THE FLIGHT PROBABILITIES, ANGULAR AND ENERGY DISTRIBUTIONS AND *P*-ODD, *P*-EVEN AND *T*-ODD ASYMMETRIES IN THE ANGULAR DISTRIBUTIONS OF THE LIGHT PARTICLES FOR THE TRUE QUATERNARY FISSION

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1. INTRODUCTION

The first pieces of experimental evidence of the existence of quaternary nuclear fission, in which two rather heavy fission fragments and two light (third and fourth) particles are generated by the fissile nucleus, were obtained in studying the reaction ^{235}U(n,f) induced by thermal neutrons [1, 2] and in studying the spontaneous fission of ^{252}Cf [3] and ^{248}Cm [4] nuclei. More detailed investigations of quaternary fission were performed in [5–7] for the fission of ^{233}U and ^{235}U nuclei that was induced by cold neutrons and in [6, 7] for the spontaneous fission of ^{252}Cf. In those studies, the yields and angular and energy distributions were analyzed for pairs of light third and fourth particles produced with the highest probability, such as (α, α), (α, t) and (t, t). Two modes of quaternary fission were singled out in the same study. The first mode corresponds to the case where all four charged particles originate from the process almost simultaneously to within a nuclear time scale of about 10^{-21} s and was called true quaternary fission. The second mode involves the escape of an unstable light third particle, which thereupon decays to two observed light particles, a third and a fourth one was called pseudoternary fission. The aim of the present study is the investigation of the true quaternary fission characteristics.

2. BASIC PROPERTIES OF THE TRUE QUATERNARY FISSION OF NUCLEI

True quaternary fission can be considered as a sequence of three processes that follow one another. The fission process begins via the emission of a first light particle $A^{(1)}$ from the neck of the fissile nucleus A and the formation of the daughter nucleus ($A - A^{(1)}$). This particle may be coincident with a third (A_3) or a fourth (A_4) particle that form the pair of light particles (A_3, A_4) emitted in the quaternary-fission process. After that, a second light particle $A^{(2)}$ coincident with particle A_3 or particle A_4 complementary to particle $A^{(1)}$ is emitted from the arising state of the neck of the daughter nucleus ($A - A^{(1)}$), with the result that the final-state nucleus ($A - A_3 - A_4$) is formed. At the last stage, this final-state nucleus breaks up into two primary quaternary-fission fragments A_1 and A_2. This statement [8] is at odds with the idea put in [9] that, in ternary fission, the fissile nucleus undergoes disintegration via two sequential rupture processes: two fission fragments arise at the first step, and the third particle escapes from the lighter fragment.

If we consider conditions for third and fourth particles in the quaternary fission of nuclei – $A_3, A_4 << A_1, A_2$; $Z_3, Z_4 << Z_1, Z_2$; and $p_3, p_4 << p$, where $\mathbf{p}_3$ and $\mathbf{p}_4$ are the momenta of the third and the fourth particle, respectively, and $\mathbf{p}$ is the relative momentum of the quaternary-fission fragments – then we can assume that the angular, mass, charge and energy distributions of fragments originating from the quaternary fission of nucleus A do not differ dramatically from the analogous distributions of fragments in the binary and ternary fission of the same nucleus A. It follows that, for true quaternary fission the condition of adiabatic motion holds throughout the stage that follows the breakup of the fissile nucleus to fission fragments [10].

In just the same way as in the cases of binary and ternary fission, the properties of the angular distributions of fragments originating from the quaternary fission cannot be described without taking into account the mechanism of pumping [11, 12] of high values of the relative orbital angular momentum $\mathbf{L}$ and spins $(\mathbf{J}_1, \mathbf{J}_2)$ of these fragments. The effect of coherent pumping of high values of the relative orbital angular momentum leads [12] to angular distributions of fission fragments such that these fragments move predominantly along the symmetry axis of the fissile nucleus, and this validates the concepts developed in [13, 14].

