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

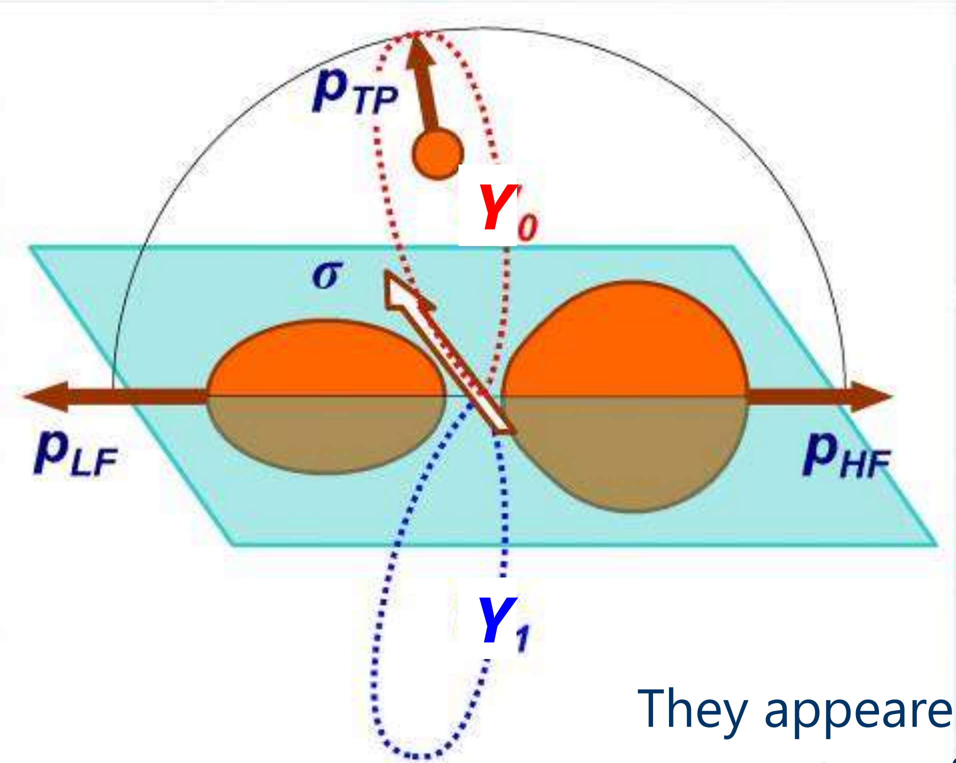
ISINN-21, Alushta, Ucraine, May 20-25, 2012

Introduction

In 2013 there will be 75 anniversary of nuclear fission discovery, but complete theory of this complex process still does not exist.

New directions and methods of researches are required.

Studies of ternary fission induced by polarized cold neutrons

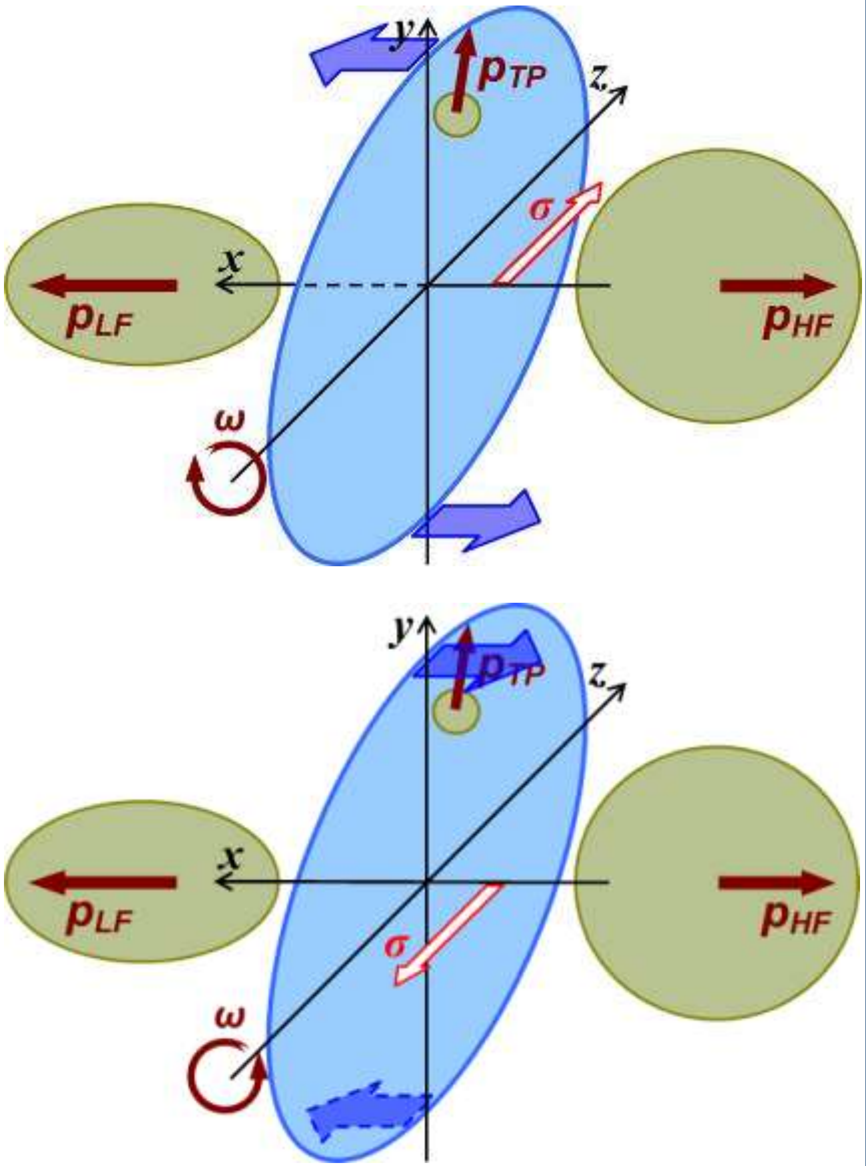


- Axial symmetry around fission axis is violated.
- $Y_1 \neq Y_0$ (~10^{-4}-10^{-2})
- Angular distribution is changing by spin flipping

