# SEARCHING FOR SHAPE ISOMERIC STATES LEADING TO TERNARY DECAY OF HEAVY NUCLEUS

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

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

## SEARCHING FOR LONG-LIVED ISOMER STATES OF $^{236}$U*

Our program of studying of ternary decays of heavy nuclei dedicated basically to the collinear cluster tri-partition process [1] discovered by us earlier was extended to searching for delayed ternary fission to be, by definition, the ternary decay of a specific shape isomer state.

Discovery of fission isomers took place in the Flerov Laboratory of Nuclear Reactions of the JINR in 1961. First fission isomer discovered was isotope of $^{242}$Am with the half-life $\tau$ = 0.014 sec. So far more than 30 fission isomers of heavy nuclei, namely, isotopes of U, Np, Pu, Am, Cm, Bk are known including short lived ones in the ns range. Fission isomers were observed via delayed fission in the actinide targets hit by ion or neutron pulse beams. Fission is only one possibility for de-excitation of the shape isomeric state located in the second potential well of the double humped fission barrier (fig. 1). Alternative way consists in the transfer to the ground state emitting gammas. Thus, conventional fission isomers are due to the specific double humped structure of the fission barrier with rather deep second well for some of the actinide nuclei. The barrier can be called “the binary one” keeping in mind that binary fission appears to occur during the descent of the system from this barrier. Evidently, a dumbbell-like shape of the system is expected in the vicinity of the scission point.

Ternary prescission configurations have been also considered in the literature and corresponding ternary fission barriers as well. For instance in [2] the binary and ternary fission has been investigated within liquid-drop model at finite temperature and including the nuclear proximity energy. Ternary potential barriers for $^{240}$Pu fissioning system are shown in fig. 2. The author’s stress that with increasing asymmetry double-humped barriers occur and, then, the possible existence of elongated but compact isomeric states. This brief indication could be a hint for new field of experiments namely ***searching for fission isomers unknown in the past based on the ternary prescission configurations.***

Much more detailed predictions concerning isomeric states along the fission ways leading to ternary fission were presented in [4]. A three-centre phenomenological model, able to explain qualitatively the quasi-molecular stage of a light-particle accompanied fission process, was developed. A new minimum of a short-lived molecular state appears in the deformation energy at a separation distance very close to the touching point. **The half-lives of some quasi-molecular states which could be formed in the $^{10}$Be and $^{12}$C accompanied fission of $^{252}$Cf are roughly estimated to be the order of 1 ns, and 1 ms, respectively.** Figs. 3 and 4 show evolution of nuclear shapes and liquid drop model deformation energy of the decaying system, respectively.

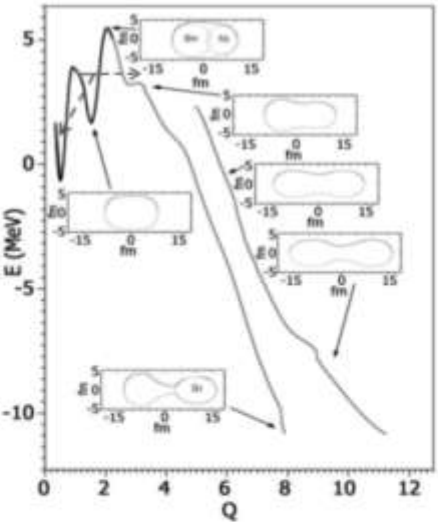



**FIGURE 1.** The bottoms of the fission valleys as a function of parameter Q (proportional to the quadrupole moment) for $^{234}$U nucleus. The arrows show possible ways of de-excitation of the shape isomeric state in the second well. (V. Pashkevich et al. [3] )

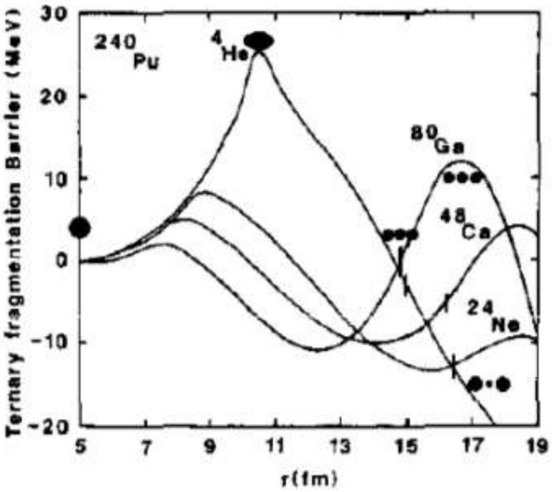



**FIGURE 2.** Ternary potential barriers as a function of the distance between the mass centers for the $^{240}$Pu nucleus (at T = 0). The central fragment is indicated on the curves and separation point by a vertical bar.

