IMPROVEMENT OF THE EXPERIMENTAL CAPABILITY IN STUDIES OF THE CLUSTER EFFECTS IN HEAVY NUCLEI

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INTRODUCTION

In accordance with our previous experiments [1–3], at least some of the fragments of binary fission of low excited actinides are born in the shape isomers states. A strongly deformed fragment is a weakly bound binary system (shape isomer) which in a solid foil, in the case of inelastic scattering, breaks up with a certain probability, even in tangential collisions with a large impact parameter. One of the breakup products is a magic core, for example $^{68,\,72}$Ni. To label the totality of the observed manifestations of such a process, especially high collinearity of the partners, we have proposed the term "collinear cluster tripartition" (CCT).

In less excited fragments, the population of the state of the shape isomer is also possible, but the system turns out to be more strongly coupled than in the previous case, and its breakup in the solid foil is observed at lower impact parameters. And in this case, at least one of the decay products turns out to be a magic nucleus, for example, $^{128,\,132}$Sn, ^{144}Ba, etc. Both decay products fly in the same direction, with a very small angle between them, in the range of 0.3^0–2^0 (experimental estimate). Moreover, one of them has energy of several MeV, which makes it extremely difficult to separately detect them with the measurement of the mass of each of the products.

Thus, the population of previously unknown states of shape isomers in fragments of binary fission of actinide nuclei occurs, in fact, in the process of binary fission, and the interaction of the fragment with a solid-state foil serves as a specific detector of the presence of such a state.

Most of the data concerning the manifestations of clustering in fissile actinides and fragments of their fission were obtained by us within the framework of the "missing mass" method. To construct an adequate model of the observed effects, *a kinematically complete experiment* with the measurement of masses, energies, and velocity vectors of all nuclei involved in the process is required. Such experiment was not performed so far, and improvement of our experimental capabilities in studies of the cluster effects currently continues.

EXPERIMENTAL FACILITIES USED IN OUR STUDIES OF THE MULTIBODY DECAYS

We investigate rather rare multibody decay modes of low excited heavy nuclei with yields in the range of 10^{-3} and lower per binary fission. These peculiarities define the general requirements for spectrometers to be used, namely of high efficiency and mosaic structure of the detector. Among known methods of ion mass-spectrometry only time of flight-energy (TOF–E) method is suitable for study of the multibody decays. The 4–π FOBOS spectrometer [4] installed in FLNR (JINR) met all of the listed requirements, and first CCT dedicated experiments [1] were performed using this facility. FOBOS spectrometer was based on the gas-filled detectors that demand complicated gas-supply system. The spectrometer consisted of 32 big modules provided relatively low granularity of the detection system (figures 1(a), (b)). In order to overcome these shortcomings, we switched to the semiconductor detectors. The whole series of experiments were performed then using different modifications of the COMETA spectrometer (COrrelation Mosaic E-T Array) [2] setup (figures 1(c), (d)).