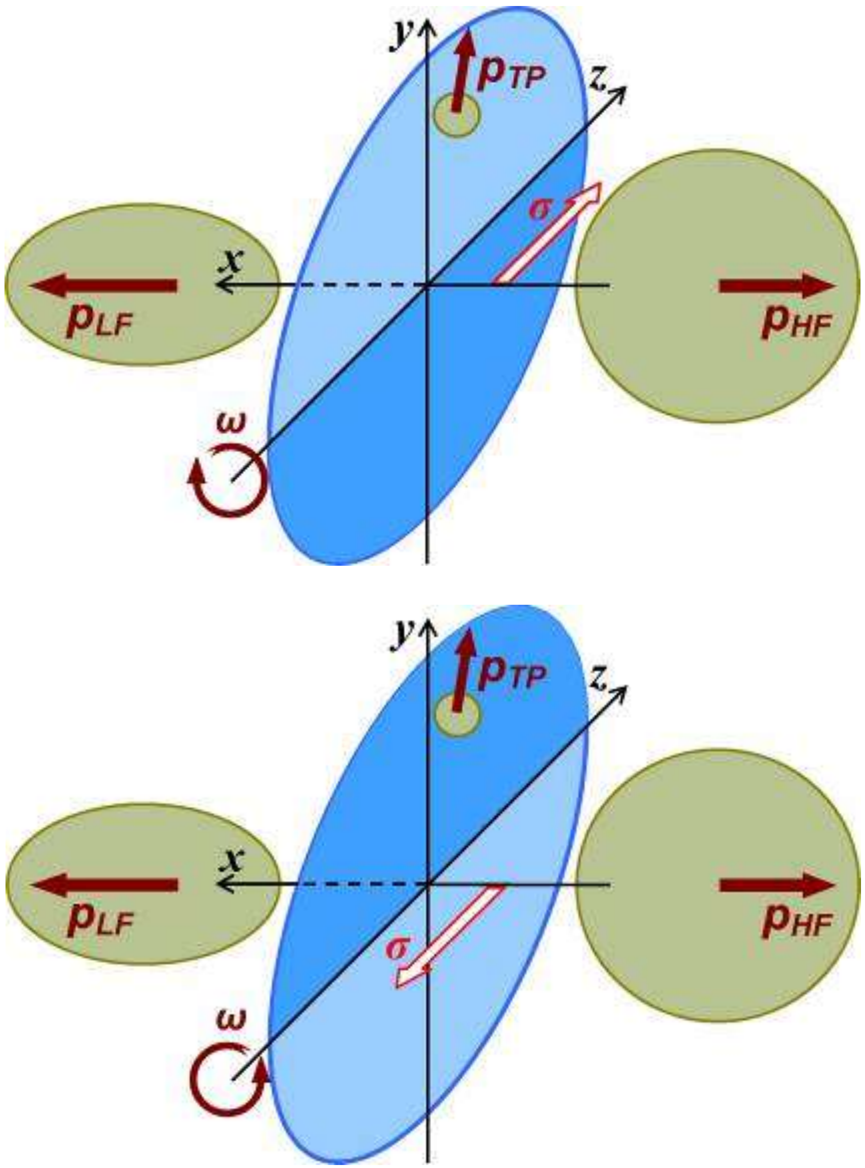
The effects are small, but measurable in relative measurements with spin flipping.

They appeared to be very sensitive to the parameters of transition states above fission barrier and to the characteristics of nuclear configuration at scission

ROT- effect

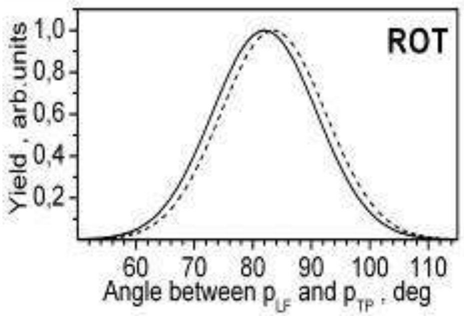


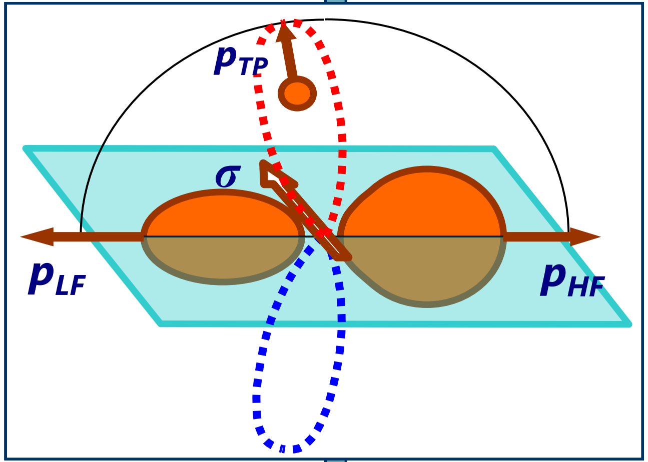
TRI- effect

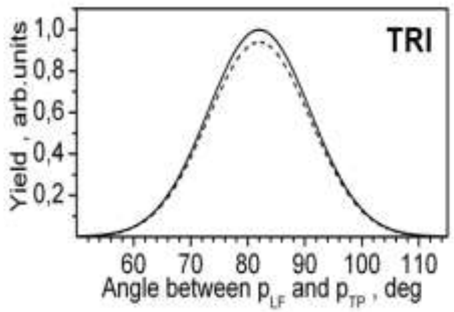


ROT- effect

TRI- effect





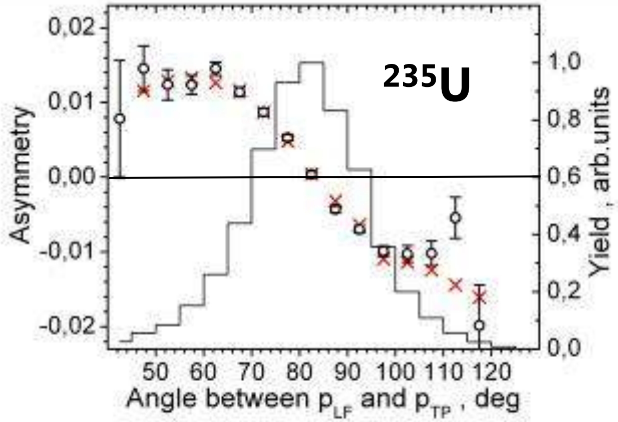


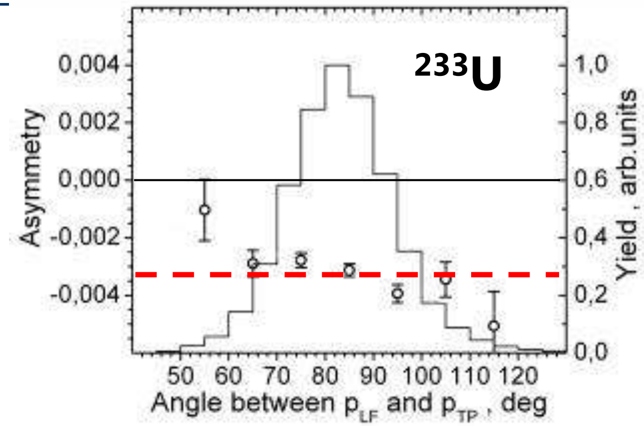
$$A(\varphi) = S_{ROT} \cdot \left(\frac{Y'(\varphi)}{2 \cdot Y(\varphi)} \right)$$

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

$$A(\varphi) = D_{TRI}$$

Spin-flip: $\sigma_0 \leftrightarrow \sigma_1$



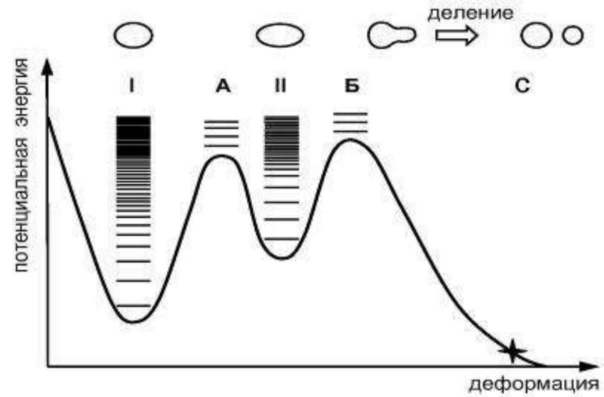


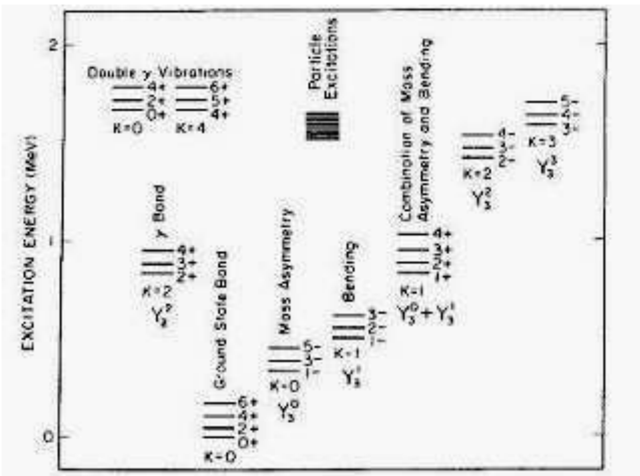
	J	S_{ROT} (angle °)	D_{TRI} ($\times 10^3$)
^{235}U(n,f)	3^- and 4^-	0.215 (5)	+1.7 (2)
^{233}U(n,f)	2^+ and 3^+	0.021 (4)	–3.90 (12)
^{239}Pu(n,f).	0^+ and 1^+	0.020 (3)	–0.23 (9)

