MEASUREMENT OF THE ROT-EFFECT IN FISSION OF ^{235}U INDUCED BY MONOCHROMATIC POLARIZED NEUTRONS WITH AN ENERGY OF 60 meV

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Contents

Historical background

The T-odd effects in fission of heavy nuclei have been known since more than a decade.

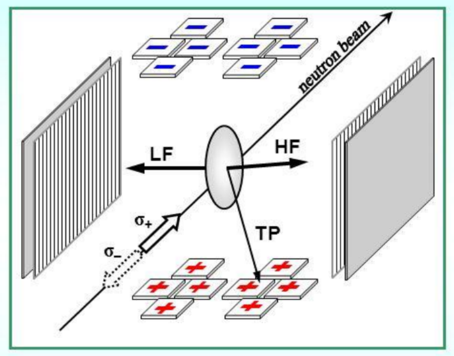
The angular distribution for one of the fission fragments (FF) and ternary particles (TP) at given neutron spin (σ) can be written as:

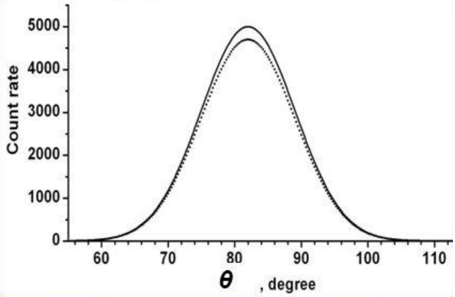
$$W(\theta, \varphi) \sim 1 + < D > \cdot \sigma \cdot [p_f \times p_\alpha]$$

p_f, p_α - momentum of one of the FFs and the TP;
D - coefficient measuring the size of the triple correlation $\sigma \cdot [p_f \times p_\alpha]$;

1998 - discovery of the TRI – effect in the ternary fission of ^{233}U

P. Jesinger, A. Kotzle , A.M. Gagarski , F. Gonnenwein , G. Danilyan et al, NIM A 440 (2000), p. 618-625





$W = 1 + D_{TRI} \cdot \sigma \cdot [p_{LF} \times p_t]$

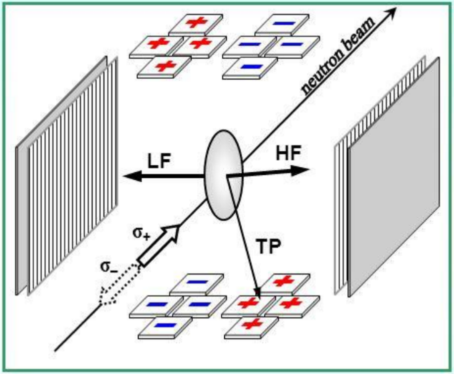
$D_{TRI} = \frac{N^0_{up} - N^1_{down}}{N^0_{up} + N^1_{down}}$

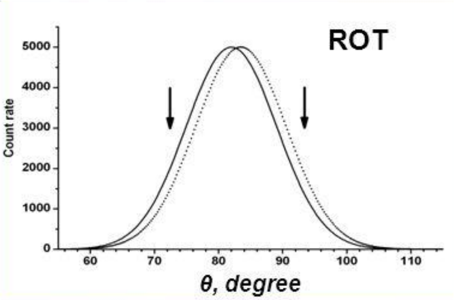
$W = (0.78 \pm 0.02) \cdot 10^{-3}$

Experiments at the ILL: ROT-effect

2005 - discovery of the ROT – effect in the ternary fission of ^{233}U

F. Goennenwein, M. Mutterer, A. Gagarski, I. Guseva, G. Petrov et al,Phys. Lett. B 652 (2007) 13.

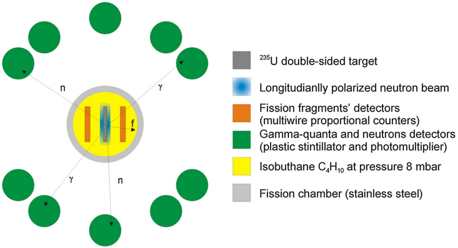




$$W = 1 + D_{ROT} \cdot \sigma \cdot [p_{LF} \times p_T](p_{LF} \cdot p_T)$$

$$A_i = \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

Experiments at the HMI (Berlin): ROT-effect in the γ-ray emission from $^{235}U(n, f)$