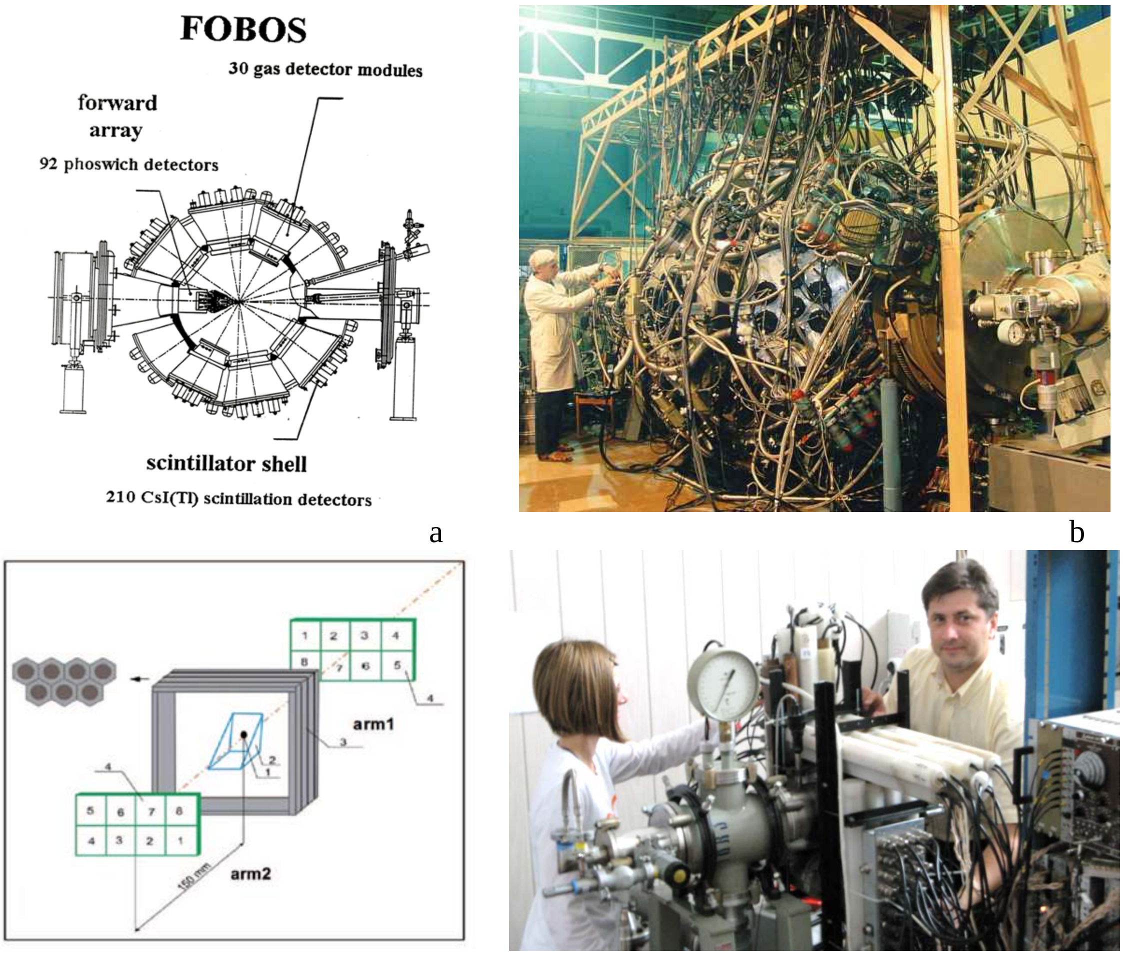
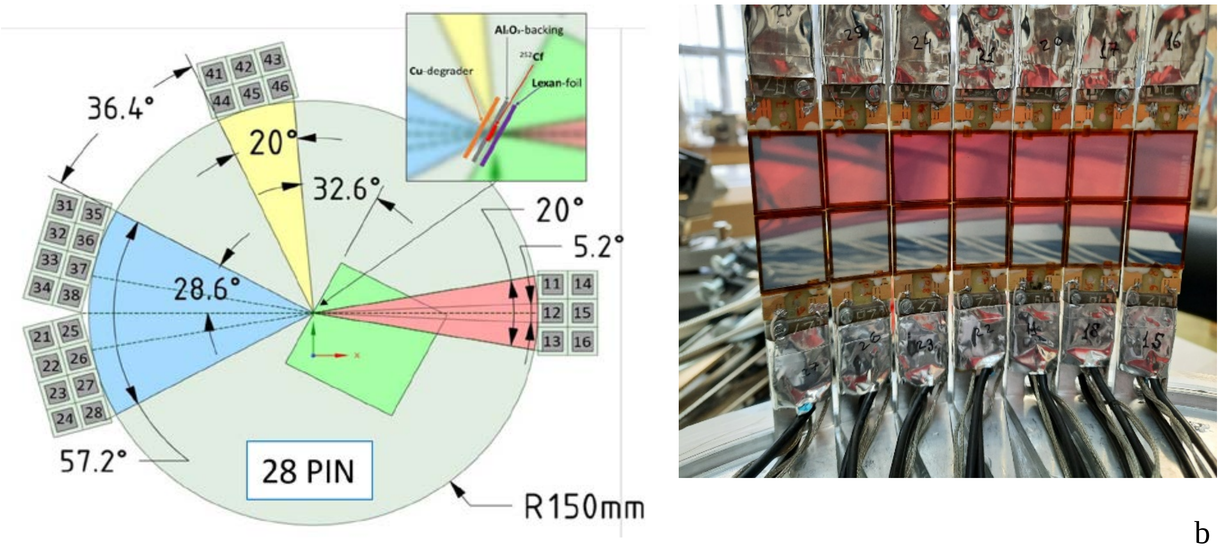


