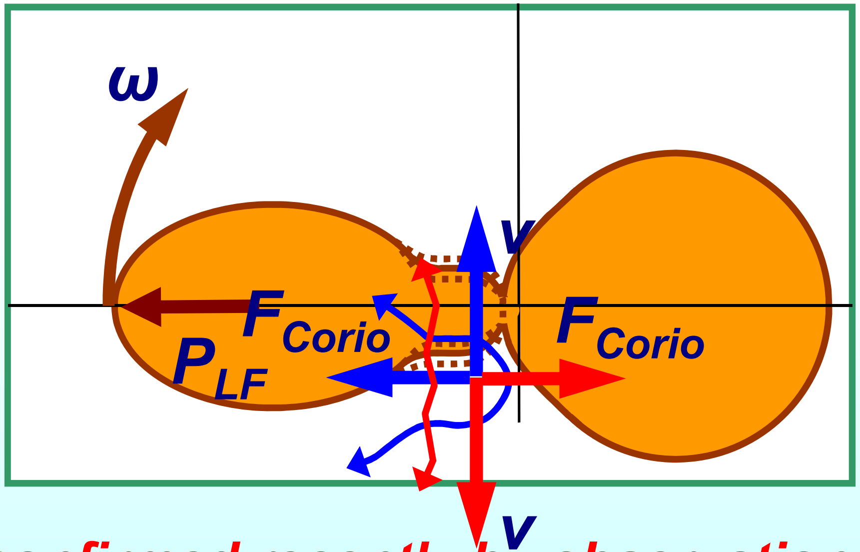
Main forces acting in rotating system

- **ROT: motion in Coulomb field <u>after scission</u> of rotating nucleus, direct indicator of the rotation, allow to determine the velocity and direction of the rotation**
- **TRI: influence of the rotation onto axial symmetry in the neck just before rupture or directly at rupture moment**

$$F_{Catap} = m \cdot \left[r \times \frac{d\omega}{dt} \right]$$

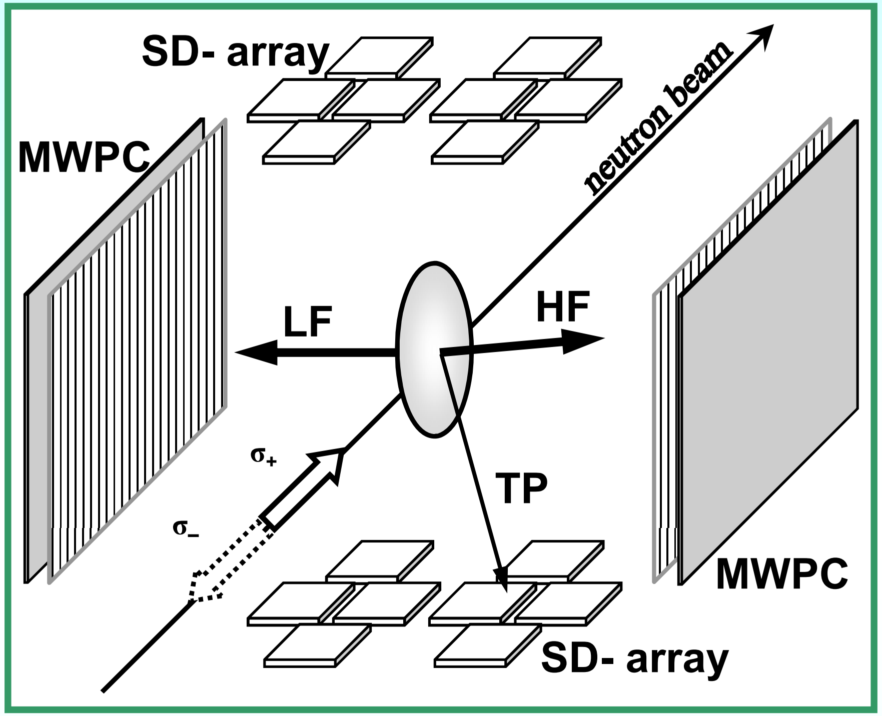
$$F_{Cori} = -2m \cdot [v \times \omega]$$





Rotation of the system had been confirmed recently by observation of "ROT-effect" for γ-rays from fragments in $^{235}U(n,f)$ **(Danilyan et al.)**

Experimental method



- **Measurement of all involved angles:**

✓Diodes size ~30x30 mm²

✓Position sensitive MWPCs (~ 2 mm)

- **Spectroscopy of fission products:**

✓Energies of TPs,

✓Masses and energies of FFs from times of flight

- **Neutron spin flip frequency 1 Hz**
- **Relative measurements**

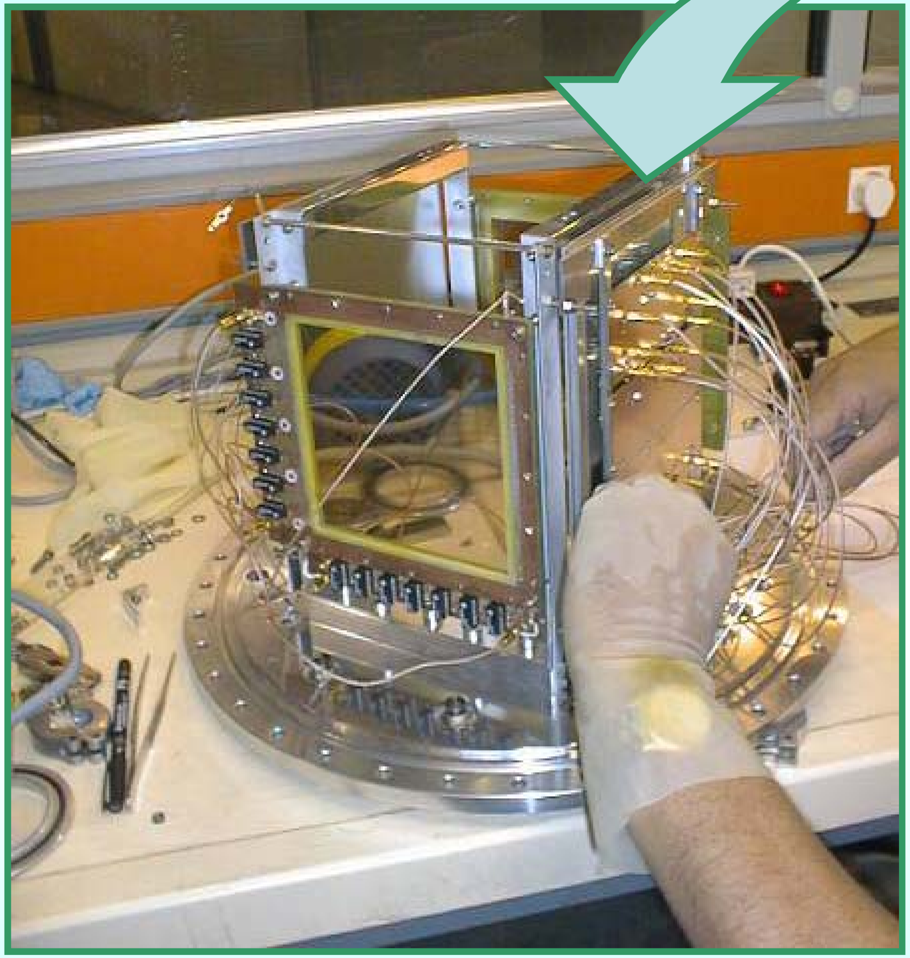
$$A(\theta,\ldots) = \frac{N^0(\theta,\ldots) - N^1(\theta,\ldots)}{N^0(\theta,\ldots) + N^1(\theta,\ldots)}$$

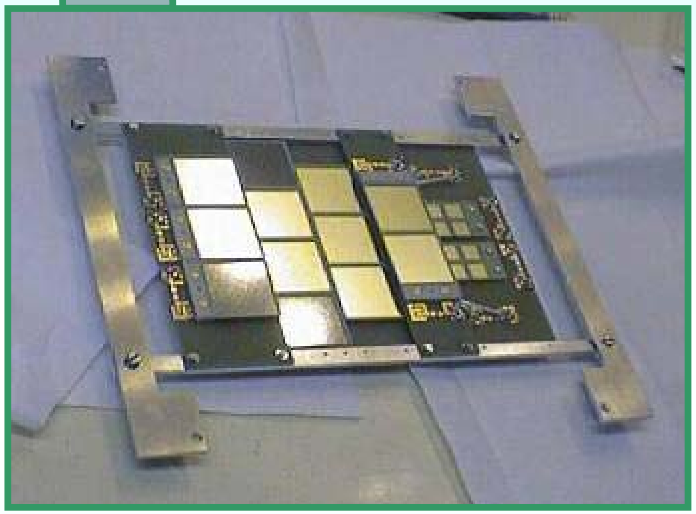
- **Control and suppression of false setup asymmetries:**

