STUDY OF SHAPE ISOMERIC STATES IN FISSION FRAGMENTS

Yu.V. Pyatkov[1,2], D.V. Kamanin[2], A.A. Alexandrov[2], I.A. Alexandrova[2], N.A. Kondratyev[2], E.A. Kuznetsova[2], V. Malaza[3], N. Mkaza[3], A.O. Strekalovsky[2], O.V. Strekalovsky[2], V.E. Zhuchko[2]

[1]**National Nuclear Research University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia**
[2]**Joint Institute for Nuclear Research, Dubna, Russia**
[3]**University of Stellenbosch, Faculty of Military Science, Military Academy, Saldanha 7395, South Africa**

INTRODUCTION

In one of our experiments aimed at studying of the new multi-body decay called collinear cluster tri-partition (CCT) [1–3] additional absorber (Ti foil) was introduced just after the source at the distance of approximately 1 mm. It was motivated by the peculiarity of the CCT manifestation in the experiments namely specific structures in the region of an essential missing mass in the fission fragments (FFs) mass correlation distribution were observed in the spectrometer arm faced to the Cf source backing only. The effect was traced back to some angular divergence between two CCT partners flying in the same direction after passing the scattering medium on the flight pass due to the multiple scattering. As a result one of them can be lost in the PIN diode frame what is observed as" missing mass" or both fragments will be detected independently in the neighboring diodes.

We have observed significant mass deficit in the total mass of the fission fragments detected in coincidence with Ti ions knocked out from the foil (fig. 1) [4]. For the sake of convenience, the FFs from such events are labeled as M_1, M_2 and M_3 in an order of decreasing masses in the ternary event. The total mass of the two heavier fragments $M_s = M_1 + M_2$ is plotted vs. the mass of the lighter fragment M_3. Such effect could be expected if the scattered fragment looks like a di-nuclear system destroying due to inelastic scattering on the Ti nucleus. A mean flight time between the Cf source and the foil does not exceed 0.1 ns. It can be regarded as a low limit for the life time of the di-nuclear system (shape isomer).

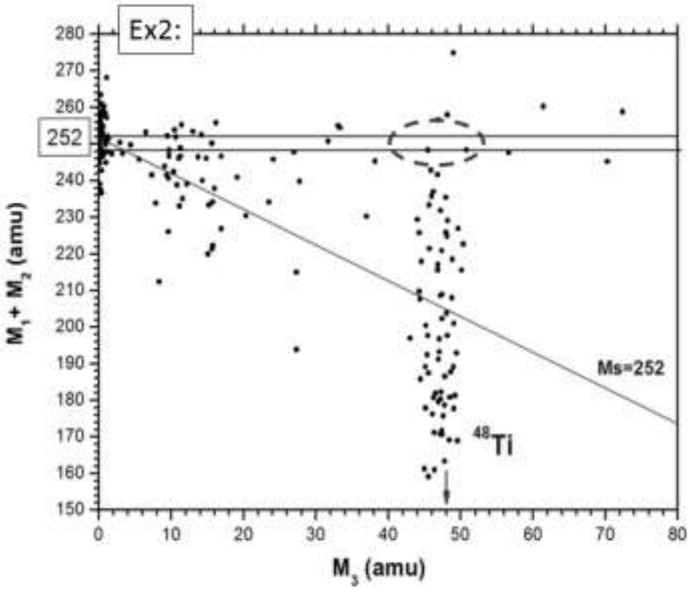


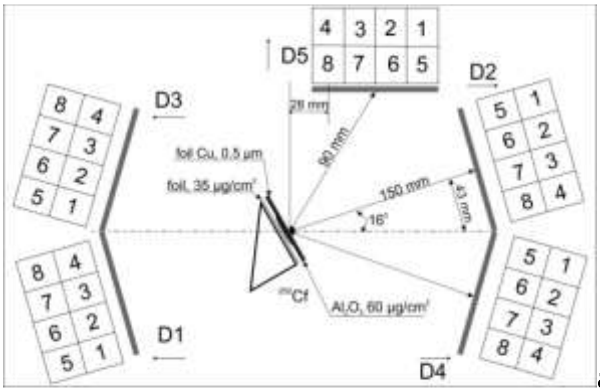
FIGURE 1. FF mass distribution from ^{252}Cf (sf) for ternary events detected in the opposite mosaics of PIN diodes. Ti foil 2.2 μm thick was used as the additional absorber.

Further experiments discussed here were dedicated to the angular dependence of the effect and estimation of the low limit of the shape isomeric states life-time.

EXPERIMENTS AND RESULTS

Additional mosaic of PIN diodes was added to the COMETA (fig. 2) setup to estimate the probability of inelastic scattering of the FFs in the tangent collisions.

