Cluster aspects of collinear cluster tri-partition (CCT)

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Abstract. New results demonstrating the so-called Ni-bump being the most populated mode of the collinear cluster tripartition (CCT) of ^{252}Cf(sf) are presented. The physical scenario of this effect is discussed. It is tested by calculations of potential energy surfaces for the fission of the intermediate fragments formed after first rupture of the mother nucleus. Fission barriers are extracted and mass asymmetries at saddles are compared with the masses of the fission fragments that take part in the Ni-bump.

1. Introduction

In our previous publications [1–4], we discussed various manifestations of a new decay channel of the low excited heavy nuclei called collinear cluster tri-partition (CCT). The most populated CCT mode was revealed in the mass correlation distribution of fission fragments (FFs) as a local region ("bump") of increased yields below the loci linked to the conventional binary fission. The bump was dubbed "Ni-bump" because it is centered at the masses associated with the magic isotopes of Ni. Intriguing features of the CCT, especially high collinearity of the CCT partners and relatively high probability comparable to that typical for conventional ternary fission have caused rather wide theoretical discussion regarding the possible physical model of the effect [5, 6]. In the majority of dedicated publications, the FFs partitions from the Ni-bump have been analyzed from the different points of view. In our publications, we have underlined that Ni-bump manifests itself at the detectable level only in the spectrometer arm that faces the source backing. So far, this fact has been left beyond the scope of all known theoretical considerations, while the backing likely plays a crucial role in the observation of the CCT experimental pattern. This work presents the results of calculations that allow us to take a fresh look at the CCT mechanism.

2. Experiment and results

The experiment was performed at the double-armed time-of-flight COMETA spectrometer in FLNR (JINR, Russia). The FFs masses were measured using time-of-flight-energy (TOF-E) method. The details of the experimental approach are presented in [4].

FFs mass correlation distribution in the region of the "Ni-bump" is presented in figure 1(a). The total collected statistics is approximately three times more than that in the previous experiment [3]. Due to the background conditions, the events with the energy of the light fragment in the range of $E_2 = (6 \div 30)$ MeV were selected. The projections of the mass correlation distributions onto M_2 axis are shown in figure 1(b). The total yield of two Ni peaks in Ex1 does not exceed $2\text{x}10^{-4}$ per binary fission, which agrees with the previously obtained value. The projection of the distribution onto M_1 axis for the range of $M_2 = (65–76)$ u (figure 1(c)) demonstrates increased yield of the heavy fragments corresponding to the magic isotopes of ^{128}Sn, ^{134}Te, ^{140}Xe, ^{144}Ba, ^{150}Ce, ^{154}Nd (their masses are marked by the arrows).

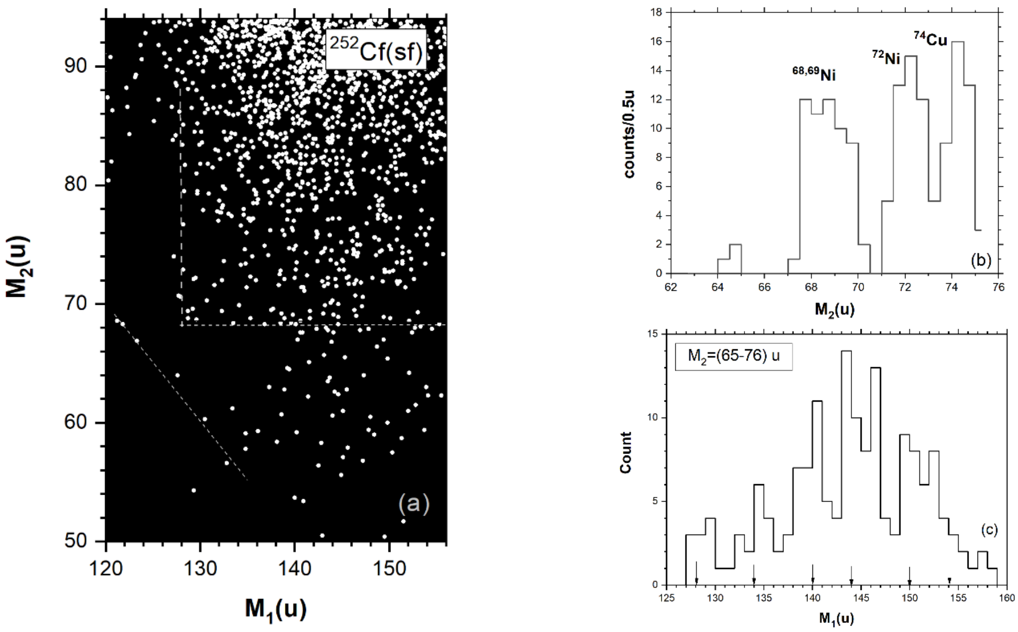

Figure 1. FFs mass correlation distribution from ^{252}Cf (sf) (a). Projection of the distribution onto M_2 axis (b), and onto M_1 axis (c), both projections are under condition that $M_2 = (65–76)$ u. The tilted line in figure 1(a) meets the condition $M_1 + M_2 = \text{const}$, the vertical line on the same plot corresponds to $M_1 = 128$ u, while the horizontal one corresponds to $M_2 = 68$ u. All the lines are drawn to guide the eye.

