ISINN-28 Agenda

P-even T-odd asymmetries in differential cross sections of fission reactions of nonorientied nuclei by cold polarized neutrons with emission of prescission and evaporation light particles

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Purpose of work

Demonstration of the possibility of describing the characteristics of P - even T - odd asymmetries in the differential cross sections of fission reactions of nonorientied target nuclei by cold polarized neutrons with the emission of light particles, such as prescission α - particles and prompt neutrons and γ - quanta in the framework of the quantum theory of fission using a single mechanism the appearance of these asymmetries, due to the influence of the Coriolis interaction of the total spin of a composite fissile nucleus on fission fragments and light particles.

Introduction

In paper [*Jessinger P., Koetzle A., Gonnenwein F. et al.* // Phys. At. Nucl. 2002. V. **65**. P. 662.], the differential cross section $d\sigma_{nf,p}/d\Omega$ was represented as

$$d\sigma_{nf,p}/d\Omega = d\sigma^{0}_{nf,p}/d\Omega + d\sigma^{1}_{nf,p}/d\Omega, \tag{1}$$

where $d\sigma^{0}_{nf}/d\Omega$ is a similar cross section of the reaction under study with the participation of cold nonpolarized neutrons $(\boldsymbol{\sigma}_{\mathrm{n}} = 0)$, and $d\sigma^{1}_{nf}/d\Omega$ is the component of the differential cross section (1), linearly dependent on $\boldsymbol{\sigma}_{\mathrm{n}}$. In this case, the ratio was used:

$$d\sigma^{0}_{nf,p}/d\Omega = \sigma^{0}_{nf} P^{0}(\theta), \tag{2}$$

where σ^{0}_{nf} is the total cross section, and $P^{0}(\theta)$ is the normalized angular distribution of emitted light particles in the reaction with nonpolarized neutrons.

To describe the asymmetry under consideration, an asymmetry coefficient of $D(\Omega)$ was introduced, determined by:

$$D(\Omega) = \left(\frac{d\sigma^{(+)}_{nf,p}}{d\Omega} - \frac{d\sigma^{(-)}_{nf,p}}{d\Omega}\right) \Bigg/ \left(\frac{d\sigma^{(+)}_{nf,p}}{d\Omega} + \frac{d\sigma^{(-)}_{nf,p}}{d\Omega}\right). \tag{3}$$

Using (1), this coefficient can be represented as

$$D(\Omega) = \left(d\sigma^{1+}_{nf,p}/d\Omega\right) / \left(d\sigma^{0}_{nf,p}/d\Omega\right). \tag{4}$$

1. Characteristics of P - even T-odd asymmetries in the differential cross sections of nuclear fission reactions with the escape of prescission α-particles

The normalized angular distribution of α - particles, $P^0(\theta)$, is the unperturbed component of cross section (2) and has the form:

$$P^0(\theta) = \left|A^0(\theta)\right|^2 = \left|\sum_l d_l Y_{l0}(\theta)\right|^2 = \left|\sum_l \{d_l\} e^{i\delta_l} Y_{l0}(\theta)\right|^2, \qquad (5)$$

where $\{d_l\}$ and δ_l are the main value and the phase of the value d_l.

$$A^0(\theta) = A^0_-(\theta) + A^0_+(\theta), \qquad (6)$$

$$P^0(\theta) = P^0_-(\theta) + P^0_+(\theta), \qquad (7)$$

where even $P^0_-(\theta)$ and odd $P^0_+(\theta)$ components of the angular distribution $P^0(\theta)$, taking into account (5-6), are represented as

$$P^0_-(\theta) = \left\{A^0_-(\theta)\right\}^2 + \left\{A^0_+(\theta)\right\}^2; \quad P^0_+(\theta) = 2\left\{A^0_-(\theta)\right\}\left\{A^0_+(\theta)\right\}. \qquad (8)$$

1. Characteristics of P - even T-odd asymmetries in the differential cross sections of nuclear fission reactions with the escape of prescission α-particles

In [*Kadmensky S.G., Titova L.V., Bunakov V.E.* // Phys. Atom. Nucl. 2019. V. **82**. № 3. P. 254; *Kadmensky S.G., Bunakov V.E., Lyubashevsky D.E.* // Bull. Russ. Acad. Sci. Phys. 2019. V. **83**. № 9. P. 1128.; *Kadmensky S.G., Lyubashevsky D.E., Kostryukov P.V.* // Phys. Atom. Nucl. 2019. V. **82**, № 3. P. 267.], the component of the differential cross section (1) $d\sigma^{1}_{nf,\alpha}/d\Omega$, taking into account the influence of the Coriolis interaction of the total spin of a composite fissile nucleus with the orbital angular momenta of fission fragments and a α - particle, can be represented in terms of the sum of the derivatives of the unperturbed angular distributions α - particles $P^{0}_{-}(\theta)$ and $P^{0}_{+}(\theta)$ included in (7) as

$$\frac{d\sigma^{1}_{nf,\alpha}}{d\Omega} = \left(\frac{d\sigma^{1}_{nf,\alpha}}{d\Omega}\right)_{-} + \left(\frac{d\sigma^{1}_{nf,\alpha}}{d\Omega}\right)_{+} = \Delta_{\alpha,-}\sigma^{0}_{nf}\frac{d\left(P^{0}_{-}(\theta)\right)}{d\theta} + \Delta_{\alpha,+}\sigma^{0}_{nf}\frac{d\left(P^{0}_{+}(\theta)\right)}{d\theta}. \tag{9}$$

1. Characteristics of P - even T-odd asymmetries in the differential cross sections of nuclear fission reactions with the escape of prescission α-particles

