# PERSPECTIVES OF THE STUDY OF COLLINEAR CLUSTER TRI-PARTITION OF HEAVY NUCLEI

D.V. Kamanin[1], Yu.V. Pyatkov[1,2], A.A. Alexandrov[1], I.A. Alexandrova[1], N. Jacobs[3],
N.A. Kondratyev[1], E.A. Kuznetsova[1], G.V. Mishinsky[1], V. Malaza[3], 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, Russia**
**[3]University of Stellenbosch, Faculty of Military Science, Military Academy, Saldanha 7395, South Africa**

## INTRODUCTION

The present paper is devoted to the observation of a new kind of ternary decay of low-excited heavy nuclei. This decay mode has been called by us ”collinear cluster tri-partition” (CCT) in view of the observed features of the effect, that the decay partners fly apart almost collinearly and at least one of them has magic nucleon composition. CCT is observed together with conventional binary and ternary fission. It could be one of the rare fission modes but for the moment it is not matter-of-fact. For instance, many years have passed between the experimental discovery of the heavy ion radioactivity and working out of a recognized theory of the process.

At the early stage of our work the process of ”true ternary fission” (fission of the nucleus into three fragments of comparable masses) was considered to be undiscovered for low excited heavy nuclei. Another possible prototype – three body cluster radioactivity – was also unknown. The most close to the CCT phenomenon, at least cinematically, stands so called ”polar emission” [1], but only very light ions (up to isotopes of Be) were observed so far.

From the theoretical side there are numerous indications on possible ternary decays of the low excited heavy nuclei with comparable masses of the decay products. Swiatecki [2] has shown within the framework of the liquid drop model (LDM) that fission into three heavy fragments is energetically more favorable than binary fission for all nuclei with fission parameters $30.5 < Z^2/A < 43.3$. In 1963 Strutinsky [3] has calculated the equilibrium shapes of the fissioning nucleus and has shown, that along with the ordinary configuration with one neck, there is the possibility of more complicated elongated configurations with two and even three necks, at the same time it was stressed, that such configurations are much less probable. Later Diehl and Greiner [4, 5] have shown a preference for prolate over oblate saddle-point shapes for the fission of a nucleus into three fragments of similar size. Such pre-scission configurations could lead to almost collinear separation of the decay partners, at least in a sequential fission process. Results demonstrating a decisive role of shell effects in the formation of the multi-body chain-like nuclear molecules were obtained by Poenaru et al. [6]. We want to refer as well on very recent theoretical articles, devoted to unusual ternary decays of heavy nuclei including CCT [7÷10]. The authors analyze the potential energy of different pre-scission configurations leading to ternary decays, and the kinetic energies of the CCT partners [11] are calculated for a sequential decay process. These results, being strongly model dependent can be considered as only the first step in the description of the CCT process.

Bearing in mind both theoretical and experimental background mentioned we came to the conclusion, that collinear tri-partition of low-excited heavy nuclear systems would be a promising field of research. The basic results obtained so far are represented here.

## THE MOST PRONOUNCED MANIFESTATION OF THE CCT

The bulk of our results were obtained within the framework of the ”missing–mass” approach. With the two-arm spectrometers binary coincidences have been measured, with a special mechanism, which blocks the registration of a third fragment, as explained below and in Fig.1. This means that only two fragments were actually detected in each fission event and their total mass, the sum Ms will serve as a sign of a multi-body decay if it is significantly smaller than the mass of the initial system.

