THE COMPARISON OF BINARY AND TERNARY FISSION CONFIGURATIONS CLOSE TO THE INSTANT OF SCISSION

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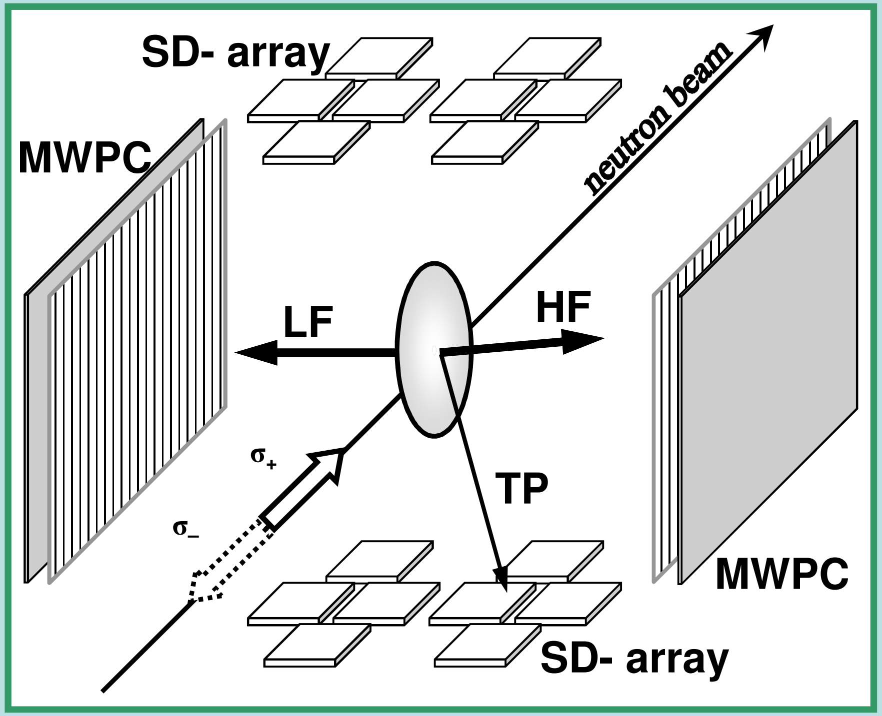
Experimental Setup for Search of the TRI-Effect



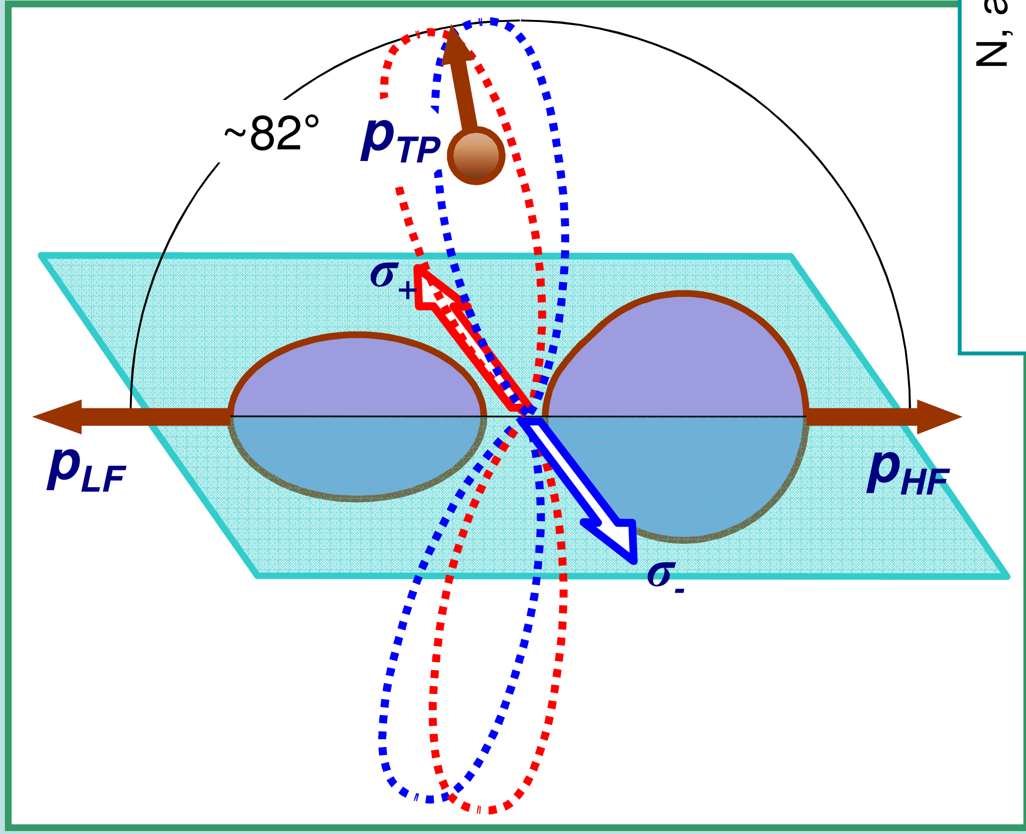
Search for a TRIple correlation B :
$B = (\boldsymbol{\sigma}\cdot[\mathbf{p}_{LF} \times \mathbf{p}_{TP}])$
(note: all vectors are unit vectors)