For obtaining deeper insight into the properties of quaternary, as well as binary and ternary, low-energy fission of nuclei, it is important to bear in mind that, in contrast to what was assumed in some fission models [15, 16, 9], the nucleus undergoing fission does not in principle have time to go over before its separation to fission fragments to excited equilibrium thermalized states characterized by rather high temperatures ($T \approx 1$ MeV). For such thermalized nuclear states possessing a high energy density, a dynamical enhancement of Coriolis interaction [17] causes a uniform statistical mixing of all possible values of the projection K of the spin J of the fissile nucleus onto its symmetry axis, and this forbids the appearance of anisotropies in the angular distributions of fragments originating from the low-energy fission of nuclei [11]. Since such anisotropies were reliably established in experiments [18–22] for angular distributions of fragments originating from binary and ternary fission, it can be concluded that the fissile system remains cold even at the stages of true quaternary fission.

Since, in the vicinity of the scission point, the fissile nucleus do not go over to equilibrium thermalized states characterized by a rather high temperature T, a significant effect of pair and superfluid nucleon-nucleon correlations on the probabilities for the formation of products of true ternary or quaternary fission survives. Because of the effect of these correlations, the highest probabilities for the formation of third and fourth particles (for true ternary fission) from groups of nucleons in the neck of the fissile nucleus are associated with such shell states of these groups for which the total orbital angular momenta are zero. The appearance of nonzero orbital angular momenta of third and fourth particles in the asymptotic region that escape from the nucleus undergoing fission is determined primarily by the action of nonspherical components of potentials of interaction of these particles [23] – first of all, Coulomb potentials – with quaternary-fission fragments and, to a smaller extent, by the potential of interaction between the third and fourth particles.

The fact that there is no sizable thermalization of excited states of the fissile nucleus for its prescission configurations leads to the conclusion that evaporation mechanisms of light-particle emission, which are extensively used [24–25] in describing the ternary fission of nuclei, are inapplicable in the cases of true ternary and quaternary fission. The concept of a nonevaporative preequilibrium mechanism of light particle emission in the ternary and quaternary fission of nuclei is based on taking into account the influence of shaking effects induced by a nonadiabatic character of the collective deformation motion of the fissile nucleus with respect to nucleon and cluster degrees of freedom of this nucleus [26, 27, 23].

3. DESCRIPTION OF THE PROBABILITIES FOR THE EMISSION OF THIRD AND FOURTH PARTICLES IN THE TRUE QUATERNARY FISSION OF NUCLEI

In the true quaternary fission of nuclei, the energy-angular distribution $W_{3,4}(\Omega_3, E_3, \Omega_4, E_4)$ of the third and fourth particles detected upon the coincidence of events in the first detector tuned to particle A_3 and the second detector tuned to particle A_4, the interaction between these particles being disregarded, can be represented in the form

$$W_{3,4}(E_3,\Omega_3;E_4,\Omega_4) = N_3^{(1)} N_4^{(2)}(3) W_3^{(1)}(E_3,\Omega_3) W_4^{(2)}(E_4,\Omega_4) + N_3^{(2)}(4) N_4^{(1)} W_3^{(2)}(E_3,\Omega_3) W_4^{(1)}(E_4,\Omega_4), \tag{1}$$

where $N_3^{(i)}$ ($N_4^{(i)}$) and $W_3^{(i)}(E_3,\Omega_3)$ ($W_4^{(i)}(E_4,\Omega_4)$) are, respectively, the probability for the appearance of a third (fourth) particle emitted first (i =1) or second (i =2) in the quaternary-fission process and its energy–angular distribution normalized to unity. For Ω_3 (Ω_4) we employ the solid angle specifying the direction of emission of the third (fourth) particle in the system, where Z axis of the laboratory frame aligns with the direction of emission of light fission fragment. The derivation of expression (1) relies on the idea, that the probability for the binary fission of nucleus ($A - A_3 - A_4$) formed after the emission of third and fourth particles is close to the probability for the binary fission of the primary fissile nucleus A. The probability $N_{3,4}$ for the emission of the pair formed by a third and a fourth particles is obtained upon integrating expression (1) with respect to the emission angles and the energies of the third and fourth particles is

$$N_{3,4} = N_3^{(1)} N_4^{(2)}(3) + N_3^{(2)}(4) N_4^{(1)}; \qquad N_{3,3} = 2 N_3^{(1)} N_3^{(2)}(3). \qquad (2)$$

