Comparative analysis of characteristics of T-odd asymmetries in cross sections of ternary fission reactions by cold polarized neutrons for the cases of the emission of prescission and evaporation third particles

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The aim of the work is to find common features in T–odd asymmetries of angular distributions of the products of triple fission of nuclei – actinides by cold neutrons with the departure of evaporative third particles (γ - quanta and neutrons) with similar asymmetries for the departure of prescission alpha particles.

1. CHARACTERISTICS OF THE T-ODD ASYMMETRIES IN THE ANGULAR DISTRIBUTIONS PRESCISSION ALPHA PARTICLES

The experimentally analyzed coefficient of the investigated T-odd asymmetry was determined by the formula [Jessinger P., Kotzle A., Gagarski A.M. et al. // Nucl. Instrum. Methods. 2000. V. 440. P. 618.]:

$$D(\Omega_\alpha) = \left(\frac{d\sigma_{nf}^{(+)}}{d\Omega_\alpha} - \frac{d\sigma_{nf}^{(-)}}{d\Omega_\alpha} \right) \Bigg/ \left(\frac{d\sigma_{nf}^{(+)}}{d\Omega_\alpha} + \frac{d\sigma_{nf}^{(-)}}{d\Omega_\alpha} \right), \tag{1}$$

where signs ($\pm$) corresponded to the cases when the vector of polarization of the incident neutron $\vec{p}_{\mathrm{n}}$, parallel to the vector $\vec{\sigma}_{\mathrm{n}}$, is directed along or against the axis Y.

In the first order by the neutron polarization vector $\vec{p}_{\mathrm{n}}$ the differential cross-section $\frac{d\sigma_{nf}}{d\Omega_{\alpha}}$ is represented as

$$\frac{d\sigma_{nf}}{d\Omega_{\alpha}} = \frac{d\sigma_{nf}^{0}}{d\Omega_{\alpha}} + \frac{d\sigma_{nf}^{1}}{d\Omega_{\alpha}}, \qquad (2)$$

where $\frac{d\sigma_{nf}^{0}}{d\Omega_{\alpha}}$ is the differential cross-section of the studied reaction with cold polarized neutrons $\vec{p}_{\mathrm{n}} = 0$:

$$\frac{d\sigma_{nf}^{0}}{d\Omega_{\alpha}} = \sigma_{nf}^{0} P^{0}\left(\theta_{\alpha}\right), \qquad (3)$$

where $P^0(\theta_{TP})$ -normalized unperturbed angular distribution of emitted α-particles, which was represented for the studied target nuclei in the form of histograms, and $\frac{d\sigma_{nf}^1}{d\Omega_\alpha}$ - addition to the cross section (2), depending on the vector $\vec{\sigma}_\mathrm{n}$ and the vector $\vec{p}_\mathrm{n}$ in the first order of perturbation theory. In this case, this value using the representations of the space isotropy and parity conservation can be expressed in terms of P-even scalar functions depending on one of the two possible combinations of vectors $\vec{k}_{TP}$, $\vec{k}_\mathrm{LF}$ and $\vec{\sigma}_\mathrm{n}$ and corresponding to triple and five correlations, which in a simplified form were discussed earlier in the works [A. Gagarski, F. Goennenwein, I. Guseva *et al.*, Phys. Rev. C 93, 054619 (2016)]

$$\frac{d\sigma_{nf}^{1}}{d\Omega_{\alpha}} = \left(\frac{d\sigma_{nf}^{1}}{d\Omega_{\alpha}}\right)_3 + \left(\frac{d\sigma_{nf}^{1}}{d\Omega_{\alpha}}\right)_5, \quad (4)$$

where

$$\left(\frac{d\sigma_{nf}^{1}}{d\Omega_{\alpha}}\right)_3 = B_3(\theta_{\alpha})\left(\vec{\sigma}_n\left[\vec{k}_{\alpha},\vec{k}_{LF}\right]\right) = B_3(\theta_{\alpha})\sin\theta_{\alpha}\cos\varphi_{\alpha}; \quad (5)$$

$$\left(\frac{d\sigma_{nf}^{1}}{d\Omega_{\alpha}}\right)_5 = B_5(\theta_{\alpha})\left(\vec{\sigma}_n\left[\vec{k}_{\alpha},\vec{k}_{LF}\right]\right)\left(\vec{k}_{\alpha},\vec{k}_{LF}\right) = B_5(\theta_{\alpha})\sin\theta_{\alpha}\cos\theta_{\alpha}\cos\varphi_{\alpha}, \quad (6)$$

values $B_3(\theta_{\alpha})$ and $B_5(\theta_{\alpha})$ depend on the even powers of the scalar product of the vectors $\left(\vec{k}_{LF},\vec{k}_{TP}\right) = \cos\theta_{\alpha}$. Then the coefficient $D(\theta_{\alpha},\varphi_{\alpha})$ (1) using the formulas (4-6) is represented as

$$D(\theta_{\alpha},\varphi_{\alpha}) = D_3(\theta_{\alpha},\varphi_{\alpha}) + D_5(\theta_{\alpha},\varphi_{\alpha}), \quad (7)$$

where

$$D_3(\theta_\alpha,\varphi_\alpha)=\left(\frac{d\sigma^1_{nf}}{d\Omega_\alpha}\right)_3 \Big/ \sigma^0_{nf}P^0(\theta_\alpha)=B_3(\theta_\alpha)\sin\theta_\alpha\cos\varphi_\alpha/\sigma^0_{nf}P^0(\theta_\alpha); \quad (8)$$

$$D_5(\theta_\alpha,\varphi_\alpha)=\left(\frac{d\sigma^1_{nf}}{d\Omega_\alpha}\right)_5 \Big/ \sigma^0_{nf}P^0(\theta_\alpha)=B_5(\theta_\alpha)\sin\theta_\alpha\cos\theta_\alpha\cos\varphi_\alpha/\sigma^0_{nf}P^0(\theta_\alpha). \quad (9)$$