Since the dependences of $P_-^0(\theta)$ and $P_+^0(\theta)$ on angles can be described by sums of the form $\sum_n A_n(\cos\theta)^n$ with even $n = 0, 2, 4, \ldots$ and odd $n = 1, 3, 5, \ldots$ values of n, respectively, it can be shown that the quantities $\frac{d\left(P_+^0(\theta)\right)}{d\theta}$ and $\frac{d\left(P_-^0(\theta)\right)}{d\theta}$ included in (9) are represented as

$$\left(\frac{d\sigma^1_{nf,\alpha}}{d\Omega}\right)_+ = B_+(\theta)\sin(\theta); \quad \left(\frac{d\sigma^1_{nf,\alpha}}{d\Omega}\right)_- = B_-(\theta)\cos(\theta)\sin(\theta), \tag{10}$$

where the coefficients $B_-(\theta)$ and $B_+(\theta)$ are related to the sums of the quantities $\cos^n(\theta)$ with even values of n. Therefore, the quantities considered in (10) satisfy the symmetry conditions:

$$\left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_+ = \left(\frac{d\sigma^1_{nf,\alpha}(\pi-\theta)}{d\Omega}\right)_+; \quad \left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_- = -\left(\frac{d\sigma^1_{nf,\alpha}(\pi-\theta)}{d\Omega}\right)_-. \tag{11}$$

1. Characteristics of P - even T-odd asymmetries in the differential cross sections of nuclear fission reactions with the escape of prescission α-particles

Then the differential sections $\left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_+$ and $\left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_-$ (10) can be represented by:

$$\left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_+ = B_+(\theta)\left(\boldsymbol{\sigma}_n\left[\mathbf{k}_{LF},\mathbf{k}_\alpha\right]\right); \quad \left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_- = B_-(\theta)\left(\boldsymbol{\sigma}_n\left[\mathbf{k}_{LF},\mathbf{k}_\alpha\right]\right)\left(\mathbf{k}_{LF},\mathbf{k}_\alpha\right). \quad (12)$$

Using the relationship of equation (4) for the asymmetry coefficient $D(\theta)$ with (2, 9) and the symmetry condition (11), we can obtain the relations:

$$\left(\frac{d\sigma^1_{nf,\alpha}(\theta)}{d\Omega}\right)_\pm = 1/2\left[D(\theta)\frac{d\sigma^0(\theta)}{d\Omega} \pm D(\pi-\theta)\frac{d\sigma^0(\pi-\theta)}{d\Omega}\right]. \quad (13)$$

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Values $\Delta_{\alpha,-}$ and $\Delta_{\alpha,+}$ calculated using the χ^2 - method for target nuclei ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu

Target nuclei	$\Delta_{\alpha,-}$	$\Delta_{\alpha,+}$	Δ_{γ}	Δ_{n}
^{233}U	0.0003	-0.00033	-0.0003	-0.00065
^{235}U	0.0015	0.0016	0.0021	0.0012
^{239}Pu	0.00017	0.0001		
^{241}Pu	0.00021	0.0005		

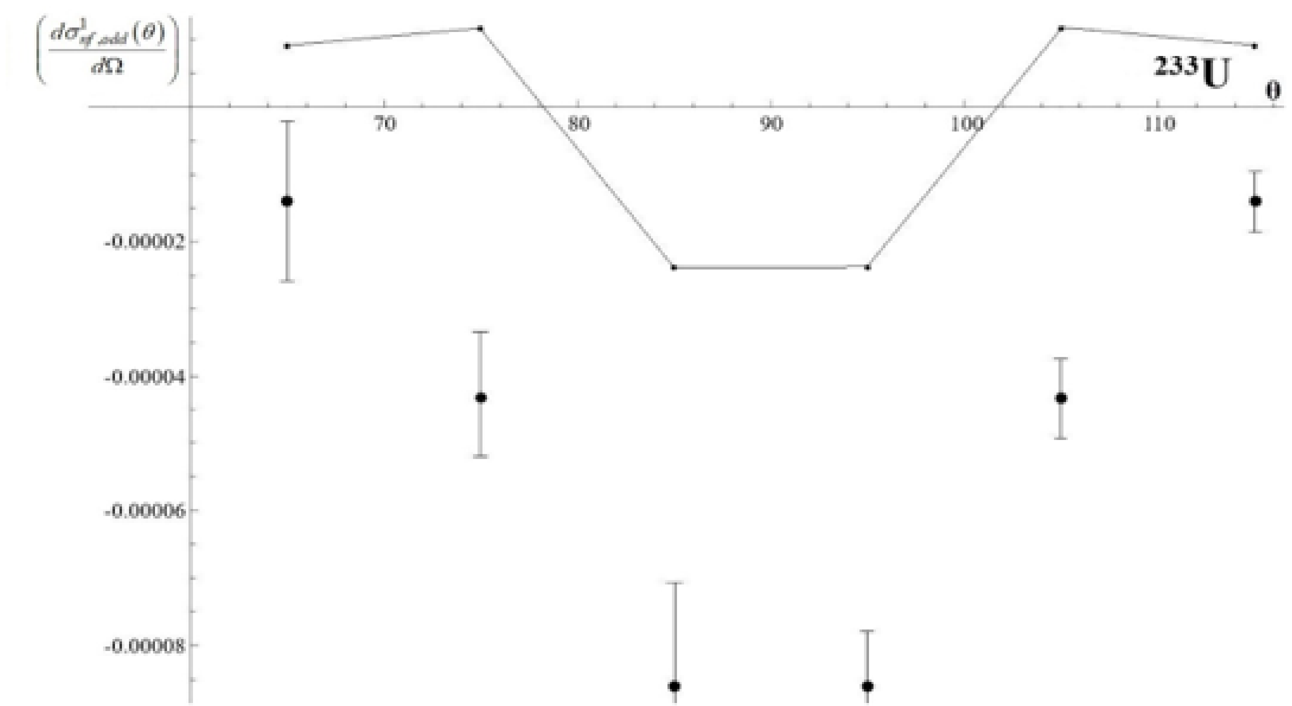

Fig. 1. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^{1}_{nf,\alpha}(\theta)/d\Omega\right)_{+}$ for the ^{233}U target nucleus