The probabilities $N_3^{(1)}$ and $N_4^{(1)}$ for the appearance of third and fourth particles escaping first in the true quaternary fission of nuclei are independent of the features of second emitted particles and are close to the probabilities for the appearance of similar particles in the true ternary fission. At the same time, the probabilities for the appearance of light particles emitted second in the course of time $N_3^{(2)}(4)$, $N_4^{(2)}(3)$ and $N_3^{(2)}(3)$ depend on which particle in the pair (A_3, A_4) escapes before the emission of the second particle. If we assume that the probabilities for the appearance per unit time of the third (fourth) particle as the first emitted one, $\lambda_3^{(1)}$ ($\lambda_4^{(1)}$), or as the second emitted one, $\lambda_3^{(2)}(4)$ ($\lambda_4^{(2)}(3)$), are independent of the particle-emission time, then the probability $N_{3,4}$ for the emission of a particle pair in expression (2) can be represented in the form

$$N_{3,4} = \left[\lambda_3^{(1)}\lambda_4^{(2)}(3) + \lambda_3^{(2)}(4)\lambda_4^{(1)}\right] \int_0^T dt_1 \int_{t_1}^T dt_2 = \left[\lambda_3^{(1)}\lambda_4^{(2)}(3) + \lambda_3^{(2)}(4)\lambda_4^{(1)}\right] \frac{T^2}{2}, \qquad (3)$$

where T is the total time interval within which the emission of the first and second particles may occur in quaternary fission. In accordance with (2) and (3), the probabilities for the appearance of the first emitted ($N_3^{(1)}$, $N_4^{(1)}$) and second emitted ($N_3^{(2)}(4)$, $N_4^{(2)}(3)$) particles are given by

$$N_3^{(1)} = \lambda_3^{(1)} T; \quad N_4^{(1)} = \lambda_4^{(1)} T; \quad N_3^{(2)}(4) = \lambda_3^{(2)}(4)(T/2); \quad N_4^{(2)}(3) = \lambda_4^{(2)}(3)(T/2). \qquad (4)$$

In this case, we can introduce the factor of reduction $g_3(4)$ ($g_4(3)$) for the probability for the appearance per unit time of the third (fourth) particle as that which was emitted second in the emission time in relation to the analogous probability for its appearance as that which was first emitted:

$$g_3(4) = \lambda_3^{(2)}(4) / \lambda_3^{(1)} = 2N_3^{(2)}(4) / N_3^{(1)}; \quad g_4(3) = \lambda_4^{(2)}(3) / \lambda_4^{(1)} = 2N_4^{(2)}(3) / N_4^{(1)}. \qquad (5)$$

Table 1. Probabilities for the appearance of α-particles and reduction factors $g_\alpha(\alpha)$ for the quaternary fission of ^{234}U, ^{236}U and ^{252}Cf nuclei [6]

Nucleus	$N_{\alpha,\alpha}$	$N_\alpha^{(1)}$	$N_\alpha^{(2)}(\alpha)$	$g_\alpha(\alpha)$
^{234}U	(0.89±0.28)×10^{-7}	(2.17±0.07)×10^{-3}	(2.05±0.65)×10^{-5}	(1.9±0.6)×10^{-2}
^{236}U	(0.54±0.17)×10^{-7}	(1.70±0.03)×10^{-3}	(1.6±0.5)×10^{-5}	(1.9±0.6)×10^{-2}
^{252}Cf	(9.72±3.26)×10^{-7}	(3.24±0.12)×10^{-3}	(15.0±5.1)×10^{-5}	(9.3±3.2)×10^{-2}

