

## Observation of a New Effect in the Ternary Fission of $^{252}\text{Cf}(\text{sf})$ with the Emission of an Alpha Particle

Yu. V. Pyatkov<sup>1),2)\*</sup>, D. V. Kamanin<sup>2)</sup>, A. O. Strekalovsky<sup>2)</sup>,  
Z. I. Goryainova<sup>2)</sup>, E. A. Kuznetsova<sup>2)</sup>, A. N. Solodov<sup>2)</sup>,  
O. V. Strekalovsky<sup>3),2)</sup>, V. E. Zhuchko<sup>2)</sup>, and A. O. Zhukova<sup>2)</sup>

Received February 15, 2023; revised February 15, 2023; accepted February 15, 2023

**Abstract**—New feature of the ternary alpha particle accompanied fission of the  $^{252}\text{Cf}(\text{sf})$  is discovered in the experiment where the masses of all the decay partners were measured by the velocity–energy method with the energy threshold exceeding one MeV. Two groups of the fission events were observed with a total mass of three detected fragments less than the mass of the parent nucleus by 4 and 8 units not counting the release of 3 neutrons. The yields of such events are orders of magnitude higher than the yields of  $^8\text{Be}$  and  $^{12}\text{C}$  in conventional ternary fission. Possible origin of unusual events is discussed.

**DOI:** 10.1134/S1063778823040300

### 1. INTRODUCTION

The conventional ternary fission with the emission of the light charged particle (LCP) is well studied mode of nuclear fission [1]. It is rather rare mode with the yield of about  $3 \times 10^{-3}$  per binary fission. About 90% of the ternary particles are known to be alphas and about 7% tritons, while the remaining fraction is a variety of LCP, going from protons to neon. Most of the ternary alphas are emitted almost perpendicularly to the fission axis, however, about 3% of the particles are emitted along the axis (polar emission). The most probable LCP energies vary from about 10 to 20 MeV.

In the typical experiments dedicated to the conventional ternary fission, the fission source is covered by the foil which is aimed to cut the alphas from the natural radioactivity. The ternary LCPs are identified by the  $\Delta E - E$  telescope, while the masses of fission fragments are measured in the frame of the “two-energies method”. The new results presented below were obtained by using the time-of-flight approach for the independent measurement of all the decay products of the multibody decay in the wide range of masses from alphas to fission fragments.

### 2. EXPERIMENT

The experiment was performed at the COMETA (Correlation M-E-T Array) setup. The layout of the

setup is shown in Fig. 1. The spectrometer consisted of four mosaics including twenty-eight PIN diodes  $1.8 \times 1.8$  cm each and the microchannel plates-based start detector. The  $^{252}\text{Cf}(\text{sf})$  source on the  $\text{Al}_2\text{O}_3$  backing, 1257 Å thick, and with a 259 Å thick gold layer on top was located at 1.5 mm from the emitting Lexan foil (3813 Å thickness) of the “start” timing detector (see the insert in Fig. 1a). The foil was vacuum sputtered with a gold layer, 210 Å thick. Each PIN diode provided both “stop” timing and energy signals for measuring the FF mass by the velocity–energy method.

The data acquisition system consisted of the multichannel fast flash-ADC (Amplitude to Digital Converter) digitizer CAEN DT574, logic blocks, providing trigger signals, and a personal computer. Current value of each signal was measured by the digitizer every 0.2 ns. Time reference point on the PIN diode signal was calculated offline using new algorithm proposed by us earlier [2]. Calculation of the FF mass with accounting for pulse-height-defect (PHD) was performed using an iterative procedure based on parametrization proposed in [3]. The calculation algorithm was presented in [4].