FIGURE 1. Design of the 4-π FOBOS spectrometer (a) and its overall view (b). Design of the COMETA setup (b). In the presented version it consists of two mosaics of eight PIN diodes each (4), microchannel-plates-based start-detector (2) with the ^{252}Cf source inside (1) and neutron belt consisting of 32 ^{3}He filled neutron counters (3). The overall view of the setup is shown in figure 1(d).

NEW IMPROVED VERSION OF THE COMETA SETUP

Accumulated experience of using the COMETA setup and new experimental tasks followed from the analysis of already obtained data initiated the development of the improved version of this facility.



a b

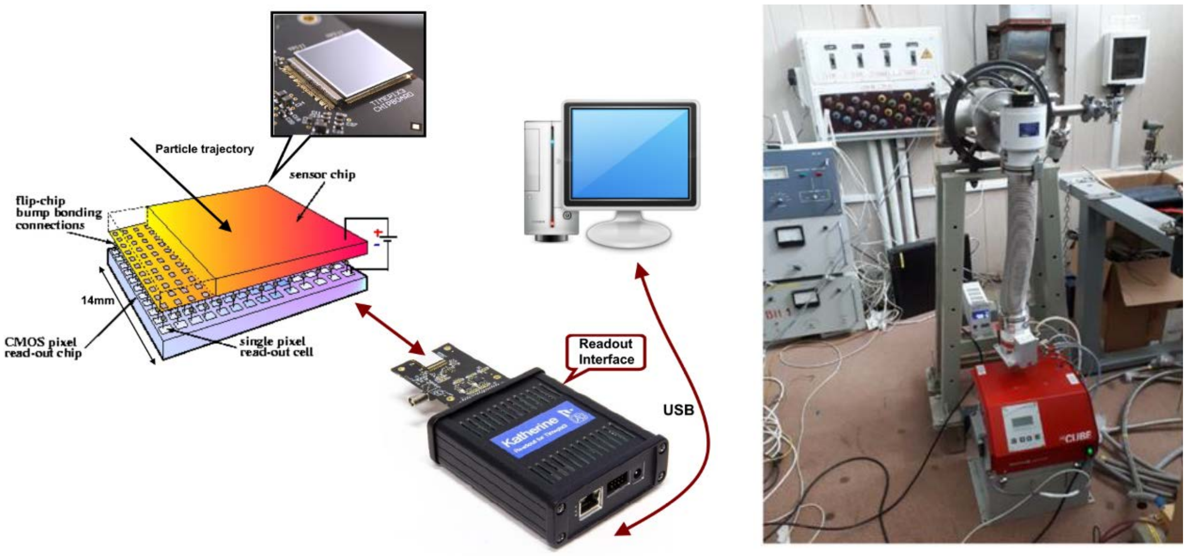
FIGURE 2. Location of the detectors in the COMETA-m setup. 28 PIN-diodes united in three mosaics are planned to use for measuring of the angular distribution of the CCT partners. Microchannel-plates-based start detector is located in the center of the design (a). Photo of the forward mosaic (b).

The following features are realized in the COMETA-m setup:

1. Measurement of the angular correlations of the ternary decay partners in a wide range of angles.
2. Strips between the adjacent PIN dioses do not exceed 2 mm which is twice as small when compared to an actual version of the spectrometer.
3. New frame bounds an active surface of PIN diode in order to suppress fission fragments (FF) scattering.
4. Rigid geometry of the detector arrangement provides better reproducibility of the results.