ROT asymmetry coefficients in units of 10^{-4}

Angle to the fission axis	^{235}U
0	-0.1 ± 0.3
$\pi/8$	$+0.8 \pm 0.2$
$\pi/4$	$+1.5 \pm 0.2$
$3\pi/8$	$+0.7 \pm 0.3$
$\pi/2$	-0.3 ± 0.3

G.V. Danilyan, P. Granz, V.A. Krakhotin, F. Mezei, V.V. Novitsky, V.S. Pavlov, M. Russina, P.B. Shatalov, T. Wilpert, Phys. Lett. B 679 (2009) 25–29

Experiments at the FRM-II: ROT-effect in γ-ray and neutron emission

G. V. Danilyan, J. Klenke , V. A. Krakhotin, Yu. N. Kopach, V. V. Novitsky, V. S. Pavlov, and P. B. Shatalov, Phys. At. Nucl., 2011, Vol. 74, No. 5, pp. 671–674.

2011 - Search for the TRI- and ROT – effects in the γ-ray and neutron emission from fission of ^{235}U at the MEPHISTO instrument (FRM-II reactor, Garching).

Summary of results for the polarized cold neutron beam

Averaged asymmetry coefficients in units of 10^{-5}

Fission product	Angle with respect to the fission axis	ROT asymmetry	TRI effect
γ-rays	67.5	20.9 ± 2.4	1.1 ± 2.5
neutrons	67.5	-0.3 ± 2.2	-0.7 ± 2.3
neutrons	22.5	15.7 ± 2.0	

Theoretical models

1. Historically the first attempt to explain the nature of the TRI-effect was based on the statistical model *(V.Bunakov, G. Petrov, F. Goennenwein. 2000, ISINN-8)*.
2. After the ROT-effect discovery the semi-classical model of deformed fissionning system rotation has been proposed*(A. Gagarski, I. Guseva, F.Goennenwein. et al)*.
3. Hypothesis of the "scission γ-emission" for the γ-rays ROT-effect explanation in the ^{235}U binary fission *(G.Danilyan et al. 2008)*.
4. Explanation of the ROT-effect for the γ-rays by the angular anisotropy of the prompt γ-rays, emitted from fission fragments *(V.Novitsky, 2010)*.
5. Calculations of the ROT-effects for the γ-rays and neutrons by Guseva, 2010
6. The quantum mechanical explanations of the T-odd asymmetry effects with taking into account the interference of neutron resonances *(V. Bunakov, S. Kadmensky, 2006 -2009)*.
7. Theoretical approach of spin-orbital interaction for T-odd asymmetry effects explanation *(A. Barabanov, 2011, ISINN-19)*.
8. Comprehensive model description of all experimental data on T-effects in ternary fission *(A.Gagarski et al, Phys. Rev. C 93, 054619, 2016)*.

The rotation is being polarized after capturing of the polarized cold neutron

$$P(J^+) = \frac{(2I+3)}{[3\cdot(2I+1)]} p_n \quad (1)$$

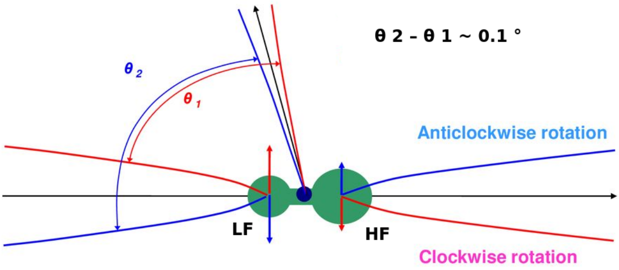
$$P(J^-) = -\frac{1}{3} p_n \quad (2)$$

Speed and direction of rotation is differ for J^+ and J^- states

$$\omega(J,K) = \begin{cases} \frac{J(J+1)-K^2}{J}\frac{\hbar}{2\Im} p_n \\ -\frac{J(J+1)-K^2}{J+1}\frac{\hbar}{2\Im} p_n \end{cases} \quad (3)$$