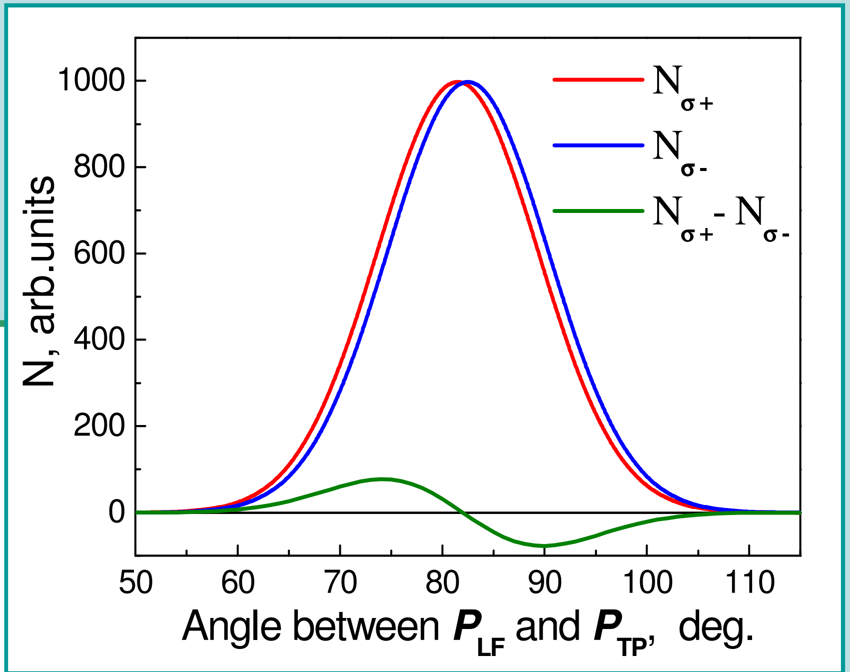
Angular distribution of TPs :
$W(\theta)\, d\Omega \sim \{1 + D\cdot B(\theta)\}\, d\Omega$
where D measures size of correlation.

Experiment: $D = (N_{\sigma+} - N_{\sigma-}) / (N_{\sigma+} + N_{\sigma-})$

LF – Light Fragment
HF – Heavy Fragment
TP – Ternary Particle (Light Charge Particle)
MWPC – Multi-Wire Proportional Counter
SD-array – Silicon Detectors

