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Examining the pros and cons of the interpretation of the collinear cluster tri-partition phenomenon

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Features of a new phenomenon—so-called collinear cluster tri-partition—are analyzed from various viewpoints. First, limitations on the angular distributions which are imposed by the general principles of quantum mechanics are considered. Second, these limitations together with the experimental data published earlier are used to estimate the effect as a whole. Third, some confirmation of the large yield of the lightest component of the tri-partition arising from geochemical data is presented.

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I. INTRODUCTION

Fundamentally new results in physics of nuclear fission obtained in experiments using FOBOS and COMETA setups were published in Refs. [1–3]. Coincident ^{252}Cf spontaneous fission events characterized by emission of the fragments with the masses $A_1 \approx 128$ to 146 ("Sn-like") and $A_2 \approx 64$ to 80 ("Ni-like"), respectively, were observed in the experiments different in design. The most surprising results of the experiments are that, first, the missing object has the mass $A_1 \approx 50$ and, second, in the FOBOS setup the coincident events are registered at the angle $180 \pm 2^\circ$, thus the detected fragments and the third missing "Ca-like" object $A_1 \approx 50$ are highly collinear in these observations. Therefore, the pattern of the observed process is distinctly different from the one typical for ternary fission. A large branching ratio of the events which is equal to $\approx 4 \times 10^{-3}$ relative to the total number of the registered fission events in the FOBOS experiment stresses an exotic character of the obtained results. In the latest paper of the FOBOS group [3] one unexpected feature of the process was revealed: The yield of the low-energy $E \approx 20$ MeV Ni-like fragment in the COMETA experiment turns out to be the most probable. Similar Sn- and Ni-like fragments were observed by the authors in the ^{235}U(n,f) process by the same group [4]. The effect was called collinear cluster tri-partition (CCT) by the authors. Unexpected properties of the CCT led the authors to the conclusion that its mechanism is most likely "almost sequential."

These results are hotly discussed now. Estimates of the potential surface and the dynamics of the tri-partition process in terms of classical mechanics are the subjects of Refs. [5–18]. Simultaneous (in all these works), sequential, and "almost sequential" (see Refs. [7,8,11,15]) scenarios of the process are considered. In these papers it was shown that the collinear arrangement of the three-fragment system at the prescission area (both binary and true ternary split are meant) is energetically favorable, i.e., potential energy in this area is minimal compared to other prescission configurations. In some works [10,14,15] the split into clusters which are close to ^{132}Sn, ^{72}Ni, and lighter residual (the last one is in between) is rated as the most probable. As it is shown in Ref. [18] explanation of the effect in the framework of classical mechanics is troublesome because the pattern of it does not look as a fly apart of three charged particles. The quantum mechanical uncertainty principle was also considered in estimates of features of simultaneous mechanism; these estimates demonstrated that "collinearity is extremely unstable and improbable in ternary fission" [18]. The conclusions of papers [15,16] do not come into conflict with the one mentioned above.

In the present paper we do not cast any doubt on the validity of the estimates concerning the Coulomb three-body dynamics presented in Refs. [15,16,18] but consider the problem from an alternative point of view. We apply advanced forms of the quantum-mechanical indeterminacy principle expressions and analyze the limits set by them on the characteristics of the angular distribution of the fragments. Estimates of the total yield of the tri-partition process fragments which are evident from this analysis are presented. Both simultaneous and sequential scenarios are considered. The above-mentioned novel namely detection of low-energy (and, consequently, central component of tri-cluster system) collinear Ni-like fragment is also in the focus of attention of the present study. The matter is that restrictions imposed on the angular distribution of the low-energy object of intermediate mass by various Coulomb and quantum-mechanical effects are significantly more severe. In addition to that the process of such a type was not a subject of theoretical consideration in Refs. [15,16,18].

The performed analysis allows one to establish a distinct line between tolerable and intolerable parameters characterizing the process. Based on this distinction we introduce some new arguments in the extensive debate concerning interpretation of the observed results which were initiated by Refs. [3,18]. Unexpected indirect confirmation of the results of Refs. [1–4] is found in geochemical data. A number of relatively simple experiments which might confirm or refute the CCT effect or its interpretation are proposed on the same basis.

It should be noted that one more exotic effect, namely significantly different spectra observed in the opposite arms in both FOBOS and COMETA spectrometers, is beyond the scope of the present paper. This line of our studies is in progress.