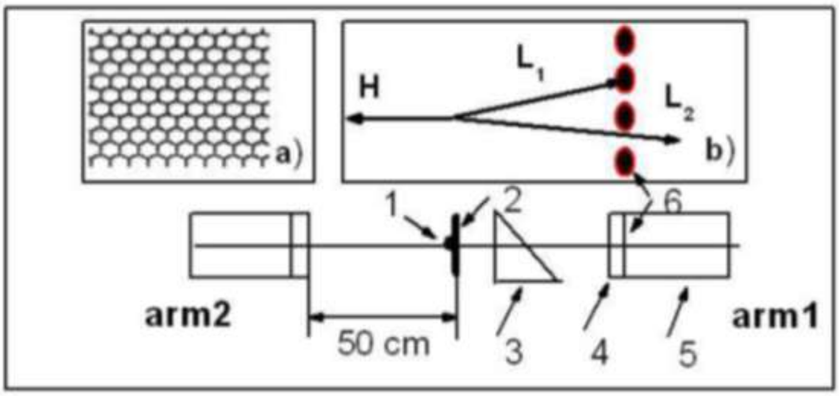

**FIGURE 1.** Scheme for coincidence measurements of two fission fragments of $^{252}$Cf (sf). The experiment has been performed at the FOBOS setup [12]. Here: 1 – Cf source, 2 –source backing, 3 – micro-channel plate (MCP) based timing ”start” detector, 4 – position sensitive avalanche counter (PSAC) as ”stop” detector, 5 – ionization chamber (BIC) with the supporting mesh, 6 – the mesh of the entrance window. The front view of the mesh is shown in the insert a), an enlarged mesh section is presented in the insert b). After passage of the two fragments through the source backing, two light fragments $L1$ and $L2$, are obtained with a small angle divergence due to multiple scattering. In b) we show that one of the fragments ($L1$) can be lost hitting the metal structure of the mesh, while the fragment $L2$ reaches the detectors of the arm 1. The source backing (2) exists only on one side and causes the mentioned angular dispersion in the direction towards the right arm1.

Fig. 2 shows in a logarithmic scale the two-dimensional distribution ($M_2$–$M_1$) of the two registered masses of the coincident fragments [13]. In the FOBOS setup used in the experiment $M_1$ is defined as the fragment mass derived from the arm pointing towards the detector arm with the additional dispersive (scattering) materials. Only collinear fission events with a relative angle of $180\pm2^0$ were selected, which corresponds to the typical angular spread for conventional binary fission fragments. The ”tails” in the mass distributions marked 3–6 in Fig. 2a extending from the regions (1) and (2) which are used to mark the conventional binary fission, are mainly due to the scattering of fragments on both the foils and on the grid edges of the ”stop” avalanche counters and the ionization chambers. We emphasize the small but important asymmetry in the experimental arrangement for the two arms, which consists in the thin source backing (50 mg/cm2 of $Al_2O_3$) of the target and the ”start” detector foil located only in arm 1 (Fig. 2a). An astonishing difference in the counting rate and in the shapes of the ”tails” (3) and (4) attracts attention. In the case shown in Fig. 2a there is a distinct bump, marked (7), on top of the latter ”tails” (4). The bump is located in a region corresponding to a large ”missing” mass. The statistical significance of the events in the structure (7) can be deduced from Fig. 2b, where the spectra of total (summed) masses Ms for the ”tails” (4) and (3) are compared. The yield of the events in the difference spectrum *c,* is (4.7±0.2)*$10^{-3}$ relative to the total number of events in the distribution shown in Fig. 2a. It is only a lower limit of the yield because the following reason. If both fragments (L1 and L2 in Fig.1) pass on and enter into the (BIC), we register a signal corresponding to the sum of the energies of the two fragments. In this case the event will be treated as binary fission with the usual parameters. The existence of the bump with the similar yield was confirmed in two other experiments carried out at the modified FOBOS spectrometer [14].