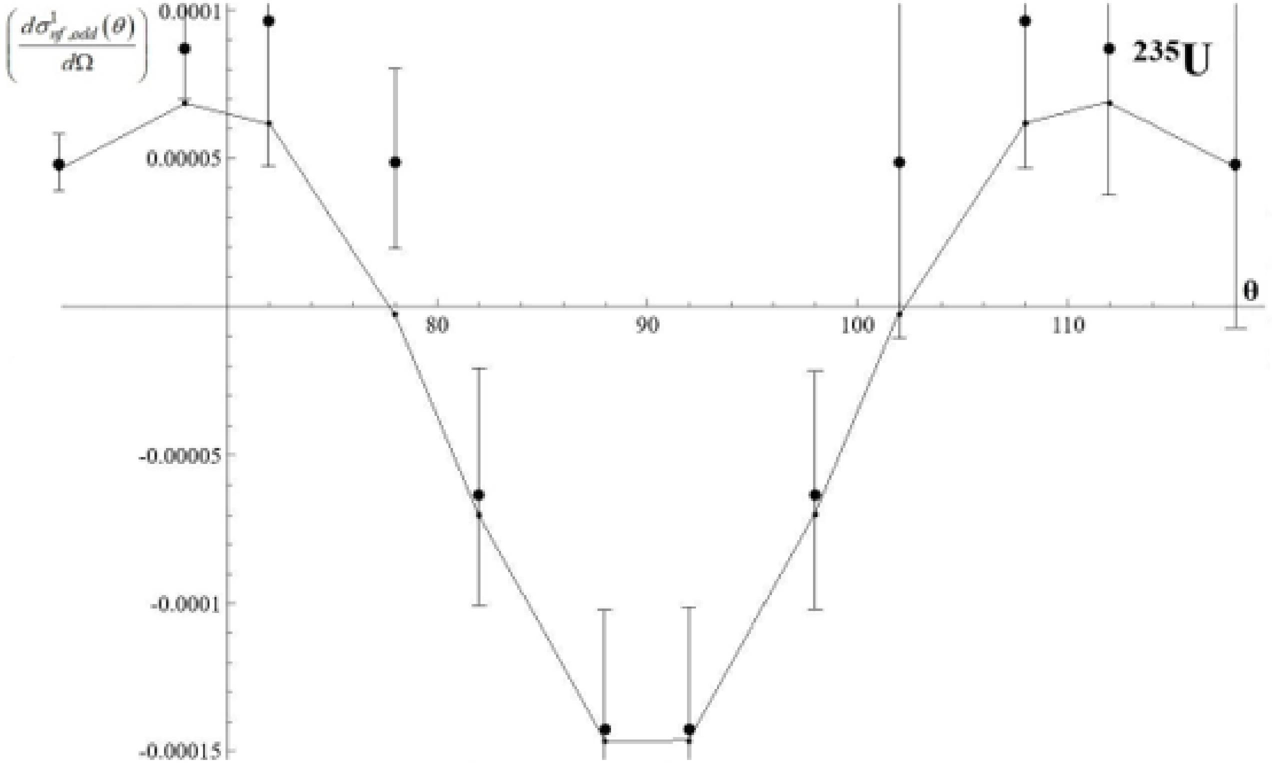

Fig. 2. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^{1}_{nf,\alpha}(\theta)/d\Omega\right)_{+}$ for the ^{235}U target nucleus

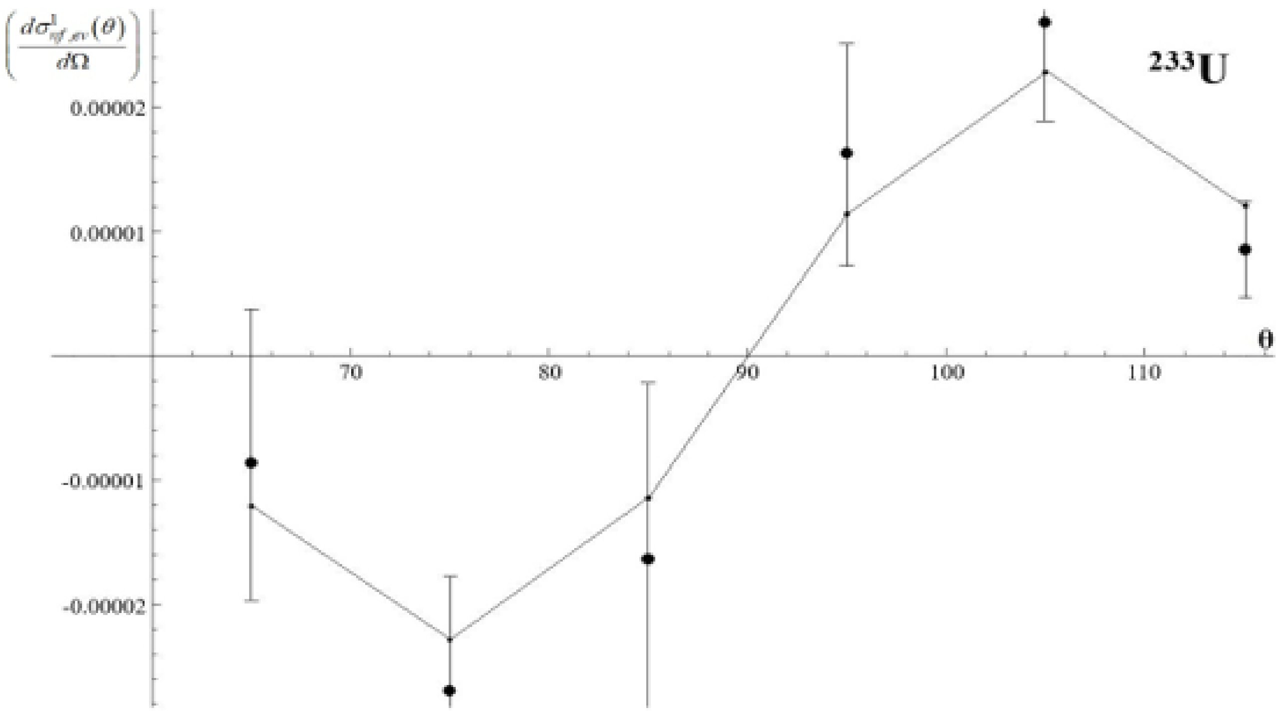

Fig. 3. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^{1}_{nf,\alpha}(\theta)/d\Omega\right)_{-}$ for the ^{233}U target nucleus