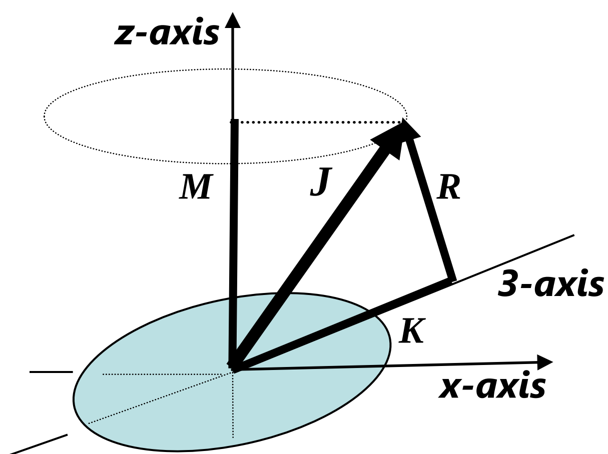
Origin of the effects is polarized rotation of compound nucleus

- States of nucleus over the barrier are collective excitations describing by quantum numbers (*J*, *K*)
- Effective angular momentum ***R*** corresponds to the rotation around perpendicular to the fission axis $R = \hbar \cdot \sqrt{J(J+1) - K^2}$
- ***R*** turns to be polarized during capture of polarized neutron, and polarizations of ***R*** are opposite for two capture states

J = *I* 1/2





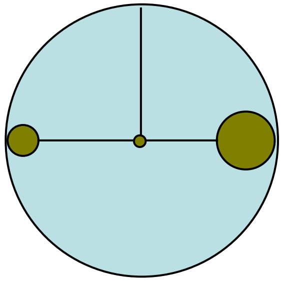


$$R_{+/-}(J,K) = \begin{cases} \dfrac{J(J+1) - K^2}{J} \cdot \dfrac{\hbar}{2} & for \quad J = I + 1/2 \\ -\dfrac{J(J+1) - K^2}{(J+1)} \cdot \dfrac{\hbar}{2} & for \quad J = I - 1/2 \end{cases}$$

Projection of R onto z-axis for +1/2 and -1/2 resonances

ROT- effect (Model)

- The collective rotation ***R*** continues also after rupture during particles acceleration in Coulomb field
- The rotation shifts light particle trajectory in the frame related with fission axis (Coriolis force)



- Coulomb force tries to keep the particles on the median plane, but since it is not infinitely strong the shift survives
- This was checked in trajectory calculation (Monte-Carlo calculations with numerical integration of motion equations)

$$Shift \sim \omega \sim R$$

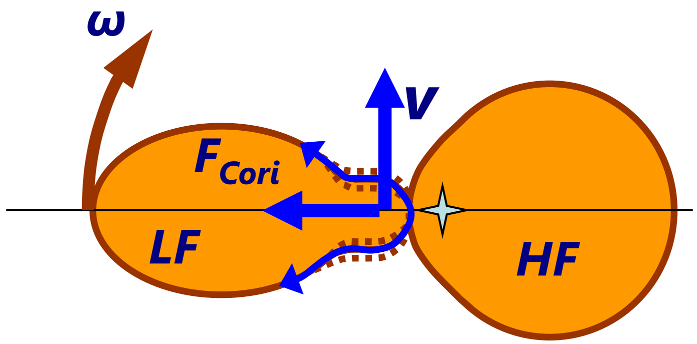
$$S = s \cdot \left[R_+ \frac{1}{1+k} + R_- \frac{k}{1+k} \right]$$

$$k = \sigma_{-1/2} / \sigma_{+1/2}$$

TRI- effect (Model)

- Rotation ***R*** breaks axial symmetry of the neck before rupture or just in the rupture moment
- It is interaction of rotation and velocity of transverse vibrations. **(Coriolis force before rupture)**

  - The heavy fragment is formed around 132 cluster.
  - The ternary particle is coming from the neck remains, which are mainly absorbed by the light fragment.
  - If the neck transversal velocity, coming from vibration, is directed along the rotation, the Coriolis will help the neck to be absorbed in the LF and decrease TPs yield in upper hemisphere.
  - If the velocity is against the rotation, the Coriolis force will help the neck to get separated from LF and increase TPs yield in lower hemisphere.



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

$$v \sim K \qquad \omega \sim R = \hbar \cdot \sqrt{J(J+1) - K^2}$$

$$D = d \cdot \left[K_+ R_+ \frac{1}{1+k} + K\_R\_ \frac{k}{1+k} \right]$$

Comparison Model-Experiment

ROT- effect

$$S = s \cdot \left[R_+ \frac{1}{1+k} + R_- \frac{k}{1+k} \right]$$

TRI- effect

$$D = d \cdot \left[K_+ R_+ \frac{1}{1+k} + K\_R_- \frac{k}{1+k} \right]$$

$$R_{+/-}(J,K) = \begin{cases} \dfrac{J(J+1)-K^2}{J} \cdot \dfrac{\hbar}{2} & for \quad J = I + 1/2 \\ -\dfrac{J(J+1)-K^2}{(J+1)} \cdot \dfrac{\hbar}{2} & for \quad J = I - 1/2 \end{cases}$$

R – effective rotation momentum, depend on *(J,K)* of fission channels – defined by the barrier structure and dynamics of rupture – not known.

K – quantum number of spin projection on symmetry axis – not known.

k – ratio of spin capture states in cross-section – experiments with oriented nuclei , evaluated nuclear data files (ENDF, etc.)

s – starting particles configuration – velocities, positions … – trajectory calculations based on known final energies and angle distributions

d – emission mechanism – most interesting, no model exist

It is reasonably to suppose, that *s* and *d* are similar for all studied nuclei, and strong variations of ROT and TRI are defined by ***k*** and ***R*** variations.

Using available data on spin states contribution in the cross section (*k*), we calculate dependences of TRI и ROT on *(J ,K)* for three nuclei.

Comparison Model-Experiment

ROT- effect

$$S = s\cdot\left[R_+\frac{1}{1+k} + R_-\frac{k}{1+k}\right]$$

TRI- effect

$$D = d\cdot\left[K_+R_+\frac{1}{1+k} + K_-R_-\frac{k}{1+k}\right]$$

ROT, degrees

235U S_{exp} = + 0,215 ± 0,005

$\sigma(J=3)/\sigma(J=4) = 0{,}57$ (Kopatch, Popov et al.)