### 3. RESULTS

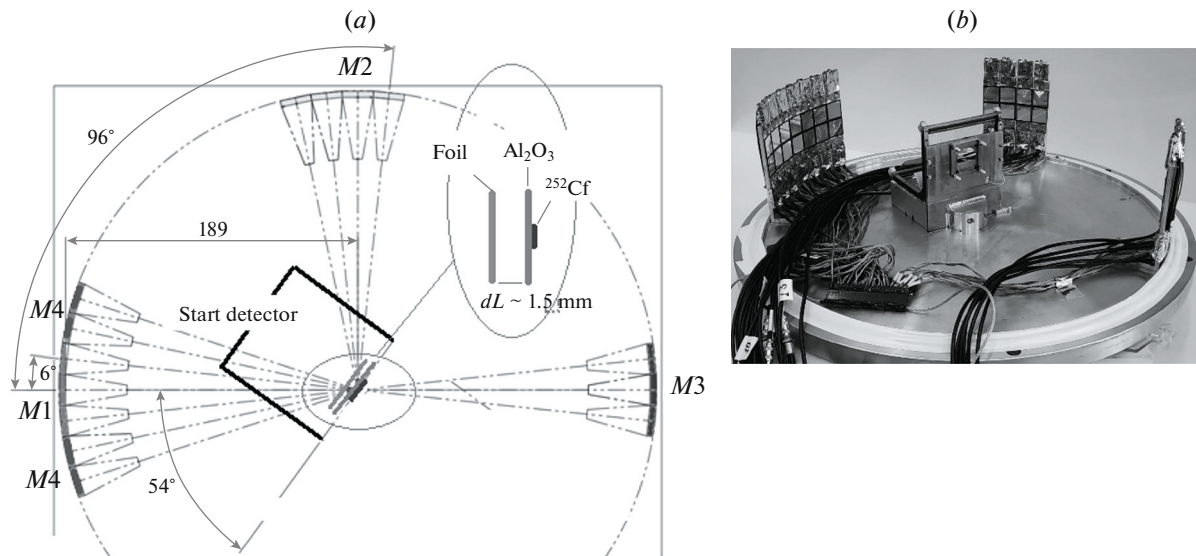
The main experimental results are presented in Fig. 2. By definition, in each ternary event  $M_1 > M_2 > M_3$ . Correlation mass distribution for the ternary events, selected under the condition that the energy of the lightest fragment  $E_3 > 7$  MeV, is shown

<sup>1)</sup>National Nuclear Research University MEPhI, Moscow, Russia.

<sup>2)</sup>Joint Institute for Nuclear Research, Dubna, Russia.

<sup>3)</sup>Dubna State University, Dubna, Russia.

\*E-mail: yvp\_nov@mail.ru



**Fig. 1.** Layout of the COMETA setup (a), photo of the detectors inside the experimental chamber (b). The spectrometer included four mosaics with twenty-eight PIN diodes in total and a “start” timing detector. The source of the  $^{252}\text{Cf}$ (sf) on a  $\text{Al}_2\text{O}_3$  backing and emitting foil of the start detector is shown in a larger scale in the insert in (a).

in Fig. 2a. Alpha particles from the natural radioactivity are rejected by such selection. The dashed tilted line corresponds to the total mass of all three detected fragments,  $M_s = 252$  u, while the dash-dotted line below corresponds to the  $M_s = 248$  u (in order to account for the mean neutron multiplicity in binary fission  $\nu_2$ ). The mass spectrum of the lightest fragments in each trio is shown in Fig. 2b. The yield ratio  $Y(^4\text{He})/Y(^3\text{H})$  is consistent with the known one [5] within 20%. All light particles were registered in mosaic M2 (Fig. 1) placed almost perpendicular to the fission axis.

The energy spectrum for the lightest fragments is shown in Fig. 2c. Mean energy of the detected LCPs is consistent with the known one [5] (marked in the figure by the arrow) within 4%. The spectrum of missing mass defined as  $M_{\text{miss}} = (252 - M_1 - M_2 - M_3 - 3)$  u is presented in Fig. 2d. The mean number of neutrons emitted in conventional ternary fission  $\nu_3 \approx 3$  [6] is taken into account.