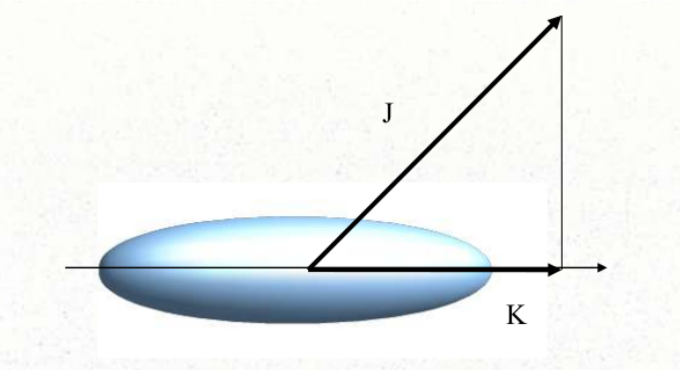
for $J^+ = I + 1/2$ for $J^- = I - 1/2$

Quasi-classical model



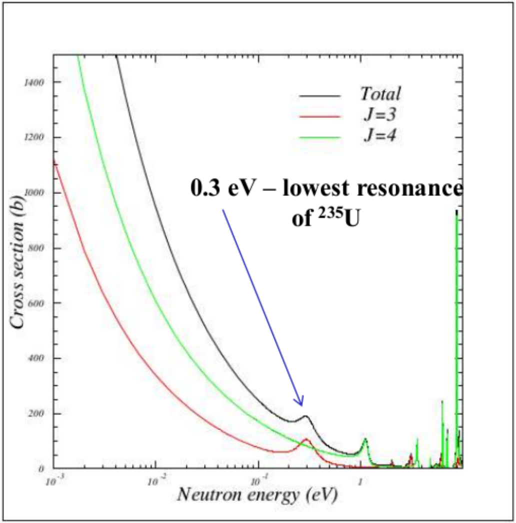
- Effect for the gamma-rays is much smaller due to smaller anisotropy
- The sign of the measured effect is different for α-particles and γ-rays
- There are no theoretical arguments for the existence of the TRI-effect for γ-rays

The role of J,K quantum numbers

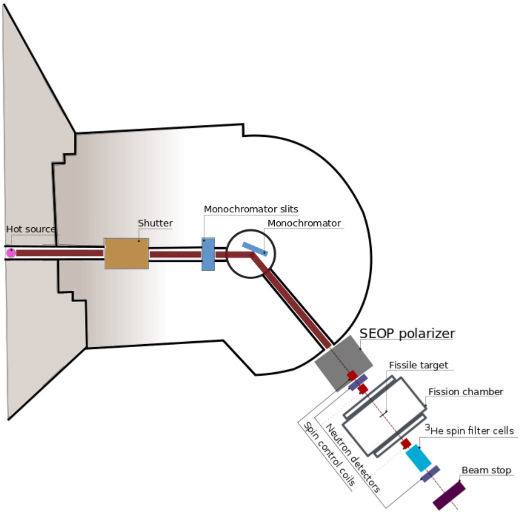


- $J\pi K$ - quantum numbers, which characterize the fission channel
- Depending on the target nucleus and incident neutron energy, different fission channels can be open (dominate)
- The "rotational"properies of the nucleus will be different for different fission channels

Spin-seperated cross section for $^{235}U(n,f)$



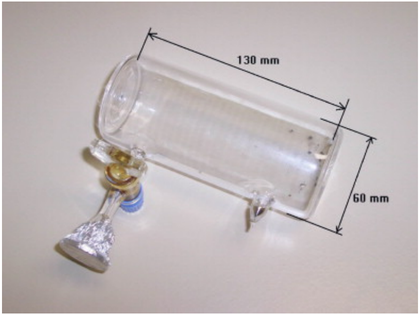
For the 0.3 eV resonance the ratio of the cross sections changes.

