COLLINEAR CLUSTER TRI-PARTITION – POSSIBLE PHYSICS BEHIND

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Abstract. Presumable scenario of one of the modes of collinear cluster tripartition (CCT) of the ^{252}Cf (sf) is proposed. It is based on bright experimental indications for clustering of the fissioning system both in binary and ternary fission. CCT is believed to occur as specific "accident" in the scenario of conventional binary fission.

INTRODUCTION: CLUSTERING IN CONVENTIONAL BINARY FISSION

First attempts to create a model of the fission process involving shell aspect were taking place in early fifties of the last century. V.V. Vladimirski [1] was may be the first who postulated that fission probability has noticeable value only if two cluster structures such as magic cores within the light and heavy fragment corresponding to the $N = 50$ and $Z = 50$, $N = 82$ shells are not destroyed. A dumbbell–like configuration consisting of two magic clusters connected by a flat cylindrical neck was considered as a typical shape of the fissioning system. Formal representation of the fissionning system as a superposition of two interacting clusters (of arbitrary nucleon composition) is exploded in cluster model of fission developed by K. Wildermuth [2]. The theory cited is unfortunately "too basic" for practical using. Well known as well multiple calculations in the frame of two-center shell model approach [3, 4]. One of the most important and reproducible results obtained is that specific features of the level scheme of the fission fragments will be borne are already defined at relatively low distance between the centers of the clusters chosen for studying. Thus final fragments can grow from the cores along with elongation of the mother system. Visual proof of clustering of the fissioning system along the descent from the fission barrier was obtained in [5, 6]. Fig. 1 shows potential energy of the fissioning nucleus ^{246}Cm corresponding to the bottoms of the potential valleys as a function of parameter Q proportional to the quadrupole moment of the system. Calculations were performed in the frame of Strutinsky approach in ten dimensional deformation spaces.

Both in valley of mass-asymmetrical shapes (3) and mass-symmetrical shapes (4) the system consists from pairs of magic clusters (Sn / Ni, Sn / Ge and so on) and nucleons left over forming a "neck" between the clusters. The map under discussion demonstrates vividly the role of magic clusters preformed in the body of the fissionnig system in appearance of fission modes. Actually the ruptures appeared to occur while system descents along the distinct valley provide fission fragments observed experimentally and treated as corresponding fission mode [5]. Similar "visual" analysis of the nuclear shape in deformation process let authors of work [7] to reveal clustering in quasifission reactions leading to superheavy systems.

Recent studies of the far asymmetric fission (fig. 2) also let come to conclusion concerning a decisive role just pair of magic clusters in fission process. As it stressed in [8]: "…fission is not only determined by the double shell closure in the heavy sphere of the scission point dumbbell configuration around A = 132 (Z = 50, N ≈ 82) but also by an effect of the double shell closure of Z = 28 and N ≈ 50 in the corresponding light sphere". As can be referred from fig. 2 mass spectra of different actinide nuclei are bounded by mass ~70 amu. It was shown in [9] that it is really isotope of Ni. The conclusion concerning the light mass boundary of mass spectra of actinides was confirmed as well by the results obtained in studying of the (p, f) reactions [10].

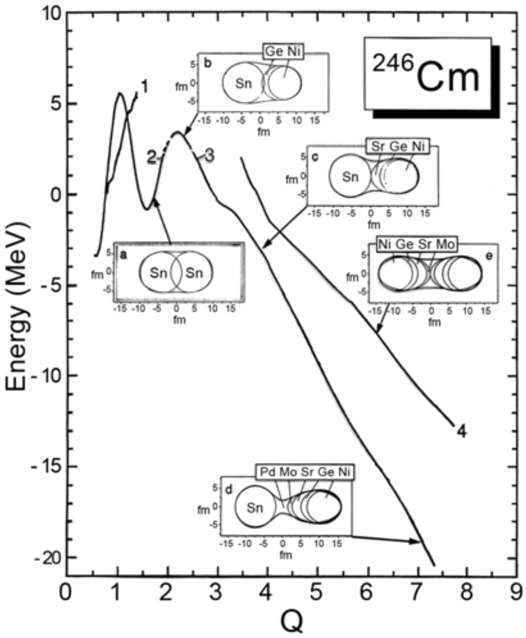

FIGURE 1. Potential energy of the fissioning nucleus as a function of its elongation.