Table 2. Probabilities for the appearance of α-particles and tritons and reduction factors $g_\alpha(\alpha)$, $g_t(t)$, $g_t(\alpha)$ and $g_\alpha(t)$ for the quaternary fission of ^{234}U nuclei [5,6]

$N_{\alpha,\alpha}$	$N_\alpha^{(1)}$	$N_\alpha^{(2)}(\alpha)$	$g_\alpha(\alpha)$	
(1.4±0.3)×10^{-7}	(2.17±0.07)×10^{-3}	(3.23±0.70)×10^{-5}	(3.0±0.7)×10^{-2}	
$N_{t,t}$	$N_t^{(1)}$	$N_t^{(2)}(t)$	$g_t(t)$	
(1.9±0.6)×10^{-9}	(0.13±0.01)×10^{-3}	(0.73±0.24)×10^{-5}	(11.2±3.8)×10^{-2}	
$N_{\alpha,t}$	$N_\alpha^{(2)}(t)$	$N_t^{(2)}(\alpha)$	$g_t(\alpha)$	$g_\alpha(t)$
(15.3±0.4)×10^{-9}	$\approx(6.0\pm1.0)\times10^{-5}$	$\approx(0.35\pm0.02)\times10^{-5}$	$\approx(5.42\pm0.47)\times10^{-2}$	$\approx(5.42\pm0.47)\times10^{-2}$

The probabilities for the appearance of pairs of different ($N_{3,4}$) and identical ($N_{3,3}$) third and fourth particles then assume the form

$$N_{3,4}=N_3^{(1)}N_4^{(1)}\left(g_3\left(4\right)+g_4\left(3\right)\right)/2;\;\; N_{3,3}=\left(N_3^{(1)}\right)^2 g_3\left(3\right). \qquad (6)$$

By using experimental data on the probabilities $N_{3,3}$ for the appearance of pairs of two identical particles, (α,α) and (t,t), in the quaternary fission of ^{234,236}U and ^{252}Cf nuclei in relation to the case of their binary fission [5, 6] and experimental data on the yields $N_3^{(1)}$ of the analogous particles in the ternary fission of the same nuclei in relation to the case of their binary fission [5, 6], we can calculate by formula (6) the probabilities for the emission of the second light particle $N_3^{(2)}\left(3\right)$ and the reduction factor $g_3(3)$. The results are presented in Tables 1 and 2. One can see that the reduction factors $g_\alpha(\alpha)$ and $g_t(t)$ are sizably smaller than unity for all nuclei considered in the present study.

This result can be explained by the action of two factors. The first factor is the change in the shell structure of the fissile nucleus neck after the emission of the first particle from it. Physically, it is clear that the formation of the first particle is affected by the Cooper pairing of predominantly outer nucleons of the fissile nucleus neck, which are characterized by a minimum binding energy. The formation of the second particle is also affected by pairing. However, this is pairing of deeper bound neck nucleons. It follows that the second particle has a substantially higher separation energy than the first particle does and, hence, a lower probability for emission induced by shaking effects. The second factor is that, for the second emitted charged particle, the potential barrier, which results from the summation of the Coulomb and nuclear potentials of its interaction with the residual fissile nucleus, is lower than the potential barrier overcome by the first emitted particle. This is due not only to the difference in the charges of the residual fissile nuclei after the emission of the first and second particles but also to the fact that the emission of the second particle occurs from a more prolate fissile-nucleus neck to which a longer distance between fission prefragments corresponds. This factor may lead to some increase in the probability for the appearance of the second particle. However, the circumstance that the values of $g_\alpha(\alpha)$ and $g_t(t)$ in Tables 1 and 2 are substantially smaller than unity gives sufficient ground to conclude that the first factor is much more important than the second factor. From Table 2, one can see that the reduction- factor ratio $g_t(t)/g_\alpha(\alpha)$ for the ^{234}U nucleus is approximately equal to four, which suggests that the shell structure of the fissile nucleus neck is rearranged much more strongly after the emission of the first α-particle than after the emission of the first triton.