USING OF THE TIMEPIX3 PIXEL DETECTORS IN STUDIES OF THE MULTIBODY DECAYS

While it is necessary to create an adequate model of the observed effects, the angular distribution of the CCT partners moving in a small open angle up to 0.3^0 has not been measured so far. For this purpose, joint work with a group from the Institute of Experimental and Applied Physics, Czech Technical University in Prague, Czech Republic has begun on the use of Timepix3 two-coordinate pixel detector [5] (figure 3(a)), with a spatial resolution of 55μ, in studies of the multibody decays. Heavy ion mass spectrometry using this detector is an original and non-trivial methodological problem. Initially the device was designed for detection of the soft photons, while in the present task we require to register heavy ions with the energies up to tens of MeV.

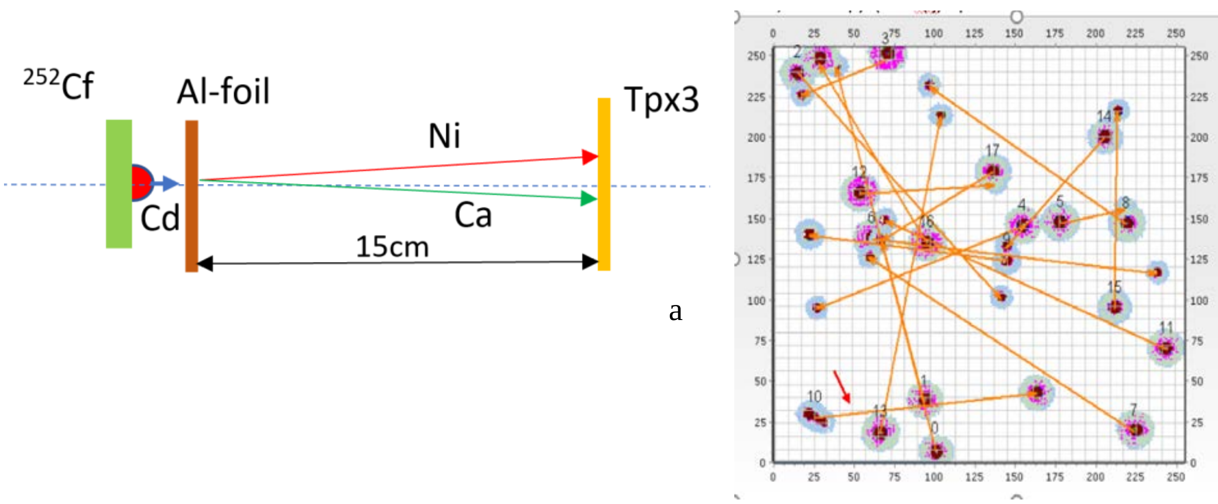


b

a

FIGURE 3. Schematical view of the Timepix3 detector with Katerine readout (a), photo of the TDS-1 (**T**ernary **D**ecays **S**pectrometer) experimental setup (b).

As the first step in the study of rare ternary decays using Timepix detectors, the following first-day experiment was performed. Detection of the “fork” of two CCT partners (for instance, the Ni/Ca pair, figure 4(a)) which hit the Timepix3 detector in a short time interval and substantially differ in their energies, gives evidence of the CCT event. Kinematical scheme of one of the CCT mode is shown in figure 4(a). Similar ternary decays were searched for in the experiment. An example of the data processing is presented in figure 4(b).



a

b

FIGURE 4. Schematical presentation of the tri-partition of the mother nucleus ^{252}Cf → Sn+Cd → Ni+Ca chosen as an example of the CCT and kinematics of the decay partners in the TDS-1 setup (a). Typical result of the data processing (b). The cluster 10 marked by the red arrow is presumably due to the CCT event, while the orange arrow connects this cluster with another one produced most likely by the Al ion knocked out from the foil by Cd-like fragment.