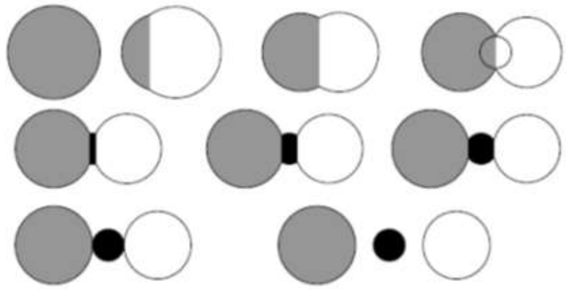


**FIGURE 3.** Evolution of nuclear shapes during the deformation process from one parent nucleus $^{252}$Cf to three separated fragments $^{146}$Ba, $^{10}$Be, and $^{96}$Sr [4].

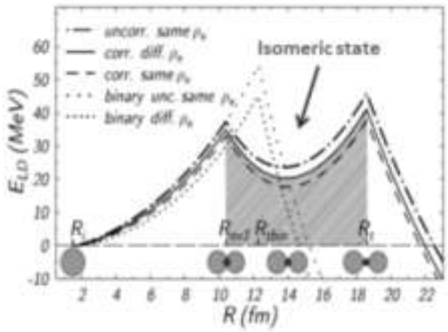



**FIGURE 4.** The liquid drop model deformation energy versus separation distance for the $^{10}$Be accompanied cold fission of $^{252}$Cf with $^{132}$Sn and $^{100}$Zr heavy fragments. The new minimum appears in the shaded area from $R_{ov3}$ to $R_t$ [4].

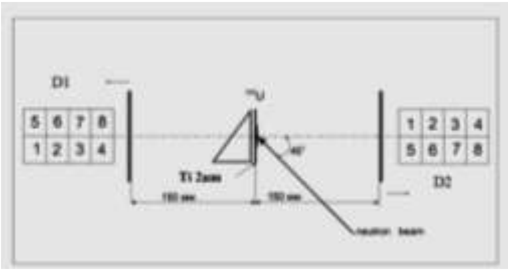
As can be inferred from Table 1 the half-lives for $^{12}$C accompanied ternary decay of $^{252}$Cf nucleus are estimated to be 1 ms and even 10 ms. Searching for such long-lived fission isomers was the goal of our recent experiment discussed below. In black: $^{12}$C accompanied ternary decay with half-lives ~1 ms & 10 ms.

Dedicated experiment was performed at the IBR-2 reactor in the Frank Laboratory of the JINR. COMETA-R spectrometer was used (fig. 5). It consists of two mosaics of eight PIN diodes each and the micro-channel based coordinate-sensitive “start” detector. Time-of-flight-energy (TOF-E) method is used for calculation of the fragments masses.

The shape of the neutron bunch looks like a peak with a long tail (fig. 6a). In order to detect the delayed fission events which are expected according to the theoretical predictions the tail was cut off with a help of the chopper. The shape of the bunch after chopper is shown in fig. 6b.

Table 1.Calculated half-lives of some quasi-molecular states $^{252}Cf$

| Particle | Fragments | | $Q_{exp}$ (MeV) | $K$ | log$T$(s) |
|---|---|---|---|---|---|
| $^{10}Be$ | $^{132}Sn$ | $^{110}Ru$ | 220.183 | 19.96 | -11.87 |
| | $^{134}Te$ | $^{104}Mo$ | 209.682 | 25.23 | -9.59 |
| | $^{138}Xe$ | $^{104}Zr$ | 209.882 | 26.04 | -9.23 |
| | $^{146}Ba$ | $^{96}Sr$ | 201.486 | 22.98 | -10.56 |
| $^{12}C$ | $^{147}La$ | $^{93}Br$ | 196.268 | 39.80 | -3.26 |
| | $^{142}Ba$ | $^{95}Kr$ | 199.896 | 42.71 | -1.99 |
| | $^{140}Te$ | $^{100}Zr$ | 209.728 | 38.21 | -3.95 |
| | $^{132}Sn$ | $^{108}Mo$ | 223.839 | 31.46 | -6.88 |