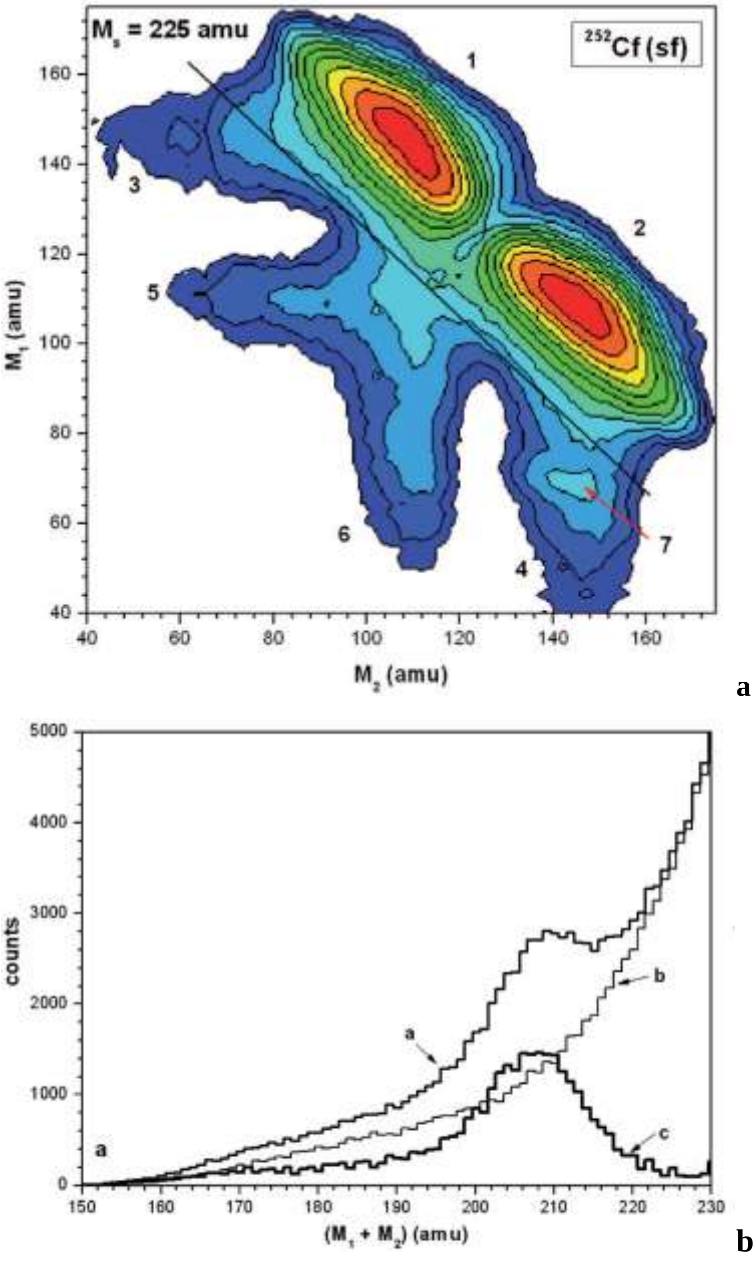

**FIGURE 2.** a) Contour map (in logarithmic scale, the steps between the lines are approximately a factor 2.5) of the mass-mass distribution of the collinear fragments of $^{252}$Cf (sf), detected in coincidence in the two opposite arms of the FOBOS spectrometer. The specific bump in arm1 is indicated by an arrow. b) the spectra of the summed masses *Ms* for the ”tails” (4 and 3) shown as spectrum *a* and *b*, respectively, are compared. The result of the subtraction of spectrum, *b*, from spectrum, *a*, (difference spectrum) is marked as *c*.

As it was stressed a specific supporting grid in the FOBOS detecting modules provides selecting of the ternary events. At the same time it serves a source of the scattered fragments forming the “tails” (Fig. 2a) simulating missing mass events. This effect is essentially suppressed in the mosaic COMETA spectrometer (Fig. 3) which lets to detect in principal all the partners of the ternary decay.