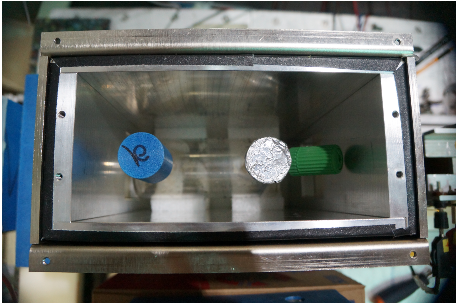


Beam parameters:

$\lambda = 1.15 (E_n \sim 0.06 eV)$
Flux: $\sim 5 \cdot 10^6 n/cm^2/s$
Polarisation: $\sim 100\%$

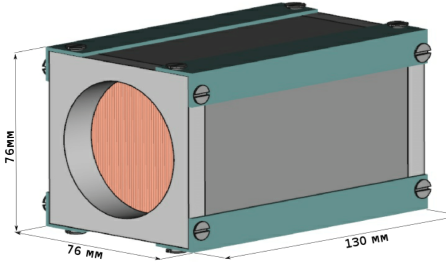
Spin filter cells





Gas pressure $\sim$ 2.5 bar

Spin control coils



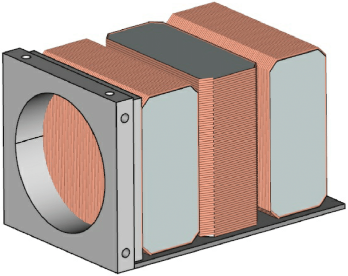
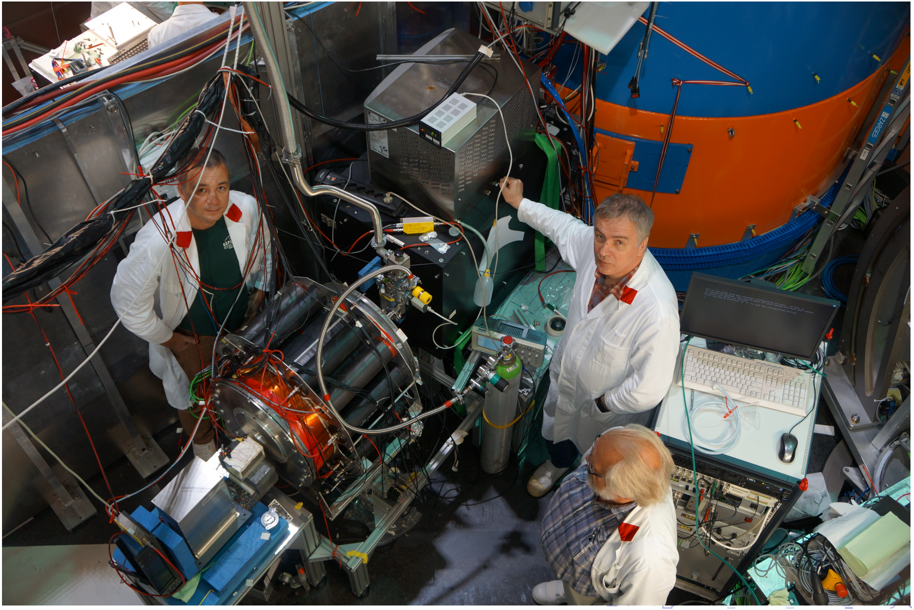
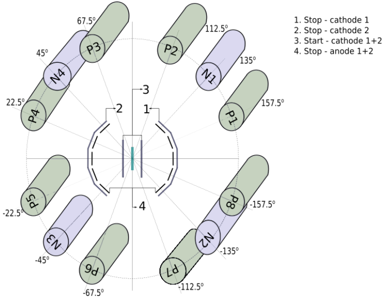


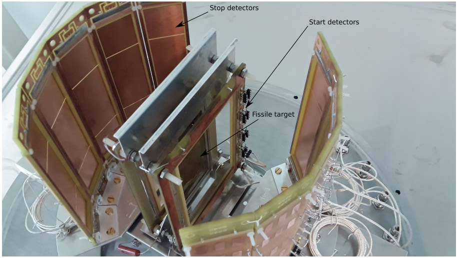
Photo of the experimental setup



Fission chamber



Layout of the experimental facility. View from the beam direction.