#### 4. DISCUSSION

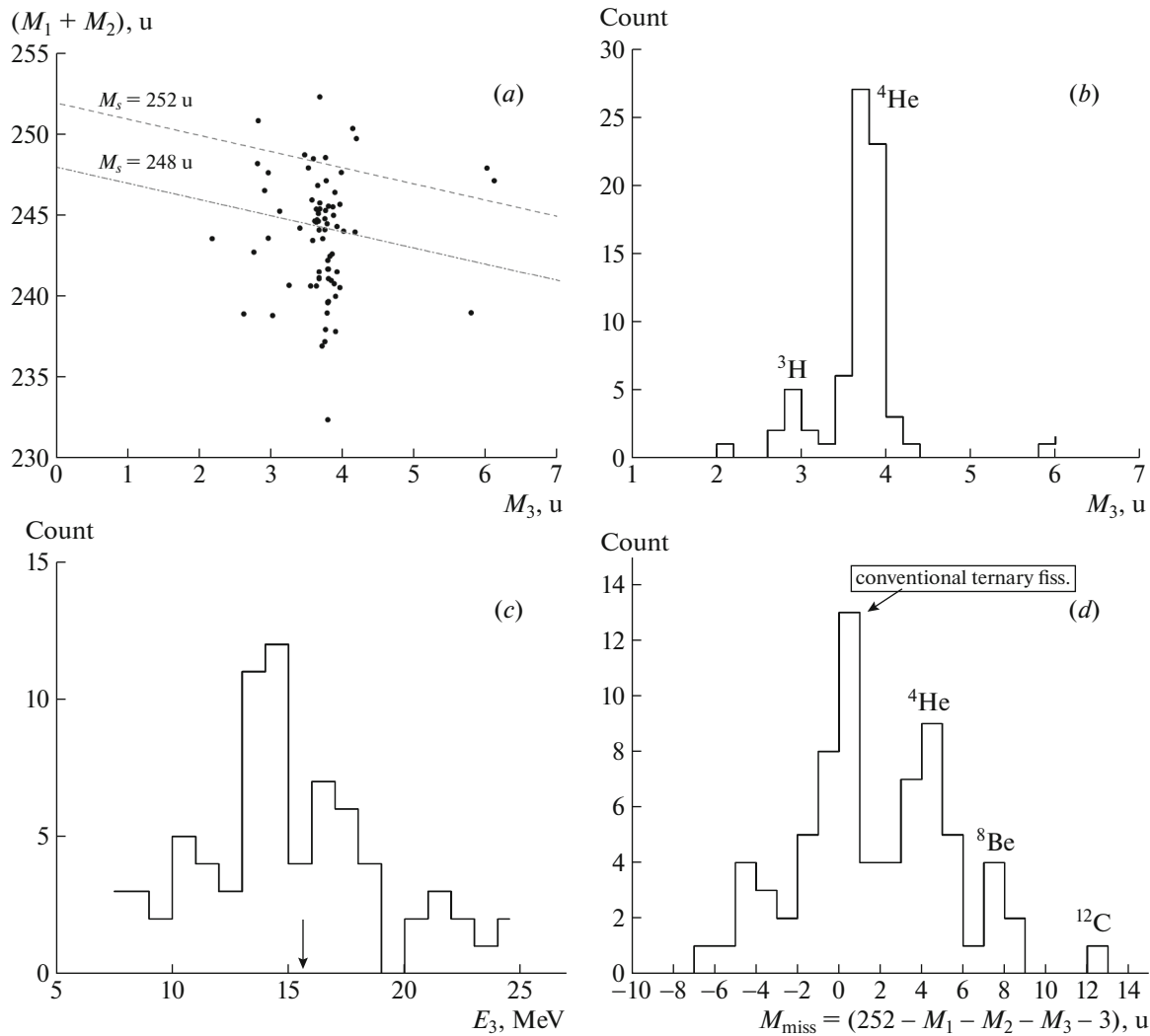
The light fragments detected in the ternary events (Fig. 2a) demonstrate the parameters characteristic of the LCPs from conventional ternary fission: they were emitted in the plane almost perpendicular to the fission axis, the yield ratio  $Y(^4\text{He})/Y(^3\text{H})$  and the mean energy of the detected particles agree satisfactorily with the known one. Even though, we have no measured nuclear charges for the absolutely reliable identification of the isotopes, the parameters listed

above can be regarded as a strong indication of the correctness of such identification.

At the same time, even the initial mass correlation distribution (Fig. 2a) shows something unexpected for conventional ternary fission. Indeed, almost half of the experimental points lie in the region of essential missing mass below the line  $M_s = 248$  u.