The additional mosaic D5 was located at approximately 700 to the symmetry axis of the setup. We can compare the spectra of total mass Ms of two FFs (fig. 3) under condition that the knocked-out Cu ion was detected in the frontal mosaics 2, 4 or in the side mosaic 5.



a


b

FIGURE 2. Layout of the COMETA setup with additional mosaic D5 of PIN diodes (a) and photo of the detectors used (b).

As can be inferred from the figure at the large angles of scattering of the knocked–out ions from the foil predominantly conventional elastic Rutherford scattering takes place. As the result M_s corresponds to the mean mass of the mother system after emission of fission neutrons (no missing mass). In contrast, in the near frontal impacts fission fragment misses essential part of its mass. In both spectra specific peak corresponding to the missing mass of ten amu is observed presumably linked with ^{10}Be nucleus. There is no such peak in the M_s spectrum of the FFs from the conventional binary fission. According to the predictions of ref. [5] some qusi-molecular states leading to the ^{10}Be accompanied ternary fission have the life-times in the picosecond range due to low barrier against the decay. Such loosely coupled states could experience a breakdown even in the tangent collisions (fig. 3).

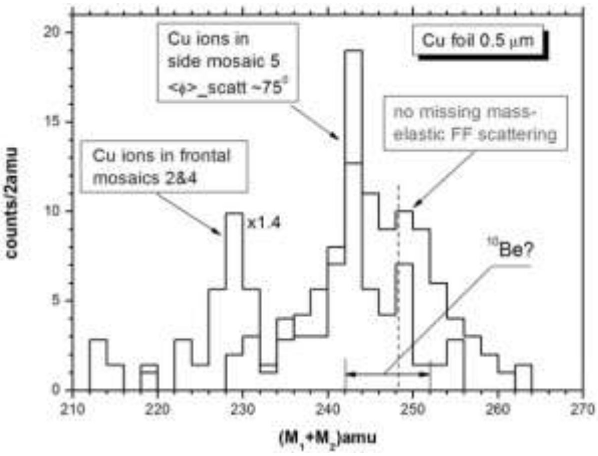


FIGURE 3. Comparison of the spectra of total mass of two FFs at different angles of the knocked-out Cu ions. Numbers of the mosaics hit by the knocked-out ion are marked in the panels with the arrows. See text for details).

Fig. 4 shows M_s spectra obtained at two different distances between the Cf source and the cupper foil. Thanks to elongation of the distance typical FF time-of-flight between the Cf source and the cupper foil increased from 0.1 ns up to 1 ns. Nevertheless, both M_s spectra show only few events in the mass region expected for elastic FF scattering (M_s ~ 248 amu). It can be treated as an indication that the life-time of the shape isomeric states in the FFs exceeds at least some nanoseconds.

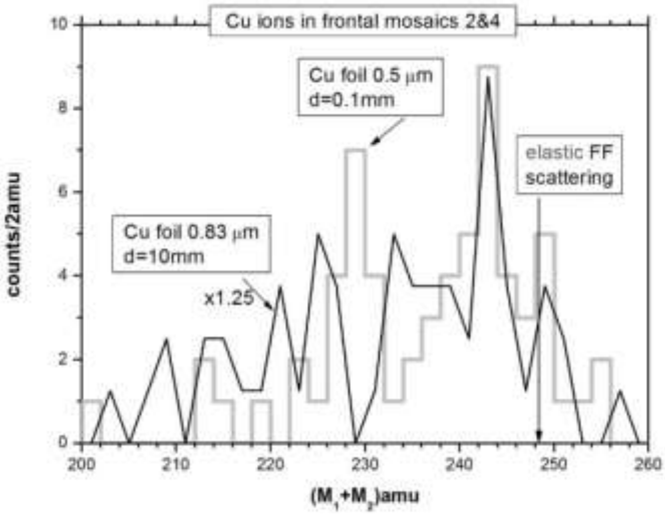


FIGURE 4. Comparison of the $M_s = M_1 + M_2$ FF spectra at two different distances (d) between the Cf sourse and Cu foil. Only a few events are seen in the region corresponding to the elastic scattering of the FF in both spectra. It means that a tipical life-time of the shape-isomeric states in the FFs exceedes 1 ns.

Next very interesting result obtained is presented in fig. 5. It is the mass spectrum of the fragments scattered in the foil and detected in coincidence with the knocked out ions. As can be inferred from the figure this spectrum radically differs from the FF mass distribution in conventional binary fission. The masses of known magic nuclei are marked in the figure by the arrows. We shell discuss this figure below.

