ESTIMATION OF THE MAGNITUDE AND SIGN OF THE ROT EFFECT FOR ^{239,241}Pu, ^{241}Am AND ^{245}Cm NUCLEI AT LOW NEUTRON ENERGY INDUCING THEIR FISSION

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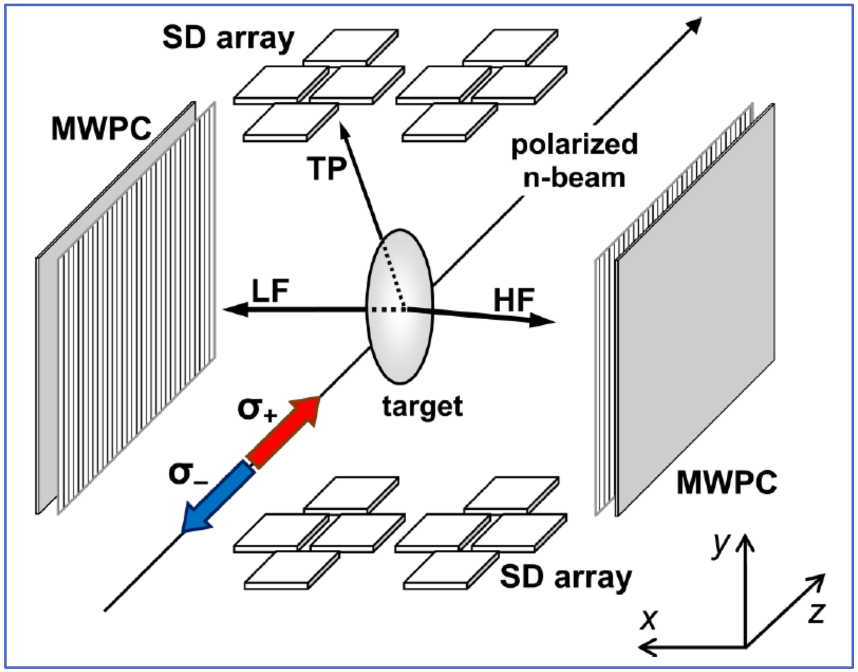
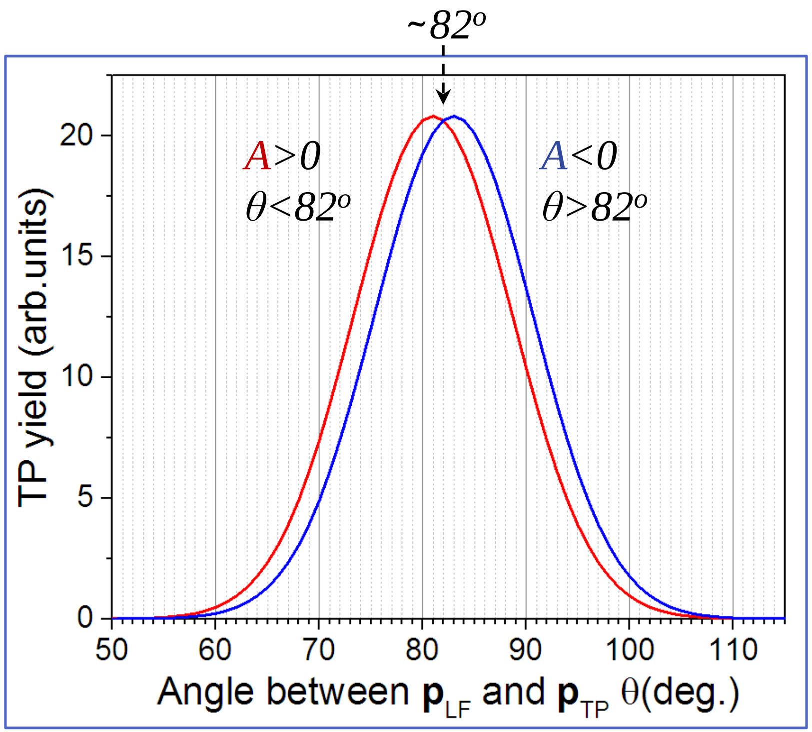
Experiments carried out in Grenoble in 2005 to identify asymmetries in the emission of light charged particles during the induced fission of ^{235}U nuclei by cold polarized neutrons laid the foundation for the study of a new effect. This was a shift in the angular distribution of α-particles, observed when the sign of neutron polarization changed.