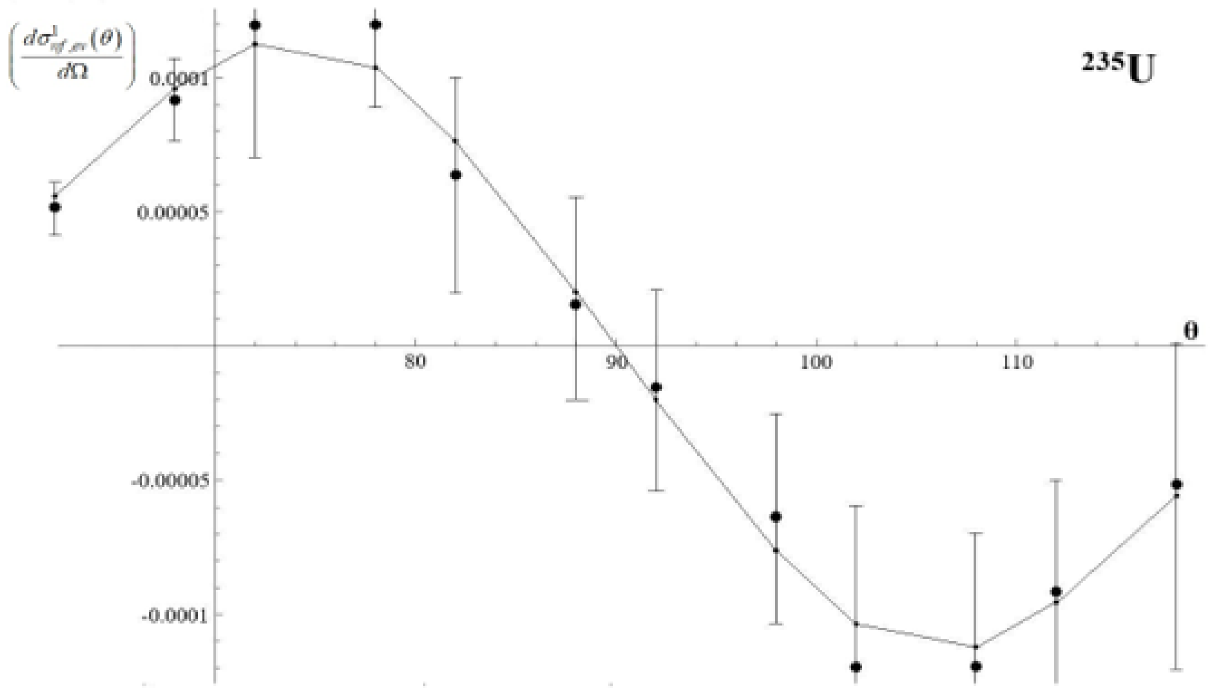

Fig. 4. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^1_{nf,\alpha}(\theta)/d\Omega\right)_-$ for the ^{235}U target nucleus

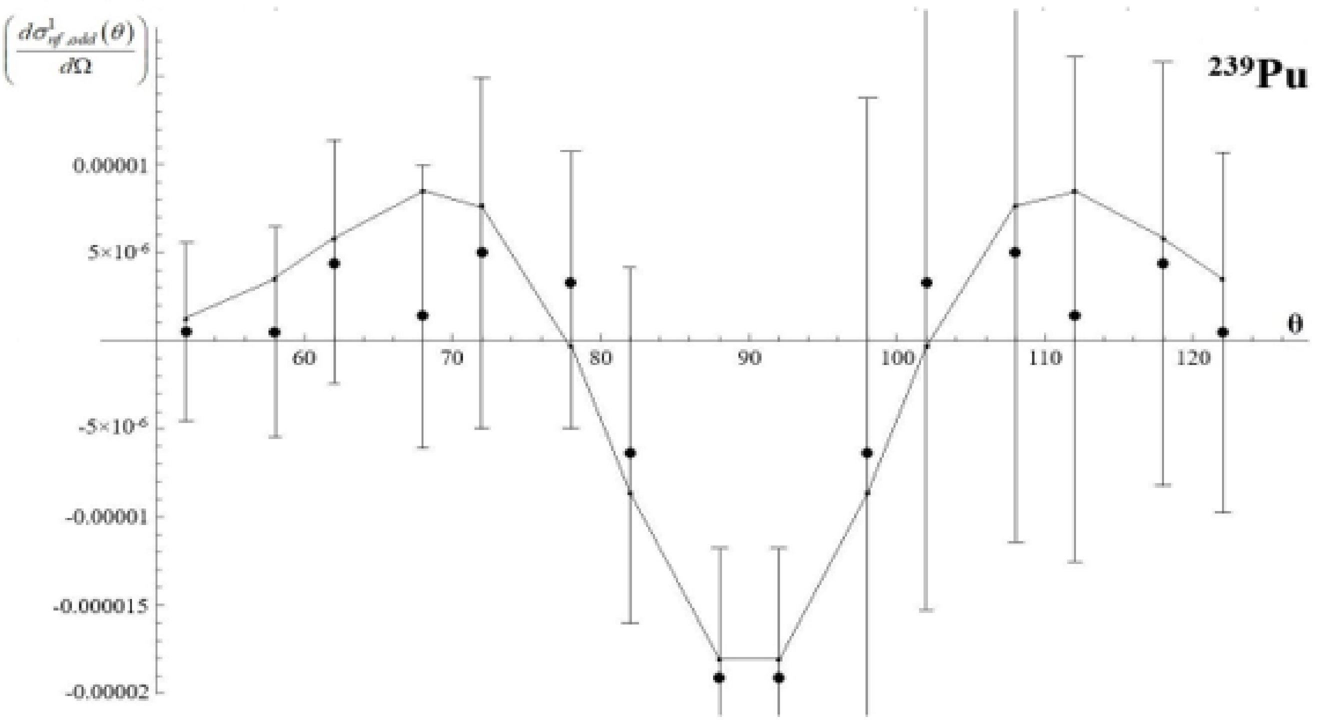

Fig. 5. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^{1}_{nf,\alpha}(\theta)/d\Omega\right)_{+}$ for the ^{239}Pu target nucleus