✓Comparing of *A* obtained for events recorded by symmetrical detector combinations

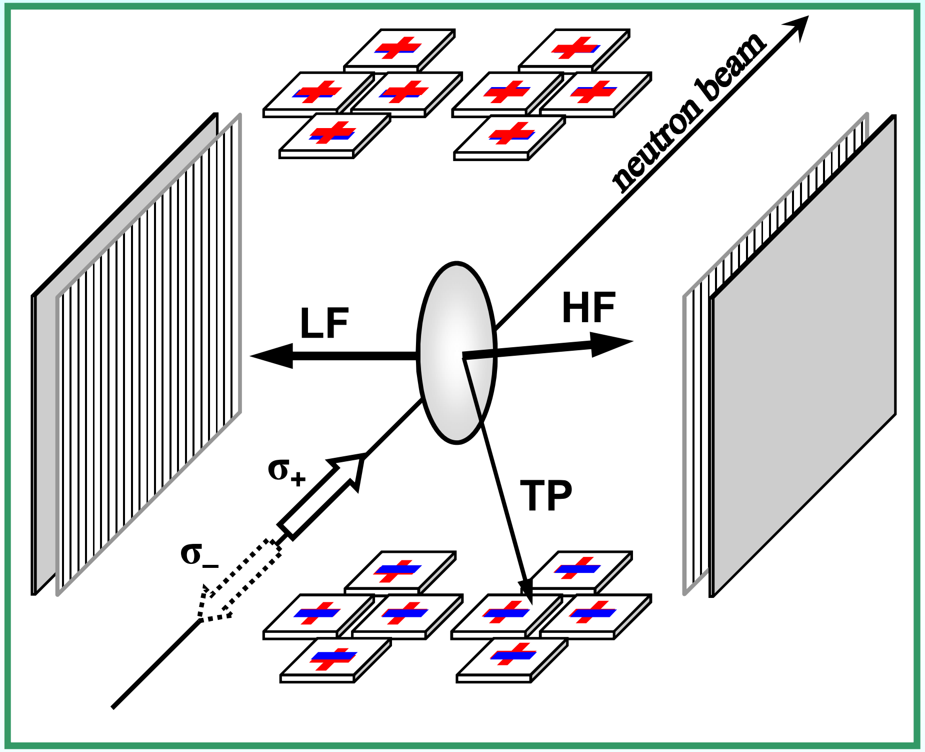
✓Depolarized neutrons beam

The set-up





The TRI-asymmetry in the counts rates



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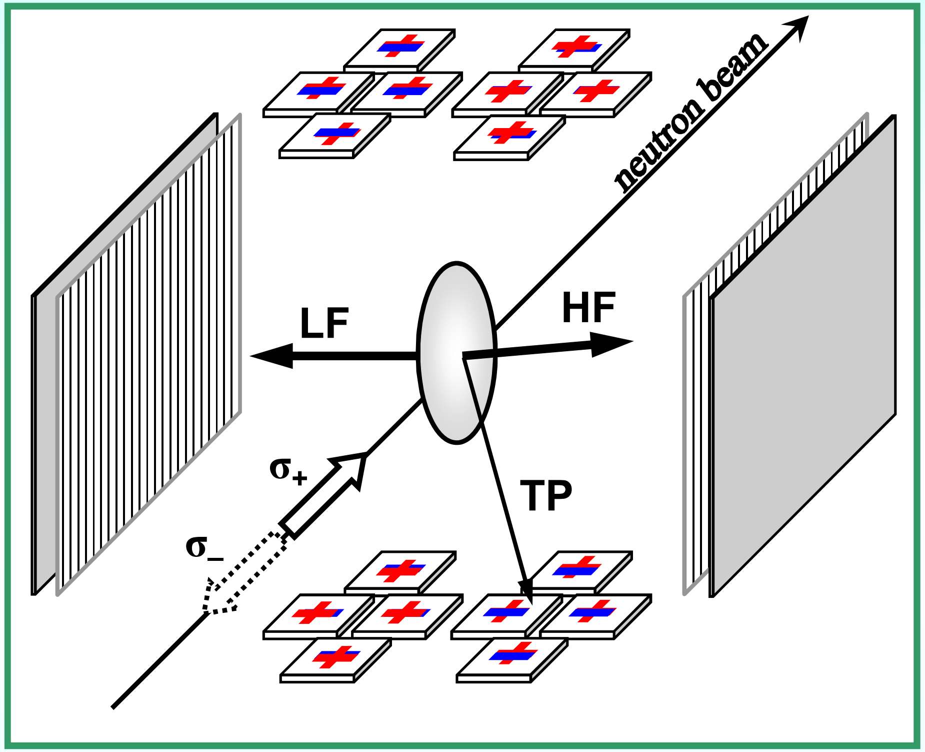
The ROT- asymmetry in the counts rates



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Dependences of the Asymmetries on LF-LCP angle

$$A(\theta) = S_{ROT} \cdot \left(\frac{Y'(\theta)}{2 \cdot Y(\theta)} \right) + D_{TRI} \qquad A(\theta) = \frac{N^0(\theta) - N^1(\theta)}{N^0(\theta) + N^1(\theta)}$$

$Y(\theta)$ – the experimental angular distribution

$Y'(\theta)$ – its derivative

S_{ROT} is characteristic parameter of ROT-effect– the angular shift between TP-distributions for the two spin polarizations

D_{TRI} characterized TRI-effect – it is one half of the relative difference in total probabilities for TPs to be emitted towards the upper (lower) hemisphere for the two spin directions

Corrections:

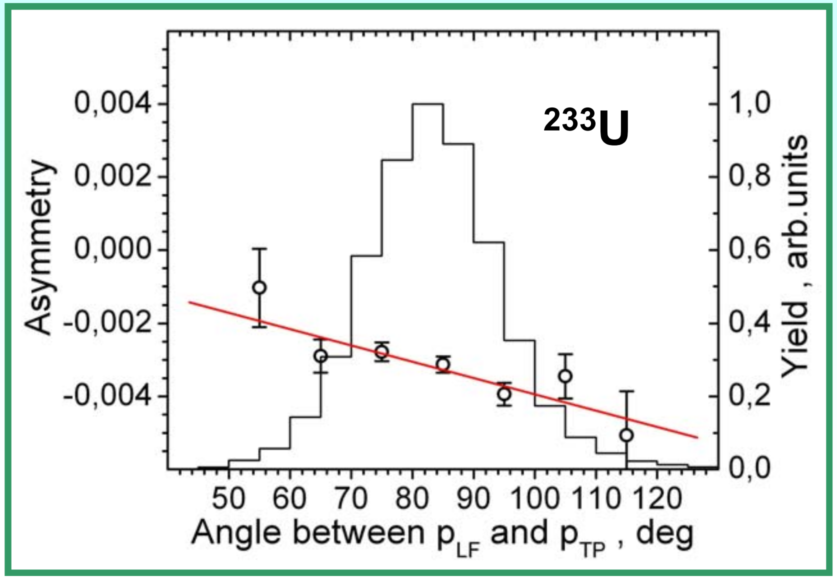
– degree of polarization of the neutron beam