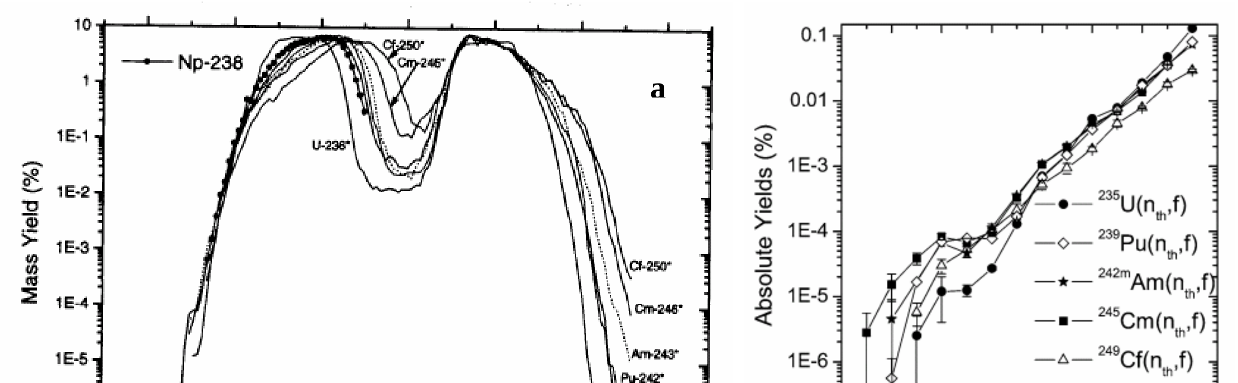

FIGURE 2. Mass yields from thermal induced fission of some actinides – a [8] and their comparison in the far asymmetric region (b) [9]. Bump centered at mass ~ 70 amu (Ni) is vividly seen.

Specific manifestations of clustering were revealed as a result of processing of the FF mass-energy distributions using methods of image analysis [11]. An example of the fine structure (FS) revealed in the distribution resulted from $^{233}U(n_{th}, f)$ reaction is presented in fig. 3. Each line of the FS consists of points with a locally increased mass yield. As can be referred from fig. 3b the "snake-like" structures asymptotically approach to the FF partitions which include magic (or double magic) fragments namely $^{132,\ 128}$Sn and Ge (neutron shell N = 50). Our treating of the FS is based on the following. Distinct valleys of the potential energy surface (PES) of the fissionning system [12, 13] (as shown, for instance, in fig. 1) give rise to the preferable trajectories (ways) of the system in the deformation space. As was shown, in any point of the system descent along the fission valley a scission can appear to occur [14] what can be detected as fission event in the space of experimental observables. In other words, the trajectory in the deformation space as a continual sequence of nuclear states in the fission valley is mapped as also continuous trajectory (smooth curve) in the plane of experimental observables [15], for instance, FF total kinetic energy and mass chosen as variables. Thus we believe [16] the FS under discussion to be an image of the distinct fission way extending "from cluster (Ge) to cluster (Sn)". Analyzing specific features of the FS we have put forward a hypothesis concerning the shape of the decaying system along the descent from the fission barrier [16]. Presumably it looks like multibody nuclear molecule based on pair of magic clusters (Ge / Sn) while residual nucleons form torus-like "neck" in between gross clusters (fig. 4). The neck could be also clusterized i.e. consists of He isotopes and neutrons. Evident difference of the shape proposed as compared to those seen in fig. 1 could be traced back to the fact that only simply connected shapes are adopted in known calculations of PES [12, 13]. Thus in the frame of the hypothesis under discussion a most compact configuration of the system looks like as shown in fig. 4a. With further elongation toroidal neck exports nucleons to the space between the tips of the gross clusters. Following to [14] we suppose that scission of the system can appear to occur at any stage of the descent (actually according [14] it could be tunneling of the system into the valley of separated fragments). The scission results in forming of two fragments. Heavy fragment unites Sn cluster and central part of the semi-torus (this part is shown in fig. 4b by the dot line), while the light one consists of Ge cluster and residual part of the torus (marked by two arrows). The scenario is supposed to be symmetric reference to gross clusters i.e. heavy fragment can be composition of the Sn cluster and residual part of the semi-torus while the Ge cluster joins its central part.