Besides the lines at the mass numbers $A = 128, 68, 72$ (figure 1(a)), an additional structure is observed. It consists of the family of lines $M_1 + M_2 \approx \text{const}$ and some lines almost perpendicular to them. The nature of the lines of the first sort was discussed in Ref. [4].

The following main features of the effect called as CCT should be taken into account while developing its physical model. Two detected CCT partners fly apart almost collinearly. The angle between their velocity vectors differs from 180^0 no more than by 7^0 and is determined by the PIN diode size. An open angle between the fragments flying in the same direction is estimated to be less than 2^0. Such kinematics allows us to suppose that we deal with the sequential ternary decay, because otherwise the middle fragment should move almost perpendicular to the fission axis as it is observed in conventional ternary fission. The CCT manifestations, such as the Ni-bump (figure 1) is observed only in the spectrometer arm facing the source backing. The fragment undergoing a break-up in the backing foil and subsequently losing some part of its mass can explain this fact. Both the sequential character of the ternary decay, i.e., the presence of a delay between the first and the second ruptures of the mother nucleus, and the break-up of the intermediate fragment in the foil are only plausible hypotheses. Under the frame of these hypotheses, it is expected that the intermediate fragment is born in the shape isomer state, and the potential well for this state must be rather shallow in order to provide high probability of the break-up due to the inelastic Coulomb scattering in the very thin foil.

In order to verify the hypotheses under discussion, the multidimensional potential energy surface (PES) was calculated using a version of the microscopic – macroscopic approach presented in Ref. [7]. The nuclear shapes are described by Cassinian ovals generalized by the inclusion of α_1, α_3 and α_4 shape parameters (mass asymmetry, octupole and hexadecapole deformations, respectively) in addition to the main fission coordinate α. Finite range liquid drop model (FRLDM) was chosen for the macroscopic energy. The results of the calculations for ^{120}Cd are presented in figure 2. This nucleus is the lighter fragment from the partition ^{120}Cd/^{132}Sn in the binary fission of the ^{252}Cf nucleus. If we had a reason to think that ^{120}Cd undergoes a second asymmetric fission (with ^{68}Ni as the heavy fragment) it would be the intermediate fragment in the ternary decay ^{252}Cf→^{68}Ni–^{52}Ca–^{132}Sn. In this way we could explain the masses of two side nuclei detected in coincidence which represent one of the constituents of the Ni-bump (figure 1(a)).

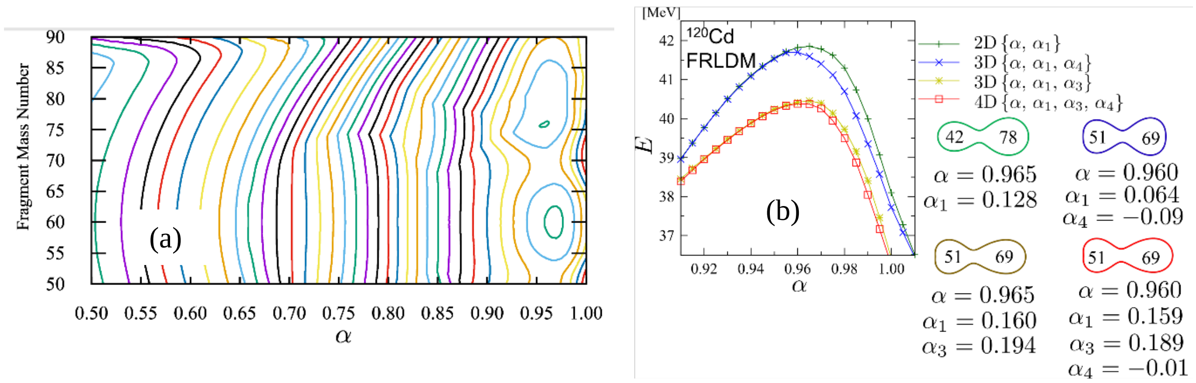

Figure 2. (Color online) Total deformation energy as a function of overall elongation (α) and mass asymmetry (α_1) for ^{120}Cd. At each point the energy is minimized with respect to α_3 and α_4. The lines are drawn at 1 MeV interval (a). (b) – fission barriers calculated for different combinations of deformation parameters (mass asymmetry – α_1, octupole – α_3, hexadecapole – α_4). The shapes of the Cd nucleus at scission are shown in the right-hand side of the figure for each deformation space considered.