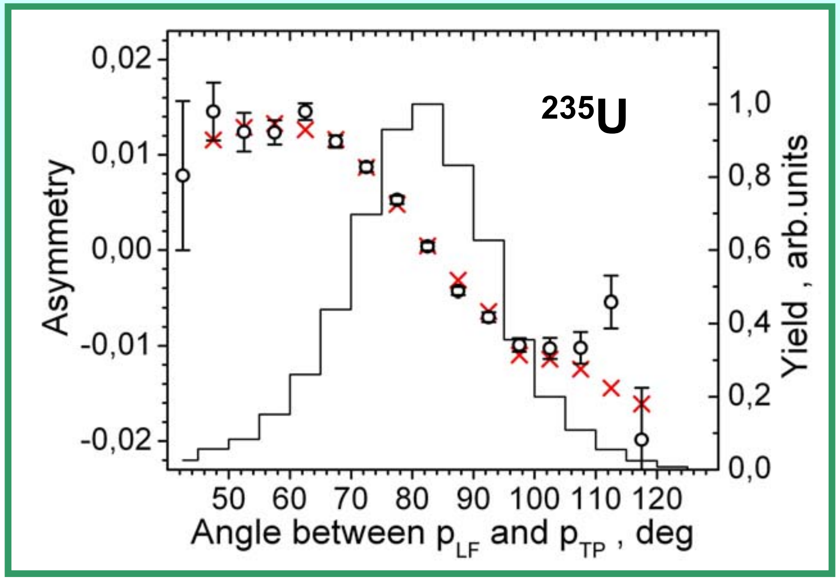
– admixture of accidental coincidences

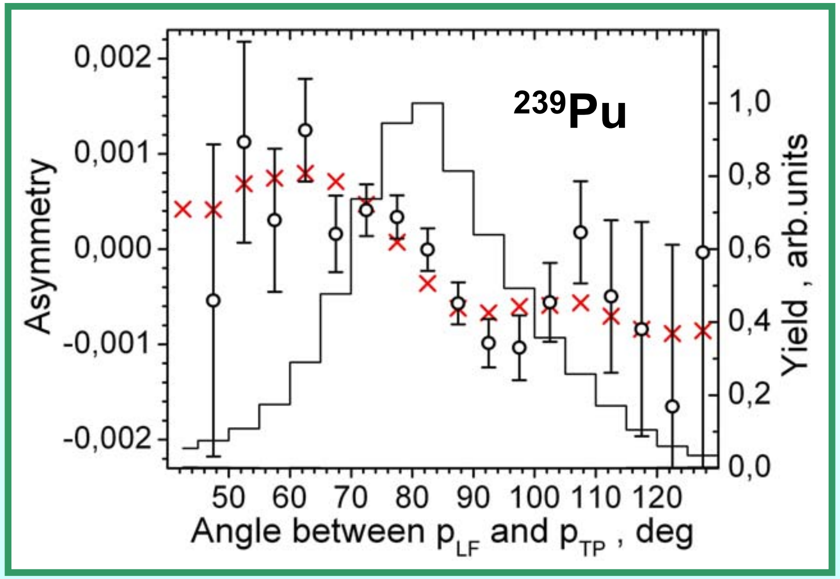
– portion of wrongly identified LF-HF

– the geometrical efficiency

Experimental asymmetry dependencies







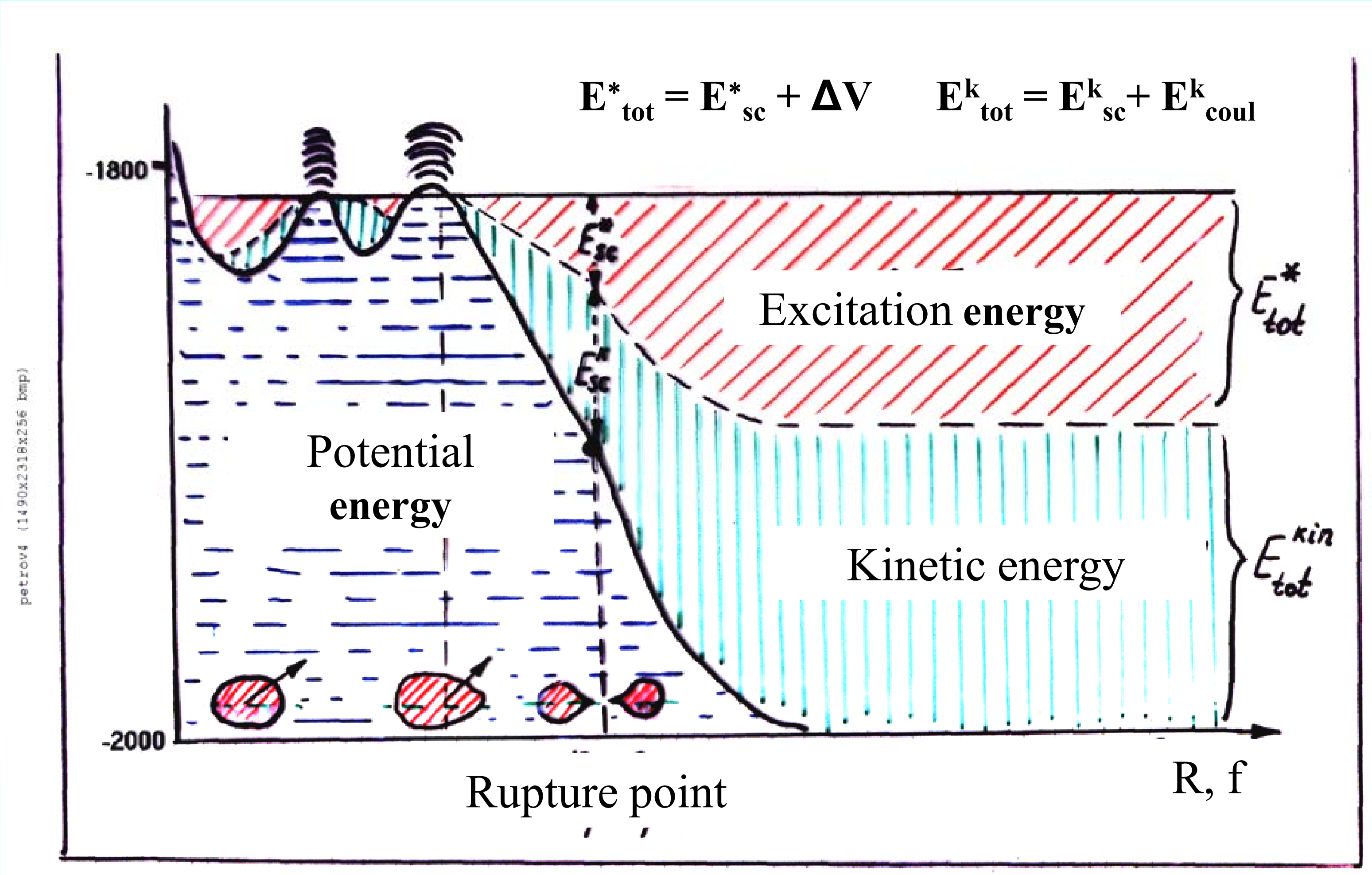
Experimental results (2005 – 2008)

TRI and ROT- effects parameters for α-particle

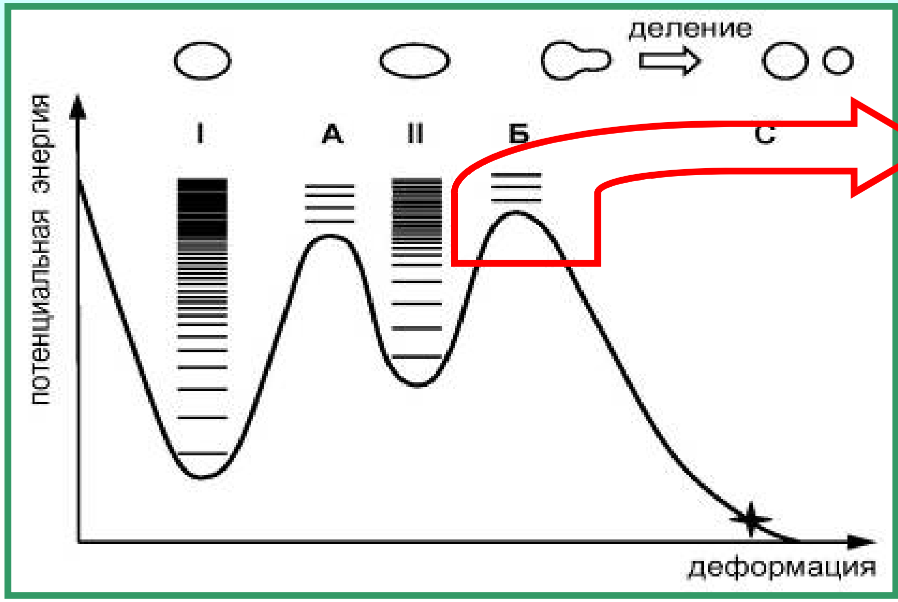
Reaction	J	S_{ROT} (°)	D_{TRI} ($\times 10^3$)
$^{235}U(n,f)$*	3^-, 4^-	(0.215 ± 0.005)	$+ (1.7 \pm 0.2)$
$^{233}U(n,f)$*	2^+, 3^+	$(0.02 \div 0.03)$	$-(3.90 \pm 0.12)$
$^{245}Cu(n,f)$	2^+, 3^+	-	$(1,30 \pm 0.12)$
$^{239}Pu(n,f)$	0^+, 1^+	(0.020 ± 0.003)	$-(0.23 \pm 0.09)$ (2008) $-(0.08 \pm 0.11)$ (2002)