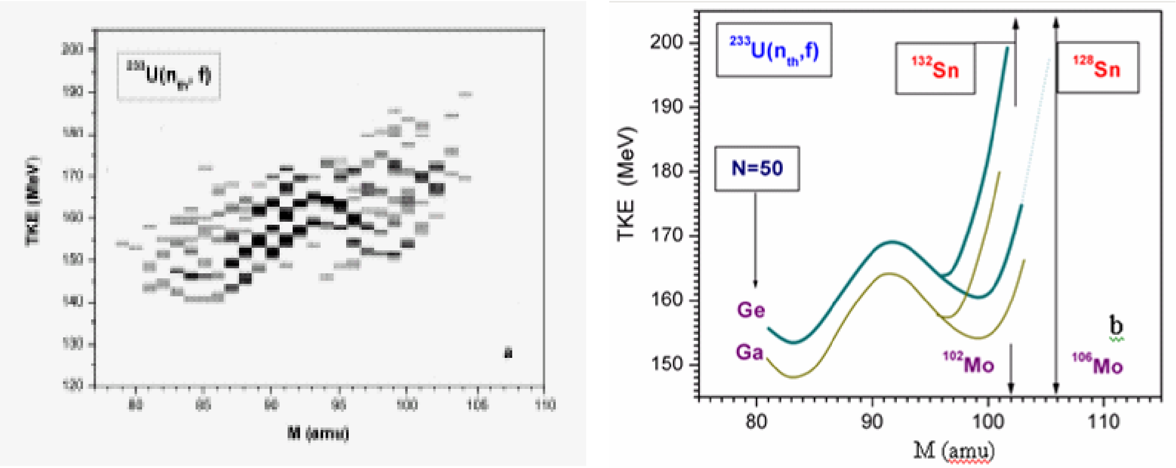

FIGURE 3. Fine structure of the FF mass-total kinetic energy distribution for the ^{233}U(n$_{th}$, f) reaction (a). Asymptotic borders of most pronounced "snake-like" structures observed indicate cluster origin of the whole image (b). Only light peak of the FF mass spectrum is analyzed here.

Summing up one can state an exclusive role of the magic clusters in the mechanism of binary fission. It is substantially more strong assertion than traditional “influence of shell effects” because clustering presupposes space localization of the corresponding nuclear object. The question arises whether conventional dumbbell-like shape of the system is really adequate to the fission process or more complicated multibody nuclear molecule (fig. 4) should be included in our consideration. It is believed that new kind of ternary decay discussed below gives arguments in favor of the latter hypothesis.

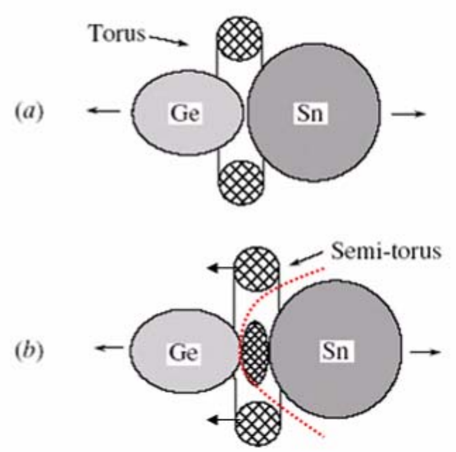

FIGURE 4. Presumable shape of the fissioning nucleus along the descent from the fission barrier [16]. See text for details.

EXPERIMENT AND RESULTS

The experiment has been carried out with the modified FOBOS spectrometer at the FLNR of the JINR. The experiment has been already discussed at this Seminar [17]. Due to the low yield of the process under study, a two-arm configuration containing five big and one small standard FOBOS modules in each arm were used. Such scheme of a double-armed TOF-E spectrometer allows the measurement of the energies and of the velocity vectors of the coincident fragments and covers ~ 16% of the hemisphere in each arm. Using experimental variables one can calculate both FF “pre-neutron” mass (Mtt) and FF mass after neutron emission (Mte). In order to provide "start" signals for all the modules wide-aperture start-detector capable to span a cone of > 100^0 at the vertex was used. Cf source was located inside the "start" detector for providing proper TOF values for both fragments of ternary decay flying in the same direction but with different velocities. Our previous experiments let us suppose the middle fragment of the three-body prescission chain to be almost at rest and highly excited. In order to exploit this feature for identifying of ternary decays the "neutron belt" consisting from 140 ^{3}He filled neutron counters was assembled in a plane perpendicular to the symmetry axis of the spectrometer, which serves as the mean scission axis at the same time. The registration efficiency does not exceed 4% for neutrons emitted in normal binary fission and it is 12% for neutrons emitted isotropically. The FF mass-mass distributions obtained under condition that more that 2 or 3 neutrons were detected ($n \geq 2$, $n \geq 3$) in coincidence with fragments are shown in fig. 5a, 5b respectively. Rectangles bounded by the magic fragments (marked by the arrows) attract attention. The CCT mode manifesting itself via structures seen in fig. 5 was identified [17] as an isotropic neutron source of multiplicity four.