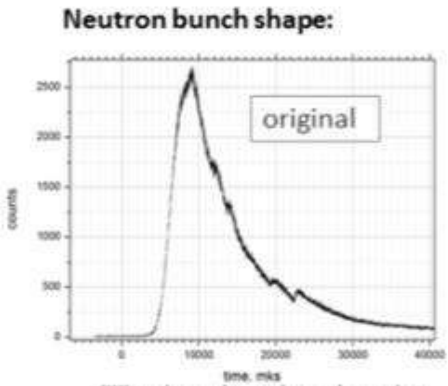
a


b

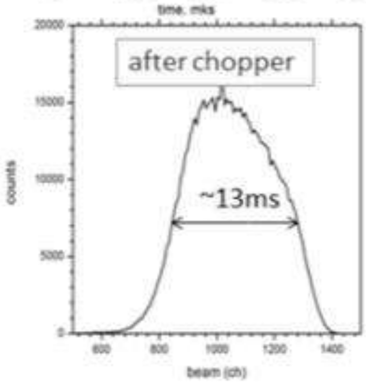

c

**FIGURE 5.** Layout of the COMETA-R spectrometer (a), its photo on the 11b channel of the IBR-2 reactor (b) and photo of the detectors used (c).

a




b





c

**FIGURE 6.** The shape of the initial neutron bunch (a), neutron bunch after chopper (b), and photo of the chopper at the exit of the neutron guide (c).

A preliminary result obtained is presented in fig. 7. The events in the vicinity of the total of the both detected fragments 233 amu (the mass of the compound system after subtraction of the mean number of emitted neutrons) are likely due to the background. At the same time there are some events corresponded to the missing mass ~12 amu which could be assigned to the $^{12}C$ accompanied <u>delayed</u> ternary fission.

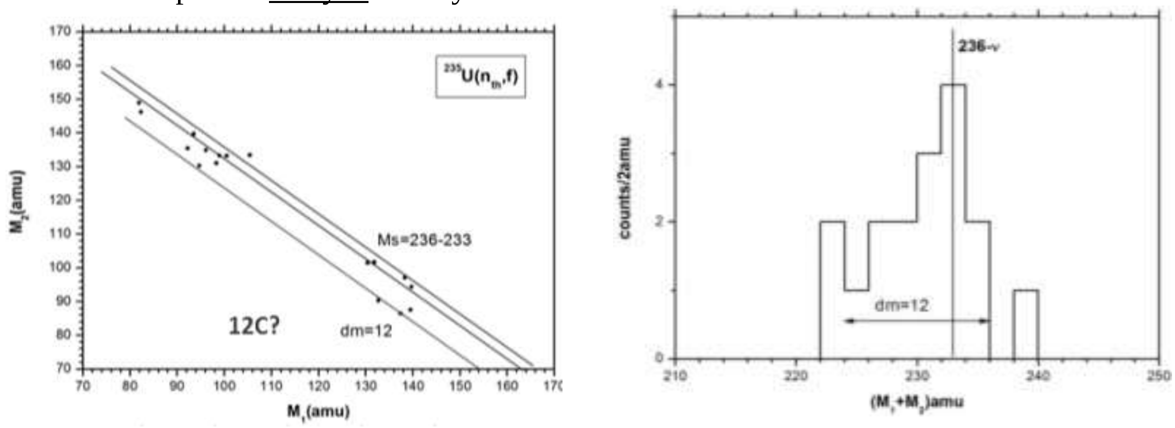



**FIGURE 7**. Mass correlation plot for the fission events took place between the neutrons bunches (a) and spectrum of the total masses of fragments pairs (b).

## NEW FAMILY OF SHORT-LIVED SHAPE ISOMERS IN $^{236}U$*?

As was mentioned above the first full scale run at the IBR-2M reactor with the COMETA-R setup was performed. We have observed a very interesting peculiarity of the FF mass correlation distribution shown in fig. 8.