Table 2 also gives the only currently available experimental data on the probabilities for the appearance of a particle pair (α,t) in the thermal-neutron-induced true quaternary fission of the target nucleus ^{233}U [5]. Since the experimental energy distribution of α-particles in the case of the emission of a (α,t) pair in the quaternary fission of ^{234}U nuclei [6] does not differ strongly from the analogous distribution of α-particles in the case of the emission of an (α,α) pair, we can assume that the relationship between the probabilities for particle emission in (1) integrated with respect to the angles Ω_3 and Ω_4 satisfies the condition $N_\alpha^{(1)}N_t^{(2)}\left(\alpha\right)\simeq N_\alpha^{(2)}\left(t\right)N_t^{(1)}$, which ensures an approximately identical contributions of the energy distributions of the first and second emitted α-particles to the total energy distribution of α-particles in the case of the emission of an (α,t) particle pair and is reducible to the form $g_\alpha(t)\approx g_t(\alpha)$. In this case, the use of the quantities $N_{\alpha,t}$, $N_\alpha^{(1)}$ and $N_t^{(1)}$ in (6) makes it possible to calculate $N_\alpha^{(2)}\left(t\right)$, $N_t^{(2)}\left(\alpha\right)$, $g_\alpha(t)$ and $g_t(\alpha)$. From Table 2, one can see that the reduction factor for the emission of an α-particle after triton emission, $g_\alpha(t)$ is 1.8 times greater than the reduction factor for α-particle emission after the escape of the first emitted α-particle $g_\alpha(\alpha)$, while the reduction factor for triton emission after the escape of the first emitted triton $g_t(t)$, is approximately two times greater than the reduction factor for triton emission after α-particle emission, $g_t(\alpha)$.

4. DESCRIPTION OF ANGULAR AND ENERGY DISTRIBUTIONS OF THIRD AND FOURTH PARTICLES IN THE TRUE QUATERNARY FISSION OF NUCLEI

In order to obtain the normalized (to unity) energy distribution of a third particle, $W_3(E_3)$, it is necessary to integrate the distribution in (1) with respect to the energy E_4 of a fourth particle and with respect to the emission angles Ω_3 and Ω_4 for the third and fourth particles and to take into account the normalization factor $N_{3,4}$ given by (2), then have

$$W_3(E_3) = \left(N_3^{(1)} N_4^{(2)}(3) W_3^{(1)}(E_3) + N_3^{(2)}(4) N_4^{(1)} W_3^{(2)}(E_3)\right) \Big/ N_{3,4}, \qquad (7)$$

where $W_3^{(i)}(E_3)$ the normalized (to unity) energy distribution of the first emitted (i =1) or the second emitted (i =2) particle. In same way the normalized (to unity) angular distribution of a third particle $W_3(\Omega_3)$ is presented in form

$$W_3(\Omega_3) = \left(N_3^{(1)} N_4^{(2)}(3) W_3^{(1)}(\Omega_3) + N_3^{(2)}(4) N_4^{(1)} W_3^{(2)}(\Omega_3)\right) \Big/ N_{3,4}, \qquad (8)$$

where $W_3^{(i)}(\Omega_3)$ the normalized (to unity) angular distribution of the first emitted (i =1) or second emitted (i =2) third particle. We now take into account the fact that the an angular $W_3^{(1)}(\Omega_3)$ ($W_4^{(1)}(\Omega_4)$) and energy $W_3^{(1)}(E_3)$ ($W_4^{(1)}(E_4)$) distributions of the first emitted particle, which coincides with a third (A_3) or a fourth (A_4) particle in the true quaternary fission are close to the known analogous distributions of a similar particle emitted in the true ternary fission. Employing (2) and (7) for the cases of the emission of two identical particles in quaternary fission, we can calculate the energy distribution $W_3^{(2)}(E_3)$ of a second particle by