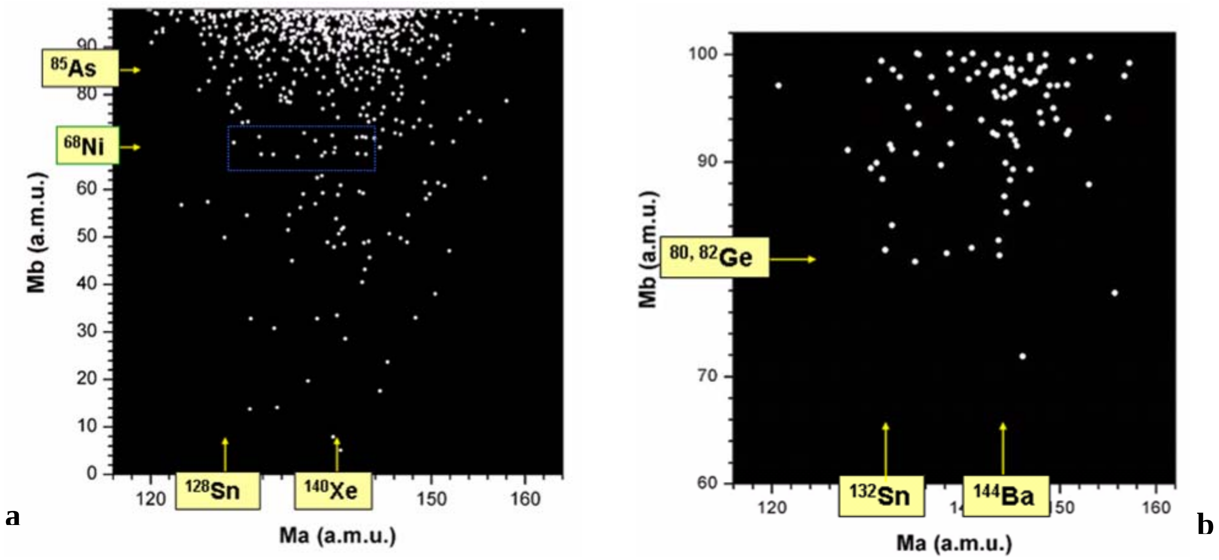

FIGURE 5. FF mass-mass distribution obtained under condition that n≥2 (number of detected neutrons) – a and n ≥ 3 – b. See text for details.

DISCUSSION

How can be treated each side of the rectangle, for instance, the low side of the rectangle in fig. 5b? The left corner corresponds to the partition ^{80}Ge / ^{132}Sn (^{40}S is missed). Than we see that the mass of the light fragment stays unchanged while the heavy fragment increases its mass up to 144 amu (presumably ^{144}Ba being also magic, ^{28}Ne is missed in this point). Observing such trend it is really reasonable to suppose that at least Ge cluster was preformed in the body of the decaying system. Just due to this obstacle Ge cluster invariably becomes light fragment observed. At the same time analyzing the vertical side of the rectangle starting from the same corner (^{80}Ge / ^{132}Sn) we come to the same conclusion reference to Sn cluster. Thus both magic nuclei prove to exist as clusters inside the system. The nucleons left over the gross clusters are distributed into two parts so as some of them join one of the gross cluster while remain nucleons form missing fragment. The conclusions above are based exclusively on the shape of the structure under analysis. Let us analyze additional information attracting, for instance, events from the box marked by the dot lines in fig. 5a. The projection of these events onto Mb axis is shown in fig. 6a. So the mass of the light fragment is really corresponds to the magic isotopes of Ni. Comparison of the Mte and Mtt masses for the heavy fragments is presented in fig. 6b. The bulk of the points lie in the vicinity of the line Mtt_a = Mte_a. It means that at each partition experimental velocity Vb_ex of the light fragment fired the "stop" detector is very close to the corresponding "binary" value Vb_bin.