To simplify, let us consider the case when the third particles fly in the plane ZX and $\varphi_\alpha=0$. Taking into consideration that the coefficients $\left(\frac{d\sigma^1_{nf}(\theta_\alpha)}{d\Omega_\alpha}\right)_3$ and $\left(\frac{d\sigma^1_{nf}(\theta_\alpha)}{d\Omega_\alpha}\right)_5$ satisfy to conditions:

$$\left(\frac{d\sigma^1_{nf}(\pi-\theta_\alpha)}{d\Omega_\alpha}\right)_3=\left(\frac{d\sigma^1_{nf}(\theta_\alpha)}{d\Omega_\alpha}\right)_3; \quad (10)$$

$$\left(\frac{d\sigma_{nf}^{1}(\pi-\theta_{\alpha})}{d\Omega_{\alpha}}\right)_{5}=-\left(\frac{d\sigma_{nf}^{1}(\theta_{\alpha})}{d\Omega_{\alpha}}\right)_{5}, \qquad (11)$$

when taking into account the formulas (8-9), we can get the rations:

$$D_{3}(\theta_{\alpha})=\left[D(\theta_{\alpha})P^{0}(\theta_{\alpha})+D(\pi-\theta_{\alpha})P^{0}(\pi-\theta_{\alpha})\right]/2P^{0}(\theta_{\alpha}), \qquad (12)$$

$$D_{5}(\theta_{\alpha})=\left[D(\theta_{\alpha})P^{0}(\theta_{\alpha})-D(\pi-\theta_{\alpha})P^{0}(\pi-\theta_{\alpha})\right]/2P^{0}(\theta_{\alpha}) \,. \qquad (13)$$

By using the methods of paper [Kadmensky S. G., Bunakov V. E., Lyubashevsky D. E., Nucl. Phys. **81**, 415 (2018)] with taking into account the influence of the Hamiltonian H_{cor}, in the first order, perturbation theory on the unperturbed amplitudes of angular distributions of fission fragments B_0 and prescission third particles A_0, emitted in the reaction of triple fission of target nuclei by cold polarized neutrons, representing the main component $\{A_0\}$ amplitude A_0 as the sum of its even $\{A_0^{ev}\}$ and odd $\{A_0^{odd}\}$ component:

$$\{A_0\} = \{A_0^{ev}\} + \{A_0^{odd}\} \tag{14}$$

the coefficient of T-odd asymmetry $D(\Omega_\alpha)$ (1) can be represented as:

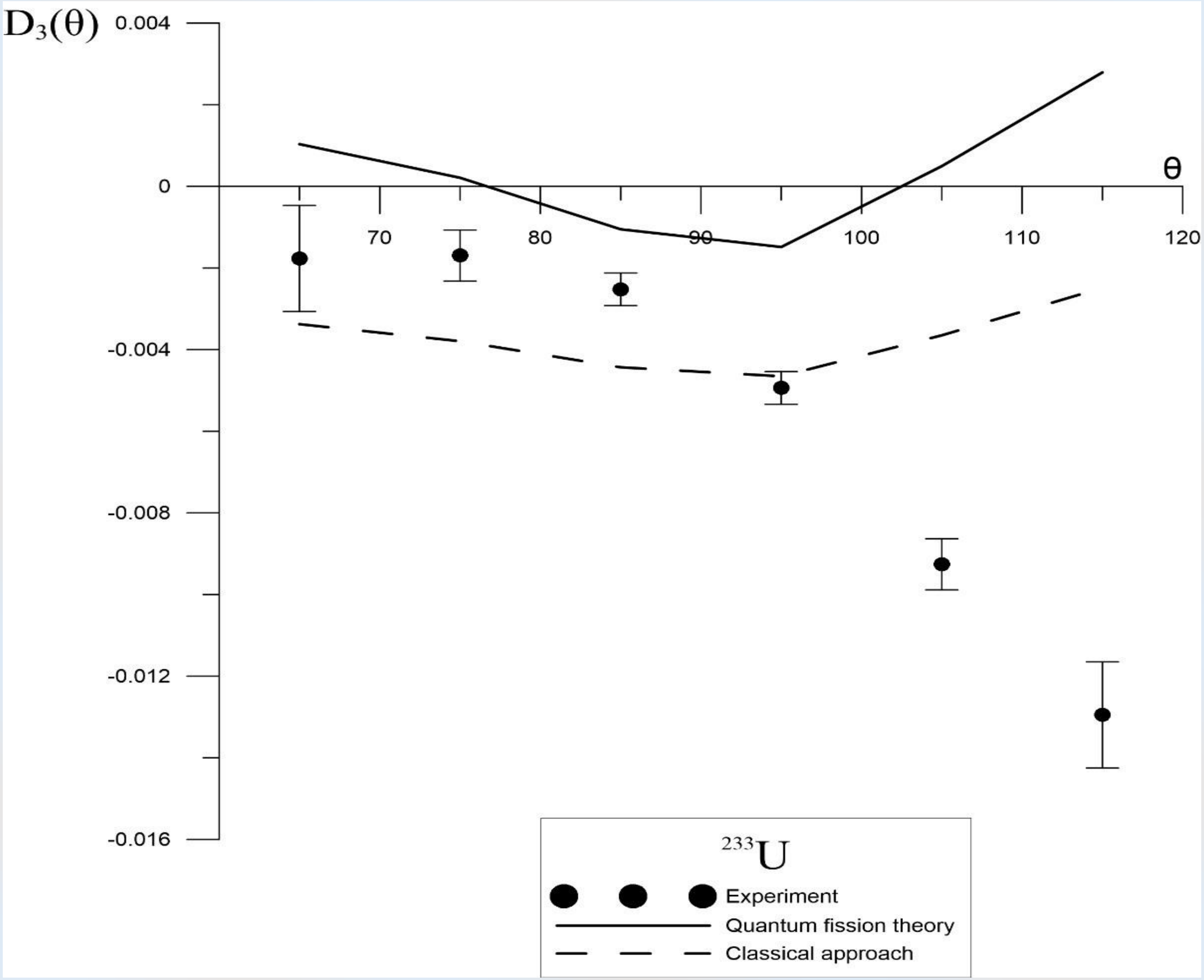
$$D(\theta_\alpha, \varphi_\alpha) = \frac{1}{\{A_0(\theta_\alpha)\}} \left[\frac{d\{A_0^{ev}(\theta_\alpha)\}}{d\theta_\alpha} \cos\varphi_\alpha (\Delta\theta_\alpha)_{ev} + \frac{d\{A_0^{odd}(\theta_\alpha)\}}{d\theta_\alpha} \cos\varphi_\alpha (\Delta\theta_\alpha)_{odd} \right], \tag{15}$$