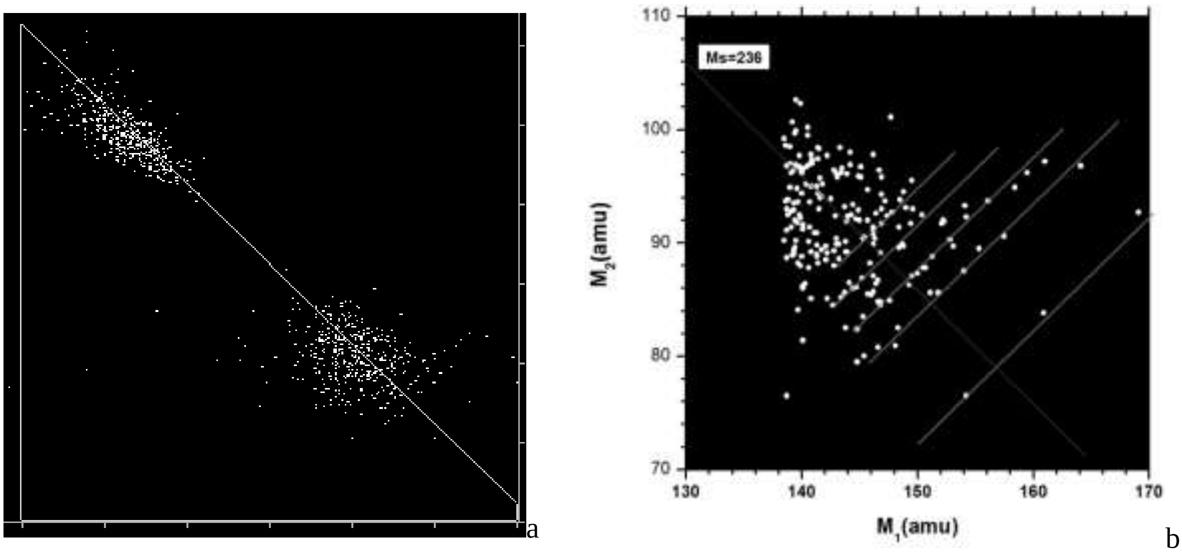
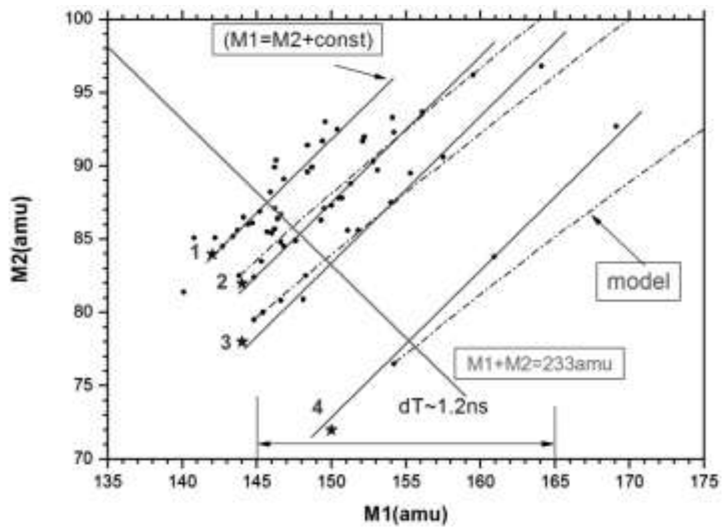


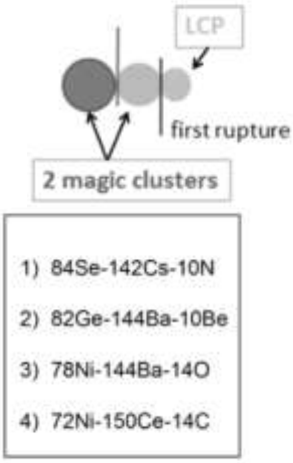

**FIGURE 8.** Mass-mass distribution of the FFs from the reaction $^{235}U(n_{th}, f)$: (a) overall view of the plot, (b) the bottom locus on a larger scale; the fine structures look like tilted lines. See text for details.

An analysis of the revealed fine structures is presented in fig. 9.




a

LCP delayed fission isomers (**L**cp delayed **F**ission **I**somers - **LFI**)




b

**FIGURE 9.** Linear fine structures in the FF mass plot shown in fig. 7 in comparison with the model predictions (a). Ternary prescission configuration decisive for the observed linear structure and the list of clusters involved (b). See text for details.

Two features of the linear structures under discussion should be emphasized. Each line starts from the point in the mass-mass distribution corresponding to a ternary prescission configuration of two magic clusters and a light charged particle (LCP). The masses of the magic clusters involved are known from the experiment (fig. 8a), while the mass of the "missed" LCP can be calculated thanks to the mass conservation law (fig. 8b). The second feature is that each line goes to the region far beyond the mass of the mother system.