$$W_3(E_3) = \left(W_3^{(1)}(E_3) + W_3^{(2)}(E_3)\right) \Big/ 2. \qquad (9)$$

Since the second particle escapes at a later instant of the evolution of the fissile nucleus on its path toward the scission point than the first particle do, we can expected, as was indicated in [28], that the second particle will interact after its emission with more prolate configurations of the fissile system than the first particle do. Therefore, the second particle experiences a weaker effect of the Coulomb potential of its interaction with the residual fissile nucleus and with fission fragments arising upon its breakup, and this will lead to a shift of the maximum of the energy distribution for the second particle toward lower energies and to the broadening of this distribution in relation to the respective distribution of similar third particles in ternary fission. Taking the approximation proposed in [5, 6] for the experimental energy distribution of α-particles in true quaternary fission of ^{235}U and ^{233}U nuclei that was induced by thermal neutrons and in the spontaneous fission of ^{252}Cf in the form of a Gaussian function normalized to unity, $W_\alpha(E_\alpha) = \left(1 \big/ \sqrt{2\pi}\, \sigma_{E_\alpha}\right) \exp\left(-\left(E_\alpha - \langle E_\alpha \rangle\right)^2 \big/ 2\sigma_{E_\alpha}^2\right)$ and characterized by a mean value $\langle E_\alpha \rangle$ and a rootmean-square deviation $\sigma_{E_\alpha} = \mathrm{FHWM} \big/ \left(2\sqrt{2\ln 2}\right)$, where FWHM is the value chosen in [5, 6] for the full width of the Gaussian distribution at half-maximum, and taking for the energy distribution $W_\alpha^{(1)}(E_\alpha)$ the analogous Gaussian distribution for the process in which the ternary fission of the same nucleus involves α- particle emission, then, by using formula (9), we can calculate the normalized (to unity) energy distribution $W_\alpha^{(2)}(E_\alpha)$ of the second emitted α-particle in the quaternary-nuclear-fission process studied here. From Table 3, one can see that the energy distributions $W_\alpha^{(2)}(E)$ calculated according to the scheme outlined above feature a shift of the maximum toward lower energies and have a width smaller than that of the distributions $W_{\alpha}^{(1)}(E)$. The latter circumstance contradicts the ideas developed above.

Table 3. Parameters of the energy distributions approximated by a Gaussian function for the ternary and quaternary fission of ^{234}U ^{236}U, and ^{252}Cf nuclei [6]

Parameters of the energy distribution	^{234}U		^{236}U		^{252}Cf	
	$\langle E_{\alpha}\rangle$, МэВ	FHWM, МэВ	$\langle E_{\alpha}\rangle$, МэВ	FHWM, МэВ	$\langle E_{\alpha}\rangle$, МэВ	FHWM, МэВ
$W_{\alpha}^{(1)}(E_{\alpha})$	15.7	9.8	15.5	9.8	15.9	9.8
$W_{\alpha}^{(2)}(E_{\alpha})$	11.3	8.2	10.7	9.3	12.7	8.6
$W_{\alpha}(E_{\alpha})$	12.9	10.9	13.0	10.9	13.7	11.3

This is because, in contrast to what was assumed in [5, 6], the energy distribution of a third particle, in quaternary fission is an asymmetric function whose effective width is larger at energies in the range of $E_{\alpha} < \langle E_{\alpha}\rangle$ than at energies in the region of $E_{\alpha} > \langle E_{\alpha}\rangle$. In order to obtain adequate values of the widths of the energy distributions for a second particle, it is necessary to improve the statistical accuracy in determining the experimental energy distribution $W_{\alpha}(E_{\alpha})$, especially in the region of its left branch. In the case of the emission of identical α-particles, the angular distribution of the second α-particle $W_{\alpha}^{(2)}(\Omega_{\alpha})$ can be calculated by following the same line of reasoning as in dealing with the energy distribution of the second particle. Unfortunately, the angular distribution of third and fourth particles that was presented in [5] for the quaternary fission of ^{233}U nuclei with the emission of an α-particle pair was measured with a poor statistical accuracy, and this prevents the calculation of the angular distribution for the second light particle. A comparison of the experimental angular distribution $W_{\alpha}(\Omega_{\alpha})$ with the distribution $W_{\alpha}^{(1)}(\Omega_{\alpha})$ obtained for the ternary fission of nuclei permits only assessing the broadening of the angular distribution $W_{\alpha}(\Omega_{\alpha})$ in relation to the distribution $W_{\alpha}^{(1)}(\Omega_{\alpha})$.