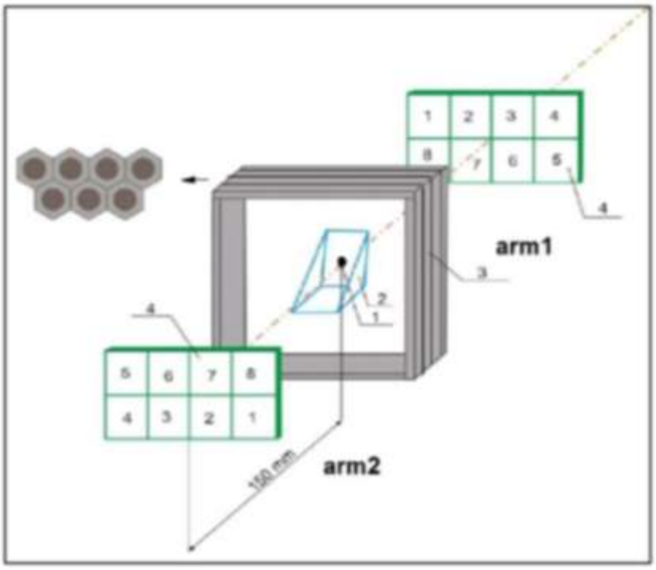

**FIGURE 3.** Scheme of the COMETA setup, which consists of two mosaics of eight PIN-diodes each (4), MCP based start detector (2) with the $^{252}$Cf source inside (1), and a ”neutron belt” (3) consisting of 28 $^{3}$He-filled neutron counters in a moderator. The cross section of the belt is marked by the arrow.

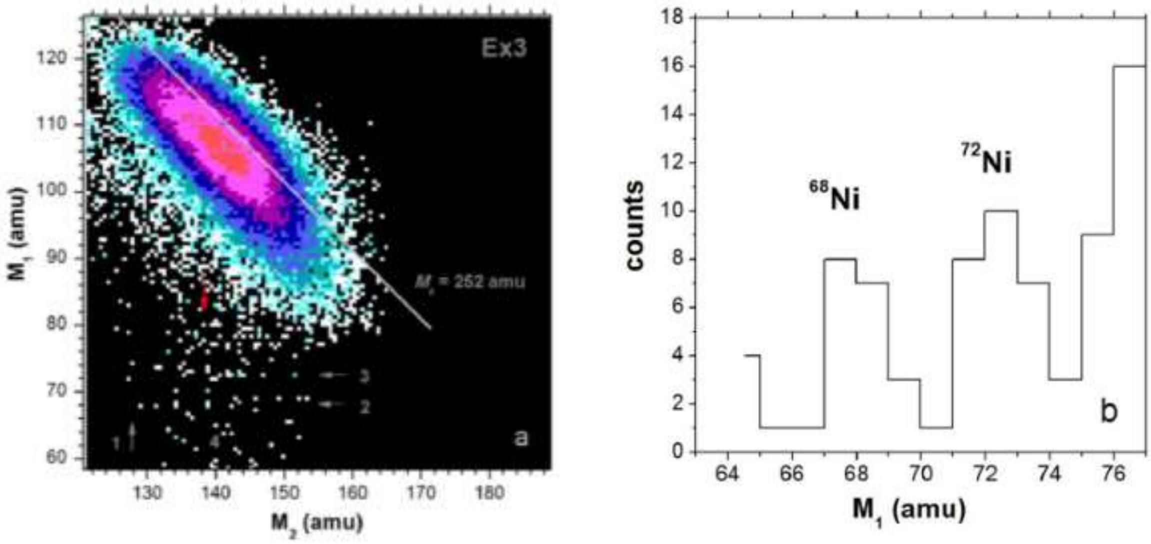

**FIGURE. 4.** Region of the mass-mass distribution for the FFs from $^{252}$Cf (sf) around the CCT–bump (similar to this marked by the arrow in Fig. 2a). Result was obtained at the COMETA setup. No additional gates were applied. The background of scattered fragments is very low due to the use of PIN-diodes (absence of a grid before the surface). An internal structure of the ”bump” seen as the horizontal lines from points (marked by the arrows, 2 and 3) is shown in Fig. 4b, as a projection.