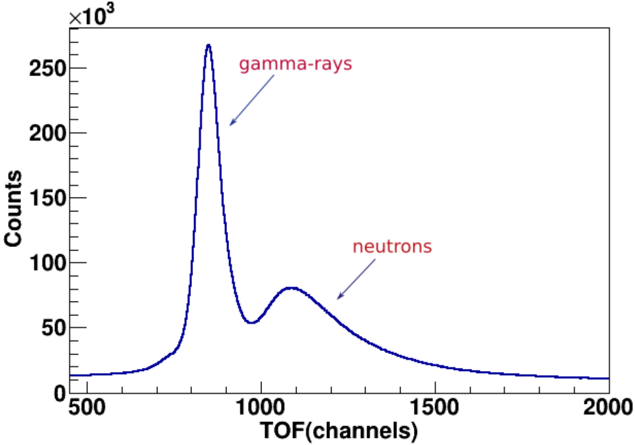
Low-pressure position sensitive multi-wire proportional counters

The chamber was filled with CF_4 gas at a pressure of about 10 mbar.

target $\rightarrow$ 82 mg of $^{235}U(99.99\%)$

Detectors of γ-rays and neutrons

- 8 cylindrical plastic scintillators at angles $\pm 22.5, \pm 67.5, \pm 112.5, \pm 157.5$
- 4 NaI scintillators at angles $\pm 45, \pm 135$



Time-of-flight spectrum from one of the plastic detectors.

Results

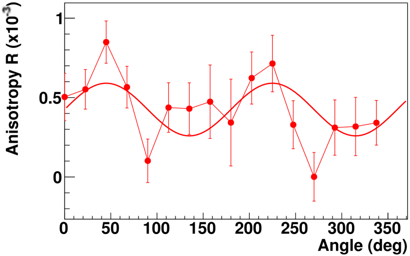
Count rates asymmetry

$$R(\theta) = \frac{N_+(\theta) - N_-(\theta)}{N_+(\theta) + N_-(\theta)}$$

The angular dependence in the first approximation can be fitted by the function

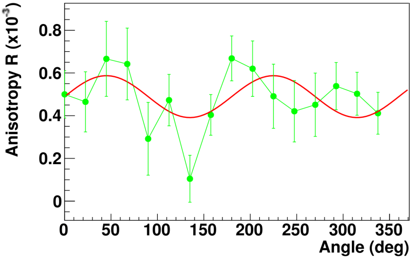
$$F = A \cdot sin(2\theta)$$

$\gamma - rays$



Average value: $(4.2 \pm 0.4) \cdot 10^{-4}$

neutrons



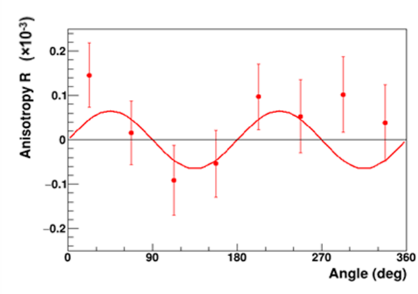
Average value: $(4.8 \pm 0.3) \cdot 10^{-4}$

Summary and outlook

- The ROT-effect has been measured for the first time in fission of ^{235}U induced by polarized monochromatic neutrons with an energy of 60 meV.
- The anisotropy parameter A determined from the experimental data for prompt gamma-rays and neutrons was established at the level of 10^{-4}. In spite of the smallness of the effects, the results are in agreement with the most modern theoretical model prediction.
- We believe that it is important to continue this type of experiments and to try extend the measurements to higher energies, e.g. to the 1.14 eV resonance where the effect should be larger than for cold neutrons and where practically only the J=4 spin state is present.

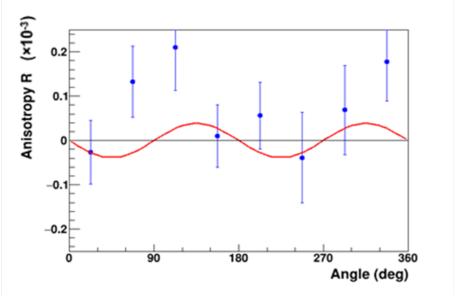
Thank you for your attention!!!

$\gamma - rays$



Average value: $(-6.5 \pm 3.9) \cdot 10^{-5}$

neutrons



Average value: $(3.8 \pm 4.1) \cdot 10^{-5}$