Really Mtt_a = Mc / (1 + Va_bin / Vb_bin), where Mc is the mass of the mother nucleus and Va_bin ≈ Va_ex. Taking into account this fact as well as the conclusion cited above that in the fission events under consideration we deal with isotropic neutron source the following scenario of the CCT can be proposed. At some elongation of the fissioning system its clusterization appeared to occur with formation of the multibody nuclear molecule consists of pair of gross magic clusters (Ni / Sn) and torus (circle of α -particles) in between (stage 1 in fig. 7). Within increasing of the distance between the gross clusters the torus exports the nucleons to the central constituent of the molecule (possibly elongated along fission axis in order to exhaust a free space between the tips of the gross clusters). It should be stressed that these two first steps are similar to those in the scenario of binary fission but the third step is substantially different. Let us suppose that due to the casual reasons after first rupture (step 3 in fig. 7) Ni cluster has time to move from the torus at the distance larger then effective radius of nuclear attraction forces. Torus at rest being an excited state of the nucleus of equal nucleon composition comes back to the “normal” shape emitting neutrons (isotropically!). After second rupture the central part of the semi-torus joins Sn cluster and acceleration of the fragments formed continues. It is interesting that Ni cluster and central fragment which permanently overtakes it would have very close velocities. In its turn this velocity is close to the velocity of the fragment of binary fission with the mass equal to the total mass of Ni cluster and central fragment. The latter explains fig. 6b.

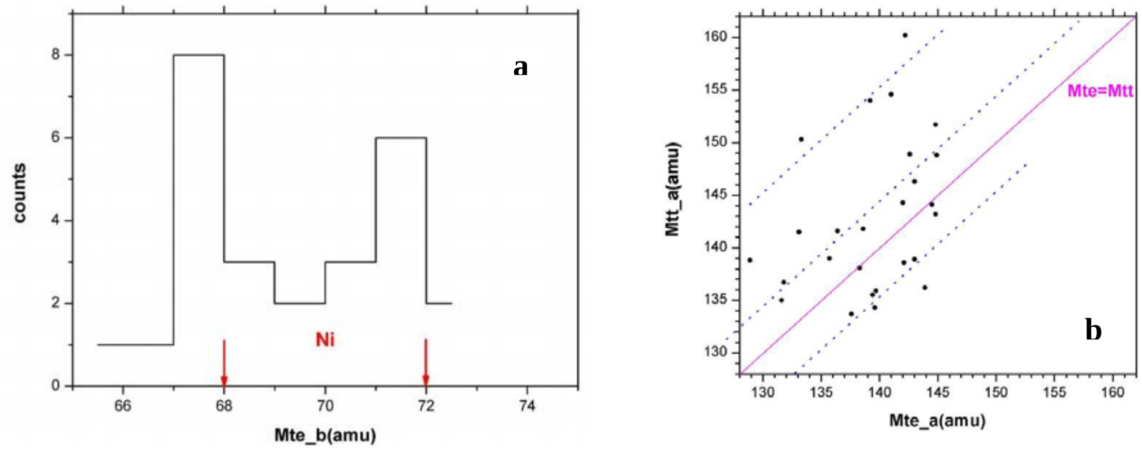

FIGURE 6. Projection of the events from the box shown in fig. 5a (a) and distribution Mte-Mtt for heavy fragments for these events (b).

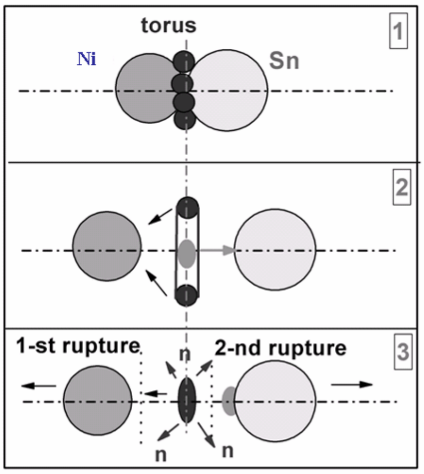

FIGURE 7. Illustration of the CCT scenario. See text for details.

Summing up we can say that CCT in the frame of the scenario proposed is treated as a specific “accident” in the scenario of conventional binary fission.

CONCLUSIONS

1. It is believed evolution of the multicomponent nuclear molecule to be decisive for the low energy fission process, at least, at the descent of the system from the fission barrier.
2. There is an intimate link between conventional binary fission and collinear cluster tripartition (CCT), namely, the latter appears to occur as a specific “accident” in the normal scenario of binary fission, at least, in the frame of the CCT mode under analysis.

ACKNOWLEDGMENTS

This work is supported in part by Russian Foundation of Basic Research, grant 09-02-00842-a.

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