(J,K)	(3,0)	(3,1)	(3,2)	(3,3)
(4,0)	0,183	0,191	0,215	
(4,1)	0,169	0,177	0,201	
(4,2)	0,128	0,135	0,159	
(4,3)	0,058	0,066	0,090	
(4,4)				

233U S_{exp} = + 0,021 ± 0,004

$\sigma(J=2)/\sigma(J=3) = 0{,}79$ (ENDF file)

(J,K)	(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
(3,3)			

239Pu S_{exp} = + 0,020 ± 0,003

$\sigma(J=0)/\sigma(J=1) = 2{,}09$ (ENDF file)

(J,K)	(0,0)
(1,0)	0,057
(1,1)	0,028

TRI (× 10^-3^)

235U D_{exp} = (+ 1,7 ± 0,2) × 10^{-3}

$\sigma(J=3)/\sigma(J=4) = 0{,}57$

(J,K)	(3,0)	(3,1)	(3,2)	(3,3)
(4,0)	0	1,2	1,7	
(4,1)	-3,5	-2,4	-1,8	
(4,2)	-6,0	-4,8	-4,3	
(4,3)	-6,1	-5,0	-4,4	
(4,4)				

233U D_{exp} = (– 3,9 ± 0,12) × 10^{-3}

$\sigma(J=2)/\sigma(J=3) = 0{,}79$

(J,K)	(2,0)	(2,1)	(2,2)
(3,0)	0	0,86	0,69
(3,1)	-2,4	-1,5	-1,7
(3,2)	-3,5	-2,6	-2,8
(3,3)			

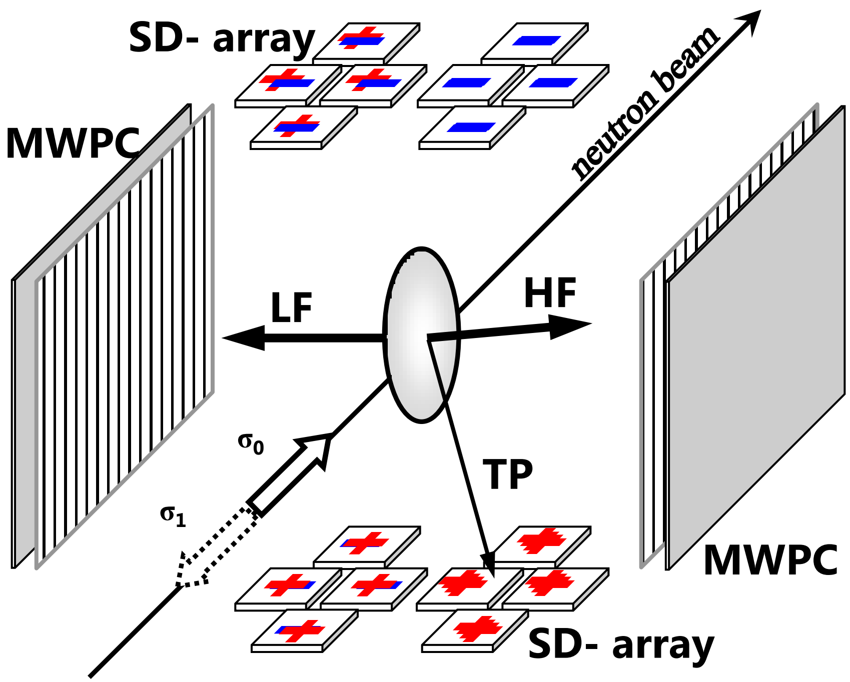
239Pu D_{exp} = (– 0,23 ± 0,09) × 10^{-3}

$\sigma(J=0)/\sigma(J=1) = 2{,}09$

(J,K)	K_- =0
(1,0)	0
(1,1)	-0,38

Experiment ^{241}Pu(n,f)

Experimental method



- Measurement of all involved angles:

✓Diodes size ~30x30 mm2

✓Position sensitive MWPCs (~ 2 mm)

- Spectroscopy of fission products:

✓Energies of TPs,

✓Separation of FFs to Light and Heavy by their times of flight

- Relative measurements (Neutron spin flip frequency 1 Hz)

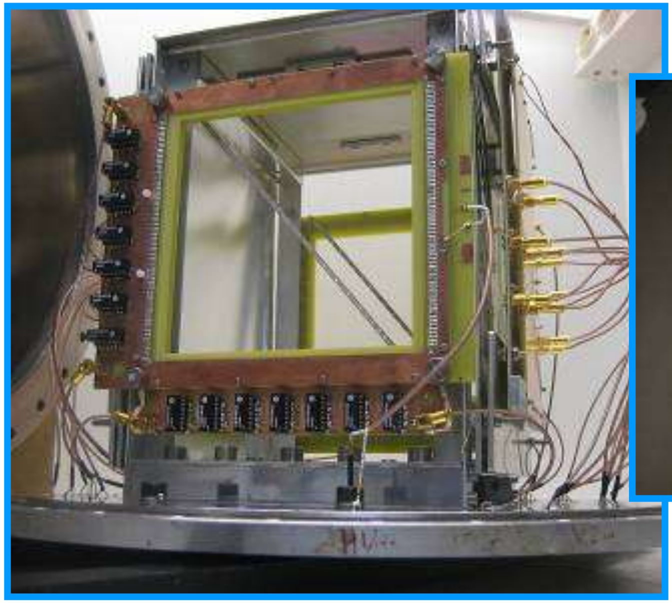
$$A(\theta,\varphi,\ldots)=\frac{N^0(\theta,\varphi,\ldots)-N^1(\theta,\varphi,\ldots)}{N^0(\theta,\varphi,\ldots)+N^1(\theta,\varphi,\ldots)}$$

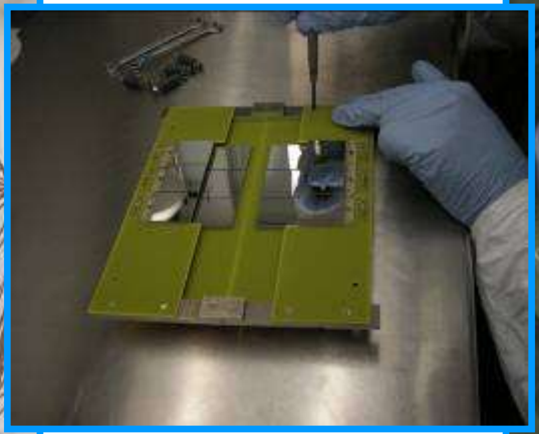
- Control and suppression of false setup asymmetries:

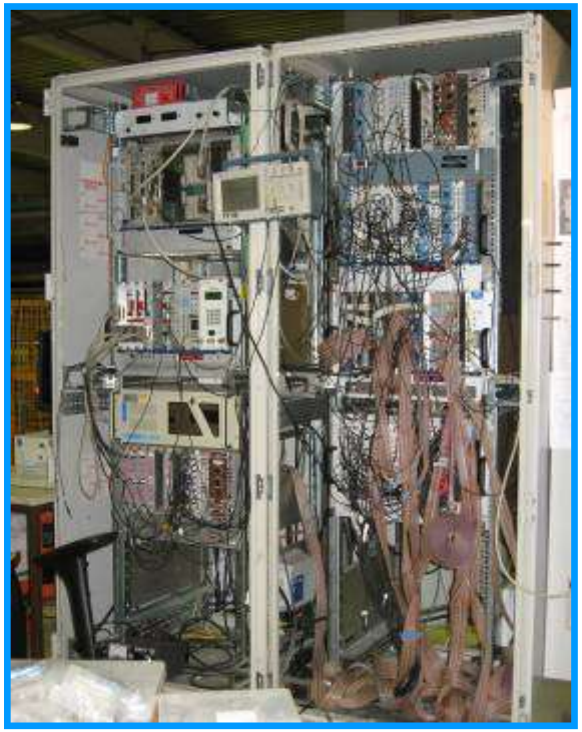
✓Comparing of *A* obtained for events recorded by symmetrical detector combinations