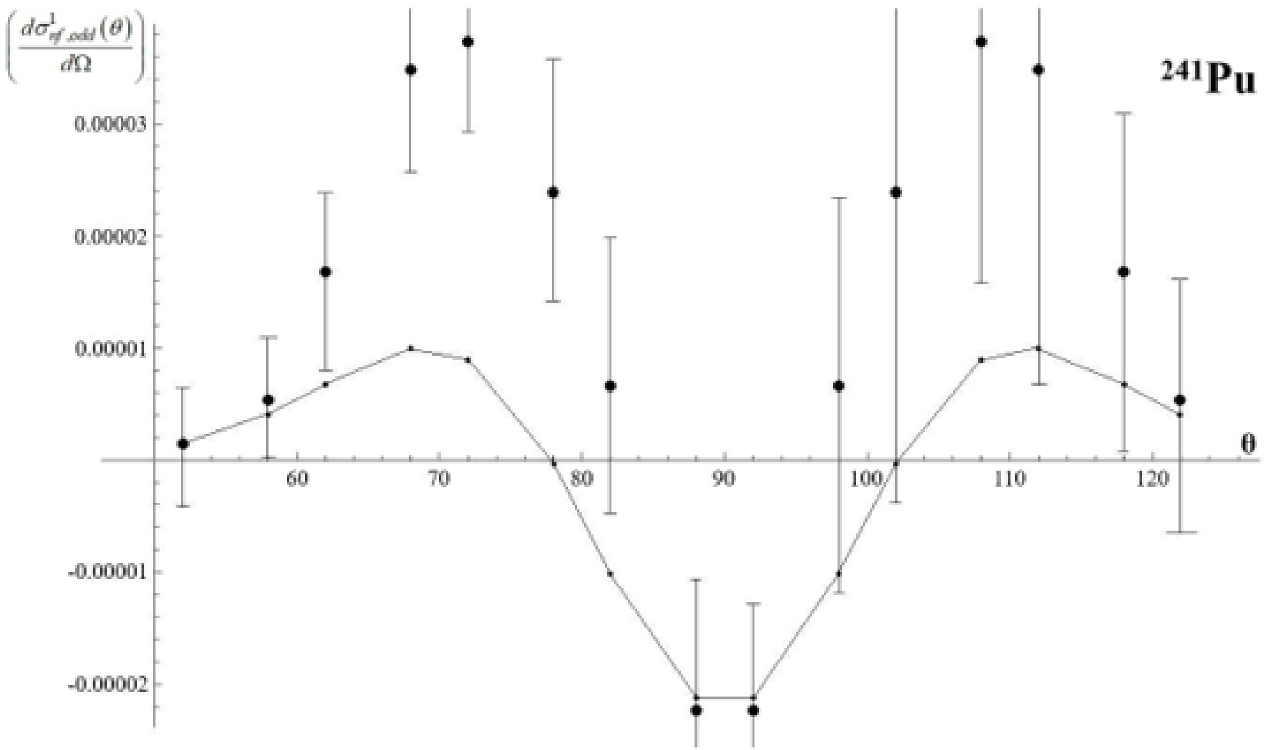

Fig. 6. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^{1}_{nf,\alpha}(\theta)/d\Omega\right)_{+}$ for the ^{241}Pu target nucleus

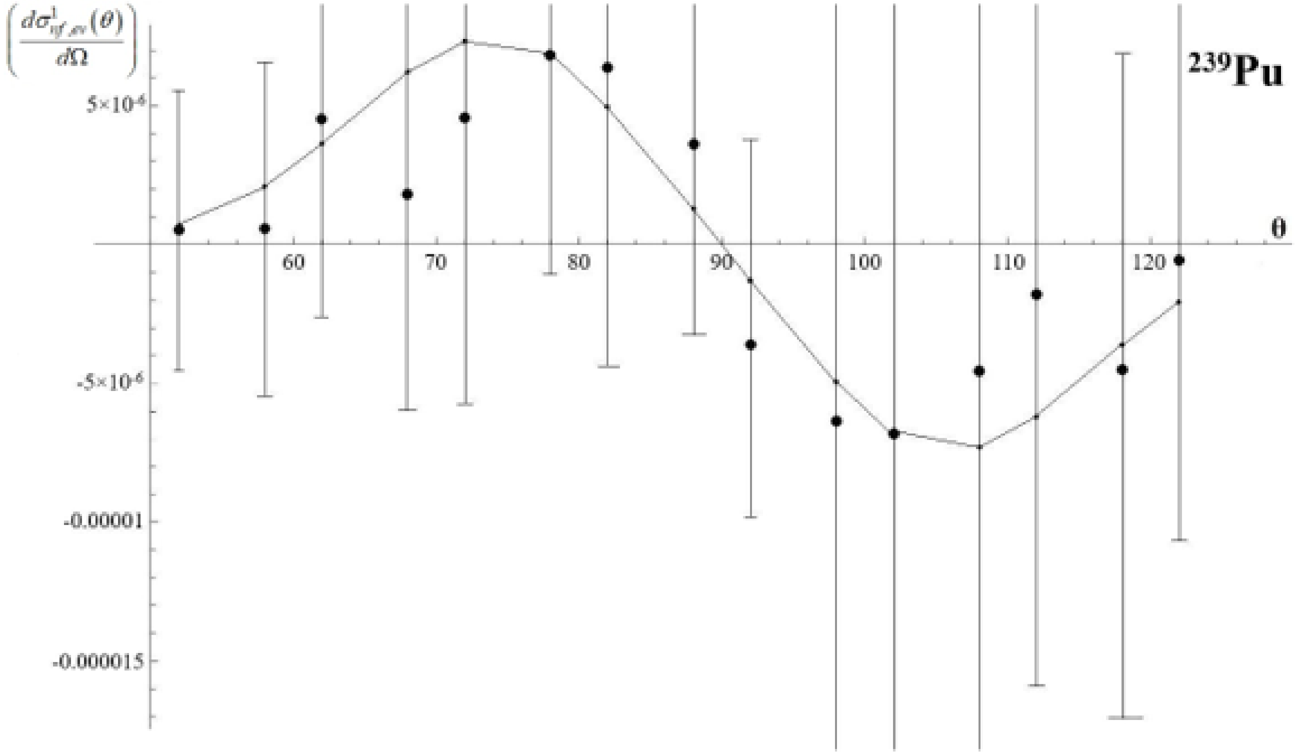

Fig. 7. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^{1}_{nf,\alpha}(\theta)/d\Omega\right)_{-}$ for the ^{239}Pu target nucleus