Experimental setup: fissile target at the center, polarized neutron beam running horizontally, two MWPCs detecting complementary fission fragments to the left and right of the target, two arrays of Si detectors above and below of the target intercepting light charged particles (ternary particles).

Red line corresponds to $\sigma_z=+1/2$

Blue line corresponds to $\sigma_z=-1/2$

$$A = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

This shift was only part of the total modification of the angular distribution caused by the neutron spin flip in this experiment. The overall change in the angular distribution can be divided into two different parts: a change in the number of detected α-particles (TRI effect) and a shift in their angular distribution (ROT effect).

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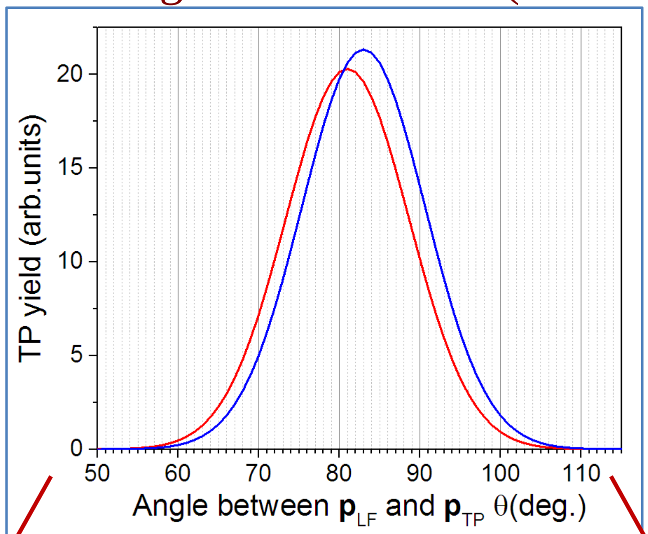
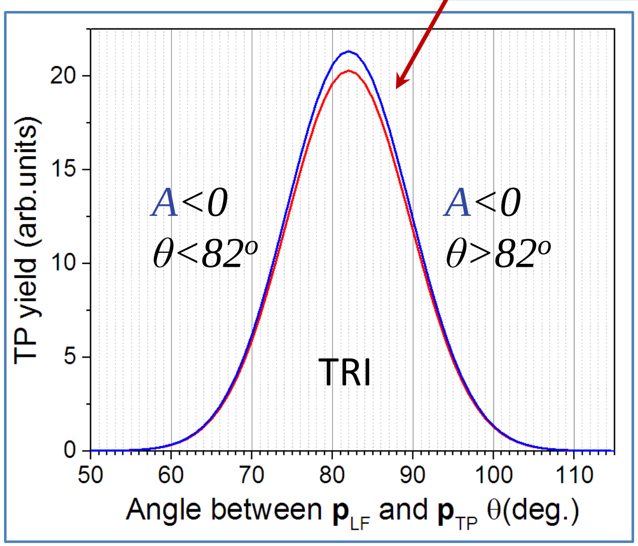
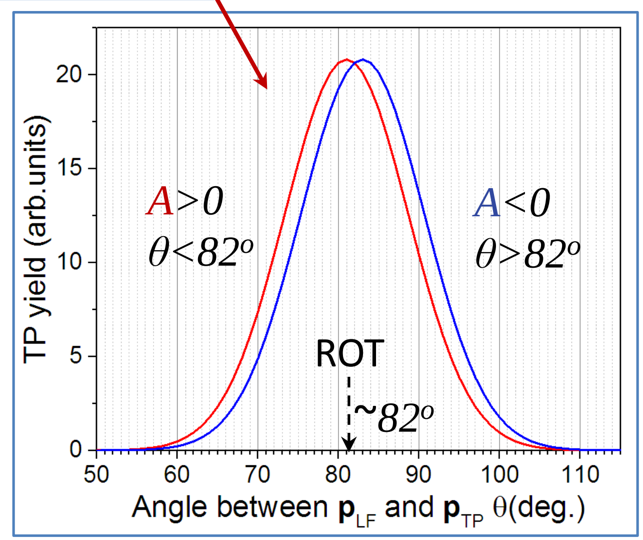
Blue line corresponds $\sigma_z=-1/2$