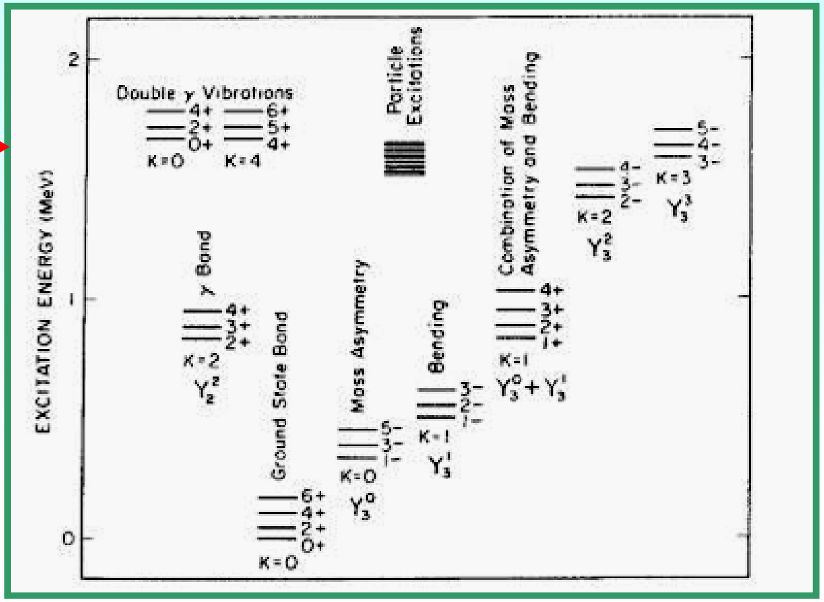
* In the cases of $^{233,\,235}U(n,f)$ D_{TRI} ($\times 10^3$) for tritons were measured being equal: - (2.9 ± 0.5) and (0.9 ± 0.6) respectively

Qualitative picture of fission process



Model of ROT-effect





Semi-classical estimation of fissioning system rotation momentum

$$R^2 = \omega^2 \mathfrak{I}_\perp^2 = \hbar^2 \cdot (J(J+1) - K^2)$$

Trajectory calculations

- **Starting scission configuration was optimized to describe known experimental angular and energy distributions of ternary particles.**
- ***Main steps:* $\sigma(J,K)$ ➔ R ➔ ω ($R \sim 0.7\ h$ for ^{235}U)**
- **To describe the main characteristics of ROT-effect ones need to know the ratios of different resonance cross-sections for two transition states (J_i and K_{ik})**

Ranges of the main parameters used in trajectory calculations of LCP emission by rotating fissioning nucleus (~$2.5 \cdot 10^9$ trajectories)

Input parameter	Symbol	Value	Unit
Mass ratio	M_H / M_L	*1.44*	
Distance between fragments	d	*20.2* (18 ÷ 22)	10^{-13}cm
Initial velocity of heavy fragment	V_H	*0.26*	10^9 cm/s
Initial distance of LCP from heavy fragment	x_α	*In between fragments*	10^{-13}cm
Initial distance of LCP from fission axis	y_α	*0 ÷ 1.83*	10^{-13}cm
Initial energy of LCP	E_α	*0.1 ÷ 1.3*	*MeV*
Initial angle of the LCP with respect to the fission axis	θ_α	*0 ÷ 180*	*degree*

TRI and ROT effects parameters

Reaction	J	S_{ROT} (°)	D_{TRI} (×10³)
^{235}U(n,f)	3^-, 4^-	0.215 ± 0.005	+1.7 ± 0.2
^{233}U(n,f)	2^+, 3^+	0.02 ÷ 0.03	–3.90 ± 0.12
^{239}Pu(n,f)	0^+, 1^+	0.020 ± 0.003	–0.23 ± 0.09

- **Variation of ROT-effect values**: may be explained by different mixtures of (*J,K*) channels in the proper cross-sections
- **Variation of TRI values** : connected with interplay between Coriolis and Catapult forces. Catapult forces are appeared always if $d\omega/dt \neq 0$, while values of Coriolis forces depend on vibrations related with different K values). Higher K ➔ lower R!

Results of the ROT-effect shift calculations in $^{235}U(n,f)$ (in degrees)

J = 4 \ J = 3	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

$\sigma(J=4)/\sigma(J=3) = 1.8$ *(Yu. Kopatch et al)*

Results of the ROT-effect shift calculations in $^{233}U(n,f)$ (in degrees)

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

$\sigma(J=4)/\sigma(J=3) = 1.5$

Results of the ROT-effect shift calculations in ^{239}Pu(n,f) (in degrees)

J = 0 \ J = 1	K = 0
K = 0	0.054
K = 1	0.027

0.027 if σ(J = 0)/σ(J = 1) = 1.53
(from the old BNL-data

But σ(J = 0)/σ(J = 1) = 4.42
(from the new BNL-data)!!!!

J	Old data
0	- 0.576
1	+ 0.296
1	+ 7.820

J	New data
1	- 150.46
1	- 15.460
0	- 6.917
0	- 0.219
1	+ 0.296
1	+ 7.820

The data analysis had shown very high sensitivity of the results to the main parameters of fission process dynamics

Nearest perspectives

1. TRI and ROT-effects measurements in $^{234}U^*$ (J =2+, 3+) with better accuracy

2. Compare TRI and ROT-effects in $^{234}U^*$ and $^{242}Pu^*$ having the same spins of transition states (J =2+, 3+)!

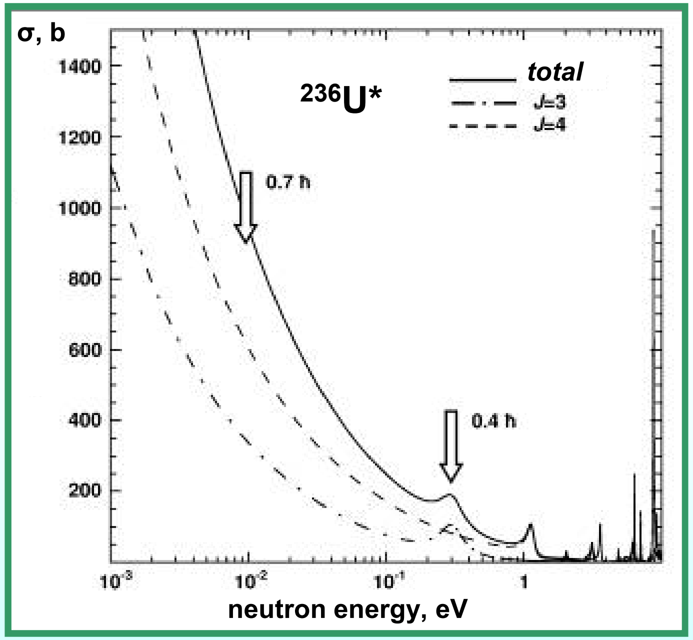
3. Compare TRI and ROT-effects in the pair $^{236}U^*$ and $^{246}Cm^*$ (J = 3, 4)

4. Direct comparison TRI- и ROT-effects values in $^{235}U(n,f)$ reaction at the energies of cold neutrons and in vicinity of 0.3 eV resonance

6. Investigate TRI- и ROT-effects values for the protons in ternary fission of ^{235}U

7. Analysis of possibility to study TRI- и ROT-effects in ternary fission of polarised ^{235}U

8. Continuation of the search investigations of TRI- и ROT-effects for fission neutrons and γ-rays in the reactions $^{233,235}U(n,f)$ ^{239}Pu