where

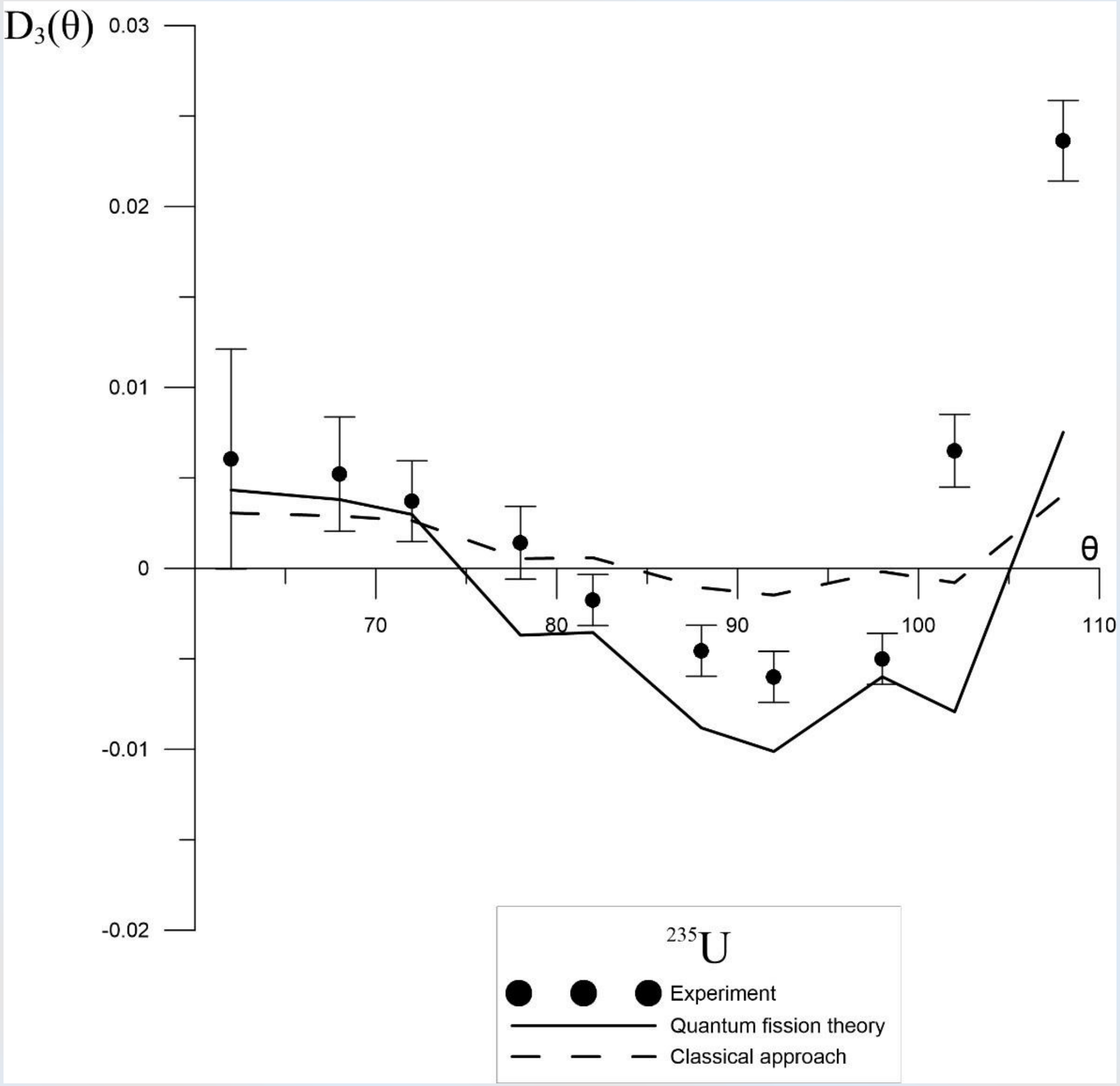
$$(\Delta\theta_\alpha)_{ev} = \frac{\sum\limits_{sJ_s \neq s'J_{s'}K_s q} \tau\omega(K_{s,} J_s, J_{s'}) A^0_{qsJ_S s'J_S 'K_S} (k^{ev} - 1) \sin\delta_{sJ_s s'J_{s'}}}{\sum\limits_{sJ_s s'J_{s'}K_s q} A^0_{qsJ_S s'J_S 'K_S} \cos(\delta_{sJ_s s'J_{s'}})}, \tag{16}$$

$$(\Delta\theta_\alpha)_{odd} = \frac{\sum\limits_{sJ \neq_s s'J_{s'}K_s q} \tau\omega(K_{s,} J_s, J_{s'}) A^0_{qsJ_S s'J_S 'K_S} (k^{odd} - 1) \sin\delta_{sJ_s s'J_{s'}}}{\sum\limits_{sJ_s s'J_{s'}K_s q} A^0_{qsJ_S s'J_S 'K_S} \cos(\delta_{sJ_s s'J_{s'}})}. \tag{17}$$