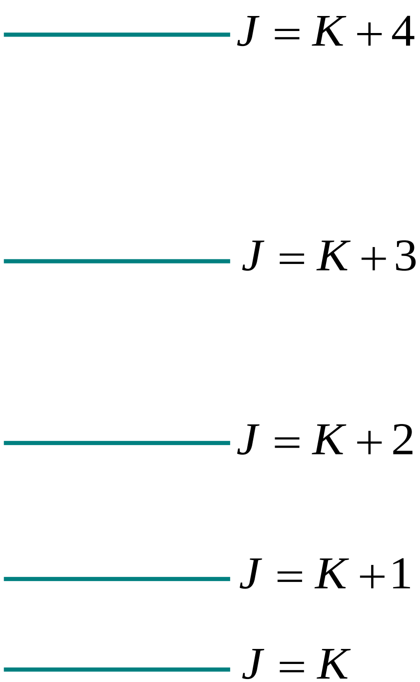
$$A = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$





The new effect was associated with the presence of rotational states in compound nuclei. These studies proved for the first time that the rotational functions previously introduced to describe the spectra of collective states of the nucleus are not just a convenient mathematical apparatus, but correspond to the real rotation of the nucleus in space.

Rotational band



The levels of the rotational band are characterized by spin J and its projection K onto the nuclear deformation axis. The sequence of levels with energy $E_{rot} \approx \frac{\hbar^2}{2\Im}[J(J+1) - K^2]$ begins with $J=K$.

In the case of induced fission by slow neutrons, 2 spin states of the compound nucleus are possible: $J_+=I + ½$ and $J\_=I$ - ½. Here I is the spin of the target nucleus.

Due to polarized neutrons fissile nuclei obtain oriented rotation. The ROT effect is proportional of the effective angular velocity:

$$ROT \sim \omega_{eff}$$

which is the weighted sum of the partial angular velocities for these two possible states. Coefficients of proportionality depend on the partial fission cross sections:

$$\omega_{eff} = \omega_+(J_+, K_+)\frac{\sigma_f(J_+)}{\sigma_f(J_+)+\sigma_f(J_-)} + \omega_-(J_-, K_-)\frac{\sigma_f(J_-)}{\sigma_f(J_+)+\sigma_f(J_-)}$$

The angular velocity of rotation of the nucleus around the neutron polarization axis (Z axis) for a given J and K can be determined as:

$$\omega(J,K) = \frac{\langle J_z(J,K) \rangle}{\mathfrak{I}}$$

Here $\mathfrak{I}$ is the moment of inertia of the divided system. Its value changes when charged objects move.

The magnitude of the moment of inertia corresponding to the time of separation of charged objects from each other can be obtained using standard trajectory calculations. These Monte Carlo simulations are used to describe the angular and energy distributions obtained from induced ternary fission experiments without neutron polarization and did not take into account rotation of fissile system.

The estimated values of effective angular velocity for the fissile system rotation with fixed J and K around the line of neutron beam polarization just after fission can be written as:

$$\omega_{+/-}(J,K) = \begin{cases} + \dfrac{J_+(J_+ + 1) - K_+^2}{J_+} \cdot \dfrac{\hbar}{2\mathfrak{I}} \cdot p_n \\ - \dfrac{J_-(J_- + 1) - K_-^2}{(J_- + 1)} \cdot \dfrac{\hbar}{2\mathfrak{I}} \cdot p_n \end{cases}$$

where p_n determines the neutron beam polarization.