DEVELOPMENT OF THE TIME PICK-OFF ALGORITHMS

To correctly measure heavy ion's TOF with PIN diodes, it is necessary to account for the so-called plasma delay effect (PDE) which is due to generation of plasma in a heavy ion track in the PIN diode. Because of the PDE, the initial relatively long part of the signal lies inside the "noise track", and the time stamp turns out to be shifted in relation to the true signal's start. It is possible to account for plasma delay by using its parameterization proposed in Ref. [6], excluding the region of small masses and energies.

Thanks to using fast digitizer and having digital images of the signals, we have developed an alternative approach aimed at finding an actual beginning of the signal. It is done by approximating its initial part that lies partially inside the noise track with parabolic curve which vertex lies on the average of the noise and serves as the "true" signal's start. The first realization of this idea was Parab-algorithm [7] which used only parabolic function for interpolation of the signal's noisy region. To increase a robustness of the algorithm against a choice of region for parabola interpolation, Parab-algorithm was followed by Parablin-algorithm [8] which seamlessly sewed parabola with a linear function that approximated points of the rising edge of the signal lying above the noisy region. Its main drawback was the need to manually choose points for linear function approximation. To further increase robustness of the method, we propose Paraspline-algorithm which describes the initial part of the signal by parabola seamlessly sewed with a spline that automatically approximates points above the noisy region, without user interference.

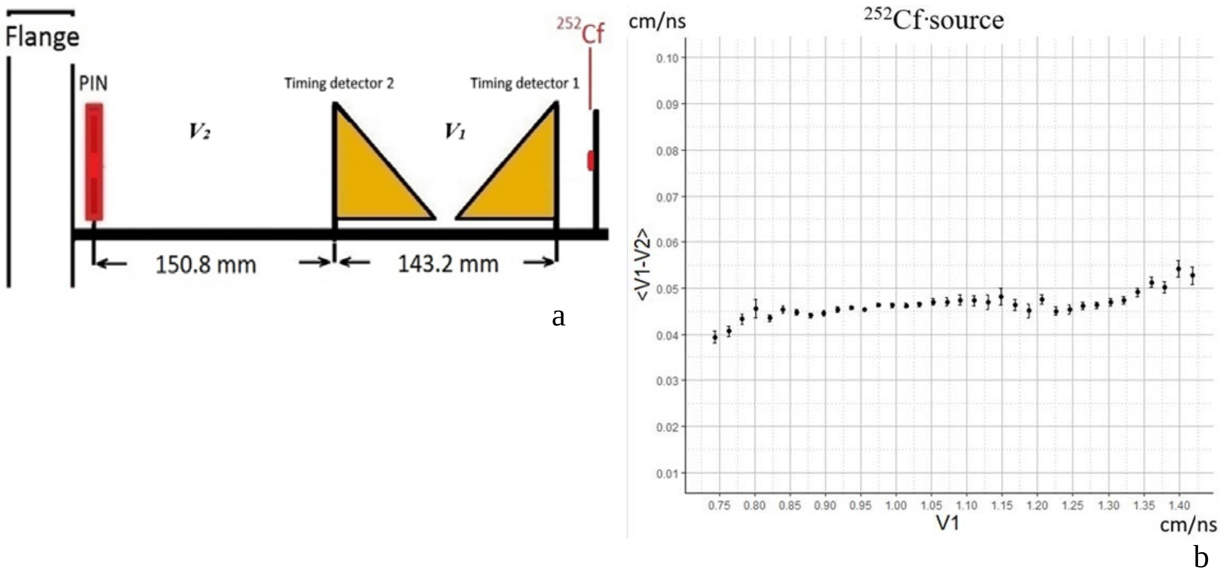


FIGURE 5. Layout of LIS spectrometer (a). Mean difference $<V_1-V_2>$ as a function of V_1 for the fission fragments from the ^{252}Cf source (b).

In order to verify Paraspline-algorithm in experiment, LIS setup was used (figure 5(a)). The FF velocity is measured sequentially on two flight-passes by means of using the timing detectors based on the microchannel plates (V_1 value) and PIN diode as a "stop" detector when V_2 value is obtained (figure 5(a)). Event by event comparison of "true" velocity V_1 and V_2 is presented in figure 5(b). Good agreement between the compared values is observed.