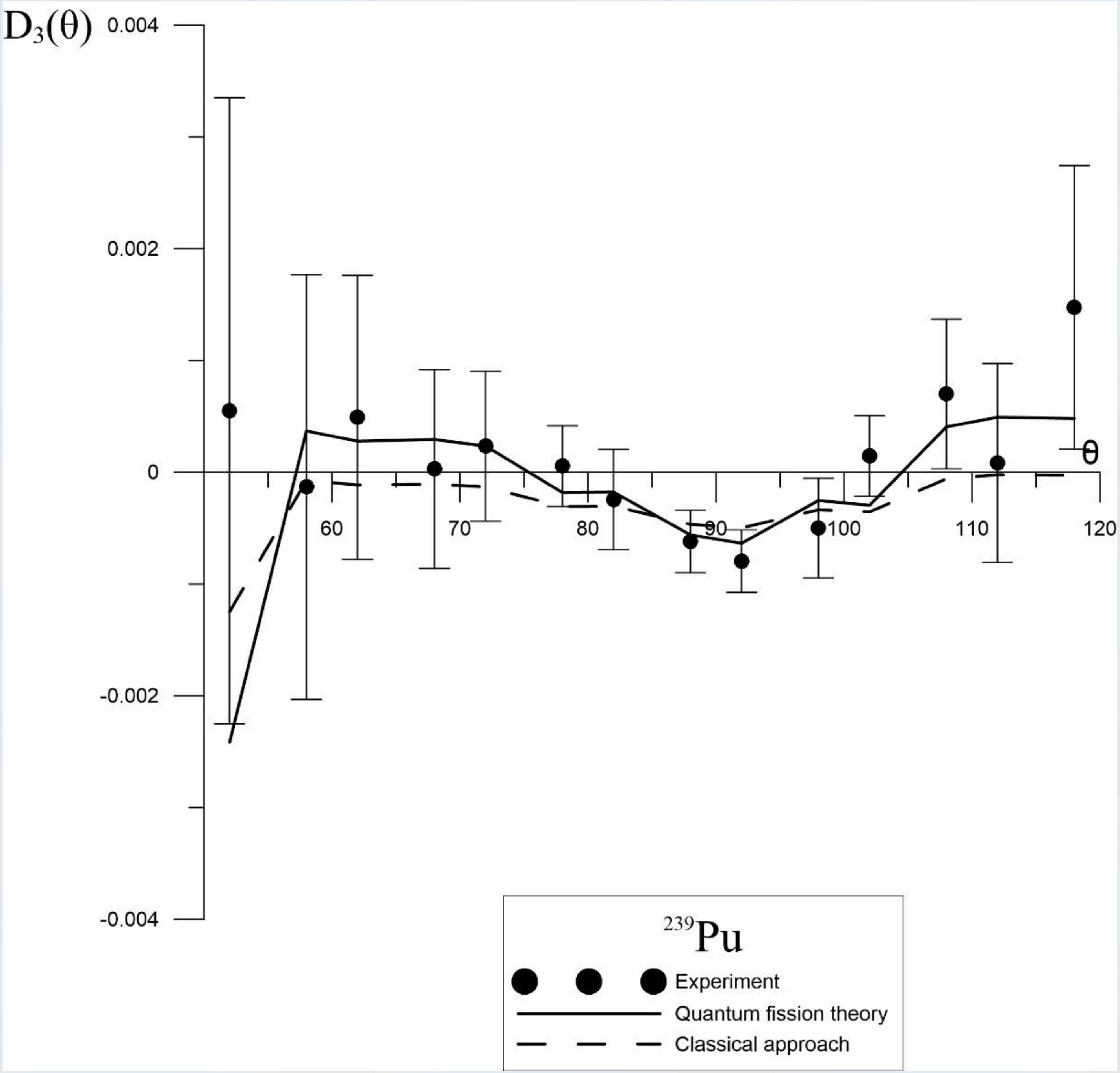
In formulas (16-17) are used the values presented in [Kadmensky S. G., Bunakov V. E., Lyubashevsky D. E., Nucl. Phys., **81**, 415 (2018)].



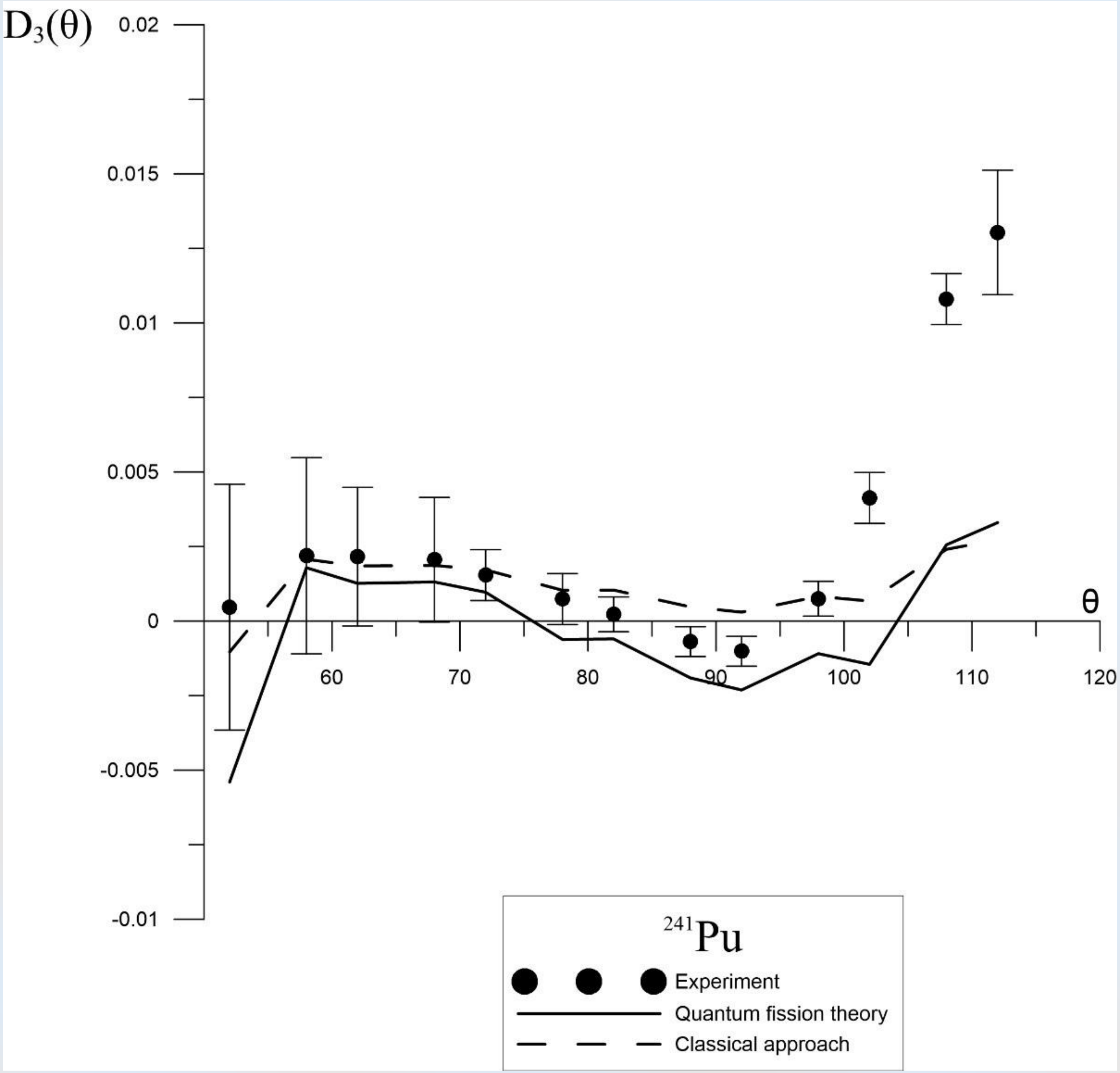
D3(θ)
0.004
0
-0.004
-0.008
-0.012
-0.016
θ
70
80
90
100
110
120
233U
Experiment
Quantum fission theory
Classical approach