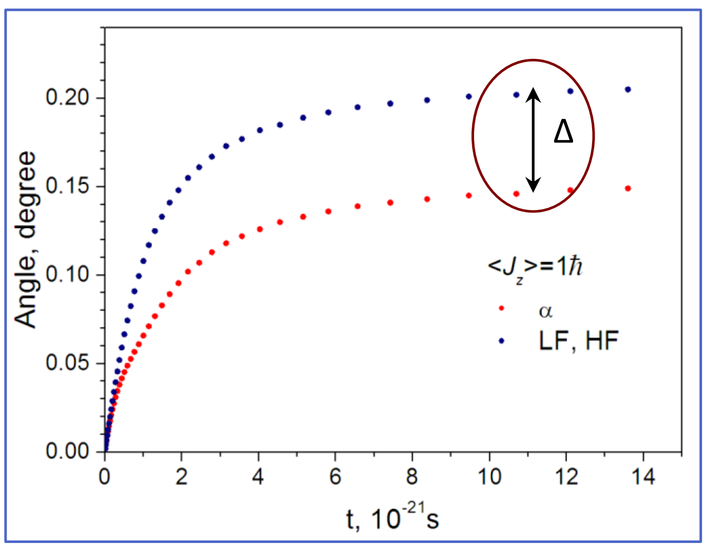
The different signs of angular velocities for J_+ and J_- indicate the opposite directions of fissile system rotation.

All formulas presented here for the effective angular velocity of rotation of a fissile system are suitable not only for induced ternary fission, but also for induced binary fission with the emission of γ-rays or neutrons.

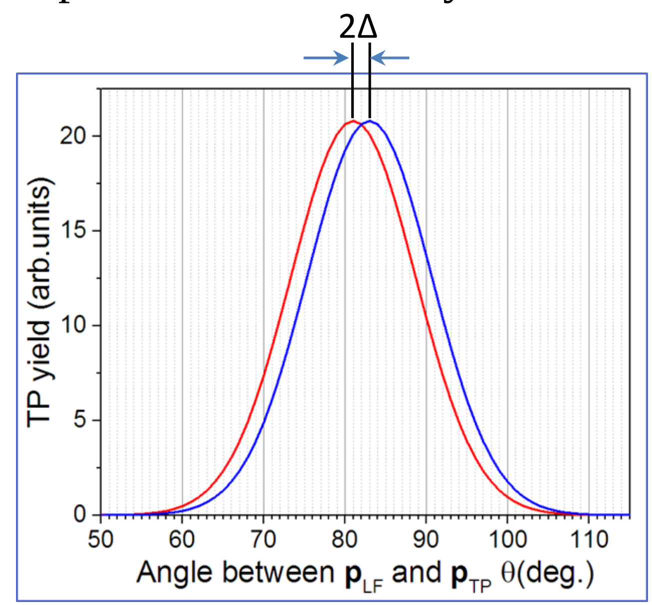
In ternary fission induced by polarized neutrons, the ROT effect manifests itself in the form of a shift in the angular distribution of light charged particles as a result of a change of the neutron beam polarization.

This effect can only be seen due to the lag Δ in the rotational motion of the light charged particle from the fission fragment.

Due to the spin flip, the angular distribution of alpha particles is shifted by 2Δ.



The angle of rotation of a charged fission object versus time



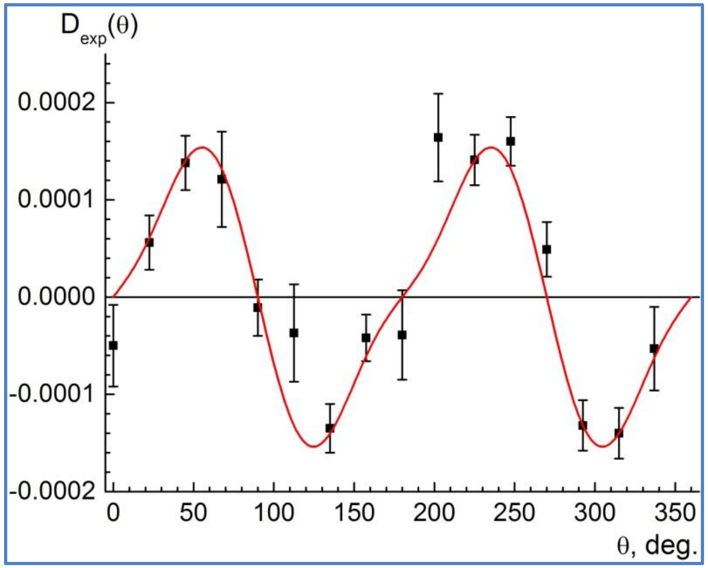
The shift in the angular distribution for ternary particle

The ROT effect in binary fission of ^{235}U induced by polarized thermal neutrons was first discovered by Danilyan's group in 2009 and confirmed by PNPI physicists in 2010. During these experiments, an asymmetry was observed in the angular distribution of gamma rays due to the neutron spin flip.