Thus, an additional fragment was likely emitted in each event, besides the detected LCP (predominantly alpha-particle) from conventional ternary fission. This assumption is confirmed by the spectrum in Fig. 2d. The main peak is centered at zero and corresponds by definition of  $M_{\text{miss}}$  to the conventional ternary fission with the emittance of alpha particle and three neutrons. The unbiased position of the main peak gives evidence that the position of each FF mass-line is correct. There are two additional peaks in the spectrum centered at masses 4 u and 8 u. They can be attributed to the  $^4\text{He}$  and  $^8\text{Be}$ , respectively. The energy balance for the events from these peaks was checked. The following decays were supposed:  $^{252}\text{Cf} \rightarrow M_1 + M_2 + M_3 + ^4\text{He} + 3n$  and  $^{252}\text{Cf} \rightarrow M_1 + M_2 + M_3 + ^8\text{Be} + 3n$ . The energy price of each neutron was estimated to be 8 MeV, while gammas were supposed to carry away 6 MeV [6]. The residual energy, which can be attributed to the kinetic energy of  $^4\text{He}$  and  $^8\text{Be}$ , respectively, does not exceed (4–7) MeV.

The following scenario could lead to the observed effect. The presumable scission configuration is presented in Fig. 3a. The alpha particle is emitted from the inter-fragment space at the moment of rupture.

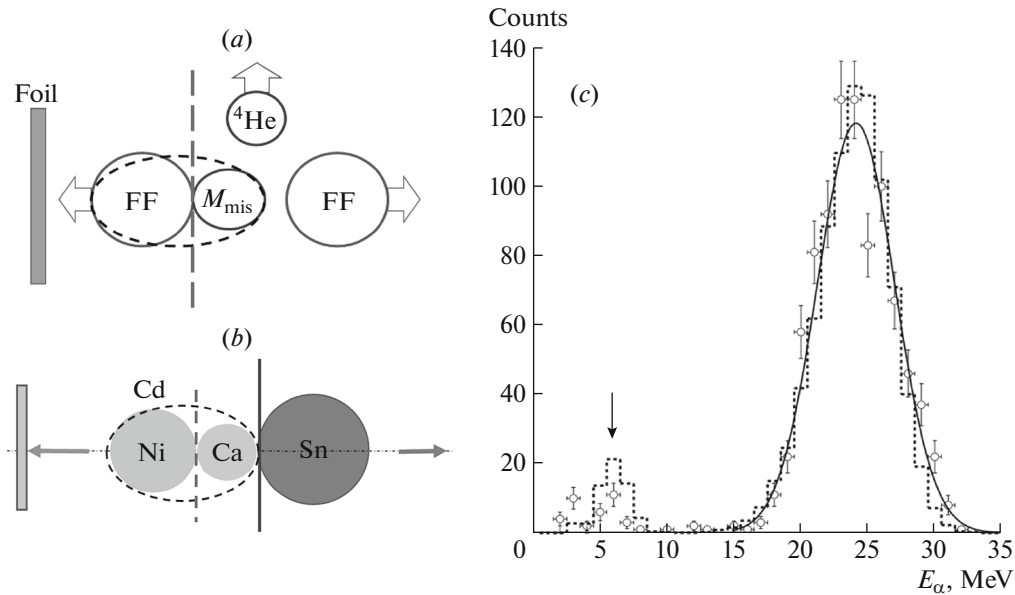


**Fig. 2.** Correlation mass distribution for ternary events (a). In each ternary event  $M_1 > M_2 > M_3$ . Spectrum of masses  $M_3$  (b) and energy spectrum for the lightest fragment in the trio (c). Spectrum of missing mass which is a difference between the mass of the mother system minus the mean number of neutrons emitted in conventional ternary fission  $\nu_3 \approx 3$  [6] and the total mass of all the detected fragments (d). See text for details.

This alpha is focused in the direction almost perpendicular to the fission axis by the Coulomb fields of the FFs. One of the FF and preformed LCP with the  $M_{\text{miss}}$  form a di-nuclear system which undergoes a break-up while passing the foil (the source backing or Lexan foil of the start detector). *Thereby, the quaternary decay takes place.* It should be stressed that the break-up delays regarding the moment of the first rupture with emission of alpha-particle. Otherwise, an LCP with the mass  $M_{\text{miss}}$  should have an energy of about  $E_\alpha$  value due to repulsion from the FFs. *Thus, a di-nuclear system (Fig. 3a) is born in the shape isomer state.* Due to deceleration after the break-up, the resultant LCP energy could be rather low. Similar scenario is realized in the ternary decay called “collinear cluster tri-partition” (CCT) [7, 8], but much heavier nuclei are involved (Fig. 3b).