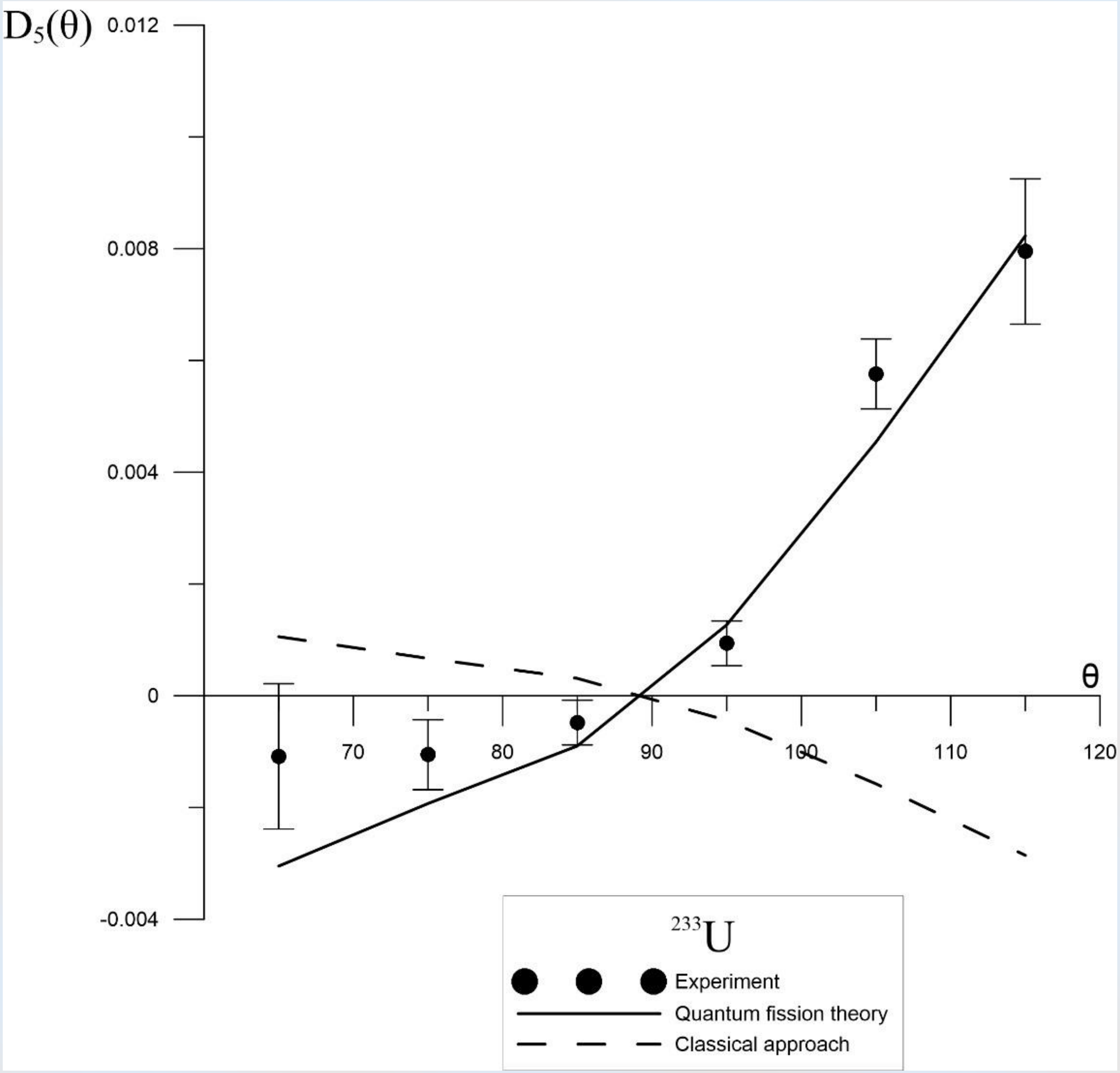


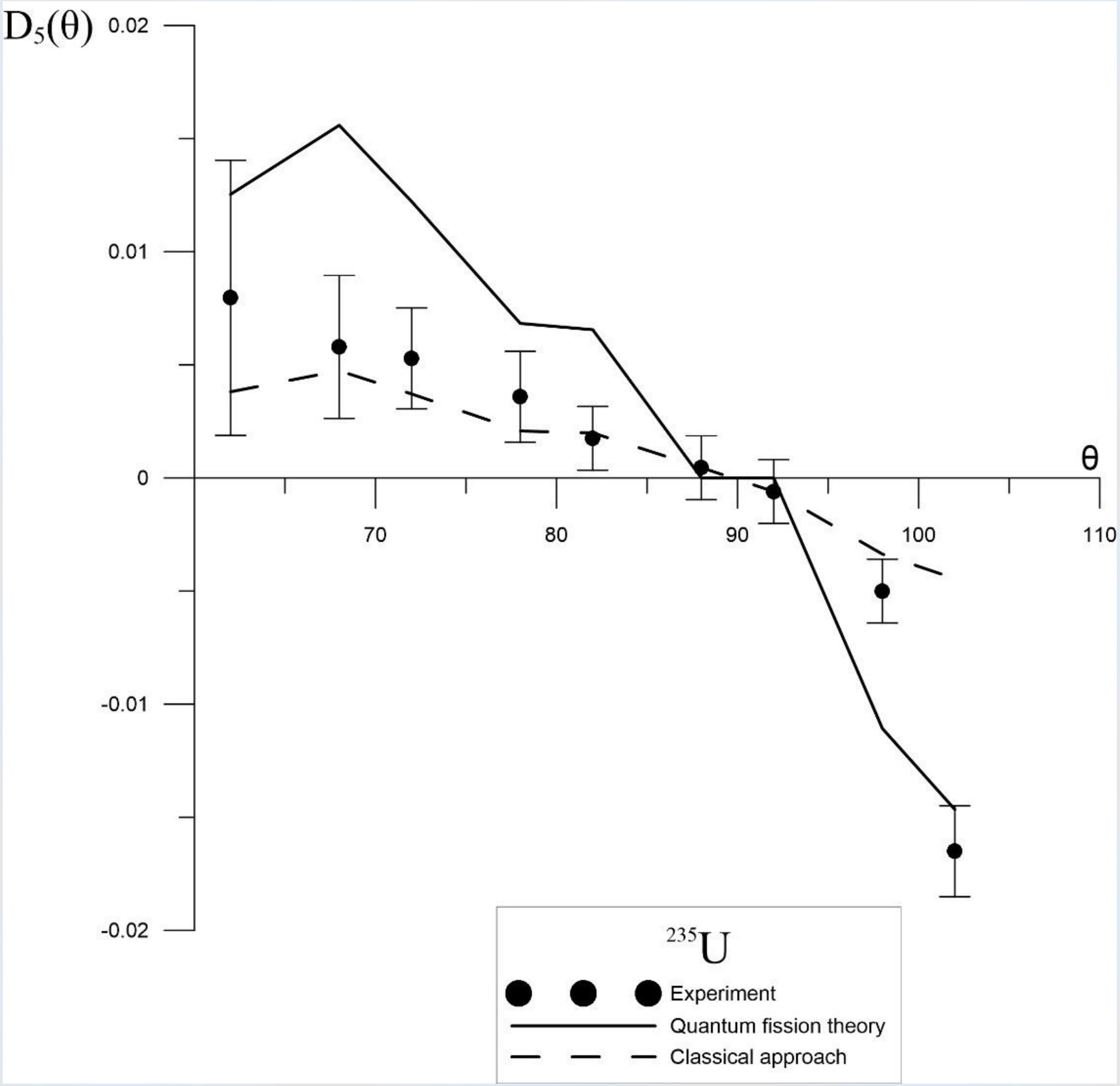
D3(θ)
0.03
0.02
0.01
0
-0.01
-0.02
θ
70
80
90
100
110
235U
Experiment
Quantum fission theory
Classical approach



D3(θ)
0.004
0.002
0
-0.002
-0.004
60
70
80
90
100
110
120
θ
239Pu
Experiment
Quantum fission theory
Classical approach


$D_3(\theta)$
0.02
0.015
0.01
0.005
0
-0.005
-0.01
θ
60
70
80
90
100
110
120
^{241}Pu