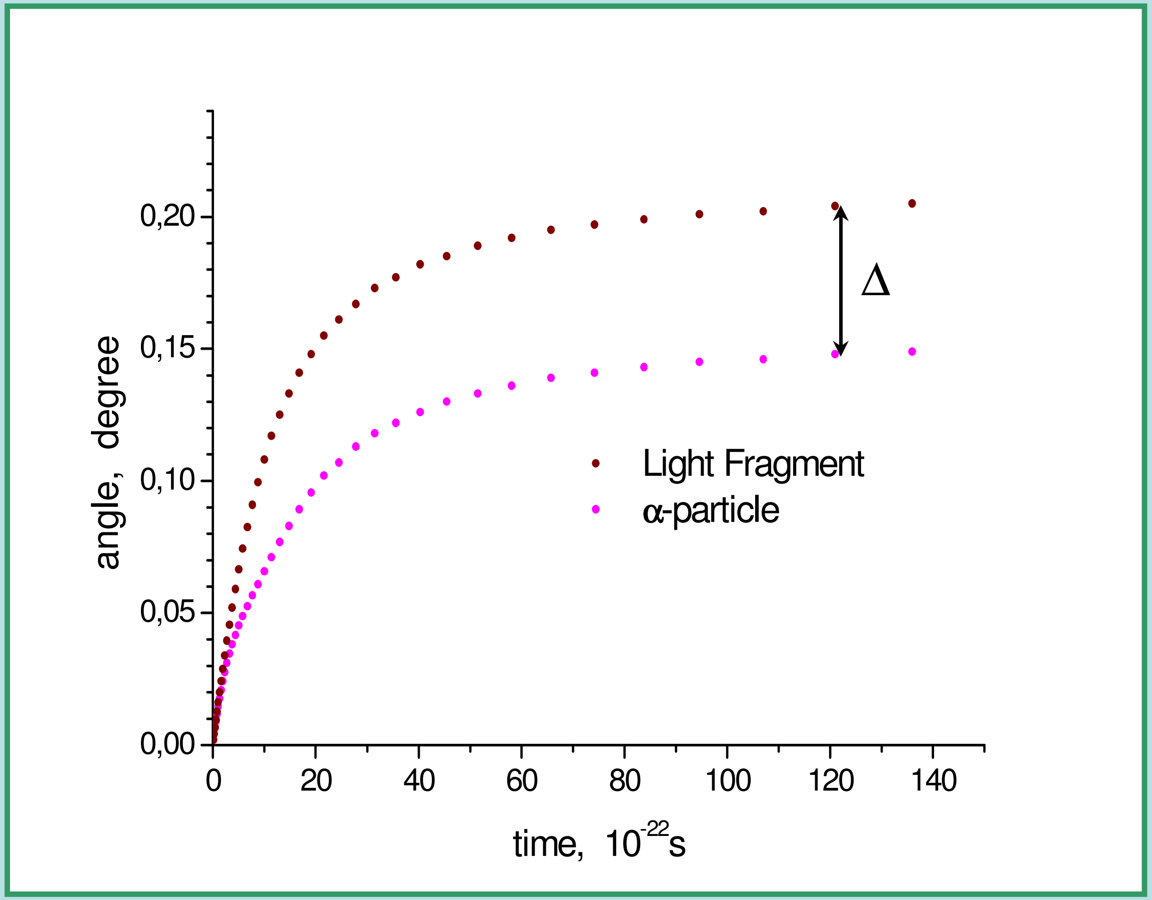
ROT-effect observation in ternary fission of ^{235}U induced by slow polarized neutrons





Asymmetry in coincidence count rates discovered for different detector combinations due to the neutron spin-flip was connected with the rotation of dividing system before rupture and named as ROT-effect [1]. The quantitative estimation of this effect was done by modified trajectory calculation [2].