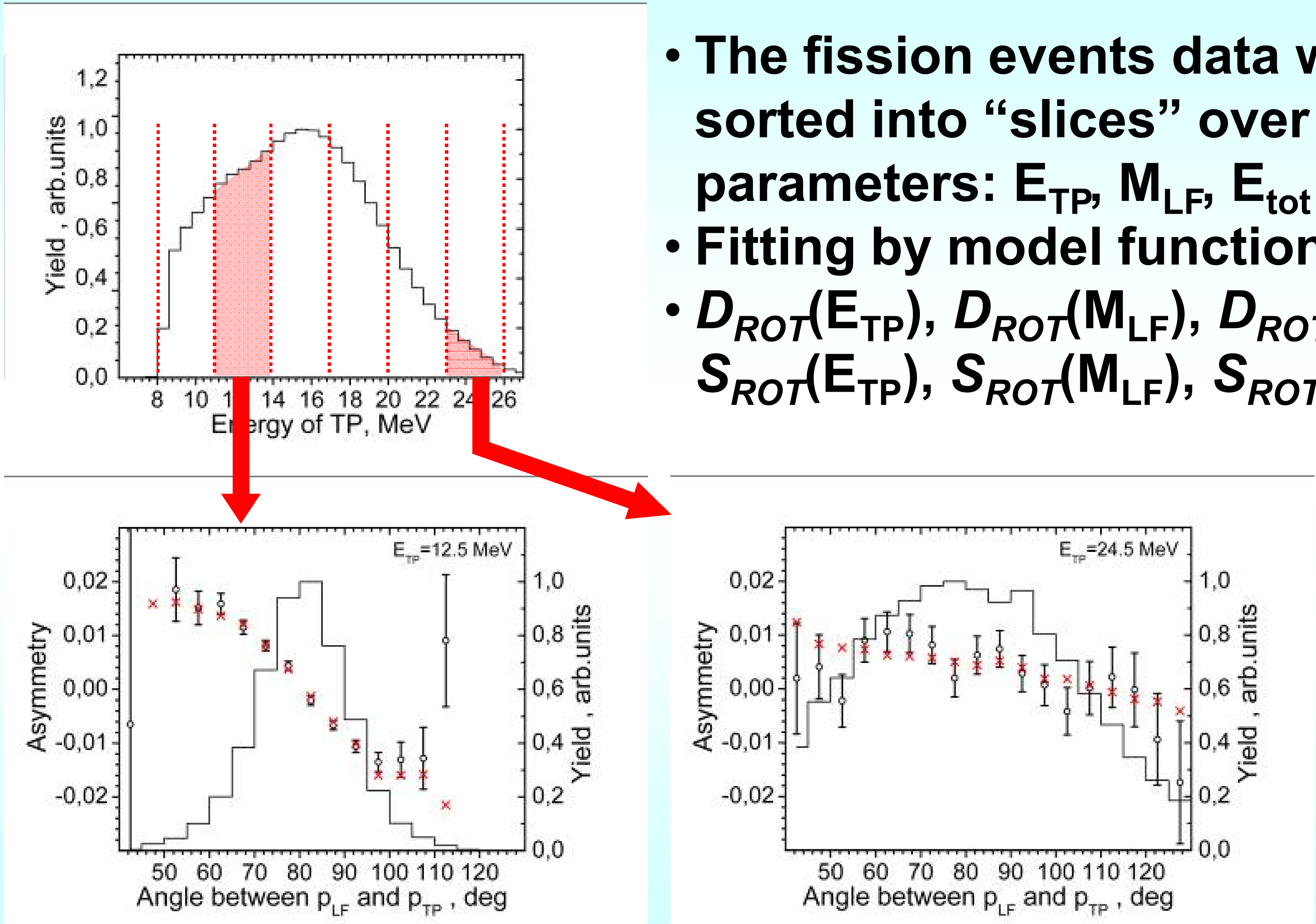


Conclusion

- **The new effects of T-odd asymmetry of the LCP emission in ternary fission being observed in the frameworks of the wide international collaboration opened the new and perspective possibilities for the studies of low energy fission dynamics.**
- **Physical results have being obtained already in the first investigations demonstrated close connections of the main characteristics of the ROT and TRI-effects with the properties of transition states and parameters of fission products near the rupture point.**
- **Taking into account the decisive role of the transition states parameters in the T-odd effect mechanism of appearance of particular interest is further development in the nuclear data acquisition for low energy neutrons initiating the fission of $^{233,235}U$ and ^{239}Pu.**
- **Detailed theoretical investigations of the T-odd asymmetry phenomena being attractive use for experimental data analysis are a prime necessity!**

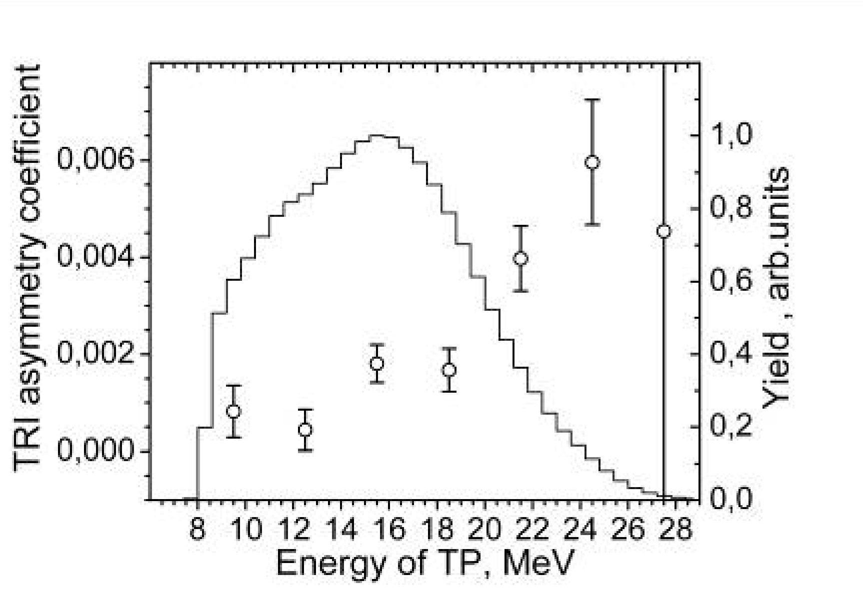
Thank you for attention!

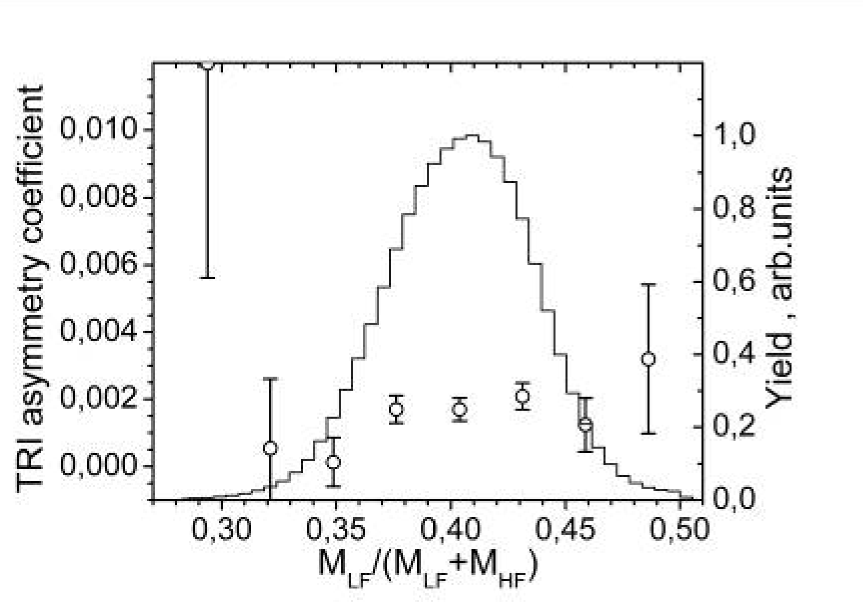
Fitting for individual slices of the parameters

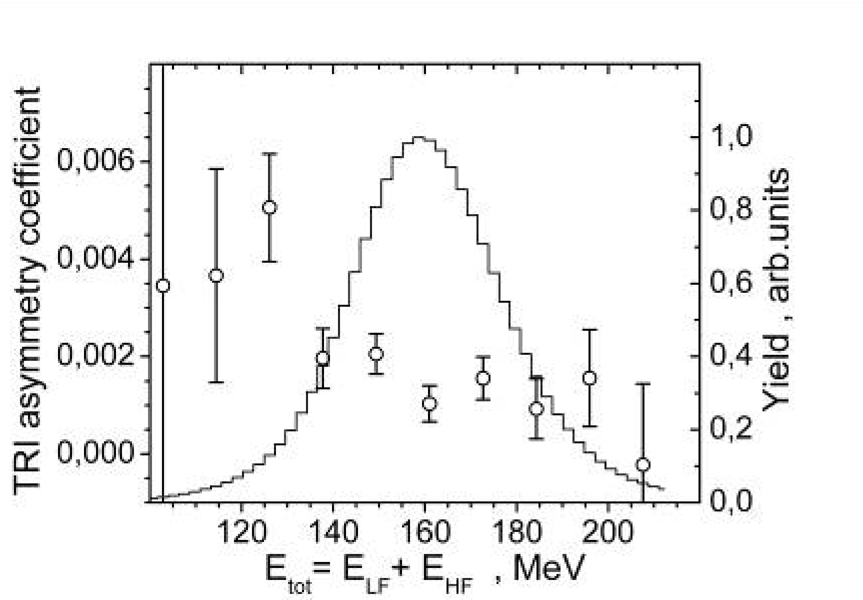


- **The fission events data were sorted into "slices" over parameters: E_{TP}, M_{LF}, E_{tot}**
- **Fitting by model function**
- **$D_{ROT}(E_{TP})$, $D_{ROT}(M_{LF})$, $D_{ROT}(E_{tot})$, $S_{ROT}(E_{TP})$, $S_{ROT}(M_{LF})$, $S_{ROT}(E_{tot})$**

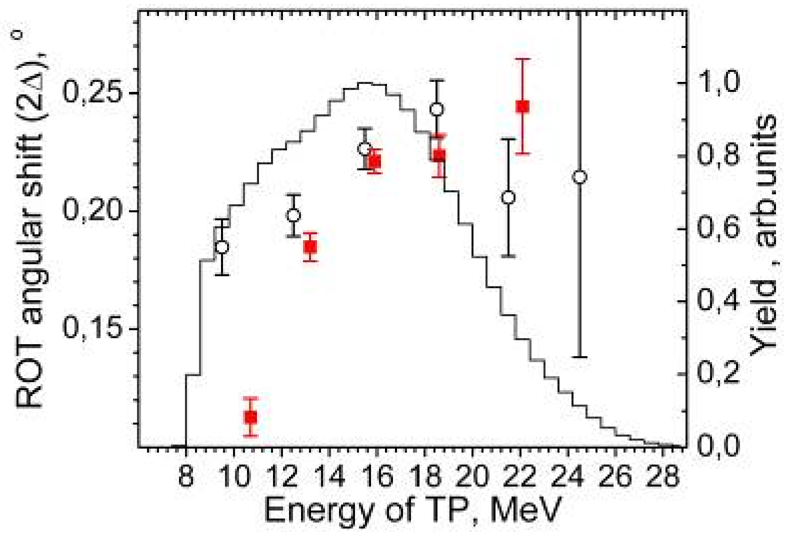
TRI-effect in ^{235}U (D_{TRI} "SCALING" coefficient)