MATHEMATICAL TESTING OF THE STATISTICAL RELIABILITY OF LINEAR STRUCTURES IN THE FF MASS-MASS DISTRIBUTIONS

A theoretical description of nuclear reactions, such as fission and quasi-fission, presents the evolution of a nuclear system in the form of trajectories in a multidimensional deformation space. Finding images of such trajectories in the space of experimentally observable variables was proposed in Refs. [9–12] as a new approach to data analysis. The trajectories look like "fine structures" in two-dimensional distributions, for example, in mass correlation distributions. By definition, *fine structure* means local regions (peaks) in a two-dimensional distribution with the yield higher than on a smooth substrate, which is the background to the sought-after effect. For finding fine structures with the given level of reliability, methods of image morphological analysis were applied in Ref. [13].

New specific fine structure which looks like a rhombic meander (figure 6(a)) has been revealed in the mass correlation distribution of the FFs from ^{252}Cf(sf) obtained at the COMETA setup. To test the hypothesis that the structure actually exists and is not a noise artifact, it was proposed to use a deep convolution network as a binary classifier trained on a large model sample and noise images [14]. The results of the testing the neuro classifier prove high statistical reliability of fine structure revealed.

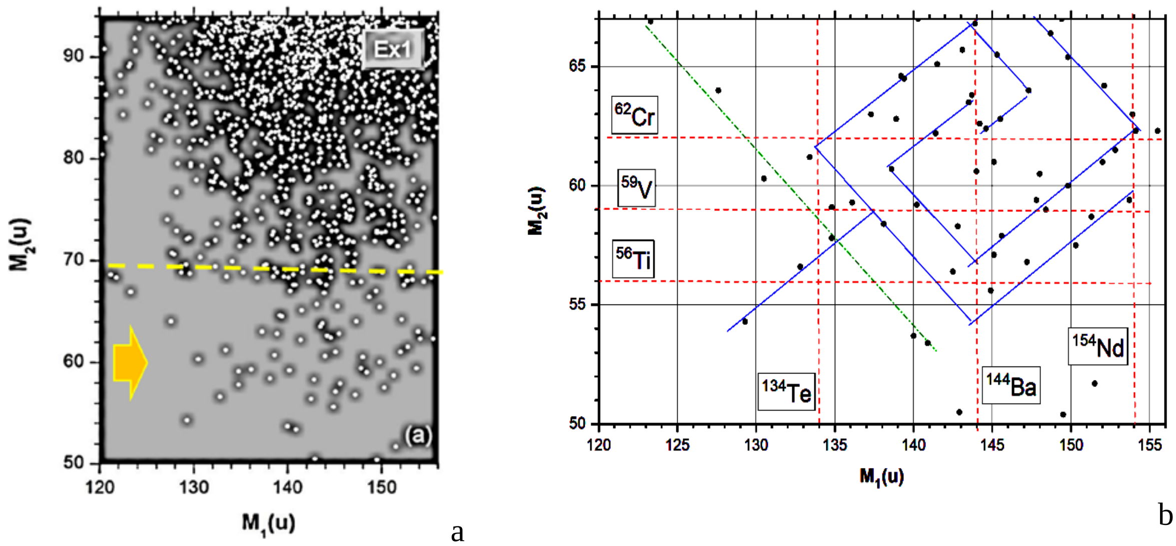


FIGURE 6. Correlation mass distribution of the FFs from ^{252}Cf(sf) obtained at the COMETA setup. Specific rhombic meander structure is marked by the arrow (a). The same structure in the larger scale (b). The meander vertexes coincide with known magic isotopes listed in boxes.

CONCLUSION

In the previous year, we have paid our attention to upgrade of the spectrometers used, mastering Tpx3 pixel detectors, and development of the data processing procedures. Our efforts aim to perform kinematically complete experiments dedicated to previously unknown ternary decays of low excited heavy nuclei.

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