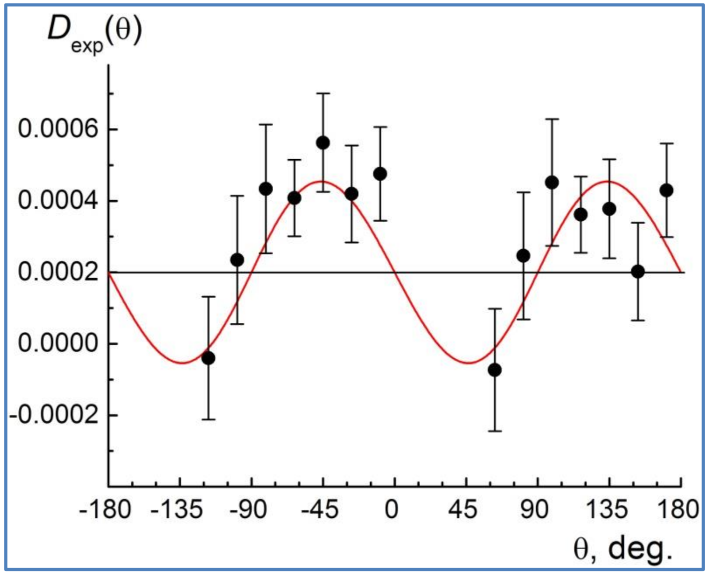
$W(\theta)\, d\Omega \sim \{1 + D\cdot B(\theta)\}\, d\Omega$
D measures size of correlation

$B = (\sigma\cdot[p_F \times p_\gamma])$
note: all vectors are unit vectors

$D_{exp} = (N_{\sigma+} - N_{\sigma-}) / (N_{\sigma+} + N_{\sigma-})$



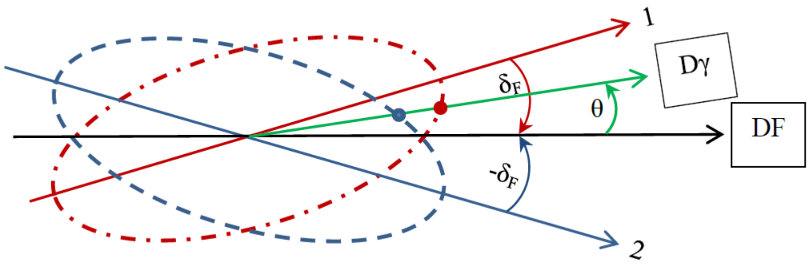
G.V. Danilyan, J. Klenke, V.A. Krakhotin, et al.
Yad. fiz, 72 (2009) p.1872



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

The discrepancy between the signs in the two experiments is due to a different sequence of vectors in the expression for $B = (\boldsymbol{\sigma}\cdot[\mathbf{p}_F \times \mathbf{p}_\gamma])$.

Scheme explaining the occurrence of ROT asymmetry in the emission of γ-quanta from fission fragments



DF – location of fission fragment detector
Dγ - location of the γ-ray detector
θ - the angle of γ-quantum registration versus DF
1, 2 - initial positions of the fission axes
δ_F and $-\delta_F$ fission axis rotation angles corresponding to σ_+ and σ_-

The red and blue ovals demonstrate the anisotropy of γ-quantum emission during fission.

$$N_{\sigma+}(\theta) = N(90^{o})(1+A\cdot\cos^2(\theta + \delta_F))$$
$$N_{\sigma-}(\theta) = N(90^{o})(1+A\cdot\cos^2(\theta - \delta_F))$$

The red and blue dots on them show the difference in the number of registered γ-quanta for two neutron polarizations for the angle θ between detectors DF and Dγ.

$$D_{exp}(\theta) = (N_{\sigma+}(\theta) - N_{\sigma-}(\theta)) / (N_{\sigma+}(\theta) + N_{\sigma-}(\theta))$$