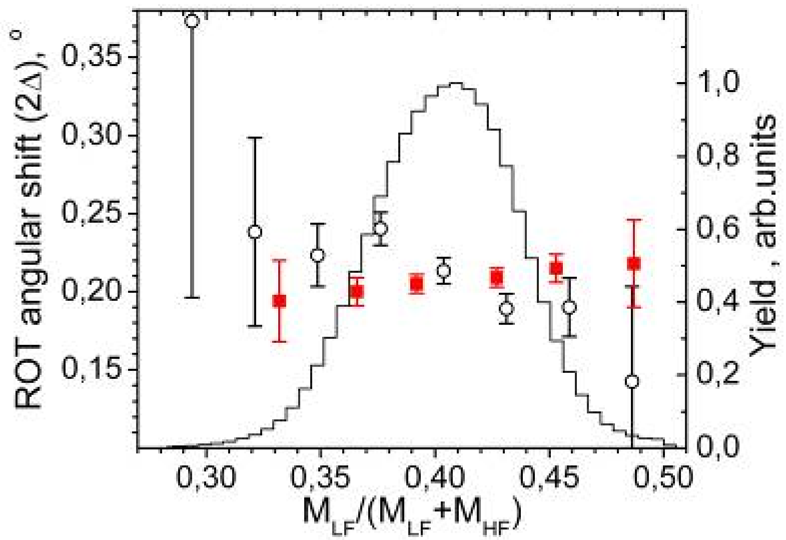


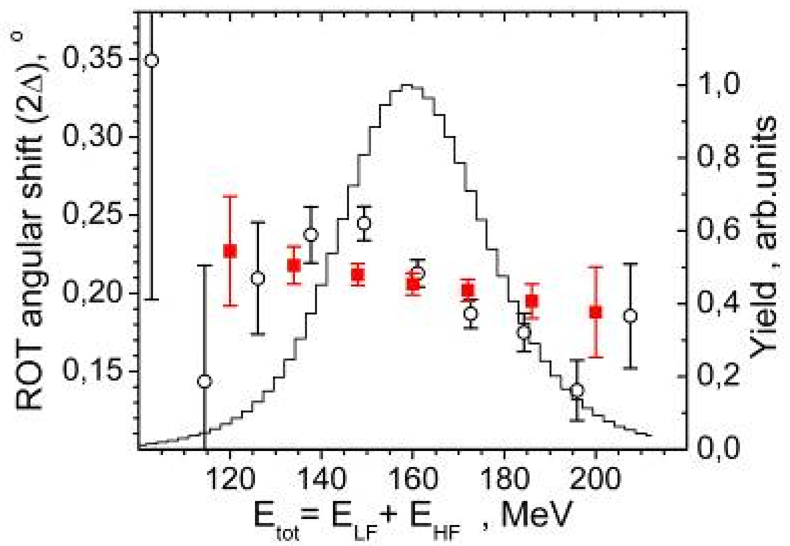




Trajectory calculations of ROT effect in ^{235}U



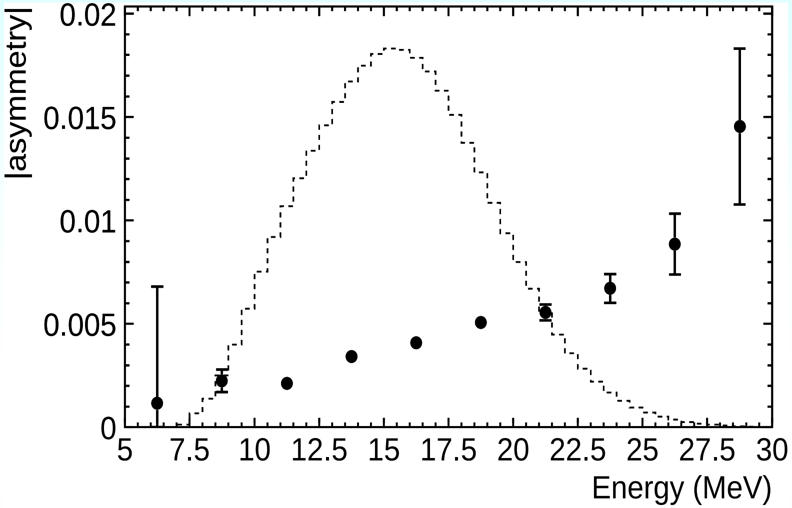


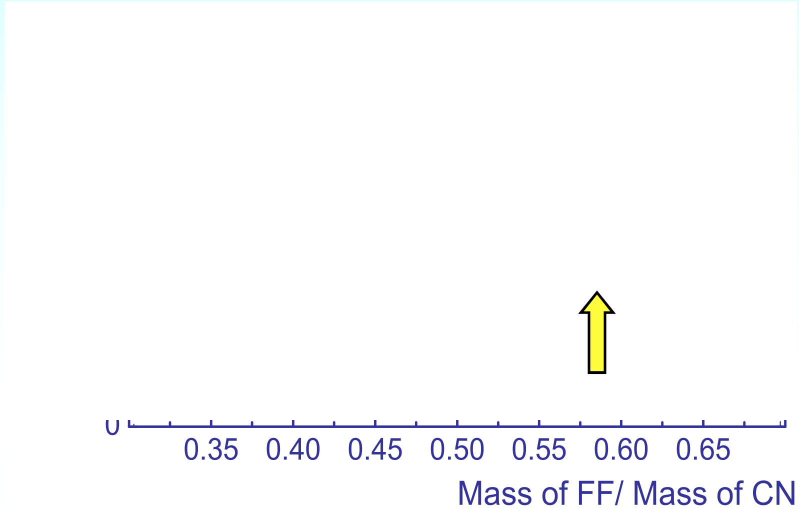


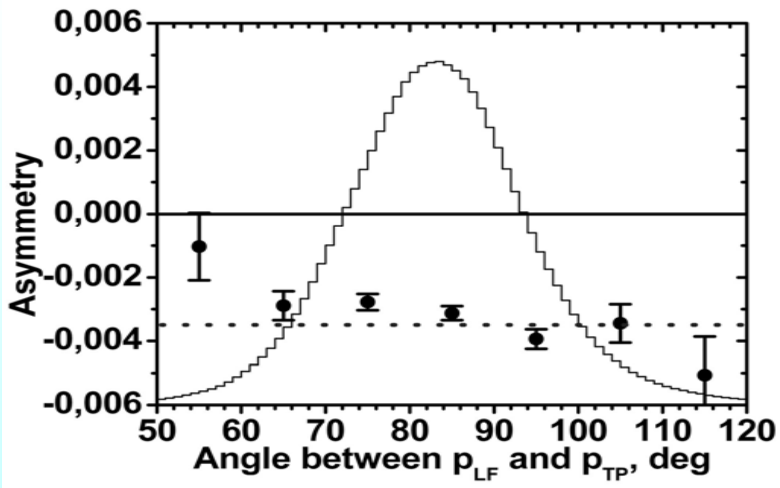
Effective momentum *R* was calculated from: $\sigma(J^{4-}) / \sigma(J^{3-}) = 1.8$ (Kopach et al.) for J^{4-} $K = 0$ and for J^{3-} $K = 2$ were taken

Основные экспериментальные результаты (TRI эффект в ^{233}U) (2000-2003 г.)