The deviation of fission objects from their primary ways due to compound system rotation



$$\text{ROT angular shift} = 2 \cdot \Delta$$

The estimation of effective angular velocity for the dividing system rotation

The angular velocity of system rotation with fixed spin J and its projection K on fission axis around the line of neutron beam polarization can be performed using quantum-mechanical expression:

$$\omega(J,K) = \frac{< J_Z(K) >}{\Im} \qquad \Im - inertia \;\; moment$$

As it was shown by S. Kadmenski and V. Bunakov [3] this expression can be written in the form:

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

I – the target spin

p_n determines the neutron beam polarization

The estimation of effective angular velocity for the dividing system rotation

If several transition states contribute to the fission process it is necessary to perform summation over all possible K values, where factors of summation are probabilities to find the component with corresponding value K in the resonance wave-function:

$$\omega_{+/-}(J) = \sum_K \left|a_K^J\right|^2 \omega_{+/-}(J, K)$$

To obtain the total effective angular velocity one should take into account the relative contribution of resonance components with different J to the total fission cross-sections:

$$\sigma_{tot} = \sigma_{I-1/2} + \sigma_{I+1/2} \qquad s = \sigma_{I-1/2} / \sigma_{I+1/2}$$

$$\omega_{eff} = \omega_{+}(J)\frac{1}{1+s} + \omega_{-}(J)\frac{s}{1+s}$$

The angular shift estimation

In process of evaluation we used the ratios of partial fission cross sections with different J, which were obtained by V. Maslov and A. Popov in multi-level approach on the base of experimental data.

^{235}U $ROT_{exp} = 0.215^{\circ}$

$\sigma(J=3)/\sigma(J=4) = 0.57$ (from A. Popov)

(J,K)	(3,0)	(3,1)	(3,2)
(4,0)	0.183°	0.191°	0.215°
(4,1)	0.163°	0.177°	0.201°
(4,2)	0.135°	0.135°	0.159°
(4,3)	0.066°	0.066°	0.090°

^{233}U $ROT_{exp} \sim 0.02^{\circ} \div 0.04^{\circ}$

$\sigma(J=2)/\sigma(J=3) = 0.79$ (from V. Maslov)

(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°

^{239}Pu $ROT_{exp} = (0.020 \pm 0.003)^{\circ}$

$\sigma(J=0)/\sigma(J=1) = 2.09$ (from V. Maslov)

(J,K)	(0,0)
(1,0)	0.057°
(1,1)	0.028°

The angular shift estimation

We have not jet experimental results of ROT-effect for the next two targets. The measurements with the isotope of Pu-241 are planned for this summer. In this case we expect rather big ROT-effect with positive sign also.

^{241}Pu $ROT_{exp} = ?$

$\sigma(J=2)/\sigma(J=3) = 0.15$ (from V. Maslov)

(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°

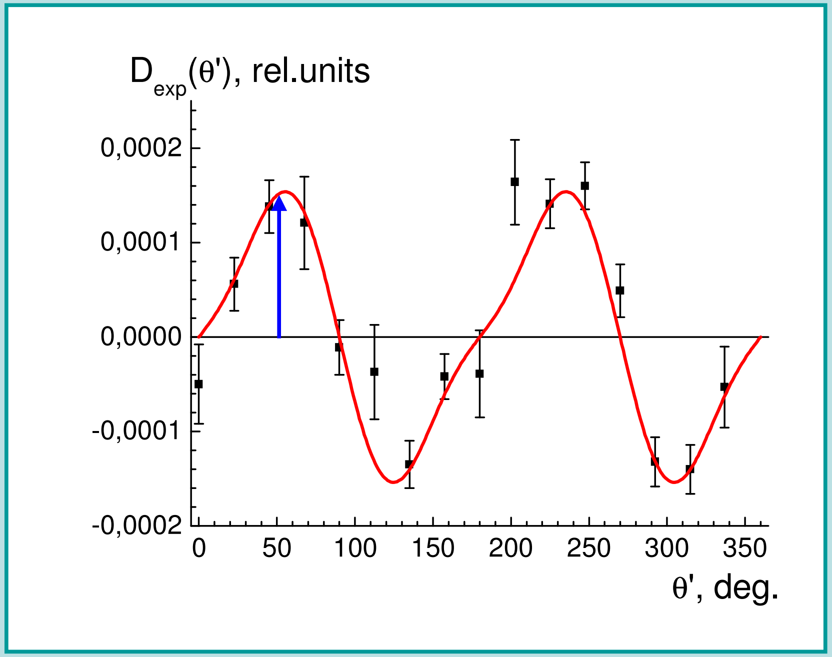
Special attention is deserved the target of Cm. This is the one element only we have estimated with sizable ROT-effect and negative sign.

