Analysis of some modes of multibody decays of low excited actinide nuclei

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Abstract. Careful studies of the fission fragments mass correlation distributions let us to reveal specific linear structures in the region of a big missing mass. It became possible due to applying of effective cleaning of this region from the background linked with scattered fragments. One of the most pronounced structure looks like a rectangle bounded by the magic nuclei. The fission events aggregated in the rectangle show a very low total kinetic energy. We propose possible scenario of forming and decay of the multi-cluster precission configuration decisive for the experimental findings. This approach is valid as well for treating of another rare decay modes discovered in the past.

1. Introduction
A lot of our previous publicati ons [1–3] were devoted to experimental findings treated as a manifestation of a new multibody decay channel of low excited actinide nuclei. In the bulk of experiments two fragments were actually detected while deficit of their total mass comparing the mass of the mother system (“missing” mass) served a sign of at least ternary decay. Keeping in mind that the detected fragments fly apart almost collinearly and at least one of them shows magic nucleon composition, we have called this decay channel “collinear cluster tri-partition (CCT)” in order to underline the likeness with known cluster decay or “lead radioactivity” where magic lead cluster plays a key role. To date the results obtained were discussed in several theoretical works [4, 5 and references therein], but they are far from the quantitate description of the phenomenon under study. Here we discuss possible scenario of one of the most pronounced CCT modes.

2. Experiments and results
Manifestations of the analyzing multibody decay mode in the fission fragment (FF) mass correlation distributions are presented in figure 1.
Figure 1. Mass distribution of the complimentary fission fragments (FFs) from $^{252}$Cf(sf) selected by requirement of their approximately equal velocities and momenta (a). Mass distribution obtained for the events with the FFs momenta beyond the “tails” of scattered FFs and experimental neutron multiplicity $n \geq 1$ (b). Mass correlation distribution for the FFs from the reaction $^{235}$U(n$_{th}$, f) with approximately equal velocities, momenta and nuclear charges (c). FFs from the same reaction with approximately equal velocities, momenta and nuclear charges (d). The vertex of the rectangular structure corresponds to the nuclear charge $z \sim 28$ (Ni isotopes). See text for details.

The spectrometers used were based on the modules of the FOBOS setup [1, 2]. The TOF-E (time-of-flight vs. energy) method for the measurements of two FF masses in coincidence with two detectors placed at 180 degrees was used in both experiments under discussion. The TOF of the fragment has been measured over a flight path of 50 cm between the “start” detector, placed next to the $^{252}$Cf source and the “stop” detectors formed by position-sensitive avalanche counters (PSAC). PSACs provided also the fragment emission angle with a pre-scission of $1^\circ$. The energies of those coincident fragments which passed through the PSACs were measured in the Bragg ionization chambers (BIC).

For searching for the isotropic component of the neutrons emitted in fission the “neutron belt” consisting of 140 $^3$He filled neutron counters was assembled in a plane perpendicular to the symmetry axis of the spectrometer which serves as the mean fission axis at the same time.

In order to estimate fragment nuclear charge the drift time of a track formed after stopping of a fragment in the gas volume of the BIC was measured in the experiment dedicated to the $^{235}$U(n$_{th}$, f) reaction (see [1, 2] for more details).

Coming back to the figure 1 we attract your attention to the rectangular structure marked by the arrows in all the plots. The low vertex of the structure lies in the vicinity of the point (68, 68) amu associated with magic Ni isotopes. The structure is reproduced in main in three independent experiments and at different FFs selection conditions. The yield of the events joined in the rectangular
structure in figure 1a does not exceed $10^{-5}$ per binary fission. The total kinetic energy (TKE) of the events in the structure lies in the range (90–140) MeV. They have almost equal momenta. Comparing a total number of events in plot 1b with similar one for $n \geq 2$ (does not shown here) in the frame of the mathematical model of the neutron registration channel used [2] we came to conclusion that a neutron source which could provide such difference, corresponds to the multiplicity $n = 2$ if neutrons are emitted isotropically or $n = 7$ if they are emitted from the fully accelerated FFs.