It should be noted that the low energy component was observed earlier for the alphas of the polar emission (Fig. 3c) in the direction opposite to the velocity vector of the FF [6]. Reported in this work quaternary fission with emission of two alphas and the yield  $Y_4 \approx 10^{-6}$  per binary fission and even three times less in [9] gives additional argument in favor of the conclusion regarding the origin of the peak marked by the icon  ${}^4\text{He}$  in Fig. 2d. The yield of this peak is comparable with the main peak in this spectrum, i.e., three orders of magnitude more than obtained in [6, 9].

Turning back to the spectrum in Fig. 2d it is necessary to comment the presence of the peak for  $M_{\text{miss}} < 0$ . For all ternary events giving rise to the peak  $M_3 \approx 4$  u and  $E_3 \approx 15$  MeV, i.e., the detected (in mosaic  $M_2$ ) LCPs are alphas from the ternary



**Fig. 3.** Scission configurations of the  $^{252}\text{Cf}$  nucleus leading to quaternary (a) and ternary decay called CCT (b). Energy spectrum of alphas from polar emission [6] (c). The low energy component is marked by the arrow.

fission. What is more, it is *cold ternary fission* without emission of neutrons.

## 5. CONCLUSIONS

For the first time the missing mass is experimentally observed in triple coincidences with the emission of an alpha particle. This observation may indicate that at least some part of  $\alpha$ -accompanied ternary fission events are realized according to the following scenario.

1. Precission configuration of the fissioning system looks like two preformed fragments and the LCP in the range of  $^8\text{Be}$ – $^{12}\text{C}$  (maybe heavier) in between them.
2. At scission of the mother system, the  $\alpha$ -particle is emitted in the direction perpendicular to the fission axis.
3. The rest of the LCP forms a di-nuclear system with one of pre-fragments.
4. The di-nuclear system being in the shape isomer state undergoes a break-up when flying through the foil.

## ACKNOWLEDGMENTS

The authors are grateful to G.G. Adamian, N.V. Antonenko, A.K. Nasirov, V.I. Furman, Yu.M. Tchuvil'sky for numerous fruitful discussions and stimulated criticism.

## REFERENCES

1. C. Wagemans, *The Nuclear Fission Process* (CRC, Boca Raton, 1991), Chap. 12.
2. D. V. Kamanin, Yu. V. Pyatkov, A. O. Strekalovsky, A. A. Alexandrov, I. A. Alexandrova, Z. I. Goryainova, N. Mkaza, E. A. Kuznetsova, V. Malaza, O. V. Strekalovsky, and V. E. Zhuchko, *Izv. Akad. Nauk, Ser. Fiz.* **82**, 719 (2018).
3. S. I. Mulgin, V. N. Okolovich, and S. V. Zhdanov, *Nucl. Instrum. Methods Phys. Res., Sect. A* **388**, 254 (1997).
4. Yu. V. Pyatkov, D. V. Kamanin, N. A. Kondratyev, A. O. Strekalovsky, S. Ilić, A. A. Alexandrov, I. A. Alexandrova, N. Mkaza, E. A. Kuznetsova, V. Malaza, G. V. Mishinsky, O. V. Strekalovsky, and V. E. Zhuchko, *J. Phys.: Conf. Ser.* **675**, 042018 (2016).
5. <https://web-docs.gsi.de/~wolle/FISSION/ternary/node2.html>.
6. V. G. Tischenko, PhD Thesis, FLNR (JINR, Dubna, 2002).
7. Yu. V. Pyatkov, D. V. Kamanin, A. A. Alexandrov, I. A. Alexandrova, Z. I. Goryainova, V. Malaza, N. Mkaza, E. A. Kuznetsova, A. O. Strekalovsky, O. V. Strekalovsky, and V. E. Zhuchko, *Phys. Rev. C* **96**, 064606 (2017).
8. Yu. V. Pyatkov, D. V. Kamanin, A. A. Alexandrov, I. A. Alexandrova, Z. I. Goryainova, E. A. Kuznetsova, A. O. Strekalovsky, O. V. Strekalovsky, V. E. Zhuchko, and V. Malaza, *Euras. J. Phys. Funct. Mat.* **4**, 13 (2020).
9. A. S. Fomichev, I. David, M. P. Ivanov, and Yu. G. Sobolev, *Nucl. Instrum. Methods Phys. Res., Sect. A* **384**, 519 (1997).