This methodically quite different experiment confirms our previous observations concerning the structures in the missing mass distributions. In this case there is no tail due to scattering from material in front of the *E*-detectors. Fig. 4a shows the region of the mass distribution for the FFs from $^{252}$Cf (sf) around the ”Ni”–bump ($M_1$ = 68–80 amu, $M_2$ = 128–150 amu). The structures are seen in the spectrometer arm facing the source backing only. No additional selection of the fission events has been applied in this case, the experiment has no background. A rectangular-like structure below the locus of binary fission is bounded by magic nuclei (their masses are marked by the numbered arrows) namely $^{128}$Sn (1), $^{68}$Ni (2), $^{72}$Ni (3). In Fig. 4b we show the projection of the linear structure seen at the masses 68 and 72 amu. Two tilted diagonal lines with Ms = 196 amu and Ms = 202 amu (marked by number 4) start from the partitions 68/128 and 68/134 (all the nuclei to be magic), respectively.

The result for the measured charges (Fig. 5) confirms the previous finding with the mass distributions, namely the existence of an additional bump linked with Ni isotopes ("Ni"–bump) in the arm with the scattering media.

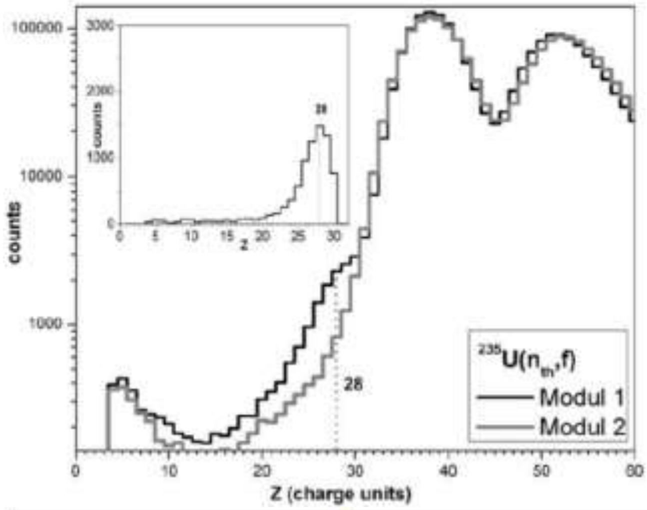

**FIGURE 5.** Nuclear charge spectra for the FF from the reaction $^{235}$U ($n_{th,}$ $f$), the FF are detected in the two opposite spectrometer arms. A difference in the yields (bump) presented in the upper panel in a linear scale is visible for the charges around $Z$ = 28 (isotopes of Ni).

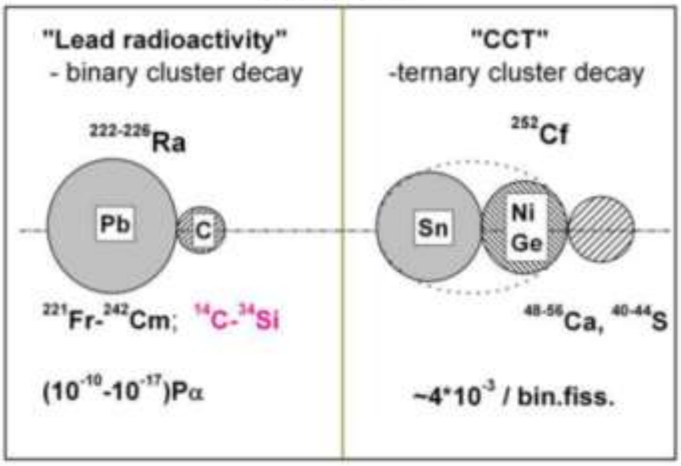

**FIGURE 6.** Cluster scheme for the comparison of the lead radioactivity with collinear cluster tri-partition.

One of the decay modes which contribute to the bump and manifests itself by the tilted ridges $M_1 + M_2$ = const can be treated as a new type of cluster decay as compared to the well-known heavy ion or lead radioactivity. Key features of both are summed up in Fig. 6. The relatively high CCT yield can be understood if one assumes collective motion through hyper-deformed pre-scission shapes of the mother systems.