$\langle D \rangle_{\alpha} = -3.9 \pm 0.12 \times 10^{-3}$ и $\langle D \rangle_{p\text{-}d\text{-}t} = -2.9 \pm 0.5 \times 10^{-3}$

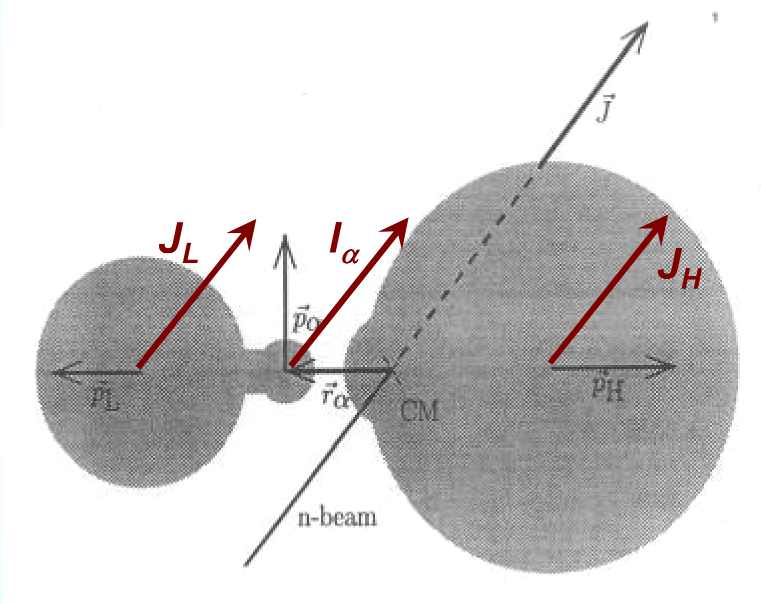




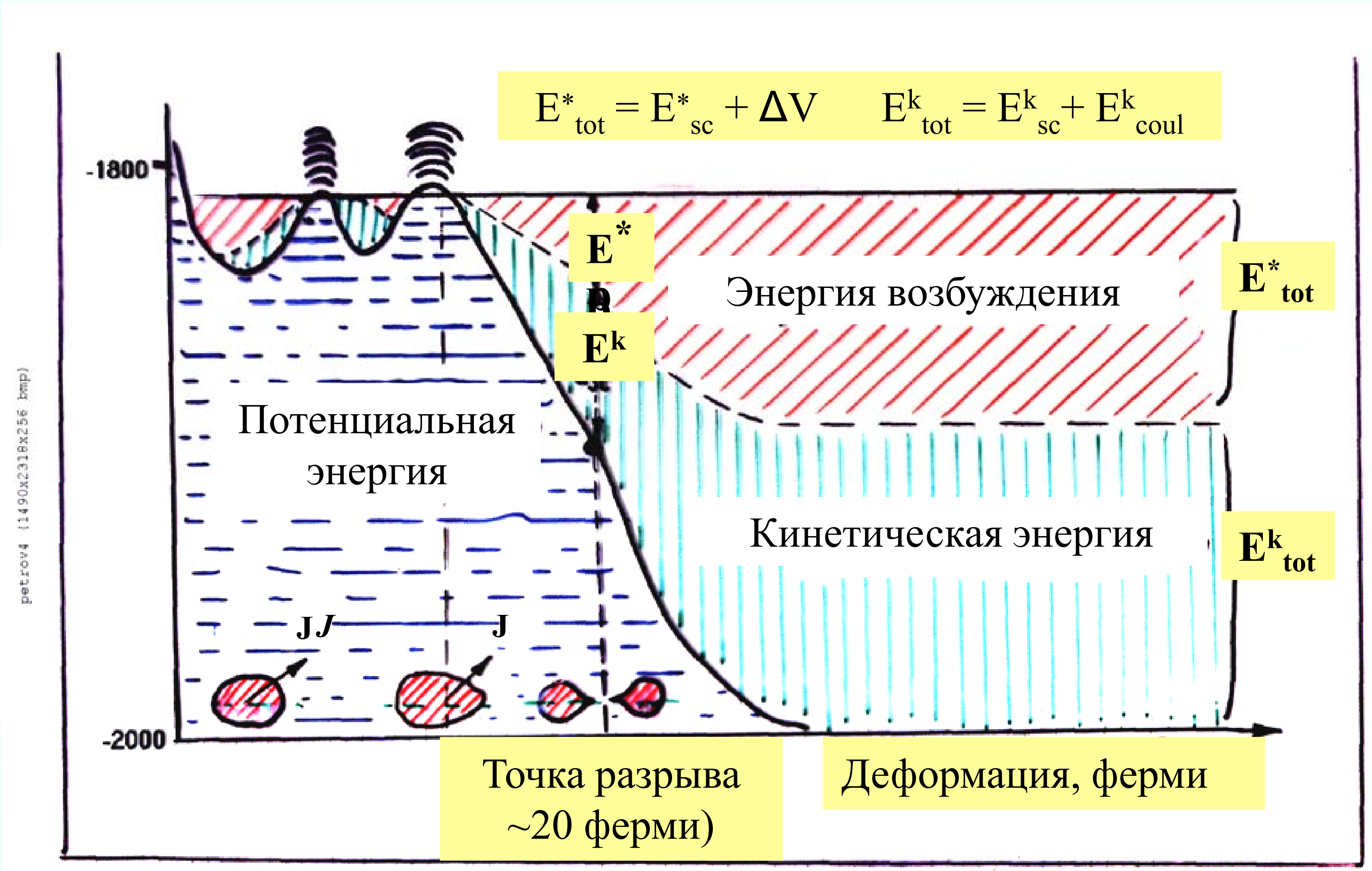


Статистическая модель Бунакова для TRI- асмметрии

- Есть некоторый вклад начального спина нейтрона в соответствующую проекцию углового момента осколков в момент деления
- ТР уносит угловой момент из делящейся системы
- В зависимости от направления эмиссии ТР, соответствующая проекция углового момента осколков увеличивается или уменьшается
- плотность уровней системы зависит этой проекции, а в статистической модели плотность уровней определяет вероятность



КАЧЕСТВЕННАЯ КАРТИНА ПРОЦЕССА ДЕЛЕНИЯ



Наиболее актуальная проблема современной физики деления – динамика спуска сильно деформированного ядра с барьера и его разрыв!

Theoretical equation for T-odd asymmetry coefficient in statistical model (*V. Bunakov et al.*)

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

- J — *Spin of compound nucleus*
- l_α — *Angular momentum of LCP*
- a_i — *Level density parameter*
- $P(J)$ — *Compound nucleus polarization*
- μ_{11} — *Polarization sharing between FF*
- E_{xi}^{sc} — *Internal fragment excitation*
- $\Im_i$ — *Moment of inertia*

Because of anticorrelation $\mathbf{E_{xi} = E_{ix}^{max} (1 - E_\alpha / E_\alpha^{max})}$ and if $\langle E_{xi} \rangle \sim 6$ MeV

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

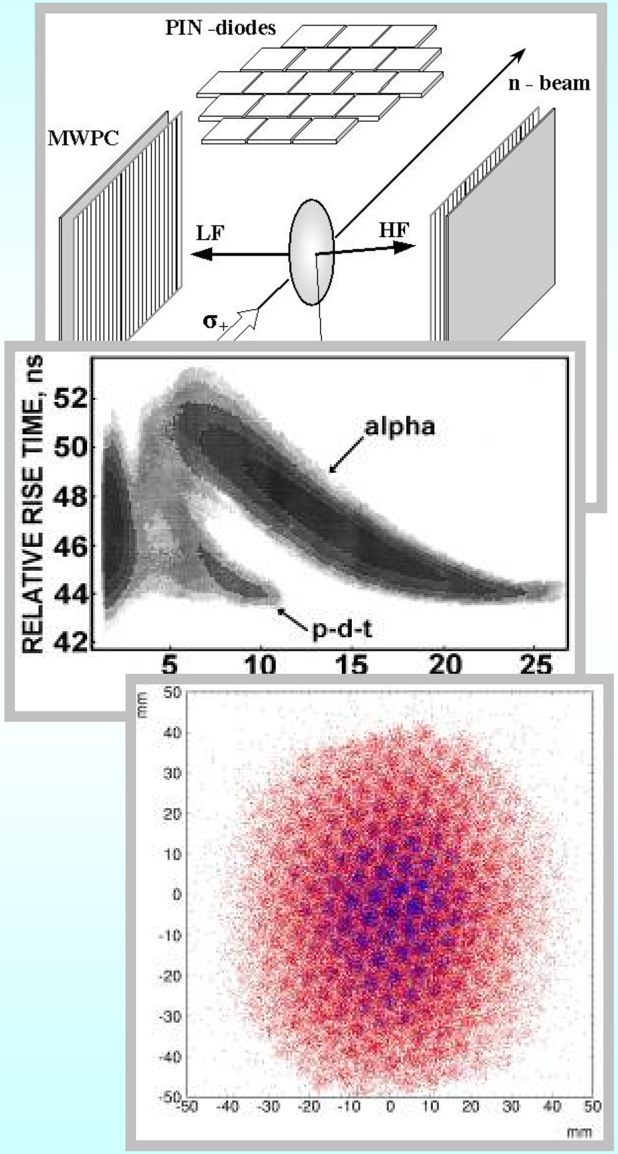
Исследование Т-нечётной асимметрии в зависимости от параметров продуктов деления