✓Switching of the guiding magnetic field direction

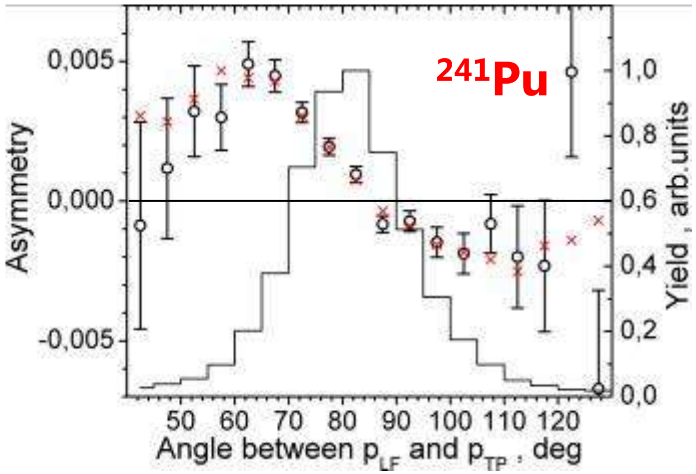
Some photos

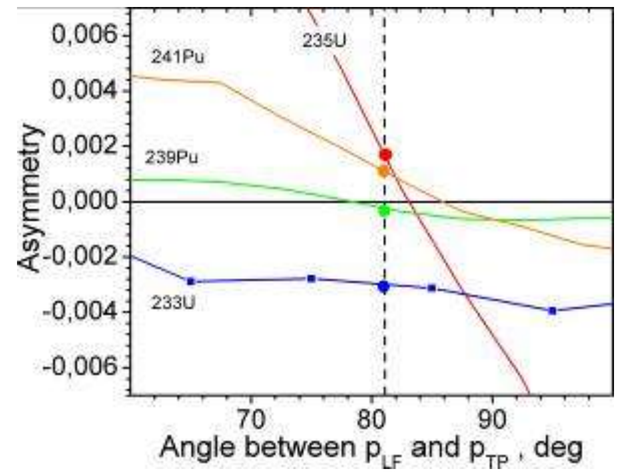






ROT и TRI effects in $^{241}Pu(n,f)$





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

Corrections:

– degree of polarization of the neutron beam
– admixture of accidental coincidences
– overlapping of LF as HF fragments groups
– the geometrical efficiency

ROT, degrees

241Pu S_{exp} = + 0,047 ± 0,004

$\sigma(J=2)/\sigma(J=3)=0{,}15$ (ENDF file)

(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)			

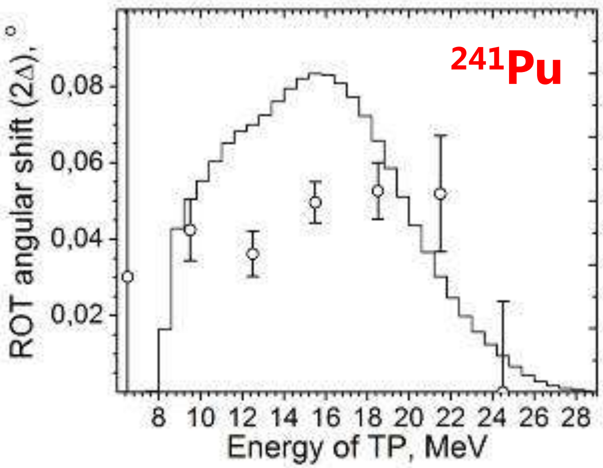
TRI (× 10^{-3})

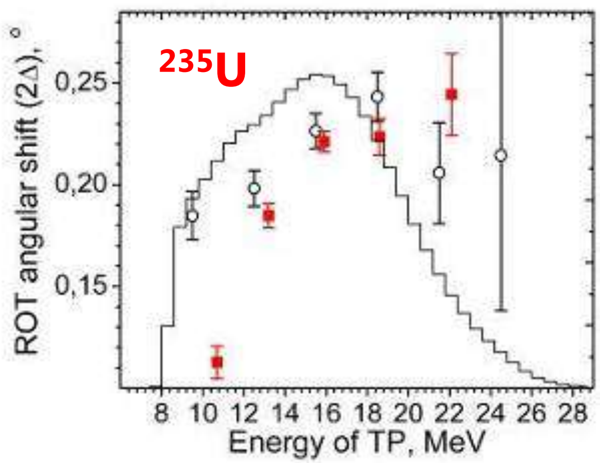
241Pu D_{exp} = (+ 1,30 ± 0,15) × 10^{-3}

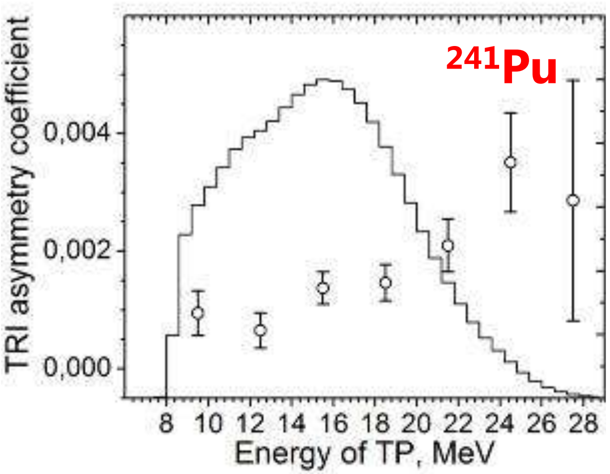
$\sigma(J=2)/\sigma(J=3)=0{,}15$

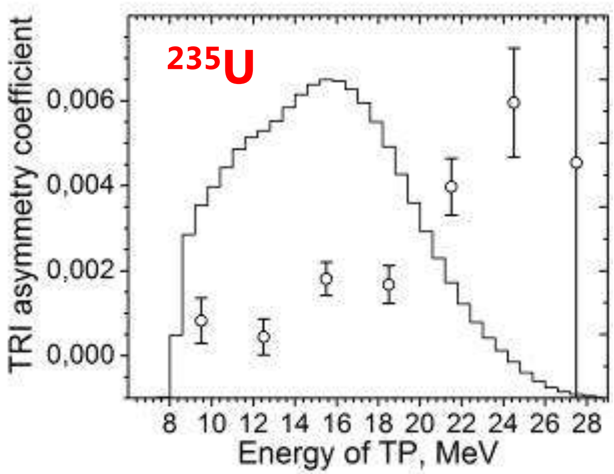
(J,K)	***(2,0)***	***(2,1)***	***(2,2)***
(3,0)	0,0	0,254	0,204
(3,1)	-3,73	-3,48	-3,52
(3,2)	-5,43	-5,17	-5,22
(3,3)			

