Nuclear Reaction Mechanisms Induced by Heavy Ions

M. G. Itkis, I. M. Itkis, G. N. Knyazheva and E. M. Kozulin

Abstract Total Kinetic Energy—Mass distributions of fission-like fragments for the reactions of ^{22}Ne, ^{26}Mg, ^{36}S, ^{48}Ca, ^{58}Fe and ^{64}Ni ions with actinides leading to the formation of superheavy compound systems with $Z = 108$–120 at energies near the Coulomb barrier have been investigated. It was found that the relative contribution of QF to the capture cross section mainly depends on the reaction entrance channel properties, but the features of asymmetric QF are determined essentially by the driving potential of composite system. A possible alternative pathway in the production of new superheavy elements near the "island of stability" is represented by the "inverse" quasifission or deep-inelastic reactions in the collision of ^{136}Xe with actinide targets.

The collision of two massive nuclei takes a special place in nuclear reactions studies due to the large number of interacting nucleons. In this type of reactions a drastic change of the reaction partners may occur that leads to different reaction mechanisms. In reactions with heavy ions at energies close to the Coulomb barrier complete fusion, quasifission (QF) and deep-inelastic collision are competing pro-cesses [1–3]. The balance between these processes strongly depends on the en-trance channel properties, such as mass asymmetry, deformation of interacting nuclei, collision energy, and the Coulomb factor $Z_1 Z_2$.

Previously in the experimental investigations the symmetric fragment region with mass $A_{CN} \pm 20$ u was often attributed to compound nucleus fission (CNF). However, a realistic description of the mass, energy and angular distributions of the reaction fragments formed in deep inelastic scattering, QF and CN-fission pro-cesses in low energy heavy ion collisions shows [4] that the potential energy sur-face for these systems is strongly modulated by shell effects and leads to the ap-pearance of deep valleys corresponding to the formation of well bound magic nuclei. In accordance with these calculations, at least three paths leading to the formation of fission-like

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fragments can be distinguished: asymmetric QF caused by the influence of proton shells with $Z = 28, 82$ and neutron shells with $N = 50, 126$; symmetric QF determined by the shells with $Z = 50$ and $N = 82$; CN-fission leading to the formation of symmetric fragments.

It is known that in superheavy composite systems QF mainly leads to the formation of asymmetric fragments with mass asymmetry ∼0.4 [1]. This type of QF process, so-called asymmetric quasifission (QFasym), is characterized by asymmetric angular distributions in the center-of-mass system and thus fast reaction times ($\sim 10^{-21}$ s) [5, 6]. The total kinetic energy (TKE) for these fragments is ob-served to be higher than that for CNF [1, 5] and hence this process is colder than CNF. Due to this reason shell effects in QF are more pronounced [7].

Figure 1 shows the mass-energy distributions of binary fragments obtained in the reactions of ^{16}S, ^{48}Ca, ^{64}Ni ions with an uranium target. The Coulomb factors are 1472, 1840 and 2576 for the ^{16}S+^{238}U, ^{48}Ca+^{238}U and ^{64}Ni+^{238}U, respectively. Some noteworthy features of the QFasym component of fragment mass distributions for the studied reactions can be highlighted at this point. Generally, in heavy-ion-induced reactions the formation of QFasym fragments is connected with the strong influence of the nuclear shell at $Z = 82$ and $N = 126$ (doubly magic lead). In fact, as was shown in Ref. [8], for the ^{48}Ca + ^{238}U reaction the maximum yield corresponds to fragments with masses 208 u. However, in reactions with lighter projectiles on a uranium target, the asymmetric QF peak shifts toward more symmetric masses [9]. By contrast, for the heavier projectile ^{64}Ni, the maximum yield of QFasym fragments corresponds to the heavy mass 215 u [8]. This trend is illustrated in Table 1 , where the positions of heavy QF fragments for these reactions are presented. But,