5. *P*-ODD AND *P*-EVEN ASYMMETRIES FOR THE TRUE QUATERNARY FISSION

The appearance of the *P*-odd and *P*-even asymmetries in the true quaternary fission induced by cold polarized neutrons, having the polarization vector $\mathbf{p}_{\mathrm{n}}$ and wave vector $\mathbf{k}_{\mathrm{n}}$, and accompanying with the flight of the prescission third and fourth particles is caused by the mechanism, which was investigated in papers [29 – 31] and lead to the transfer of mentioned asymmetries, which occur for binary fission fragments, to the cases of the analogous asymmetries for the third particle emitted in ternary fission of the same nuclei. The coefficient of the asymmetry $D_3^{(\mathrm{q})}$ for the third particle emitted in the true quaternary fission is represented as

$$D_3^{(\mathrm{q})} = \left(\frac{N_3^{(1)}N_4^{(2)}}{N_{3,4}}\eta^{(1)} + \frac{N_3^{(2)}N_4^{(1)}}{N_{3,4}}\eta^{(2)}\right)\left(A_{\mathrm{LF}}^{(\mathrm{b})}\left(\mathbf{p}_{\mathrm{n}},\mathbf{k}_3\right) + \left(A_{\mathrm{LF}}^{\mathrm{LR}}\right)^{(\mathrm{b})}\left(\mathbf{p}_{\mathrm{n}},[\mathbf{k}_{\mathrm{n}},\mathbf{k}_3]\right)\right). \qquad (10)$$

where $\eta^{(i)} = a_1^{(i)}\sqrt{4\pi/3}$; $a_1^{(i)}$ are coefficients in normalized to unity angular distribution angular distribution of the first emitted (i=1) or second emitted (i=2) third particle $W_3^{(i)}(\Omega_3) = \sum_l a_l^{(i)} Y_{l0}\left(\theta_{3,\mathrm{LF}}\right)$, and $\theta_{3,\mathrm{LF}}$ is an angle between the third particle flight direction $\mathbf{k}_3$ and light fission fragment flight directions. For ternary fission the analogous coefficient $D_3^{(\mathrm{t})}$

for the third particle is defined by formula (10) with the substitution of the first term in brackets by coefficient $\eta^{(1)}$. In the case of the appearance of pairs of identical particles in quaternary fission, when $N_{3,3} = 2N_3^{(1)}N_3^{(2)}$ (2), the first term in brackets in formula (10) is equal to $\left(\eta^{(1)} + \eta^{(2)}\right)/2$. The angular distribution of the second emitted α-particle is broader and has a shift of the maximum from θ_3=90º toward lower angles in relation to the respective distribution of the first emitted α-particle, which coincides with the angular distribution of the α-particle in ternary fission. Therefore coefficient $\eta^{(2)}$ in (10) has lower values than coefficient $\eta^{(1)}$, so the asymmetry coefficient $D_3^{(\mathrm{q})}$ (10) for quaternary fission has smaller values in comparison with the analogous coefficient $D_3^{(\mathrm{t})}$ in ternary fission.