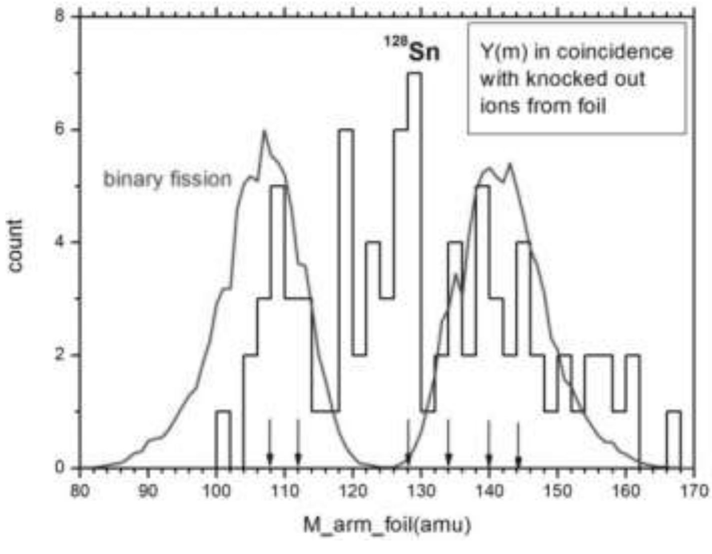


FIGURE 5. Mass spectrum of the fragments detected in coincidence with the ions knocked out from the foil and in the same arm with them. See text for details.

DISCUSSION

Experimental spectrum presented in fig. 5 can be understood basing on known manifestations of clustering in binary fission. This topic has been already considered in our paper [5] including the review of the original publications. The basic idea concerning the decisive role of pair of magic clusters as the cores for the formation of respectively light and heavy fragments was confirmed and detailed in both experimental and theoretical works [6–8]. In accord with these views we suppose the bulk of the fragments directly after scission of the mother system look like a di-nuclear system consisting of the magic core and light cluster to be some part of the neck. Actually this system can be treated as a shape isomer state of the whole fragment. Something similar was discussed in [9], where local minima in the fission barrier of the $^{296}_{116}$Lv were interpreted in the following way:" These intermediate minima correspond to the shape isomer states. From analysis of the driving potential we may definitely conclude that these isomeric states are nothing else but the two-cluster configurations with magic or semi-magic cores surrounded with a certain amount of shared nucleons." In our case only one of two clusters is a magic one. Just these magic clusters likely form the mass spectrum shown in fig. 5.

In accordance with our experiments typical life-time of the shape isomers observed exceeded 1 ns. Exciting indication on true life-time of these states can be inferred from ref. [10]. A search for isomeric ɤ decays among fission fragments from 345 MeV/nucleon ^{238}U has been performed at the RIKEN Nishina Center RI Beam Factory. In flight fission of a uranium beam has been used as production reactions to populate isomers. Fission fragments were selected and identified using the superconducting in-flight separator BigRIPS and were implanted in an aluminum stopper. The fast isotopic separation and identification of reaction products, which take place in several hundred nanoseconds, allow event-by-event detection of isomeric γ rays at the focal plane of the separator with small decay losses in flight. A total of 54 microsecond isomers with half-lives of ~0.1–10 μs were identified. At least some of the isomers observed are supposed to be shape isomers. It is reasonable to suppose these microsecond isomers half-lives to be an upper limit for half-lives of the FF shape isomeric states observed in our experiments.

Strong theoretical support for existence of shape isomer states in fission fragments provides as well recent calculations of P. Möller and coworkers [11]. Potential energy surfaces as functions of spheroidal, hexadecapole, and axial asymmetry shape coordinates for several thousands of nuclei from A = 31 to A = 290 were calculated. The deformations and energies of all minima deeper than 0.2 MeV were tabulated. It gives a possibility to identify nuclei for which a necessary condition for shape isomers occurs, namely multiple minima in the potential-energy surface. It is known that the lifetime of the shape isomer depends on the overlap between the nuclear wave functions of the shape isomer and the ground state, the excitation energy of the shape isomer, and the height of the saddle separating the shape isomer and the ground state [11]. Unfortunately estimation of the shape isomer lifetimes is beyond the scope of the cited work while it would be extremely interesting for the isomers predicted in the mass region of the fission fragments (fig. 6).

Whether all the structures assigned to the CCT actually are resulted from the brake-up process discussed here? Negative answer follows from the following mass correlation distributions obtained at the FOBOS spectrometer [2] (fig. 7).

The rectangular structure bounded by the magic fragments is symmetric relative to the line $M_1 = M_2$ (fig. 7a). In other words we observe the same effect in both spectrometer arms while the source backing which plays a role of the "brake-up medium" takes place in one of them only. Some additional structures being also symmetric relative to the spectrometer arms are seen in fig. 7b (marked by the arrows). Thus, at least in the reported case we observe some clearly nonrandom events linked with big missing mass (116 amu when two ^{68}Ni nuclei were detected) and resulted indeed from a multi-body decay of the Cf nucleus.