The following physics is standing presumably behind the structures at hand. Apparently we deal with the ternary decay of the configuration shown in the upper part of fig. 9b. After first rupture in the prescission chain LCP gives start signal while delayed decay of the di-nuclear system consisting of two magic nuclei appears to occur after random time defined by its life-time. Both magic clusters flying apart will get equal additives to the time-of-flights and consequently overestimated masses. Modeling in the frame of this hypothesis (dash-dot lines in fig. 9a) shows that the delay sufficient for reproducing experimental points lie in the nanosecond region. By analogy with known "beta delayed fission" such phenomenon can be called "LCP delayed fission isomers (**L**cp delayed **F**ission **I**somers – **LFI**)".

Linear structures, similar to those discussed above, we have observed earlier in spontaneous fission of $^{252}$Cf (fig. 10).

# CONCLUSION

1. Along with well-known fission isomers manifesting themselves via delayed binary fission of the mother system fission isomers based on the ternary prescission configurations leading to ternary delayed fission were predicted.
2. So far the latter type of fission isomers has not been discovered experimentally. Thus, this field is of great interest for investigation.
3. We have performed the experiment aimed at searching for delayed $^{12}$C accompanied ternary fission in $^{235}$U($n_{th}$, f) reaction. Very preliminary result obtained does not contrary

to the tested hypothesis. Evidently more statistics and accurate estimation of the background are needed. It is in our nearest plans.

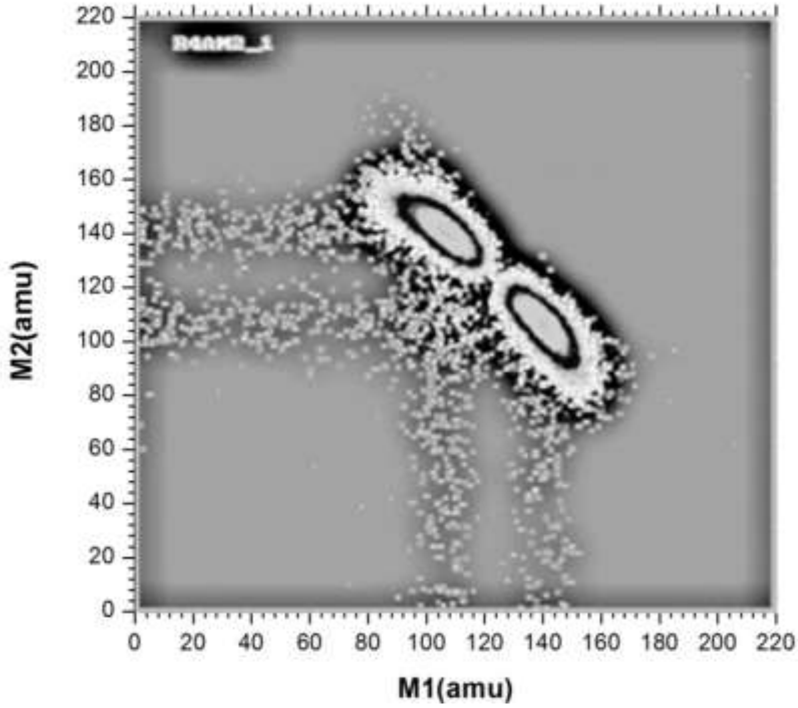



**FIGURE 10.** Linear structures in the mass correlation plot of the FF from $^{252}$Cf (sf). The experiment was performed at the COMETA setup.

## ACKNOWLEDGMENTS

This work was supported in part by the Department of Science and Technology of the Republic of South Africa (RSA), Bundesministerium für Bildung und Forschung (Germany), and Russian Foundation for Basic Research [project no. (RSA_a) 14-02-93960].

## REFERENCES

1. D.V. Kamanin, Yu.V. Pyatkov, "Clusters in Nuclei - Vol.3" ed. by C. Beck, Lecture Notes in Physics 875, pp. 183-246 (2013).
2. G. Royer and J. Mignen, J. Phys. G: Nucl. Part. Phys. 18, 1781 (1992).
3. V.V. Pashkevich, Yu.V. Pyatkov, A. V. Unzhakova, Int. J. Mod. Phys. E18, 907 (2009).
4. D.N. Poenaru, B. Dobrescu et al., J. Phys. G: Nucl. Part. Phys. 26 (2000) L97–L102.