## CONCLUSIONS FROM THE NEUTRON GATED DATA

The results of our previous experiments let us to assume that there are several CCT modes [15], with the middle fragment of the three-body pre-scission chain with very low velocity after scission. Such fragments are expected to emit neutrons almost isotropically. The neutrons emitted from the moving binary fission fragments are focused predominantly along the fission axis. In order to exploit this difference for revealing the CCT events, the ”neutron belt” was assembled in a plane perpendicular to the symmetry axis of the spectrometer (Fig. 3). According to modeling and previous experiments, the detection efficiency is estimated to be ~5% and ~12% for the neutrons emitted in binary fission and from an isotropic source, respectively. The array of neutron counters of the similar geometry was exploited earlier at the modified FOBOS spectrometer [14]. One of the results obtained at the COMETA setup is presented in Fig. 7.

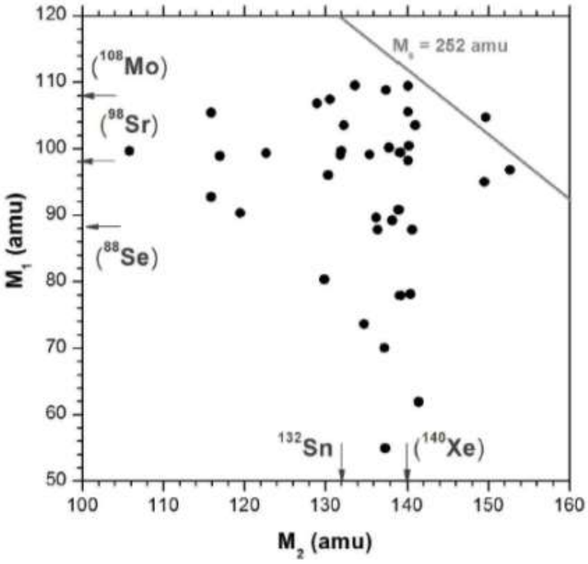

**FIGURE 7.** Results obtained at the COMETA set-up: mass-mass distribution of the FFs from ${}^{252}$Cf (sf) under the condition those three neutrons ($n$ = 3) were detected in coincidence and an additional selection with the gate in the FF velocity-energy distribution [14].

As can be inferred from the figure, the rectangular structure seen in its upper right corner is bounded by the nuclei with the masses in the vicinity of known magic nuclei (shown in the brackets). These masses (except of double magic ${}^{132}$Sn) were calculated based on the unchanged charge density hypothesis for the fission of the${}^{252}$Cf nucleus. Actually we know that at least three neutrons were emitted in each fission event presented in the figure. A change in the nuclear composition of the mother system can lead to a shift of the masses of the magic nuclei if neutrons were emitted from the decaying system (pre-scission neutrons). Likely this is what we observe here. For the upper right corner of the rectangle both mass and charge conservation laws are met only if the upper side of the rectangle corresponds to${}^{109}_{43}$Tc nucleus while mass 140 amu corresponds to the isotope combination of ${}^{140}_{55}$Cs.

The structure manifests itself exclusively thanks to the difference of the neutron sources for the fragments appearing in both binary fission and CCT, respectively. These two decay modes must differ in the neutron multiplicity or/and in their angular distributions of the emitted neutrons in order to provide the higher registration efficiency for neutrons linked with the CCT channel. At the same time the excitation energy of the system at the scission point defined as *Eex* = *Q* – TKE (where *Q* is the reaction energy, TKE – is the total kinetic energy of all the decay fragments), is known from our experimental data. It does not exceed *Eex* = 30 MeV. This value of the excitation energy is high enough to allow for the emission of three or four neutrons, which corresponds almost to the mean neutron multiplicity of binary fission. Thus the neutron source linked with the new CCT channels must have a much smaller velocity as compared to conventional binary fragments, or it can be almost at rest in the extreme case [11]. The latter agrees with the hypothesis put forward above that we deal with the pre-scission neutrons at least for very light missing masses.

Thus, the neutron gated data confirm an existence of the rectangular structures bounded by the magic nuclei in the FF correlation mass distributions. Analysis of the structures let to suppose that at least some of the CCT modes are linked with the emission of four pre-scission neutrons on the average.