3. Discussion

Observation of the Ni isotopes in fission of actinides has a long lived history. In experiment at the gamma-sphere using gamma-gamma coincidence technique [6] two modes were reported for the Ba/Mo partition. The modes essentially differ by the multiplicity of the emitted neutrons. To the second unusual mode neutron multiplicity $n = 7–10$ neutrons and TKE $\sim 154$ MeV were assigned. In order to reproduce these experimental findings it was supposed [7] the following cluster configuration of the $^{252}$Cf nucleus in the scission point (row №1 in table 1).

| №  | Precission cluster configuration | Comments |
|----|---------------------------------|----------|
| 1  | $^{10}$B$_8$–$^{10}$Mo$_8$      | Binary fission via 4–cluster prescission configuration [6, 7]. |
| 2  | $^{78}$Ni–$^{74}$Ni–$^{54}$Ca–$^{54}$Ti | Binary fission via 4–cluster prescission configuration [11 and this work]. |
| 3  | $^{26}$Ne–$^{82}$Ge             | Prescission configuration of $^{252}$Cf. |
| 4  | $^{14}$Ba–$^{10}$Mo             | The missed fragments are marked by the red oblique cross. The sequence of ruptures is marked by the numbers in the rectangles. True ternary fission (CCT) takes place. |
| 5  | $^{14}$Ba–$^{10}$Mo             | Quaternary decay via 4–cluster prescission configuration (this work) appears to occur. |
| 6  | $^{26}$Ne–$^{72}$Ni–$^{72}$Ni–$^{82}$Ge | |

In studies of far asymmetric fission of actinides a shoulder in the FFs mass yields linked with Ni isotopes was revealed [8–10]. Corresponding mass splits show rather low TKE ($\sim 140$ MeV for $^{252}$Cf(sf) [8]. It can be provided if the following prescission configuration is supposed (row №2 in table 1).
The data of our experiment performed in JYFL (Jyväskylä, Finland) give another example of clustering in spontaneous fission of $^{252}$Cf. The experiment was performed using a double armed time-of-flight spectrometer based on timing detectors with micro channel plates and silicon surface barrier detectors (figure 2a) [11]. TOF–E method was applied to measure the FFs masses. Due to the construction of the timing detectors the spectrometer had relatively low transparency for the detected FFs. Specific linear structures were revealed in the FFs $M_a - M_b$ mass correlation distribution for the events selected by the gate $w1$ (figure 2b) defined on the TOF–E distribution of the FFs detected in one arm of the spectrometer. Some of the selected events correspond to the relation $M_s = M_a + M_b = \text{const}$ i.e. to the fixed missing mass. The $M_s$ spectrum obtained is shown in figure 2d.

![Figure 2.](image)

**Figure 2.** Photo of the experimental setup installed at JYFL (a). It includes Cf source (1), four micro-channel based timing detectors (2) and two PIN diodes (3). TOF–E plot for the detected FFs (b). The events from the box $w1$ are under analysis. Mass correlation distribution for the FFs from the box $w1$ (c). The line corresponded to $M_s = 144$ amu (presumably $^{144}$Ba) is marked by the arrow. The bulk of the events from box $w2$ are corresponded to the fixed missing masses including $dM = 252 - (M_a + M_b) = 144$ amu (d).

As can be inferred from the figure 2c in the same experiment we observe both the events corresponding to the missed $^{144}$Ba fragment and the events where one of the fragments is equal to $^{144}$Ba. We suppose the prescission cluster configuration in this case is similar to that proposed in [7] (row № 3 in table 1). Scission scenario for the events with missed $^{144}$Ba fragment is shown in the next row № 4 while the opposite case when this fragment was detected is illustrated in row № 5. Thus we
suppose true ternary fission takes place. One of two fragments flying in the same direction can be missed at the flight pass due to the limited transparency of the timing detectors.

In order to reproduce very low TKE (~90 MeV) for the events around the vertex of the rectangle (72, 72) amu in our data in figure 1, it should be assumed precission configuration and sequence of ruptures shown in table 1, row №6. After two initial ruptures residual $^{144}$Ba nucleus clustered into two $^{72}$Ni clusters should stay almost at rest. In this case after scission of $^{144}$Ba nucleus TKE of Ni clusters will be equal to their interaction energy at the Coulomb barrier to be also ~90 MeV. Such hypothetical scission scenario is supported by the events from box w3 in figure 2b. The difference between mass of the mother system and total masses of two complimentary fragments from the box reproduces well the total masses of the fragments from the rectangle marked by the arrow in figure 1b. In other words, the box w3 joins the utmost clusters from the configuration №6 in table 1. Basing on the parameters of these events we have estimated kinetic energy of the central fragment just after utmost clusters fly apart. It does not exceed some MeV to be in line with the hypothesis put forward.

Summing up, in the frame of scenario of sequential ternary scission of four-cluster prescission configuration of mother nucleus (the last row of table 1) we reproduce quite satisfactory and self consistently experimental data including prediction that two neutrons are emitted isotropically i.e. from the neutron source to be at rest.

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