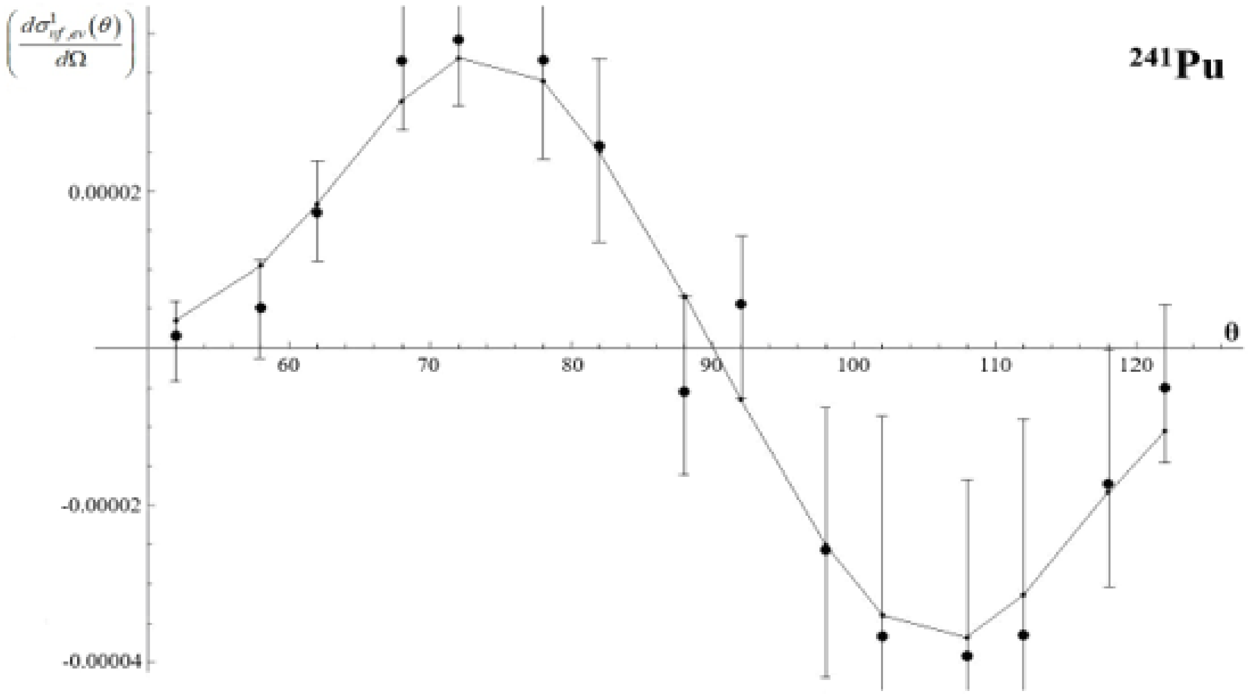

Fig. 8. Experimental (closed circles) and calculated within the framework of the quantum approach - continuous line cross section $\left(d\sigma^1_{nf,\alpha}(\theta)/d\Omega\right)_-$ for the ^{241}Pu target nucleus

2. Characteristics of P - even T - odd asymmetries in the differential cross sections of nuclear fission reactions with the emission of prompt gamma quanta and neutrons

The unperturbed experimental angular distributions $P^0(\theta)$ of prompt neutrons and γ - quanta are determined by:

$$P^0(\theta) \sim \left(1 + A\cos^2\theta\right), \qquad (14)$$

where θ is the angle between the direction of emission of prompt neutrons (γ - quanta) and the direction of emission of a light fission fragment. Since in this case $P^0(\theta) = P^0_-(\theta)$, using (9) for an even component $\left(d\sigma^1_{nf,p}/d\Omega\right)_-$ we can get:

$$\left(\frac{d\sigma^1_{nf,p}(\theta)}{d\Omega}\right)_- = \Delta_{n,\gamma}\frac{dP^0(\theta)}{d\theta}\quad , \qquad (15)$$

where $\Delta_n\left(\Delta_\gamma\right)$ are the angles of rotation of the wave vectors of the prompt neutron $\mathbf{k}_n$ (γ - quantum $\mathbf{k}_\gamma$) relative to the direction of the wave vector $\mathbf{k}_{LF}$ of the light fission fragment.