## RESULTS FROM THE TRIPLE COINCIDENCES

Evidently, for almost collinear decay partners a probability of their independent detection even by the spectrometer of high granularity decreases rapidly with multiplicity. Nevertheless ternary events caused by multi-body decays were detected in our experiments at the mosaic spectrometers. For instance, ternary events observed in the reaction $^{238}$U + $^{4}$He (40 MeV) [15] are presented below. In the following three events magic or double magic Sn nuclei were detected as the heaviest fragments (Table 1). Corresponding light fragment (deformed magic nucleus) was clusterized in the scission point forming di-nuclear system. Presumably, its brake-up appears to occur due to inelastic scattering on the material of start-detector. Such hypothesis is based on the fact that a momentum conservation law is not met in all three events.

**TABLE 1.** Mass conservation law is met in the events presented

| Point number | Decay scheme |
|---|---|
| 1 | $^{128}$Sn + $^{32}$Mg + $^{80}$Ge + **2n**<br>----------------<br>$^{112}$Ru |
| 2 | $^{132}$Sn + $^{68}$Ni + $^{42}$S<br>-------------<br>$^{110}$Ru |
| 3 | $^{130}$Sn + $^{72}$Ni + $^{40}$S<br>-------------<br>$^{112}$Ru |

In the next set of events the decaying system was also fully clusterised i.e. its mass was exhausted by two magic constituents. ”Initial” clusters undergo fragmentation leading to formation of two di-nuclear systems. In contrast with previous case both ”initial” clusters are relatively soft deformed nuclei. Some examples of the events under discussion are presented in Table 2. Really detected fragments are shown by a bold.

## PERSPECTIVES

In order to increase radically the registration efficiency in the cinematically complete experiments i.e. with the direct registration of all (three and more) decay partners we are developing new methodical approaches. The following one is among them. Digital image of the current impulses from the two CCT partners hitting the same PIN-diode during registration gate can be obtained using fast flesh-ADC (”double-hit” technique). Both energy and time-reference linked with each signal from PIN diode will be calculated event by event. In our recent experiments in addition to standard analog electronics the multichannel 5 GS/s switched capacitor waveform digitizer DT5742 was set. Signals from all detectors were connected to active splitters and fed to proper inputs of our standard DAQ electronics and to the digitizer in order to compare different approaches of the FF spectrometry.

**TABLE 2.** Di-nuclear systems based on deformed magic constituents

| Point number | Decay scheme | Point number | Decay scheme |
|---|---|---|---|
| 1 | $^{121}$Ag+ $^{23}$F + $\mathbf{^{65}Mn}$ + $^{33}$Al<br>------------- --------------<br>$^{144}$Ba $^{98}$Sr | 4 | $^{140}$Xe+ $^{25}$Ne + $\mathbf{^{62}Cr}$ + $^{15}$C<br>------------- -------------<br>$^{165}$Gd $^{77}$Zn |
| 2 | $^{113}$Ru+ $\mathbf{^{31}Mg}$ + $^{78}$Ni + $^{20}$Ne<br>------------- --------------<br>$^{144}$Ba $^{98}$Sr | 5 | $^{134}$Te+ $\mathbf{^{30}Ne}$ + $^{50}$Ca+ $^{27}$Ne + **n**<br>------------- --------------<br>$^{164}$Gd $^{77}$Zn |
| 3 | $^{130}$Sn+ $\mathbf{^{13}C}$ + $^{62}$Cr + $^{33}$Mg + **3n**<br>------------- --------------<br>$^{144}$Ba $^{95}$Rb | 6 | $^{110}$Tc+ $^{11}$Be + $^{62}$Cr + $\mathbf{^{58}V}$<br>------------- -------------<br>$^{121}$Ag $^{121}$Ag |

## CONCLUSIONS

1. Clear manifestations of a new kind of at least ternary decay of low excited heavy nuclei (CCT) were observed so far in series of our experiments [16].
2. Close to collinear kinematics of the recession of the decay products and magic composition of at least one of them are the key features of new decay.
3. The properties of isotropic neutron sources can be assigned to some of the multiple CCT modes.

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