II. CCT PHENOMENON AND THE UNCERTAINTY PRINCIPLE

A preliminary estimate may be obtained using the angle–angular momentum uncertainty principle expression,

$$(\Delta L_x)^2(\Delta \sin\varphi)^2 \geqslant \hbar^2(\cos\varphi)^2/4, \tag{1}$$

where L_x is the projection of the angular momentum on the x axis. Taking into account that the root mean square deviation (RMSD) of the total angular momentum is $|\Delta L| \geqslant \sqrt{\sum_{k=x,y,z}(\Delta L_k)^2}$ and the angular momentum distribution (AMD) according to the habituated notion of fission process is limited by the value $L_{\max} \approx 10\hbar$ one can estimate the width of the angular distribution cone. It is at least not less than 5°. Yet, this condition is not sufficient because it is necessary for the cone to be formed by a very specific superposition of the Legendre polynomials. Otherwise the fragments produced with not-too-low total intensity and emitted to the "side petals" of the angular distribution would be easily detected in various experiments. To explain this discrepancy one should assume, first, that the CCT possesses a very specific AMD with large $L_{\max}$ and, second, actual angular distribution of the CCT is wider than the experimental angular "window." The presented estimate, however, is valid for the simultaneous but not for the sequential process in the case that any mechanism giving rise to orientation of the axis of a primary split product deformation takes place. Indeed, the angular momentum of a product of the secondary split is unlimited for a sequential tri-partition.

To analyze this case a more accurate approach can be applied. Let us consider ^{252}Cf sequential decomposition to Sn-like, Ni-like, and Ca-like fragments. The latter two are products of Cd-like intermediate system decay. For the ground states of the Cd-like system and its fragments ("Ni" and "Ca"), maximum energy release of the decay Q is equal to 20 MeV. At the same time even with the assumption that the distance between "Ni" and "Ca" effective centers of charge at the instant the strong interaction between them diminishes to negligible value is equal to enormously large value $d_0 = 16$ fm, the height of the potential barrier turns out to be 51 MeV. Thus the additional excitation energy of Cd-like nucleus which is not less than 31 MeV is necessary. Moreover this statement is related to the deformation component of the excitation energy only. Therefore this nucleus is bound to be in a hyper-deformed state. The "almost sequential" scenario demonstrates a very similar pattern. For completeness it is reasonable to present the same characteristics of ^{238}U decomposition to Sn-like, Ni-like, and the residual fragments (the residues may be ^{38}Si or ^{40}S nuclei). For the Mo-like partner of the Sn-like fragment the decay Q value is negative and equal to –8 MeV and –4 MeV as a maximum for Si and S while the barrier height is 35 MeV and 37 MeV, respectively. Thus the additional excitation energy of Mo-like nucleus which is not less than 43 MeV and 41 MeV, respectively, is necessary.

So the reliable proof of the hypothesis of sequential or "almost sequential" mechanisms of the CCT in future experimental and theoretical works would be the discovery of extremely high-energy fission isomers in the medium-mass nuclei area.

Let us return to the analysis of tolerable angular distribution of the CCT. The sequential scenario of the ^{252}Cf tri-partition is considered as an example. The angles are measured from the axis of the first split. The decaying Cd-like system is considered at the instant when the strong interaction of the fragments becomes negligible. It is suggested in the sequential scenario that the second split takes place at a distance D where the influence of the Sn-like fragment on the dynamics of "Cd" decay is negligible, too. This does not necessarily mean that the process of the longitudinal acceleration of the fragments is completed. Therefore both the sequential and "almost sequential" mechanisms are, strictly speaking, the subjects of the consideration. In these conditions the lateral component of the linear momentum of each fragment at the infinity $p_\perp$ depends on d_0 as well as the initial lateral displacement distance $r_{\perp,0}$ and the initial lateral linear momentum $p_{\perp,0}$. So it can be presented in the following way:

$$p_\perp = pr_{\perp,0}/d + p_{\perp,0},$$

where

$$p = \sqrt{2Z_1Z_2e^2m_2m_3/d_0(m_2+m_3)}$$

is the linear momentum of the central fragment at the infinity in the reference frame connected with the Cd-like fragment center of mass, m_2 and m_3 are the masses of Ni- and Ca-like fragments, respectively, $d = d_0m_3/(m_2+m_3)$. The RMSD of the value $p_\perp$ is determined using the general expression of the RMSD of any observable quantity which is as follows:

$$\Delta F = \sqrt{\sum_{i=1}^{n}\langle(\partial F/\partial x_i)^2\rangle(\Delta x_i)^2}. \tag{2}$$