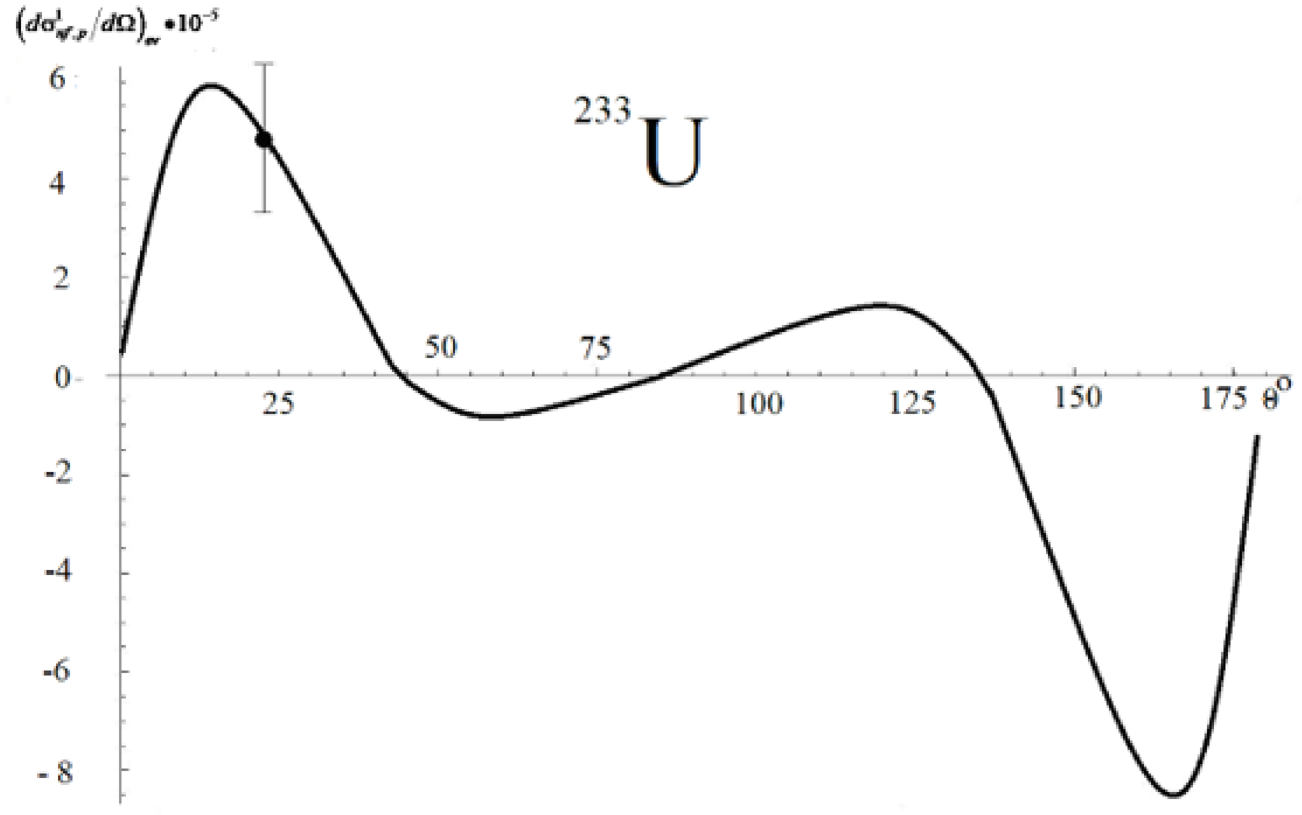

Fig. 9. Cross section $\left(d\sigma^1_{nf,p}/d\Omega\right)_-$ for ^{233}U neutrons

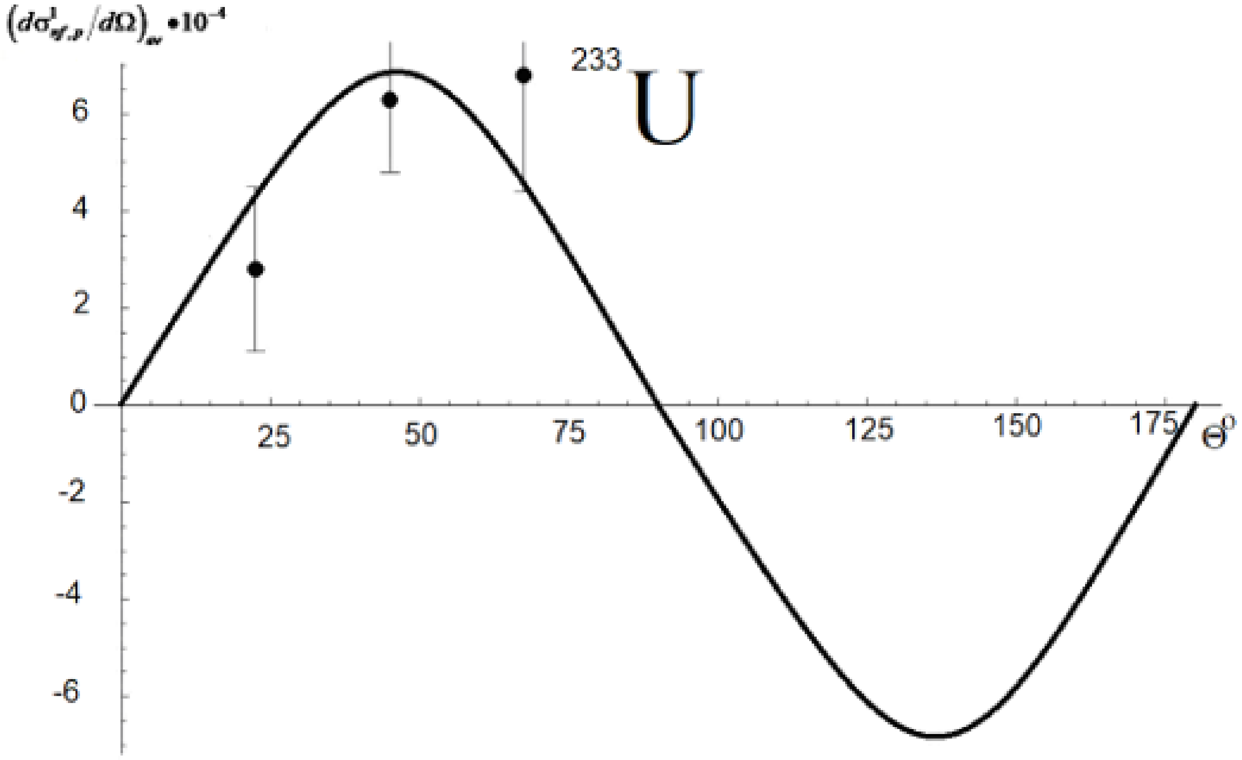

Fig. 10. Cross section $\left(d\sigma^1_{nf,p}/d\Omega\right)_-$ for evaporative ^{233}U γ - quanta