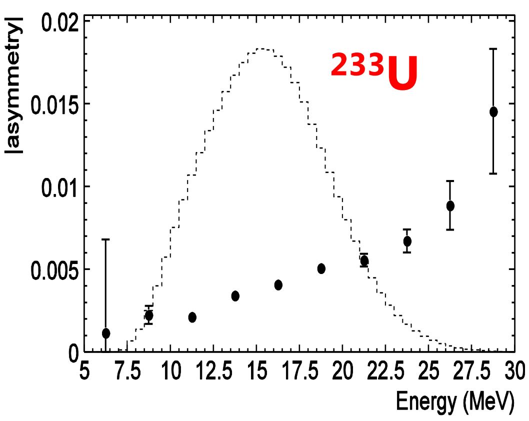
ROT и TRI эффекты в ^{241}Pu(n,f)







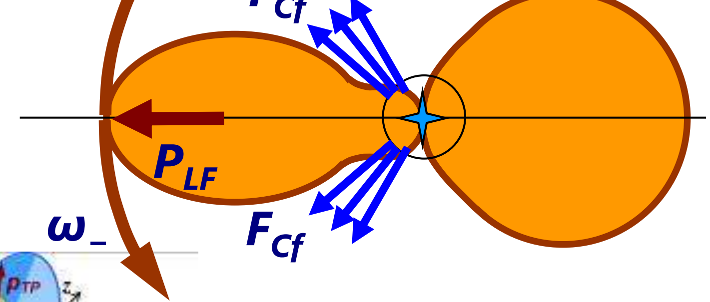




Centrifugal Effect – expectations

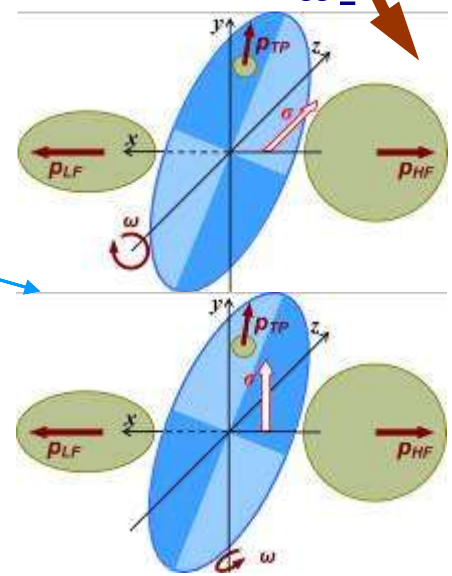
Model –
«drops emitting from rotating wheel»

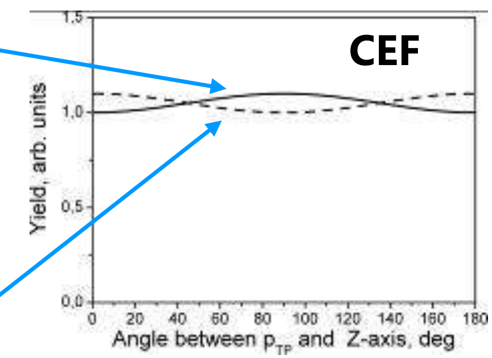
$$F_{Cf} = \omega^2 \cdot r$$



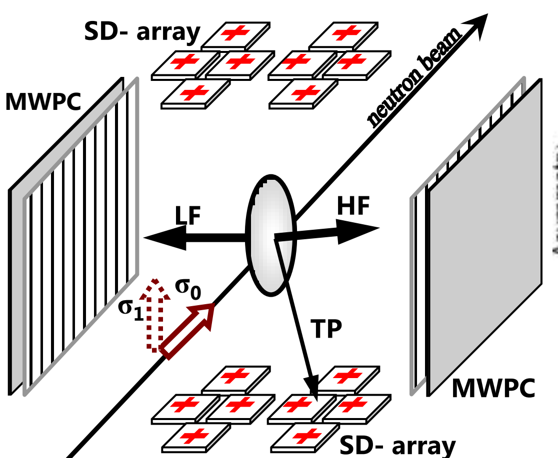
We expected to see:

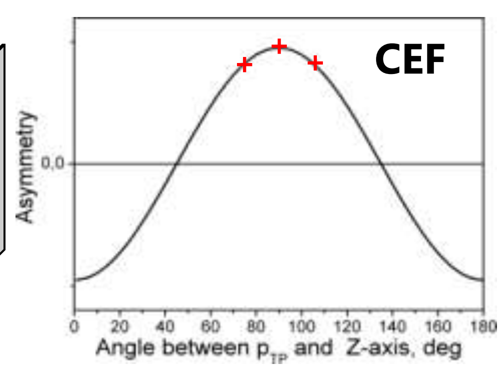
Angular distributions





Asymmetry with spin tilt

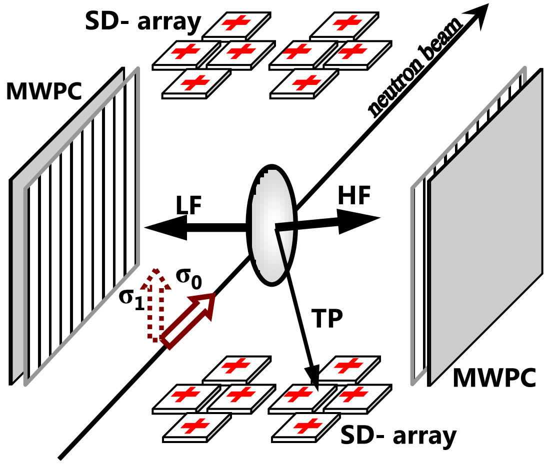




$$A(\theta) = \frac{Y^0(\theta) - Y^1(\theta)}{Y^0(\theta) + Y^1(\theta)}$$

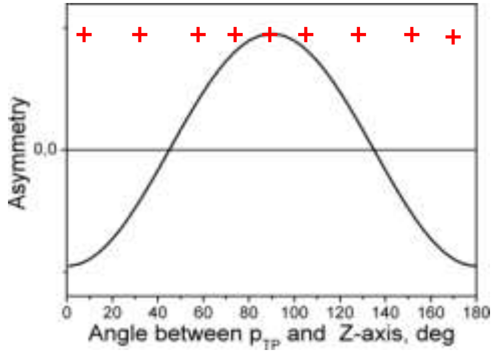
$$C = c \cdot \left[R_+^{\,2} \cdot \frac{1}{1+k} + R_-^{\,2} \cdot \frac{k}{1+k} \right]$$

Centrifugal Effect – reality



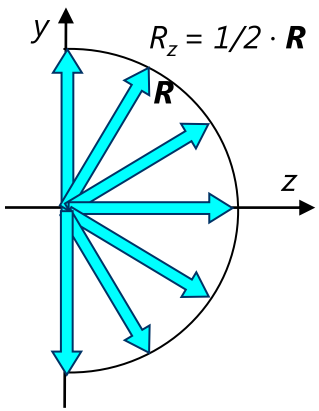
Asymmetry of LCP-FF coincidences: +0.0033(2)

Instrumental false asymmetry: +0.0034(1.5)



Resulting CEF:
−0.0001(2)

- We erroneously supposed that ROT effect should be **necessary** accompanied by CEF-effect.
- **But**, since ***R*** has some distribution of its projections, on *z*-axis, it very well can be that ***R*** will be polarized, but not aligned. In this case CEF will be averaged to zero.
- ***R*** projection population after capture of s-wave neutrons **can not be aligned** – it is supposed to be quantum mechanical theorem.
- The CEF effect definitely could be observed**, but** only if we provide the compound nucleus orientation by some other way, not by capturing of s-wave polarized neutron.