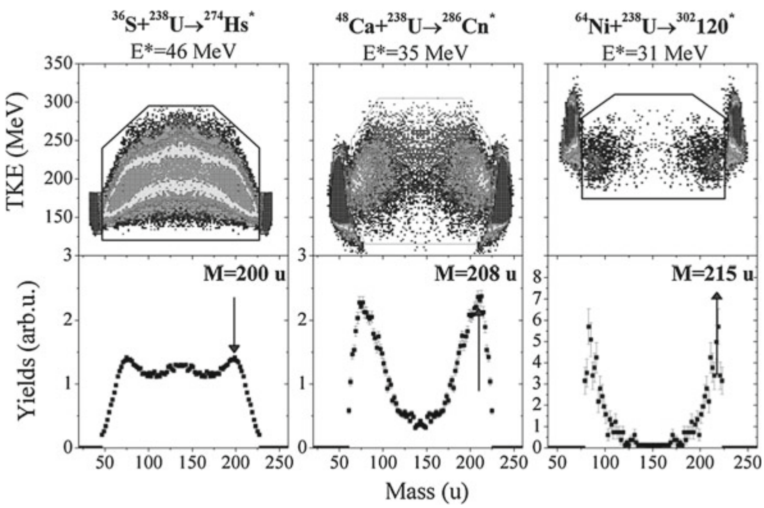

Fig. 1 Mass-energy distributions for the reactions ^{36}S, ^{48}Ca, ^{64}Ni +^{238}U at energies close to the Coulomb barrier

Table 1 Positions of heavy peaks in the primary mass distributions of QFasym fragments in reactions with heavy ions

Reaction	Z_1Z_2	M_H	M_H^{Shell}	Exchanged nucleons	Reference
^{26}Mg + ^{248}Cm	1152	185±5	202.5	68	I. Itkis et al. [10]
^{30}Si + ^{238}U	1288	178	199.3	60	K. Nishio et al. [9]
^{36}S + ^{238}U	1472	200±3	202.5	38	I. Itkis et al. [10], K.Nishio et al. [9]
^{40}Ar + ^{238}U	1656	204	204.5	34	K. Nishio et al. [9]
^{48}Ca + ^{238}U	1840	208 ±2	208.5	30	E. Kozulin et al. [8]
^{64}Ni + ^{238}U	2576	215±3	216.5	23	E. Kozulin et al. [8]

in the formation of the asymmetric QF component, also the closed shell in the light fragment at $Z = 28$ and $N = 50$ could be effective, together with the shells $Z = 82$ and $N = 126$, and could lead to the shift of the asymmetric QF peak. Based on the simple assumption of an N/Z equilibration, the masses of the light and heavy fragments corresponding to these closed shells were calculated. In Table 1 M_H^{Shell} is a heavy fragment mass averaged over all these shells. The obtained values of M_H^{Shell} are in good agreement with the experimental ones, except for the more asymmetric ^{26}Mg + ^{248}Cm and ^{30}Si + ^{238}U reactions. For these reactions the Coulomb repulsion is expected to be smaller. This may lead to longer reaction times before separation for asymmetric QF and thus allow for larger numbers nucleons to be exchanged. For the other more symmetric reactions with heavier projectiles, the major part of the asymmetric QF peak fits into the region of the $Z = 82$, $N = 126$ and $Z = 28$, $N = 50$ shells. The maximum yield of the asymmetric QF component is a mixing between all these shells.

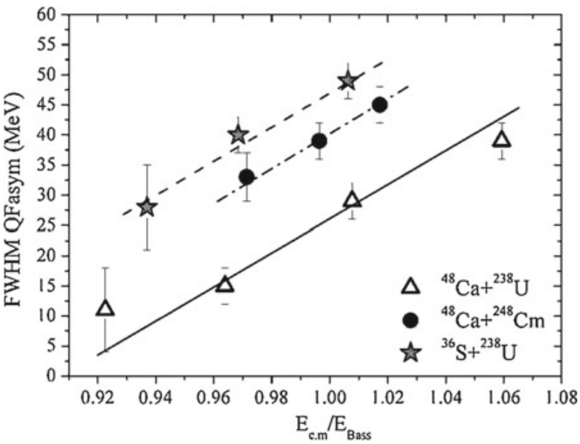

Fig. 2 The widths of QFasym mass distributions as a function of the energy above the Bass barrier for the reactions ^{36}S+^{238}U, ^{48}Ca+^{238}U and ^{48}Ca+^{248}Cm