It is exactly what the PES in figure 2(a) shows: a narrow saddle region centered at the mass ≈ 70 u. So ^{120}Cd fissions asymmetrically but not with the double magic ^{78}Ni as heavy fragment. This is unexpected. More precisely, for a deformation space restricted to (α, α_1), the saddle point corresponds to the mass 78 u but its descents to 69 u if at least octupole deformation (α_3) is added. Thus, the most probable calculated partition of the ^{120}Cd agrees well with the experimentally observed one (figure 1(b)). As can be inferred from figure 2(b), the one humped fission barrier is predicted. More detailed calculation of the PES may be needed to search for an additional shallow well that provides a shape isomer state expected from the experimental findings.

Similar calculations were also performed for ^{112}Ru, ^{108}Mo, ^{98}Sr which play the role of the intermediate fragments in the partitions ^{112}Ru/^{140}Xe, ^{108}Mo/^{144}Ba, ^{98}Sr/^{154}Nd. The saddle points in the PES for these intermediate fragments correspond to the following magic isotopes ^{52}Ca, ^{52}Ca and ^{46}Ar. Thus, for the intermediate fragments lighter than ^{120}Cd, ^{69}Ni is no longer the most likely product of the break-up. The question remains: what is the cause of the occurrence of the of the lines M_2 = const, manifesting as the peaks in figure 1(b)?

The first explanation could be as follows. In fact, the “line” is only the sequence of separate loci having the same center. Indeed, there is a specific structure below the line M_2 = 68 u (figure 1(a)) consisting of the lines $M_1 + M_2$ = const, or missing mass M_{miss} = const (one of such lines, for example, is marked by the tilted line), and almost perpendicular to them. As it was shown in Ref. [4] the manifestation of the line corresponded to the constant missing mass may be due to the preformation of the magic pear-shaped core in the body of the mother system. In its turn, the magic heavy nuclei are preferably formed in the decays of the cores (figure 2 (c)).

The alternative explanation is based on the analysis of the kinematics of the ternary decay. The kinematical parameters of three partners of the ternary decay under condition that momentum and energy conservation laws are met is shown in figure 3. Each vertical section gives possible velocities and energy of the decay partners. For some of the events, the signals from Ni and Ca fragments overlap in the PIN diode, which leads to the overstimation of the registered mass. As can be inferred from the figure, the sign of the Ca velocity changes inside the experimental energy range of the ^{132}Sn fragment. It means that the signals from Ca and Sn fragments can also overlap leading to the overstimation of the mass of the heavy fragment. As a result at least some points on the sides of a right angle with a vertex at a point (128, 68) u (figure 1(a)) are due to the signal superposition.

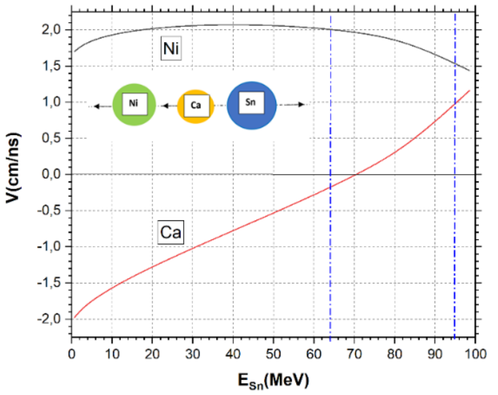

Figure 3. (Color online) Kinematical parameters of three partners of the ternary decay ^{252}Cf→^{68}Ni–^{52}Ca–^{132}Sn for the prescission excitation energy *E** = 40 MeV. By definition, momentum and energy conservation laws are met. The experimental energy range of the ^{132}Sn fragment is marked by dash-dot vertical lines.

3. Conclusions

- Basing on the experimental findings, the key points of the physical model of the most populated CCT mode, called the Ni-bump are proposed. After the first rupture of the very deformed fissioning system, the intermediate fragment is born in the shape isomer state. The fragment undergoes a break-up while passing through a thin solid-state foil.
- In order to verify the proposed model, the multidimensional potential energy surface (PES) for the intermediate fragments ^{120}Cd, ^{112}Ru, ^{108}Mo, ^{98}Sr was calculated using the microscopic–macroscopic approach. The saddle points in the PES of all the fragments coincide with the light magic nuclei, the only point that coincides with ^{69}Ni is the one for ^{120}Cd.
- The results of the calculations allowed us to formulate additional versions of the decay scenario leading to the manifestation of the Ni-bump. The multiple manifestations of the magic nuclei in both the results of experiment and calculations indicate a decisive role of clustering in the CCT phenomenon.

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