^{245}Cm $ROT_{exp} = ?$

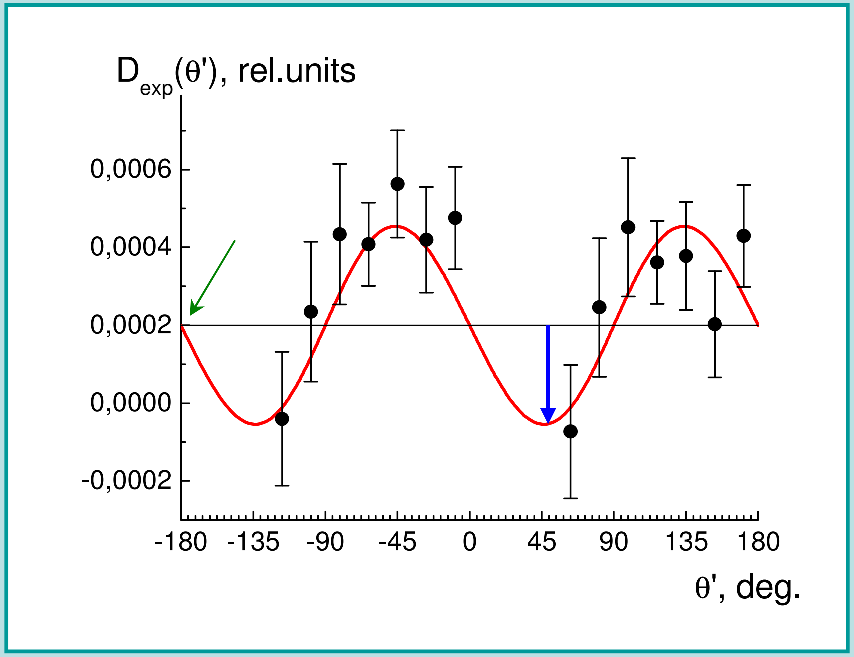
$\sigma(J=3)/\sigma(J=4) = 5.7$ (from V. Maslov)

(J,K)	(3,0)	(3,1)	(3,2)
(4,0)	-0.159°	-0.140°	-0.084°
(4,1)	-0.162°	-0.143°	-0.087°
(4,2)	-0.172°	-0.153°	-0.097°

The gamma count rate asymmetry versus the angle of gamma-quantum registration



G.V. Danilyan, J. Klenke, V.A. Krakhotin, et al.
Yad. fiz, 72 (2009) p.1872

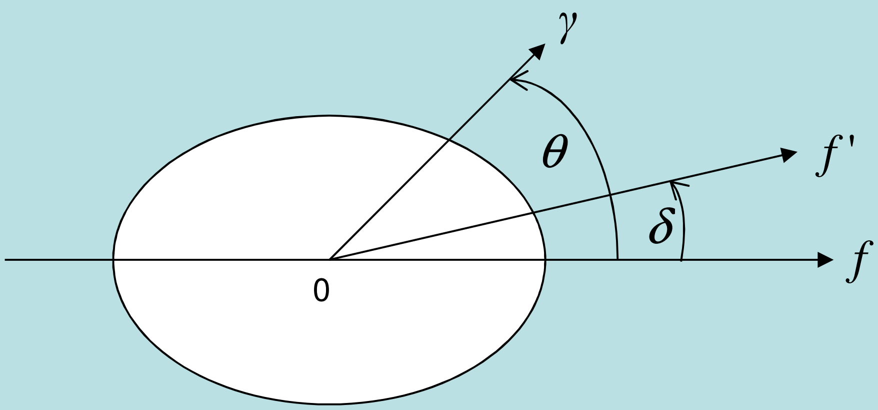


G.V. Val'sky, A.M. Gagarski, I.S. Guseva, et al.
Izv. RAN, ser.fiz., 74 (2010) p.793

If one takes into account a systematic shift in experimental data of PNPI group, which is equal 0.0002, it is possible to deduce that absolute values are in a good agreement but their signs are opposite. Such discrepancy may be connected with a different order of vectors in the triple correlation. This order determines the frame of reference. Our vector combination was: $\left(\vec{\sigma}\cdot[\vec{p}_f\cdot\vec{p}_\gamma]\right)$.