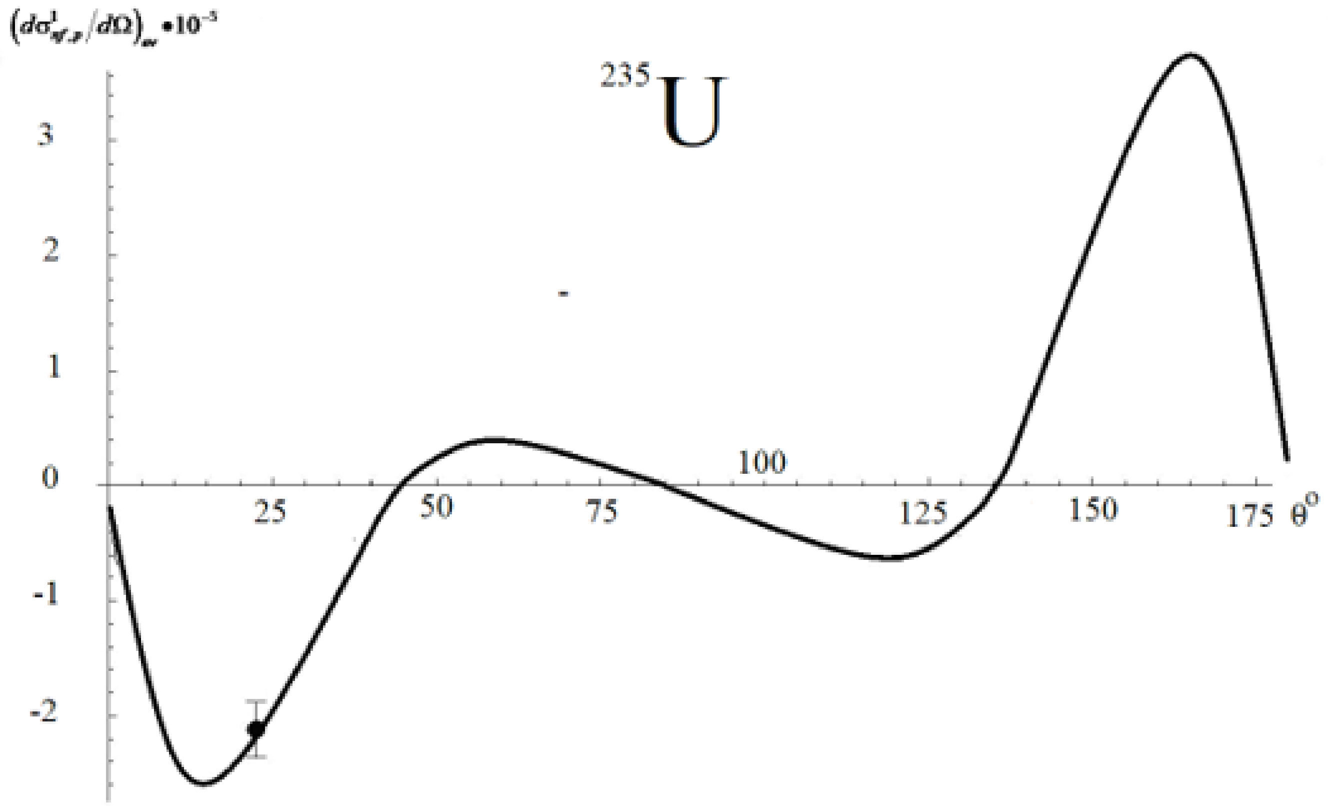

Fig. 11. Cross section $\left(d\sigma^1_{nf,p}/d\Omega\right)_-$ for ^{235}U neutrons

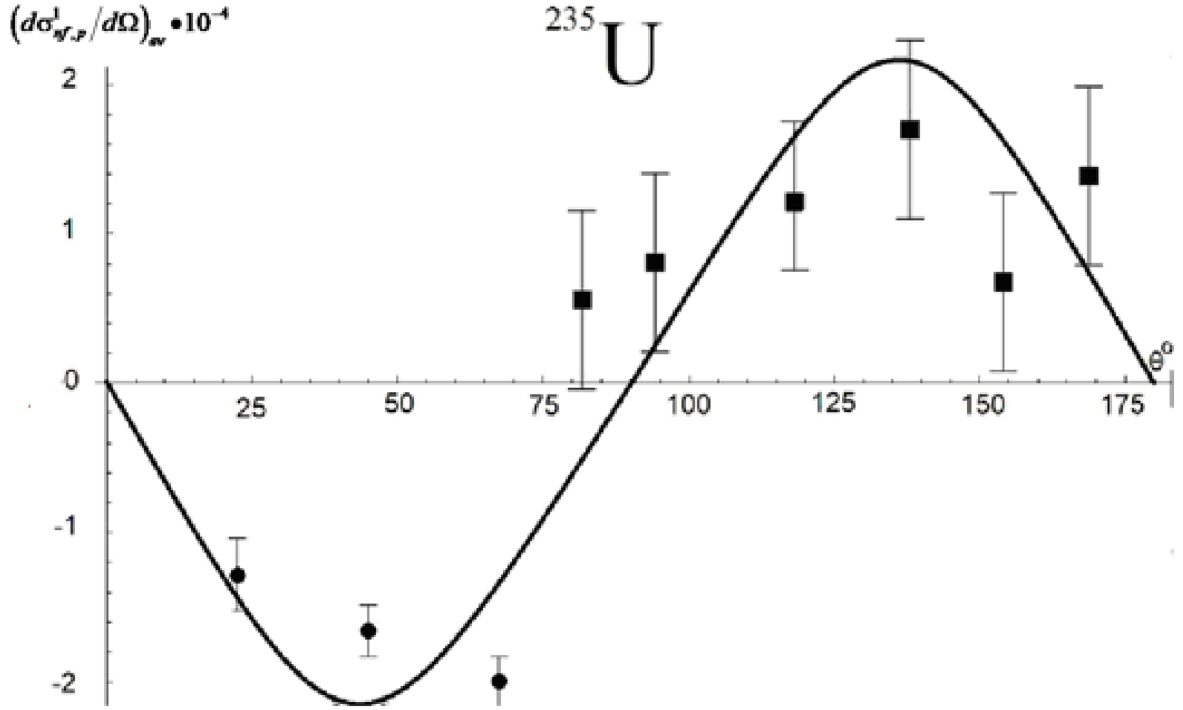

Fig. 12. Cross section $\left(d\sigma^1_{nf,p}/d\Omega\right)_-$ for evaporative 235U γ - quanta, where the circles are experimental data from [*Danilyan G.V., Krakhotin V.A., Novitsky V.V. et al.* // Phys. Atom. Nucl. 2014. V. **77.** № 6. P. 677.], and the squares are similar data from [*Gagarski A., Goennenwein F., Guseva I., et al.*, // Phys. Rev C. 2016. V.**93**. P.054619.]

Conclusion

1. The existence of a single mechanism for the appearance of ternary $(\boldsymbol{\sigma}_n,[\mathbf{k}_{LF},\mathbf{k}_3])$ and $(\boldsymbol{\sigma}_n,[\mathbf{k}_{LF},\mathbf{k}_3])(\mathbf{k}_{LF},\mathbf{k}_3)$ quintuple P - even, T - odd scalar correlations in the differential cross sections of reactions of ternary nuclear fission by cold polarized neutrons with the release of prescission α - particles due to the influence of the Coriolis interaction of the total spin of a rotating fissile system with the orbital moments of fission fragments and α - particles was confirmed.
2. The connection of P - even T - odd asymmetries in the angular distributions of prompt neutrons and γ - quanta emitted from fragments of binary fission of nuclei by cold polarized neutrons with quintuple $(\boldsymbol{\sigma}_n,[\mathbf{k}_{LF},\mathbf{k}_3])(\mathbf{k}_{LF},\mathbf{k}_3)$ scalar correlations caused by the influence of the Coriolis interaction of the total spin of a rotating fissile system with the orbital angular momenta of fission fragments was demonstrated.

Thank you for attention!