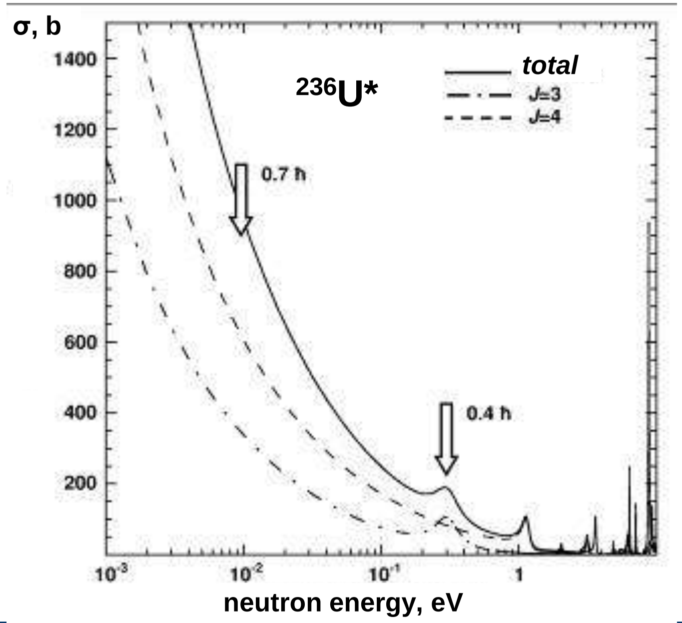
Conclusion and outlook

- The ROT and TRI correlations appeared to be very sensitive to the parameters of transition states above fission barrier and to the characteristics of nuclear configuration at scission ➔ Their study looks very promising for obtaining new information on fission process, namely, about the least studied stage of the process– rupture of a nuclear matter
- Both effects were observed in ^{241}Pu(n_{th},f). The ROT and TRI results can be jointly fitted by combinations of (3, 0) + (2, 1) (*J*, *K*) channels. The spins contributions to the cross section should be taken as $\sigma(J=2)/\sigma(J=3) = 1.56$.
- CEF-effect is within the experimental error bars (−1   2) x 10^{-4}
- Perspectives:

✓ Study of ^{245}Cm(n,f) (J = 3+, 4+)

✓Comparison of the TRI- и ROT-effects in resonances of 236U*

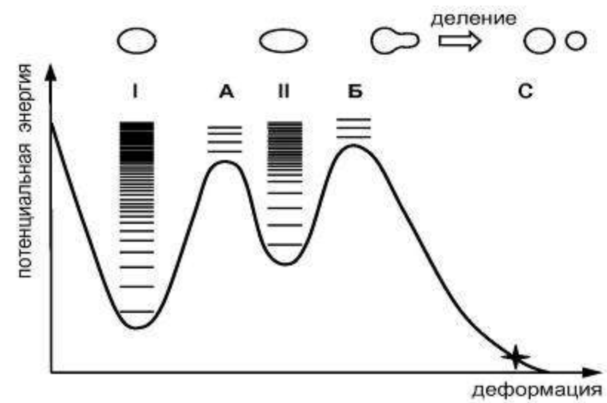
✓More detailed experiment with ^{235}U(n,f) (type of ternary particle, fission fragments masses and energies)

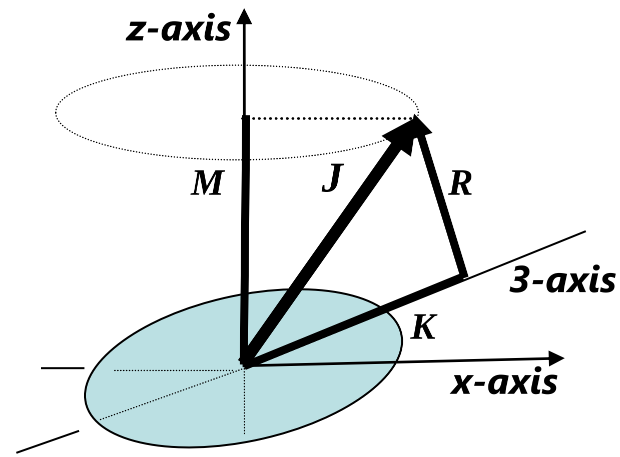


Thank you for attention.

Ориентированное вращение ядра

- Захват поляризованного нейтрона → поляризованное компаунд ядро со спином $J = I \quad 1/2$
- Переходные состояния в над барьером деления являются коллективными возбуждениями с квантовыми числами (J, K)
- В адиабатическом процессе и в точке разрыва ядро сохраняет коллективное движение, описываемое (J, K) квантовыми числами. Вращению ядра перпендикулярному оси соответствует эффективный угловой момент R
- Момент R также оказывается поляризован. <u>Причем поляризации противоположны для двух спиновых состояний</u>