Experiment
Quantum fission theory
Classical approach


D5(θ)
0.012
0.008
0.004
0
-0.004
70
80
90
100
110
120
θ
233U
Experiment
Quantum fission theory
Classical approach



D5(θ)
0.02
0.01
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-0.01
-0.02
θ
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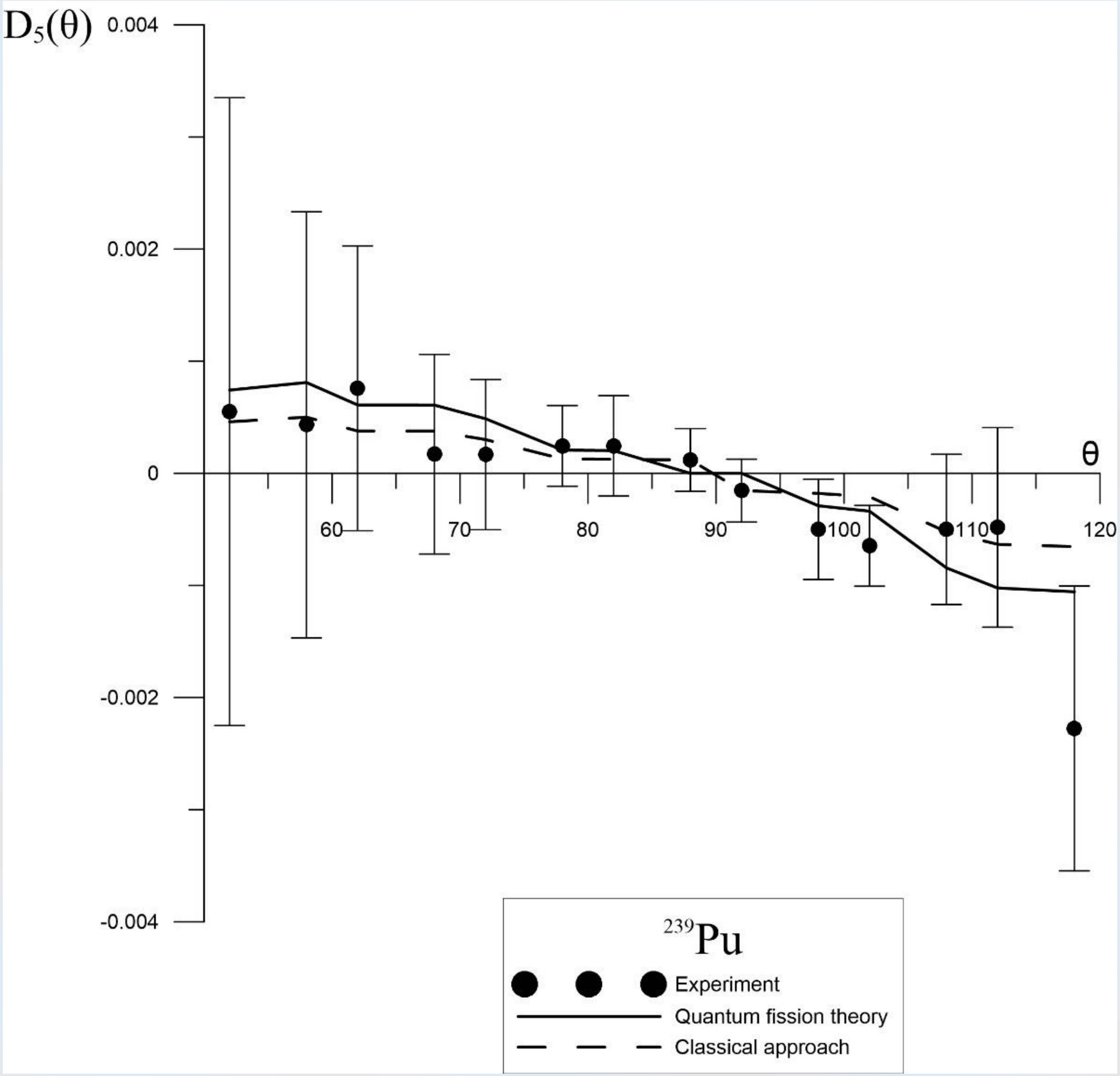
235U
Experiment
Quantum fission theory
Classical approach