The scheme of gamma count rate asymmetry calculations

This effect explanation was based on the idea of a conservation of primary fission fragment spin orientation and on gamma radiation anisotropy generated by this spin in the reference frame of fragment centre-of-mass.



$$N(\theta') = N(90^\circ)\cdot(1 + A\cdot\cos^2(\theta))$$

$$\theta' = \theta - \delta \quad if\ \sigma > 0$$

$$\theta' = \theta + \delta \quad if\ \sigma < 0$$

f - initial orientation of fission axis (at the moment of scission)

f' – the final direction of fission fragment motion due to compound system rotation

θ – the angle of γ-quantum emission with respect to initial direction of fission axis

θ' – the angle of γ-quantum registration versus fission fragment

The coefficient of gamma ROT-asymmetry

If following Strutinsky the gamma count rate without nuclear system rotation can be written this way:

$$N(\theta) = N(90^o) \cdot (1 + A \cdot \cos^2 \theta),$$

were *A* is the coefficient of anisotropy, the count rates corresponding to different neutron spin polarizations are :

$$N^+(\theta') = N(90^o) \cdot (1 + A \cdot \cos^2(\theta' + \delta)) \quad \textit{if} \;\; \sigma > 0$$

$$N^-(\theta') = N(90^o) \cdot (1 + A \cdot \cos^2(\theta' - \delta)) \quad \textit{if} \;\; \sigma < 0$$

In experiment the angular dependence of asymmetry coefficient was measured:

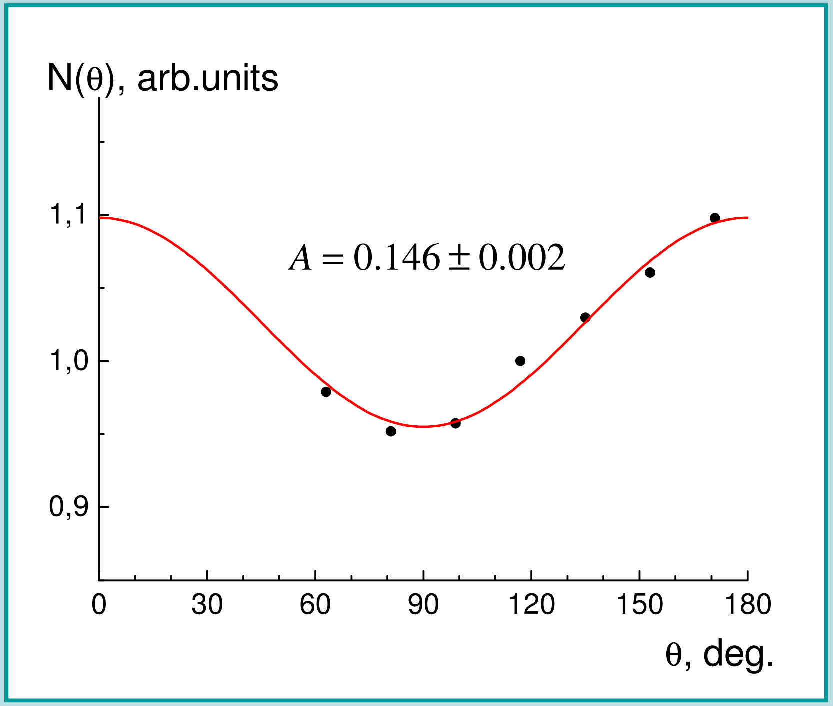
$$D_{\exp}(\theta') \equiv \frac{N^+(\theta') - N^-(\theta')}{N^+(\theta') + N^-(\theta')}$$