As a result it takes the form,

$$\Delta p_\perp = \sqrt{(p/d)^2(\Delta r_{\perp,0})^2 + (\Delta p_{\perp,0})^2}, \tag{3}$$

in which RMSDs of lateral displacement distance and lateral linear momentum are denoted $\Delta r_{\perp,0}$ and $\Delta p_{\perp,0}$, respectively. Using habituated expression of indeterminacy principle $(\Delta r_k)^2(\Delta p_k)^2 \geqslant \hbar^2/4$ one can express the lower limit of the value $p_\perp$ as

$$\Delta p_\perp \geqslant \sqrt{(p/d)^2(\Delta r_{\perp,0})^2 + \hbar^2/4(\Delta r_{\perp,0})^2}. \tag{4}$$

After deducing the minimum of the radicand contained in Eq. (4) this inequality is reduced to the form $\Delta p_\perp \geqslant \sqrt{p\hbar/d}$. So the lower limit of the width of the fragment angular distribution cone in the (almost) sequential scenario takes the form,

$$\Delta\varphi > \Delta(\sin\varphi) = \Delta p_\perp/p \geqslant \sqrt{p\hbar/p_{\mathrm{lab},i}^2 d}, \tag{5}$$

where $p_{\mathrm{lab,i}}$ $(i = 2, 3)$ is the linear momentum of the corresponding fragment in the laboratory reference frame. Evidently taking into account the interaction of each fragment with the Sn-like nucleus will result in the increase of the just obtained minimal angles. At the same time the impact of this nucleus on the lateral motion of the fragments drops

TABLE I. The lower limit of the width of the angular distribution cone $\Delta\varphi$ of the Ni-like fragment, grad.

d_0, fm / $E_{\mathrm{lab},2}$, MeV	9.4	11.4	16
20	11.7°	9.2°	7.9°
100	5.2°	4.1°	3.5°

down rapidly with the growth of the distance between it and the Cd-like fragment $R_{1,23}$. The effect becomes a fortiori negligible in the case that the second split takes place at $R_{1,23} = D \approx 100$ fm. The time taken to pass this distance is about 10^{-20} s. This time is not enough to emit a neutron or a gamma quantum. Thus the hypothesis of existence of high-energy fission isomers with such a tiny half-life turns out to be sufficient. On the other hand the hypothesis looks nonconflicting with the theory of nuclear processes.

To the contrary at small ranges $R_{1,23}$ the impact of Sn-like nucleus is strong. Therefore one can conclude that the simultaneous mechanism of tri-partition is bound to result in the pattern typical for ternary fission.

Let us express relationship (5) in a more explicit form,

$$\Delta(\sin\varphi) \geqslant (Z_2 Z_3 e^2/2\mu c^2)^{1/4}(\hbar c/E_{\mathrm{lab,i}})^{1/2} d_0^{-3/4}. \qquad (6)$$

Numerical estimates derived from Eq. (6) are presented in Table I. The values of “the strong interaction switch-off” distance d_0 are chosen to be equal to the following: the contact distance $(A_2^{1/3} + A_3^{1/3})r_0$, $(r_0 = 1.2$ fm), the widely used in heavy ion physics value $(A_2^{1/3} + A_3^{1/3})r_0 + 2$ fm, and the above-mentioned large value 16 fm. The energies of the Ni-like fragment chosen for demonstration in the table correspond to the positions of energy distribution maximums in the COMETA experiment which are presented in Ref. [3]. It should be noted here that the conditions of the FOBOS and COMETA experiments are significantly different to compare the branching ratios of the CCT and the binary fission obtained in these experiments. On the other hand the statistics of the latter one is not large. Because of that the estimates presented below are based on the data obtained in the high-statistics FOBOS experiment. Evidence from the COMETA measurements concerning only the energy distribution is exploited.

The $\Delta\varphi$ values demonstrate the following. First, the angular distribution of the fragments is wider than the experimental angular “window” 2° in an arbitrary credible speculation. For example, assuming “absolutely cold” CCT and the distance $d_0 = 16$ fm one can obtain the angular width $\Delta\varphi = 2.8°$ while as observed in the experiments the neutron yield of the CCT process is more or less equal to the yield of the binary fission and so the most probable CCT events are not “cold.” Second, in the case that the Ni-like fragment is slow (and thus turns out to be central) the distribution cone is much wider than the experimental angular “window.”

At the same time the concept of almost collinear geometry of the ternary fission is not directly discarded by the minimal values $\Delta\varphi$ presented in Table I. Indeed, as it was declared in Ref. [3], a specially designed experiment is required to extract the almost collinear Ni- or Ca-like fragment. This statement remains reasonable if even $\Delta\varphi \approx 10°$ is assumed. All the just discussed points are inherent to the neutron-induced fission of ^{235}U and, probably, to other fission processes in actinides.