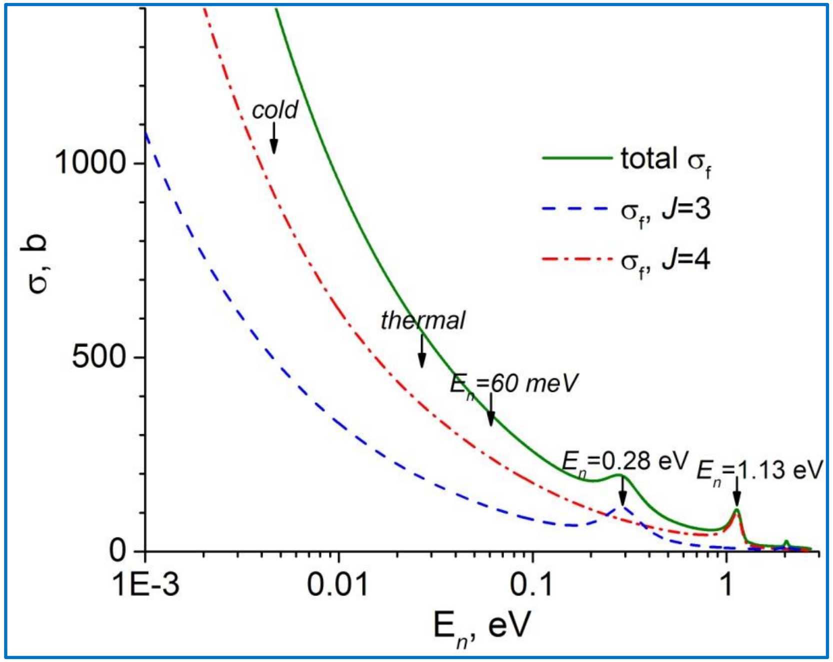
Using the fact that the anisotropy value is small, we can rewrite this expression in terms of the rotation angle of the fission fragment δ_F:

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

In **ternary fission** induced by cold polarized neutrons with an energy of 4.5 meV, the ROT symmetry was studied for 4 target nuclei: **^{235}U, ^{233}U, ^{239}Pu and ^{241}Pu**.

The ROT effect with the emission of **γ-quanta** was studied in the **binary fission** of the target nucleus **^{235}U**, induced by thermal neutrons, neutrons with an energy of 60 meV, as well as resonant neutrons with an energy of about 0.3 eV.

Two partial angular velocities possible at low neutron energies **have different signs** and they **compete**. The greater the contribution of one of them, the more clearly the effect corresponding to this component is manifested.