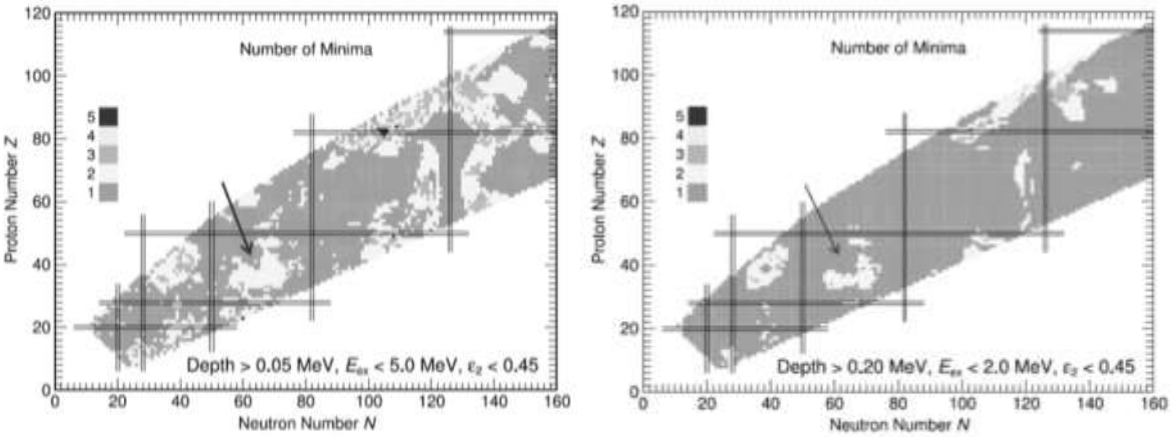
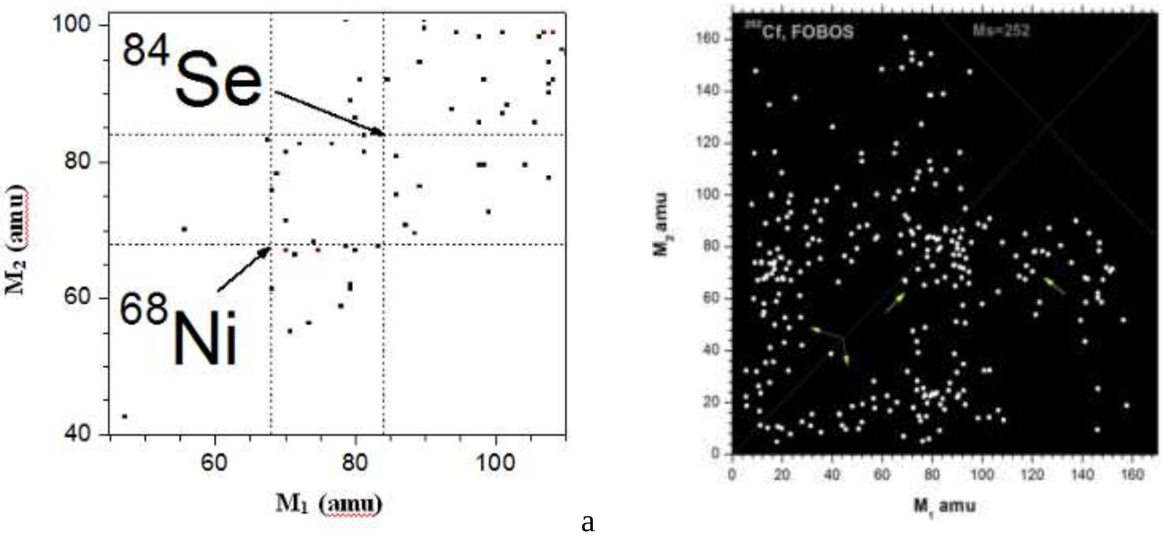


FIGURE 6. Number of minima found with deformation $\epsilon 2 < 0.45$. Only the ground-state and isomer minima that are deeper than 0.2 MeV and with energies relative to the ground state less than 2.0 MeV were counted [12]. Region of typical fission fragments is marked by the arrow.



a b

FIGURE 7. Mass correlation distributions of the FFs from ^{252}Cf (sf) under condition that only fission events with almost equal momenta and velocities were selected (a); b – the same initial data gated by the experimental neutron multiplicity (n = 1) and momentum box beyond the “tails” of the scattered fragments.

CONCLUSIONS

1. New mechanism of ternary decay based presumably on the break-up of the fragment in the shape-isomeric state due to inelastic scattering in the metal foil is observed.
2. Mean life-time of the isomers is estimated to be more than 1 ns.
3. The brake-up takes place predominantly in the frontal impacts.
4. Break-up is only one of the different ways leading to the collinear cluster tri-partition (CCT).

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