Taking into consideration a smallness of the angle delta for fission axis rotation this coefficient can be written by this equation:

$$D_{\exp}(\theta') \approx \frac{A \cdot \left[\cos^2(\theta' + \delta) - \cos^2(\theta' - \delta)\right]}{2 \cdot [1 + A \cdot \cos^2(\theta')]} \approx \frac{-A \cdot \delta \cdot \sin(2\theta')}{[1 + A \cdot \cos^2(\theta')]}$$

It is necessary to mention that anisotropy for gamma emission in the reference frame of fission fragment centre-of-mass does not differ essentially from this one in laboratory system.

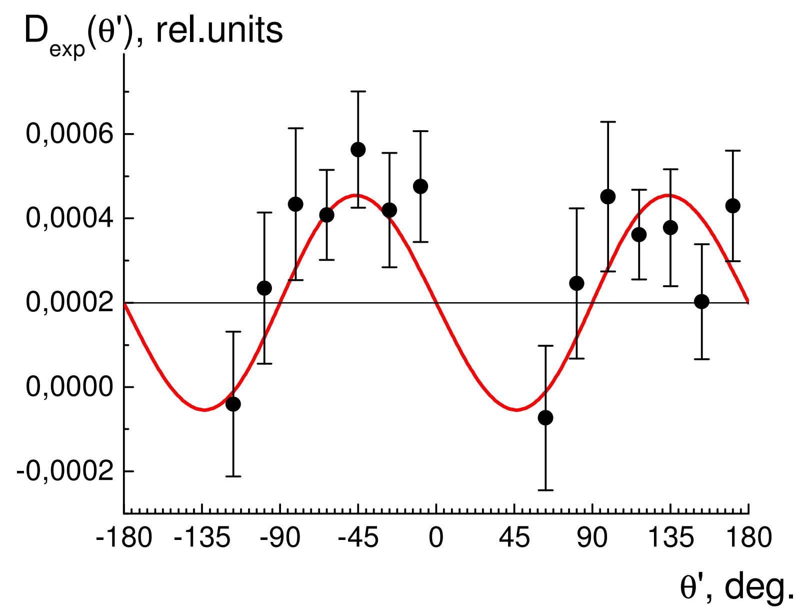
The coefficient of anisotropy A was measured in the same experiment and corresponds to the same energy interval, which was used for gamma ROT-effect observation gamma ROT-asymmetry.



The least squares estimation for experimental data of gamma ROT-asymmetry

The hypothesis for calculations:

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

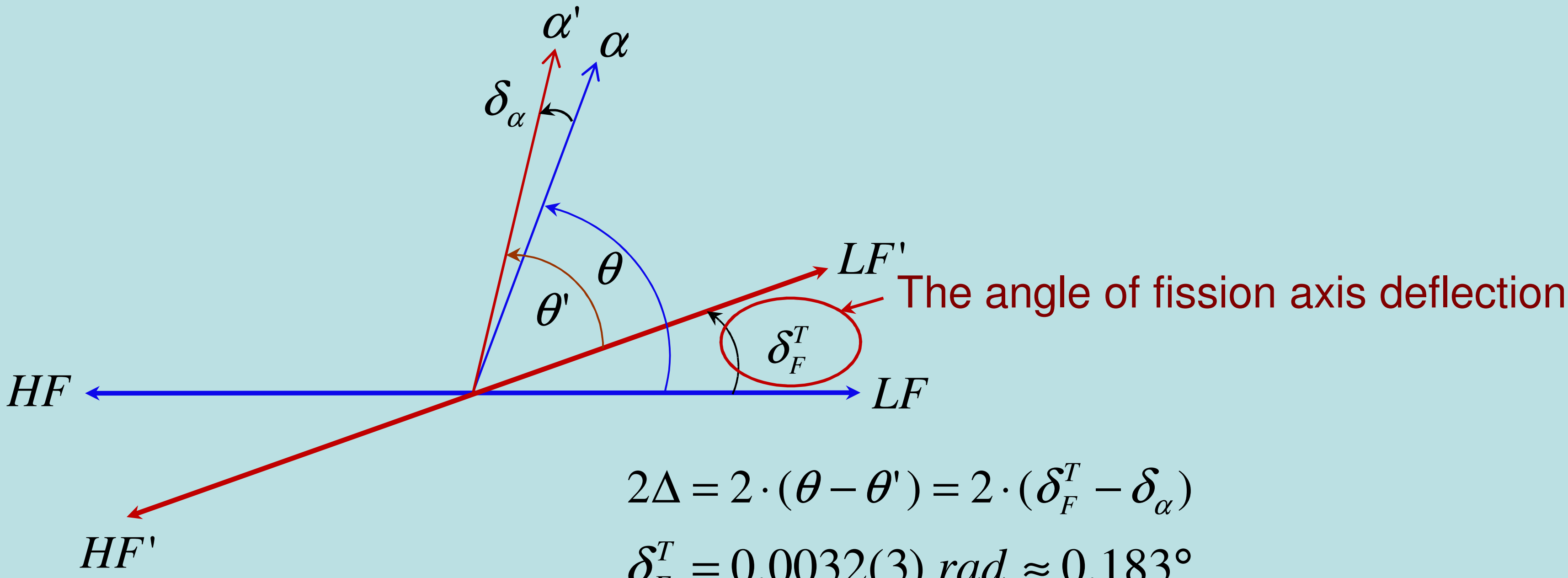


So, only the value δ in the last equation is not known. This angle characterizes rotation of fission axis in binary fission and corresponding angular shift for gamma distribution. We can get it by least squares estimation of experimental data for gamma ROT-asymmetry using required hypothesis which has one parameter only.

$$\delta = 0.0018(5)\ rad$$

The scheme of the ROT-effect origin in ternary fission

Here *LF*, *HF*, *α* – initial directions of fragments and light charge particle motion at the moment of scission. The final object directions, which were obtained due to nuclear system rotation, are labeled by primes. In experiment we can see directly only the double lag of ternary particle relative to the fission axis deflection. But for both binary and ternary ROT-effect comparison we have to use namely the angle of fission axis deflection. In ternary fission we can get it by trajectory calculations on the base of experimental result for the angular shift.



$$2\Delta = 2\cdot(\theta-\theta') = 2\cdot(\delta_F^T-\delta_\alpha)$$

$$\delta_F^T = 0.0032(3)\ rad \approx 0.183°$$

$$\delta_F^B = 0.0018(5)\ rad \approx 0.103°$$

Conclusion:

As we can see both angles of axis deflection in ternary and binary fission have the same sign. Although their absolute values are not differ very much, nevertheless it is necessary to point out that the angle of fission axis deflection obtained for binary fission process is about 1.8 times smaller than for ternary fission.

This result may be the consequence of different moments of inertia. It can serve as a proof that close to the instant of scission compound system has more elongated configuration in binary fission than in ternary case. This result agrees with the conclusion, which was made by Mutterer [4], that the fragment deformation in ternary fission is considerably less than in binary fission.

So the exact correlation between two angles of fission axis rotation (in binary and ternary fission) can help to specificate these fission configurations.

References:

1. *A.M. Gagarski, I.S. Guseva, F. Goennenwein, et al., ISINN-14, JINR, Dubna, 2006, p. 93;*
2. *I.Guseva, Yu.Gusev, ISINN-14, JINR, Dubna, 2006, p. 101; AIP Conf. proc., 2009, vol. 1175, p. 355;*
3. *V. Bunakov, S. Kadmensky, Proc. Int. Sem. ISINN-16, Dubna JINR, 2009, pp. 325-332;*
4. *V.Mutterer, Proceedings of the Scientific Workshop on Nuclear Fission Dynamics, 27-29 September, 2010 Sinaia, Romania, edited by F.-J. Hambsch and N. Carjan, p. 69.*

Thank you very much for your attention!