6. *T*-ODD ASYMMETRIES FOR THE TRUE QUATERNARY FISSION

Let's consider the case, when in the true quaternary fission of the nonpolarized nucleus by cold polarized neutrons the pair of the two prescission α-particles occur. The first α-particle is registered by the first detector, the second one – by the another second detector. The appearance of the *T*-odd asymmetries in the angular distributions of the both α-particles emitted in quaternary fission is connected with the influence of the Coriolis interaction of fissile nucleus total spin with the orbital momenta of the mentioned α-particles and can be taking into account in the first order of the perturbation theory [32]. The influence of the Coriolis interaction onto α-particles has an additive character, that allow to distinguish *T*-odd asymmetries for α-particles registered by the first and second detectors. Then coefficient of *T*-odd asymmetry $D_\alpha^{(\mathrm{q})}$ for the registered by the first detector α-particle, when the Z axis of the laboratory frame is directed along the light fission fragment's flight direction, is defined as

$$D_\alpha^{(\mathrm{q})} = p_{\mathrm{n}} \cos\varphi \frac{\sum\limits_{i=1,2} \Delta\theta^{(i)} \left|A_0^{(i)}(\theta)\right| \left[\left|\frac{d\bar{A}_{\mathrm{ev}}^{(i)}(\theta)}{d\theta}\right| \sin\left(\bar{\delta}_{\mathrm{ev}}^{(i)} - \delta_0^{(i)}\right) + \left|\frac{d\bar{A}_{\mathrm{odd}}^{(i)}(\theta)}{d\theta}\right| \sin\left(\bar{\delta}_{\mathrm{odd}}^{(i)} - \delta_0^{(i)}\right)\right]}{\sum\limits_{i=1,2} \left|A_0^{(i)}(\theta)\right|^2}. \quad (11)$$

In formula (11) $\Delta\theta^{(i)}$ is averaged by neutron resonances pairs, which are exited after the capture of the cold polarized neutron by target-nucleus, rotation angle for the flight direction of the α-particle, caused by the rotation of the polarized fissile nucleus; $\left|A_0^{(i)}(\Omega)\right|$ ($\delta_0^{(i)}$) is absolute value (phase) of the α-particle angular distribution amplitude, which is non-perturbed by the interaction of the polarized fissile nucleus rotation, $\left|\bar{A}_{\mathrm{ev}}^{(i)}(\theta)\right|$ and $\left|\bar{A}_{\mathrm{odd}}^{(i)}(\theta)\right|$ ($\bar{\delta}_{\mathrm{ev}}^{(i)}$ and $\bar{\delta}_{\mathrm{odd}}^{(i)}$) are absolute values (phases) of even and add components of the α-particle angular distribution amplitude, which is perturbed by the Corilos interaction and defines the structure of *ROT*- and *TRI*- *T*-odd asymmetries respectively [31]. The analogous coefficient $D_\alpha^{(\mathrm{t})}$ for α-particle in ternary fission is represented by formula (11) with terms $i = 1$. Since the normalized non-pertubed angular distributions $W_\alpha^{(i)}(\Omega)$ of the emitted firstly ($i = 1$) and secondly ($i = 2$) α-particles in true quaternary fission don't sufficiently differ, and Coriolis interactions, which take into account the influence of polarized fissile nucleus collective rotation onto the first and second α-particles, have the same structure, one may expect that the absolute values and phases of the angular distribution amplitudes for the first and the second α-particles in (11) are close to each other. Therefore the angular dependence of the *T*-odd asymmetry coefficient $D_\alpha^{(q)}$ (11) for true quaternary fission is close to the analogous dependence of coefficient $D_\alpha^{(t)}$ for true ternary fission. This implies that the conception of *T*-odd *TRI*- and *ROT*-asymmetries for ternary fission is correct and for quaternary fission. Taking into account, that the rotation angle $\Delta\theta^{(i)}$ is sufficiently higher for the first emitted α-particle ($i = 1$), than for the second ($i = 2$), because of more long time τ of the fissile nucleus rotation onto the first emitted α-particle, it is expected that the absolute values of the coefficient $D_\alpha^{(q)}$ for the quaternary fission are lesser than the absolute values of the analogous coefficient $D_\alpha^{(t)}$ for ternary fission.

This work was supported by the Russian Foundation for Basic Research (09-02-00653-a).

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