D5(θ)
0.004
0.002
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-0.002
-0.004
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θ
239Pu
Experiment
Quantum fission theory
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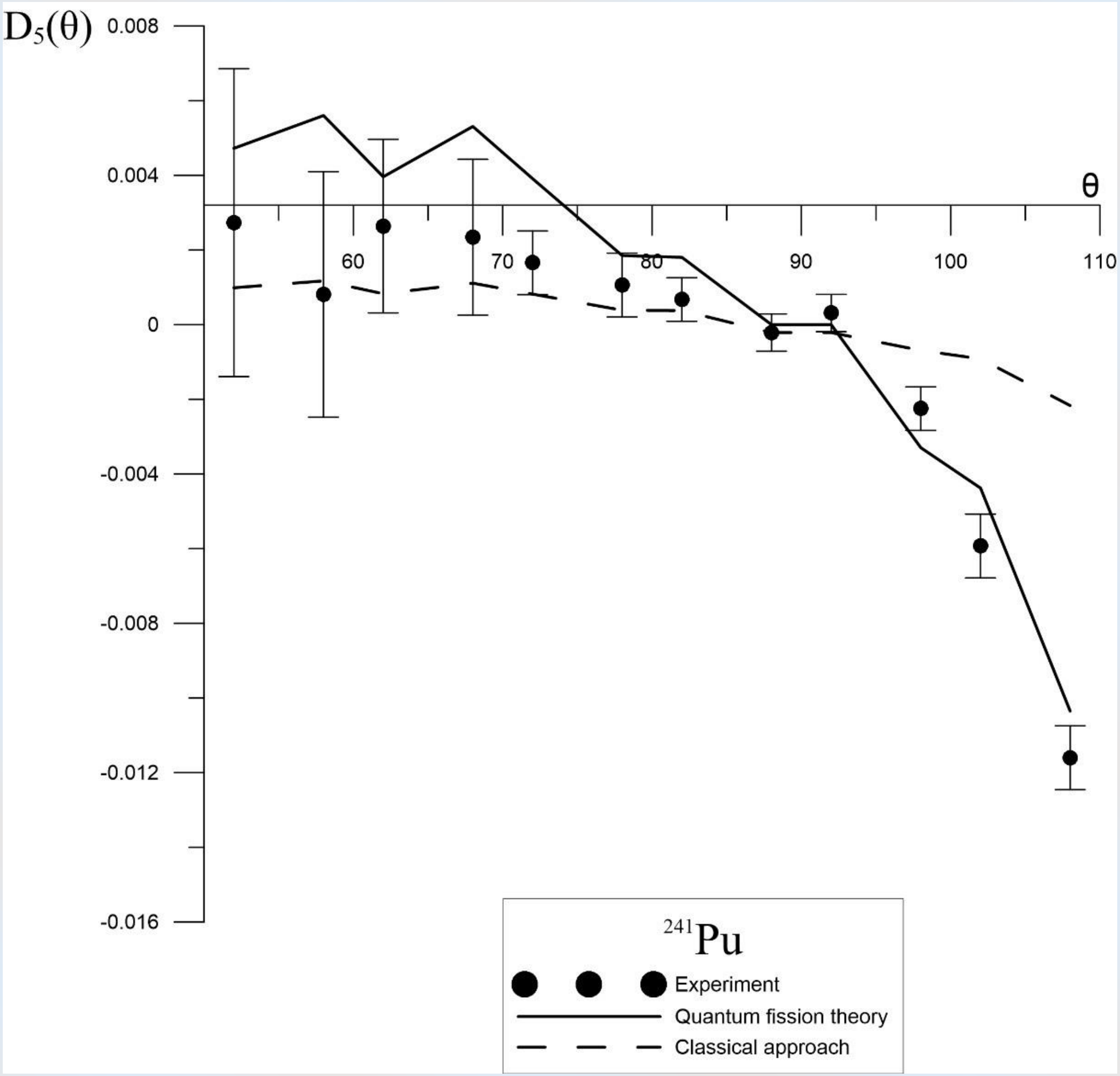

D5(θ)
0.008
0.004
0
-0.004
-0.008
-0.012
-0.016
θ
60
70
80
90
100
110
241Pu
Experiment
Quantum fission theory
Classical approach

2. CHARACTERISTICS OF THE T-ODD ASYMMETRIES IN THE ANGULAR DISTRIBUTIONS OF EVAPORATION γ-RAYS AND NEUTRONS

Experimental studies of the angular distributions of evaporative neutrons emitted from thermalized light (+) and heavy (–) fragments of a fissile nucleus system in laboratory system of coordinates (l.s.c.):

$$P_n(\theta_n) = P_n^0(\theta_n^0)\left[f_{n+}(\theta_n^0) + f_{n-}(\theta_n^0)\right]. \tag{18}$$