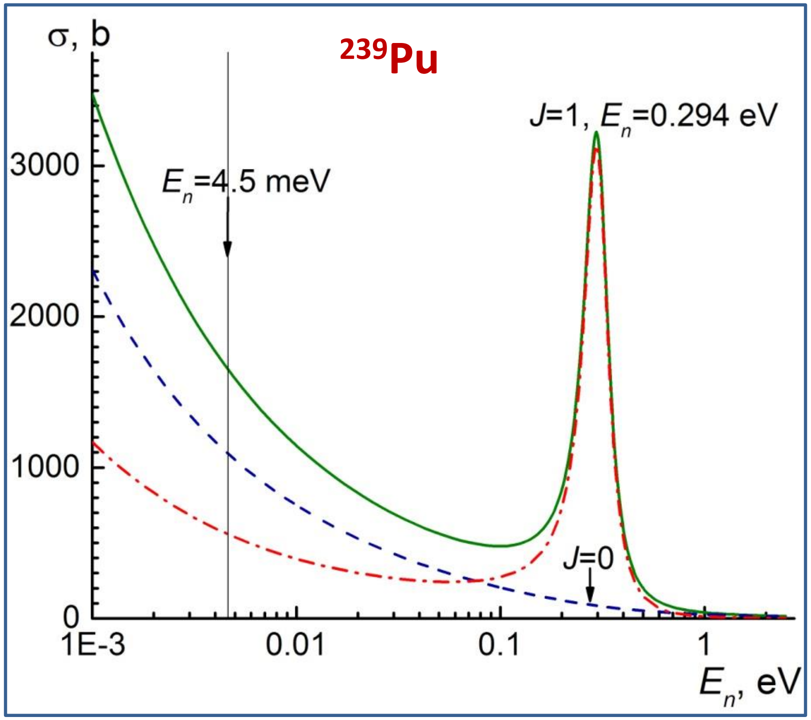


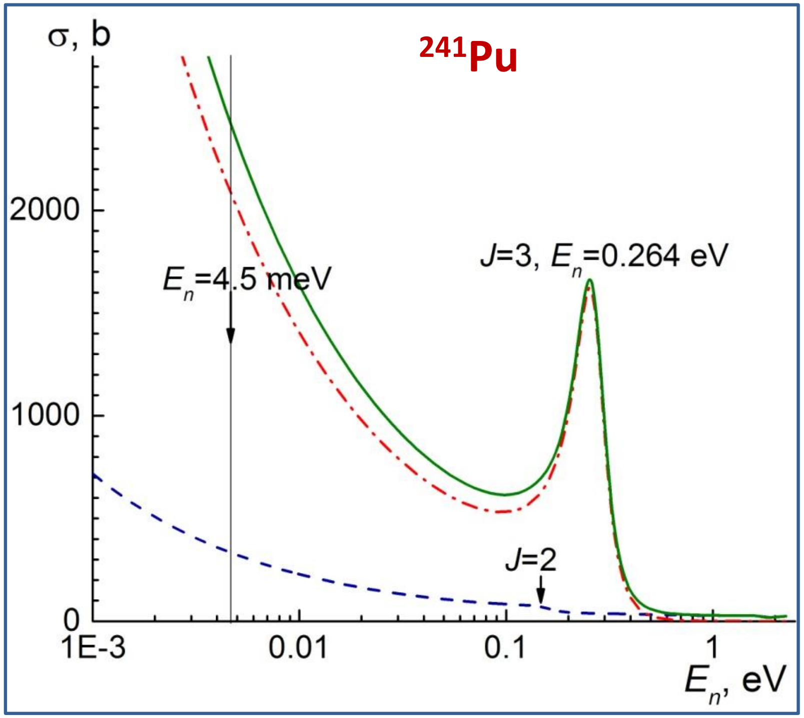
Therefore, it seems obvious that it is more advantageous to measure the effect at resonant neutron energies.

Although the study of ROT asymmetry for neutron resonance energies seems to be the most relevant, the choice of a resonance with an energy of about 0.3 eV for the target ^{235}U turned out to be unsuccessful.
This choice is unfortunate because the competing partial fission cross sections are almost equal to each other.

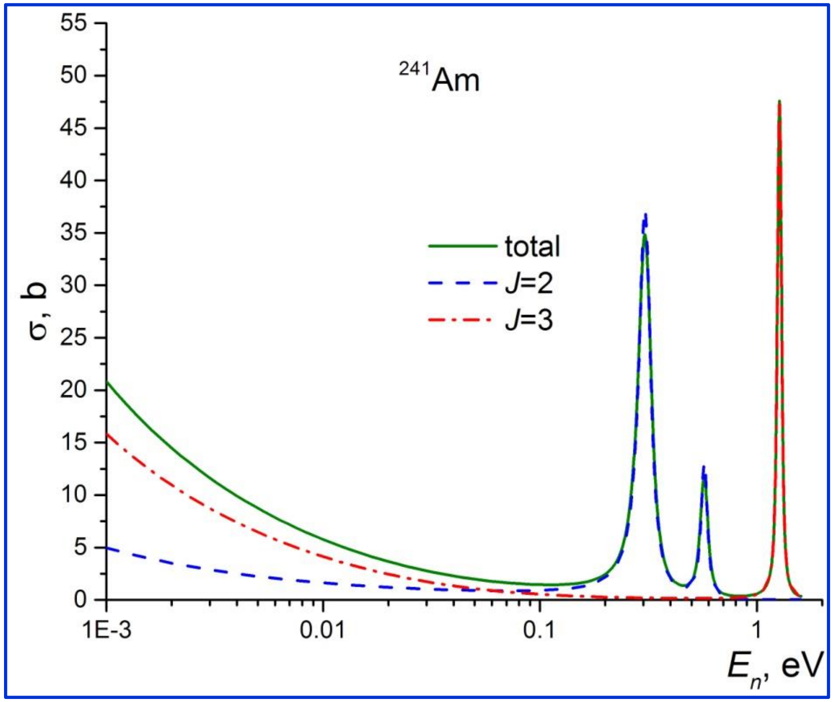
The ROT effect in ternary and binary fission by polarized neutrons of plutonium isotopes it is proposed to measure at the resonance with E_n=0.294 eV for the **^{239}Pu** target and E_n=0.264 eV for the **^{241}Pu** target.