- **Нейтронный пучок (PF1 в ИЛЛ):**
  <λ> ~ 4.5Å; $\Phi_{capture}$ ~6×10^8 n/cm^{2}s; продольно поляризован ~ 94 ± 1 %; радиочастотный флиппер 1 Гц
- **Мишень ~3.4 мг ^{233}U (UF_4) ~100 мкг/см^2 на тонкой титановую пленке (~100 мкг/см^2)**
- **12 + 12 PIN диодов для TP, каждый 30 × 30 мм, толщина 380 мкм**
- **Определение типа частицы по времени нарастания сигналов с PIN диодов**
- **Координатная чувствительность MWPC (~2 мм по обеим координатам) ⇒ положение на мишени и углы ⇒ можно определить:**

– массу осколков : $M1/M2 \approx T1/T2$,

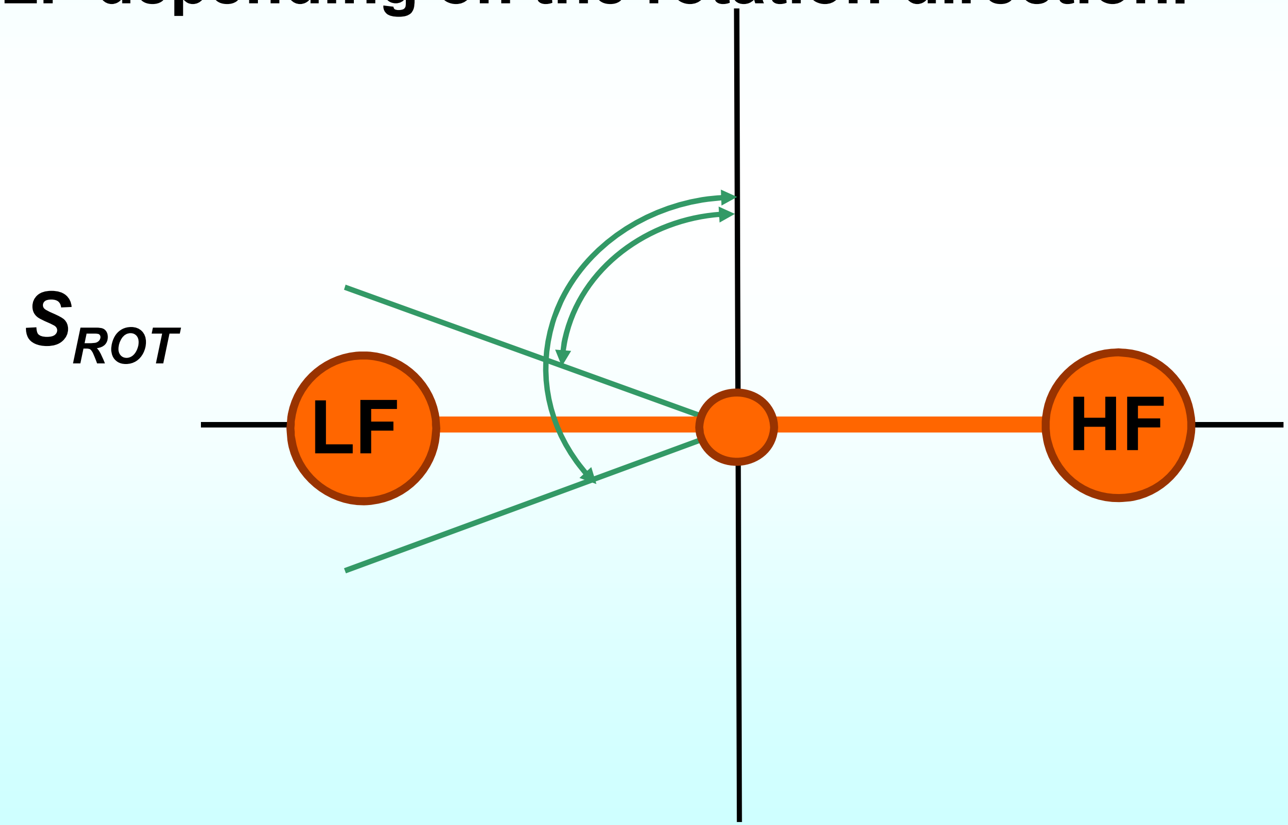
– кинетическую энергию: $E=E1+E2 \approx L2 \cdot A/2T1 \cdot T2$

(Разрешение невелико ☹, поскольку $\Delta T/T$**~1/10)**

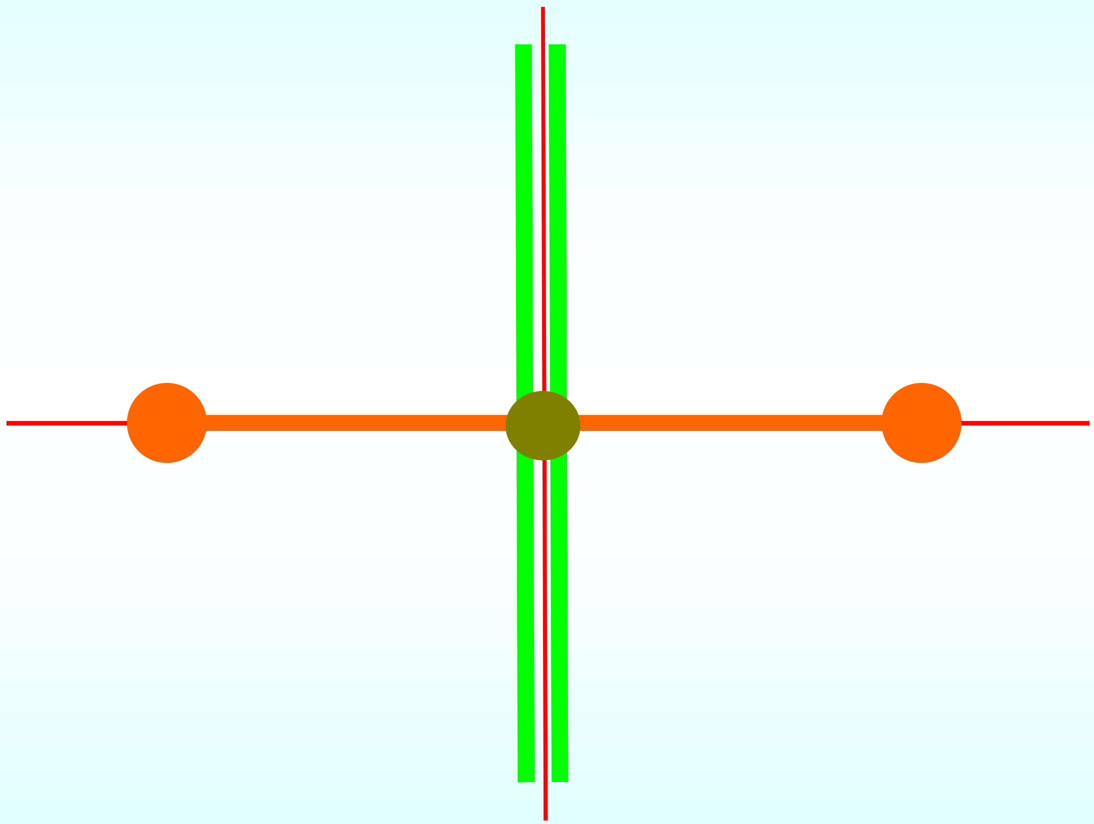


Model of ROT-effect

- The collective rotation lasts also during the acceleration phase of TPs in Coulomb field of the FFs.
- The rotation deflects the LCP trajectory in the coordinate frame linked with FFs towards or away from the LF depending on the rotation direction.



Модель ROT-эффекта



TRI-EFFECT OF T-ODD ASYMMETRY FOR THE LIGHT CHARGED PARTICLE EMISSION IN TERNARY FISSION

$W(\Omega) = 1 + \langle D_{lcp} \rangle \cdot \boldsymbol{\sigma_n}$瘢$\mathbf{p_f} \times \mathbf{p_\alpha}]$

nucleus spin / <D>	$^{234}U^*(+2, +3)$	$^{236}U^*(-3, -4)$	$^{240}Pu^*(+1, +0)$	$^{246}Cm^*(+2, +3)$
$\langle D_\alpha \rangle \cdot 10^{-3}$	$-(3.90 \pm 0.12)$	$+(1.24 \pm 0.15)$	$-(0.08 \pm 0.11)$	$+(1.30 \pm 0.48)$
$\langle D_t \rangle \cdot 10^{-3}$	$-(2.9 \pm 0.5)$	$+(0.90 \pm 0.61)$	—	—

Questions to the theory:

- Different values of TRI-effects in very similar fissioning systems
- Absence of TRI-effects in ^{239}Pu fission (relatively small spin ets)
- Very similar TRI-effects for α and t-particles with different spins

Remark: ***Search for TRI- u ROT-effects for neutrons***
will be performed in the framework of the PNPI of RAS
Program for the search and investigations so called
"scission neutrons" emitted near the rupture point.
Studies of "ROT-effect" for γ-rays will be performed in connection with a problem of large oriented moments of fission fragments.