In formula (18) $P_n^0(\theta_n^0)$ – experimental angular distribution of evaporative neutrons in the system of the center of mass (s.c.m.) of light fission fragment:

$$P_n^0(\theta_n^0) = A_n\left(1 - a_n \sin^2\theta_n^0\right). \tag{19}$$

In the formula (18) $f_{n\pm}(\theta_n^0)$ are coefficients of transition from s.c.m. of the fission fragments in l.s.c.:

$$f_{n\pm}\left(\theta_n^0\right)=\frac{\left(1\pm 2\beta_{n\pm}\cos\theta_n^0+\beta_{n\pm}^2\right)^{1/2}}{\left|1\pm\beta_{n\pm}\cos\theta_n^0\right|}. \tag{20}$$

$$\cos\theta_n^0=-\beta_{n\pm}\sin^2\theta_n+\cos\theta_n\sqrt{1-\beta_{n\pm}{}^2\sin^2\theta_n}. \tag{21}$$

since from the relation (21) for γ-quanta should be the condition of coincidence of the angles in s.c.m. with angles in l.s.c.: $\theta_\gamma^0=\theta_\gamma$.

$$P_\gamma\left(\theta_\gamma\right)=2P_\gamma^0\left(\theta_\gamma\right)=2A_\gamma\left(1-a_\gamma\sin^2\theta_\gamma\right), \tag{22}$$

Therefore, in [I. S. Guseva, A. M. Gagarski, Gusev Y. I., Petrov G. A., Vall ski G. V.// Phys. Part. Nucl. Lett. **10**, 331 (2013)] coefficient $D_\gamma\left(\theta_\gamma\right)$ for vaporization of γ-rays is built with the use of formulas (22) and formulas (14-15) with the ejection member D_{TRI} and the replacement values Δ on the δ_{LF} :

$$D_\gamma(\theta_\gamma) = \delta_{LF} \cdot \frac{dP_\gamma^0(\theta_\gamma)}{d\theta_\gamma} \Big/ P_\gamma^0(\theta_\gamma) = -\frac{a_\gamma \delta_{LF} \sin 2\theta_\gamma}{1 - a_\gamma \sin^2 \theta_\gamma}. \qquad (23)$$

When using formulas (18-19), the coefficient $D_n(\theta_n)$ for evaporative neutrons is constructed in the same way, which can be represented by the formula:

$$D_n(\theta_n) = \left[f_{n+}(\theta_n^0) \frac{dP_n^0(\theta_n^0)}{d\theta_n^0} + f_{n-}(\theta_n^0) \frac{dP_n^0(\theta_n^0)}{d\theta_n^0} \right] \frac{\delta_{LF}}{P_n^0(\theta_n^0)\left[f_{n+}(\theta_n^0) + f_{n-}(\theta_n^0) \right]}. \qquad (24)$$

In the framework of quantum fission theory [Bunakov V. E., Kadmensky S. G., Lyubashevsky D. E. / / Nucl. Phys. 2016. Vol. 79, P. 198.; Kadmensky S. G., Bunakov V. E., Lyubashevsky, D. E. // Nucl. Phys. 2017. Vol. 80, P.447.; Kadmensky S. G., Titova L. V. Lyubashevsky, D. E., Izv. RAN. 2017. Vol. 81, P.792] in [Kadmensky S. G., Bunakov V. E., Lyubashevsky, D. E. // Izv. RAN 2018. Vol. 81, P.415] the coefficient of T-odd asymmetry for prescission α-particles was constructed $D(\theta_\alpha)$, based on the effect of only the rotational mechanism on the angular distributions of the fission fragments and α-particles in the form of (15-17). Applying these formulas to the calculation of a similar coefficient for evaporative γ-quanta at $\varphi_\gamma = 0$, when using the formula (22), it is possible to obtain:

$$D_\gamma\left(\theta_\gamma\right) = \frac{1}{P_\gamma^0\left(\theta_\gamma\right)} \frac{d\left\{P_\gamma^0\left(\theta_\gamma\right)\right\}}{d\theta_\gamma} \bar{\delta}_{LF}, \qquad (25)$$

where $\bar{\delta}_{LF}$ is the effective angle of rotation of the direction of departure of a light fission fragment at the transition from its wave vector $\vec{k}_{LF}^0$ at the time of the rupture of the fissile nucleus system to the asymptotic wave vector $\vec{k}_{LF}$:

$$\bar{\delta}_{LF} = \frac{-\sum\limits_{sJ_s \neq s'J_{s'}K_s q} \tau\omega\left(K_{s,} J_s, J_{s'}\right) A^0_{qsJ_S s'J_S 'K_S} \sin\delta_{sJ_s s'J_{s'}}}{\sum\limits_{sJ_s s'J_{s'}K_s q} A^0_{qsJ_S s'J_S 'K_S} \cos(\delta_{sJ_s s'J_{s'}})}. \qquad (26)$$

Applying formulas (15-17) to the calculation of a similar coefficient for evaporative neutrons at $\varphi_n = 0$, when using formulas (18-20), we can obtain the expression:

$$D_n\left(\theta_n\right)=\left[f_{n+}\left(\theta_n^0\right)\frac{dP_n^0\left(\theta_n^0\right)}{d\theta_n^0}+f_{n-}\left(\theta_n^0\right)\frac{dP_n^0\left(\theta_n^0\right)}{d\theta_n^0}\right]\frac{\bar{\delta}_{LF}}{P_n^0\left(\theta_n^0\right)\left[f_{n+}\left(\theta_n^0\right)+f_{n-}\left(\theta_n^0\right)\right]}, \quad (27)$$

where the angle θ_n^0 in s.c.m. is expressed as an angle θ_n in l.s.c. using the formula (21).

CONCLUSION

In the present work, a very important result has been obtained, which states that the classical approach based on the method of trajectory calculations to the description of the coefficients of T-odd asymmetries in the angular distributions of instantaneous γ-quanta and neutrons, as well as prescission α-particles emitted in the fission of oriented nuclei-targets cold polarized neutrons, in principle, is not applicable due to the absence in this approach of considering the interference of pitch amplitudes of the different neutron resonances of the compound nucleus. It shows that the approach based on the quantum fission theory, in contrast to the classical approach, has the ability to describe a number of subtle characteristics of the processes of fission, for example, changing the signs of the studied coefficients in the transition from one core to another.

Thank you for your attention!