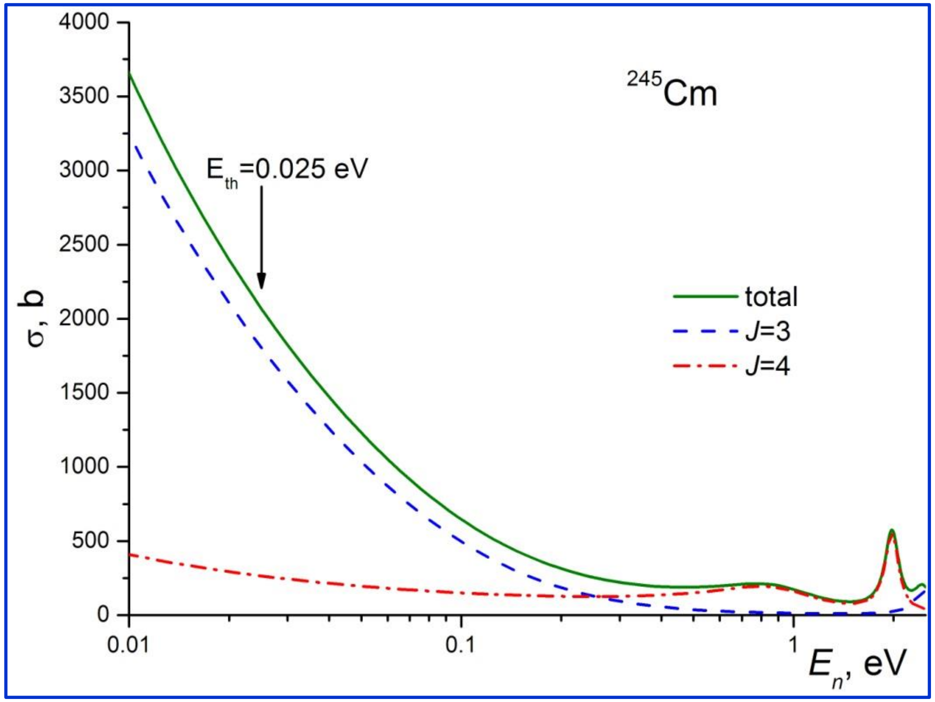
1. The magnitude of the effects expected at the indicated resonance energies will be significantly greater than those previously obtained for these targets in ternary fission at E_n=4.5 meV.
2. The fractions of impurity partial cross sections with a spin different from the spin of the resonance itself are small.
3. The influence of resonances introduced at neutron energies E_n<0 eV is weak.





The ^{241}**Am** and ^{245}**Cm** targets, which **have not previously been used** to study the ROT effect, may be interesting in that when using them, not only effects of **significant magnitude** are expected, but also of the **opposite sign** with respect to the effects for all four isotopes that were previously studied at cold or thermal energies neutrons. Experimental confirmation of the negative sign of the effect will mean the dominant rotation of the compound nucleus of this isotope around the neutron polarization axis **counterclockwise**.





Conclusion

Although the ROT effect was discovered about 20 years ago, during all this time only 4 nuclei have been studied. Moreover, there has not been a single successful measurement of this effect at neutron energies corresponding to resonances.

However, studying the ROT effect at resonances can be very important, because with a successful choice of the target nucleus and neutron resonance energy, one should expect a small influence of the partial fission cross section competing with the resonance one, as well as a small influence of resonances from the negative energy region, the reliability of the parameters of which cannot be verified.

Measurements under such conditions will lead to a better understanding of this effect.

THANK YOU FOR YOUR ATTENTION!