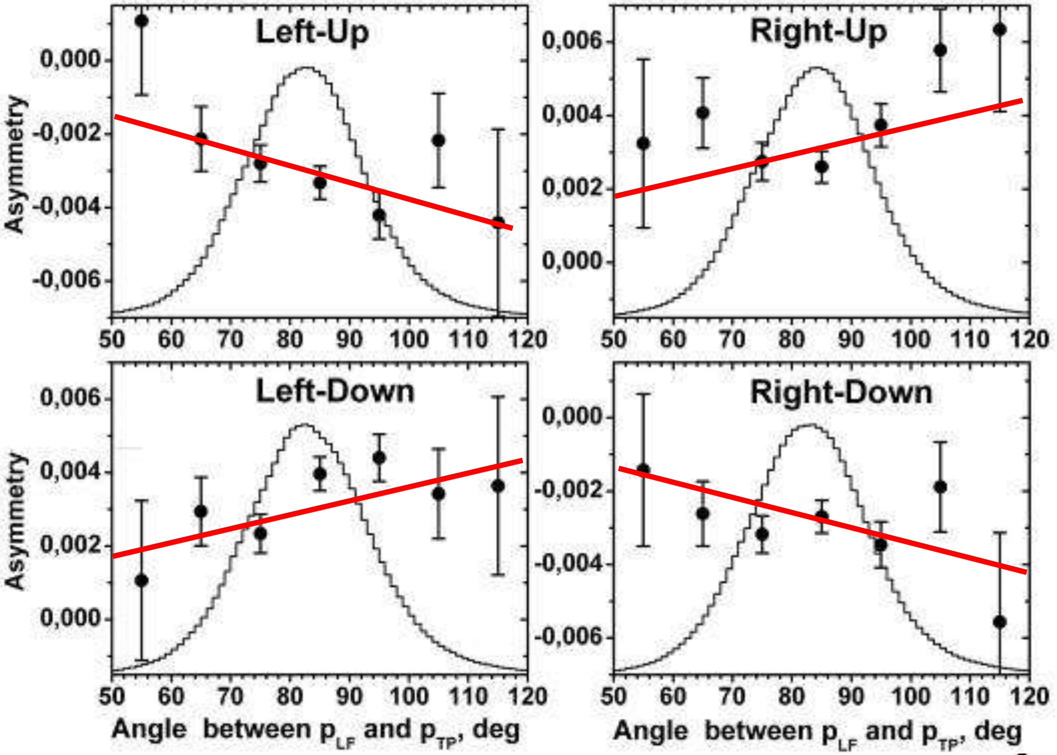


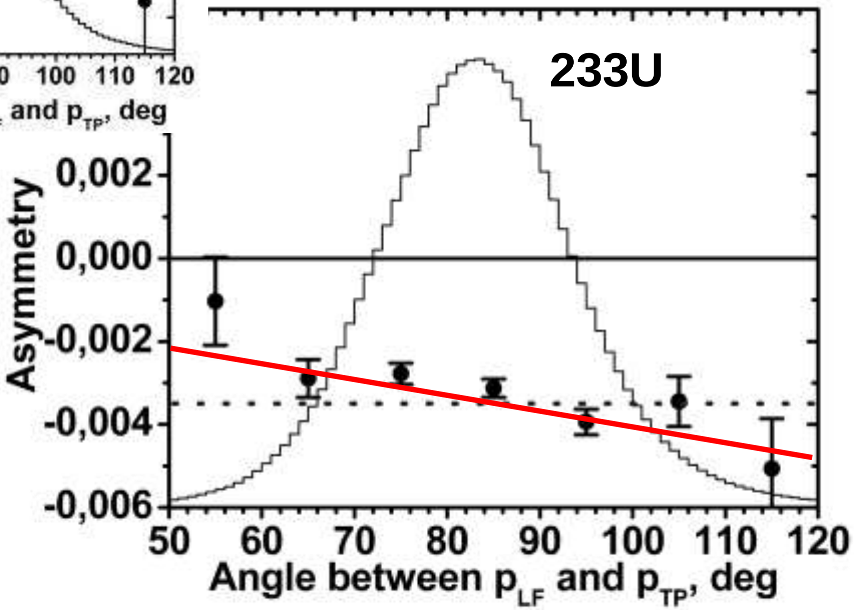


$$R = \hbar \cdot \sqrt{J(J+1) - K^2}$$

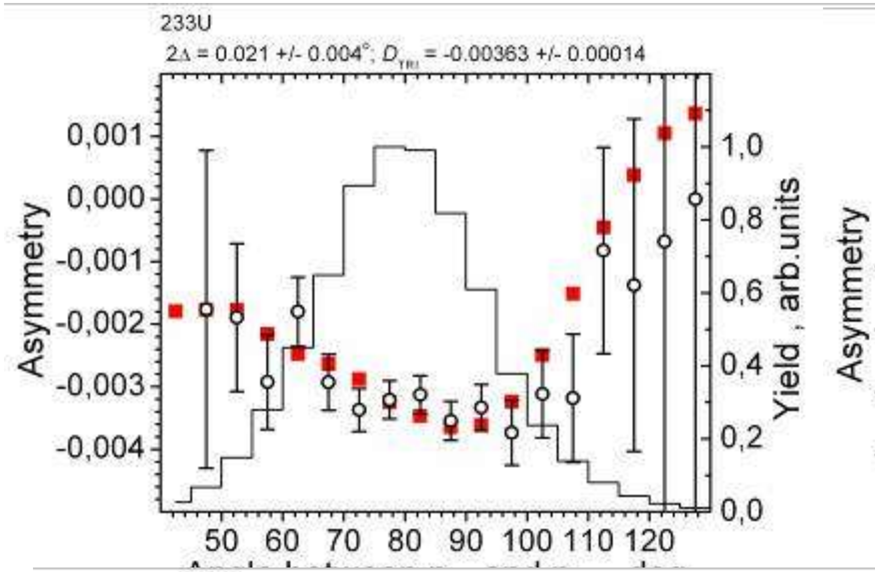
$$R_{+/-}(J,K) = \begin{cases} \dfrac{J(J+1)-K^2}{J} \cdot \dfrac{\hbar}{2} & \text{for} \quad J = I + 1/2 \\ -\dfrac{J(J+1)-K^2}{(J+1)} \cdot \dfrac{\hbar}{2} & \text{for} \quad J = I - 1/2 \end{cases}$$

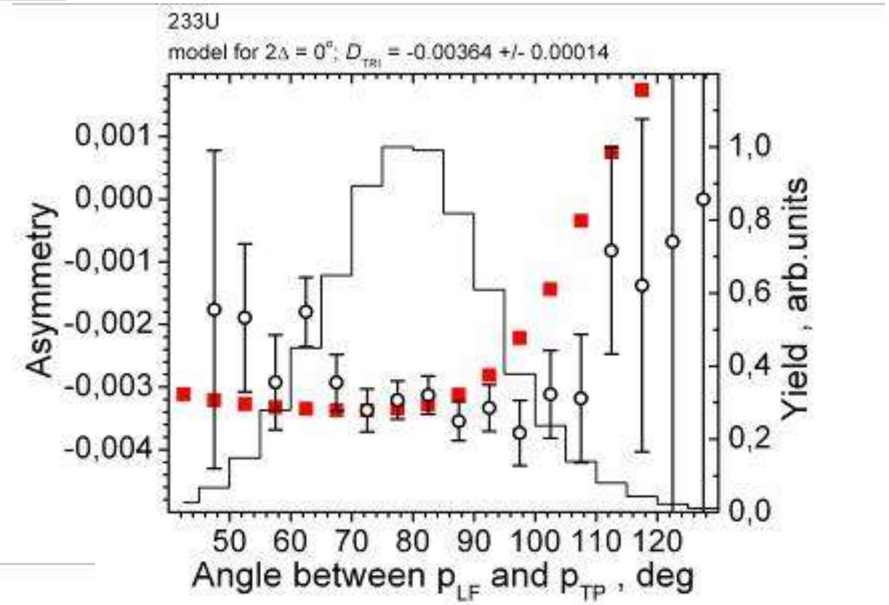
Угловая зависимость асимметрии (^{233}U(n,f), продольная поляризация)

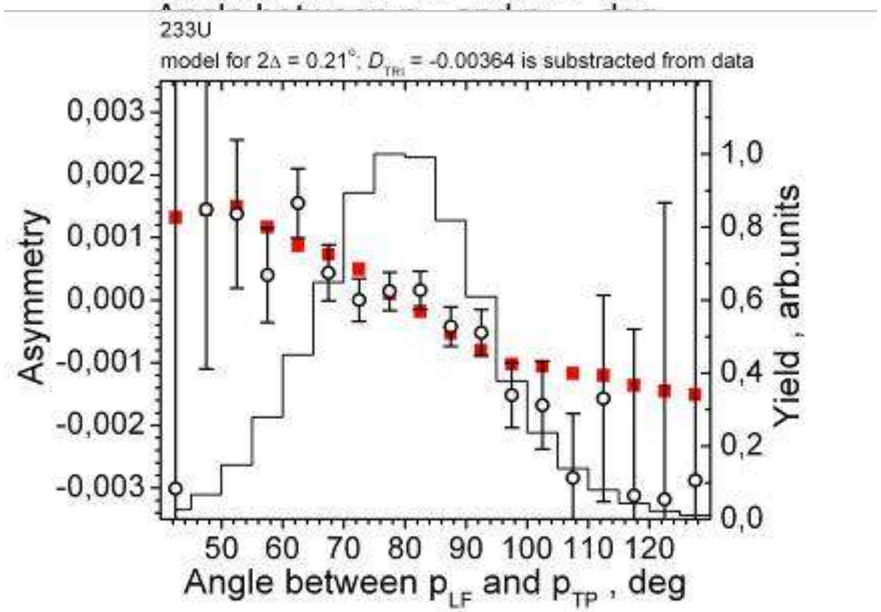




Угловая зависимость асимметрии ($^{233}U(n,f)$, продольная поляризация)







Угловая зависимость асимметрии ($^{239}Pu(n,f)$, продольная поляризация)