The possibility of the angular distribution width to be much greater than 2° was rejected in the previous papers at the very beginning probably because in that case the CCT yield would be enormously great because of the quadratic dependence of the yield on the angular width of the distribution cone. Indeed, the values of the relative CCT yield conforming to the typical (see Table I) minimal angular widths 4°, 8°, and 9° obtained in the current study are equal to 1.6×10^{-2}, 6.4×10^{-2}, and 8.0×10^{-2}.

III. CCT PHENOMENON AND GEOCHEMICAL DATA

At first glance the presented values go far beyond the area of acceptable quantities. Nevertheless, surprisingly, there is a supporting evidence for this possibility. It was obtained in the geochemical researches. Excess of ^{38,40}Ar isotopes in uranium ore was analyzed in these studies. The results are published in Ref. [19] and presented in details in monograph [20]. These excess isotopes may be in principle the residues of the CCT process.

Let us list the main points of this analysis. Abnormal abundance of ^{38}Ar in various samples of the uranium ore is a well-confirmed fact. A typical ratio of abundances A_{38}/A_{36} in the samples extracted from various deposits is on the average 8 times greater than in the atmosphere. The author involved in the analysis of the data on all the nuclear reactions induced by neutrons and α particles which are generated by uranium and its secondary products bringing about formation and destruction of argon isotopes. Five of them: ^{35}Cl(α, n)^{38}K, ^{35}Cl(α, p)^{38}Ar, ^{35}Cl(n, γ)^{36}Cl, ^{37}Cl(n, γ)^{38}Cl, and ^{41}K(n, α)^{38}Ar exert primary impact on the Ar isotope abundances. Correlations between Ar and Cl isotopes as well as Ar and K isotopes were studied. Searches for the correlations of isotope abundances in various uranium deposits, as well as the correlations of location of these isotopes in the crystal structure of one and the same sample were performed. No correlation was revealed. So the reactions under discussion play a minor role in ^{38}Ar isotope production. Effects related to the diffusion of Ar isotopes from the ore were also analyzed. The principal conclusion presented in Ref. [19] is that most of the excess ^{38}Ar is produced by a spontaneous decay process of uranium nuclei. According to the author’s estimates the yield of the radiogenic ^{38}Ar is of the same order as the total yield of the products of ^{238}U spontaneous fission process. This result looks exotic but is in good agreement with the just presented estimates of the CCT yield.

It should be noted that the results of geochemical analysis have to be used with a certain caution. Indeed, the same approach being applied in the study of the production of ^{40}Ar in the same ^{238}U spontaneous decay process resulted in the unlikely high relative probability of this process and the result should undoubtedly be rejected. At the same time there is a significant difference of two results under discussion. The matter is that the one related to ^{40}Ar isotope excess was deduced on the basis of the stability of the A_{40}/A_{38} ratio in various deposits only while the basis of the former result, as we have just demonstrated, is much more wide and solid. There is another feature which poses great difficulties to deduce a reliable value of ^{40}Ar yield in some ^{238}U spontaneous decay process. It is the great "background" appearing because of the dominating source of radiogenic ^{40}Ar namely the β decay of ^{40}K. So the failure of the approach in the description of ^{40}Ar yield in some ^{238}U disintegration does not mean that it is inadequate to describe another example, ^{38}Ar yield in particular.

IV. CONCLUSIONS

In summary the following points need to be made.

In the current study the limits imposed by quantum mechanical principles on angular distribution of a tri-partition process are obtained. The sole model parameter namely "the strong interaction switch-off distance" d_0 is involved in the most accurate estimate. This parameter, however, is somewhat strongly limited by modern knowledge of nuclear dynamics.

The estimates give a proof that the ternary fission process cannot be precisely collinear in principle. The concept of approximate collinearity is meaningful only. It is demonstrated that only the sequential and "almost sequential" mechanisms may result in quasicollinear events.

The above-mentioned limitations together with the experimental data on collinear cluster tri-partition published in Refs. [1–4] are used to estimate the probability of this process. The yield of the process related to binary fission yield turns out to be very large. An independent estimate of the yield of the fragment of the mass A = 38 in spontaneous decay of ^{238}U in uranium ore is presented. It is shown that these estimates are in a good qualitative agreement.

The estimates allow one to propose some relatively simple approaches which offer alternatives to the usually discussed experiment using the Lohengrin facility. The performed estimates may be of use in the design of corresponding experimental setups. These approaches are the following.

(1) Search for the quasicollinear events characterized by significant ($\geqslant 5^\circ$) deviation from collinearity.
(2) Use of the method of photoemulsion detecting of fission fragments. A marker of the CCT is the elliptic cone form of the trace of a pair of quasicollinear fragments. A single fragment makes the circular cone trace.
(3) Study of isotopic composition of argon in nuclear reactor wastes.

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