Besides the position of peaks in the mass distributions of QFasym fragments, also the widths of these peaks vary for different "ion-target" combinations even in the case of the formation of the same composite systems. Figure 2 presents the width of QFasym mass distributions as a function of the energy above the Bass barrier for the reactions $^{36}S+^{238}U$, $^{48}Ca+^{238}U$ and $^{48}Ca+^{248}Cm$. Notice, that for all studied reactions the width increases with a similar slope with increasing collision energy. Nevertheless, the absolute values are different: at energy of the Bass barrier the width is about 47 u for the $^{36}S+^{238}U$, about 26 u for the $^{48}Ca+^{238}U$ and about 40 u for the $^{48}Ca+^{248}Cm$. So, it is not a function of mass or charge number of composite system. For these reactions the driving potentials as a function of mass asymmetry and distance between mass centers have been calculated in the diabatic approximation using the proximity model with the help of Nuclear Reaction Vision Project (NRV) [11]. These potentials are shown in Fig. 3 for the case of distance between mass centers of about 13 fm (scission point). It is clearly seen that the deepest narrow minimum at mass close to 208 u corresponds to the reaction $^{48}Ca+^{238}U$ that is the case of the narrowest QFasym mass distribution. Not only the deepnesses of the minima around the mass of 208 u, but also their positions are different for these reactions. The calculated position of the minimum of the diving potential agrees with the position of peaks in the experimental QFasym mass distributions. Thereby, the driving potential calculated in diabatic approximation qualitatively reproduces the main features of QFasym mass distributions. While the relative contribution of QF to the capture cross section mainly depends on the reaction entrance channel properties, the features of asymmetric QF are determined essentially by the driving potential of composite system.

Coming back to the $^{26}Mg+^{248}Cm$ and $^{36}S+^{238}U$ reactions leading to the formation of the same composite system, the difference between the peak positions of the

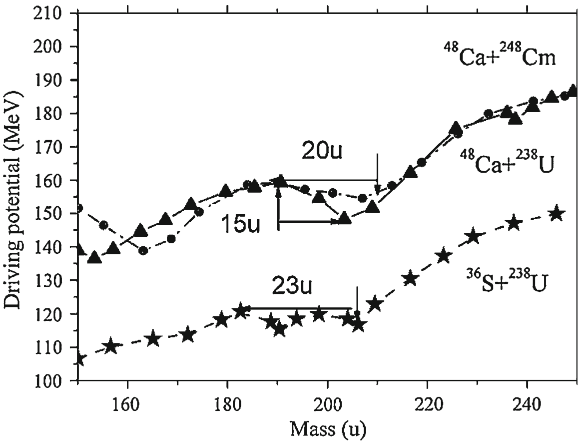

Fig. 3 The driving potentials as a function of reaction fragment mass at scission point for the reactions $^{36}S+^{238}U$, $^{48}Ca+^{238}U$ and $^{48}Ca+^{248}Cm$

QFasym fragment mass distributions may be connected also with the shape of the driving potential. The driving potential for this composite system has two wide small local minima at fragment mass of about 190 and 205 u (see Fig. 3). Due to the small value of $Z_1 Z_2 = 1152$ for the ^{26}Mg+^{248}Cm reaction the composite system is closed to the CN shape than in the case of the ^{36}S+^{238}U ($Z_1 Z_2 = 1472$). Thus, due to the difference in the entrance channels for these reactions the QFasym process may come by different ways and lead to the formation of various fragments.

For the reactions ^{58}Fe+^{244}Pu and ^{64}Ni+^{238}U leading to the formation of the same composite system of ^{302}120, the positions of the QFasym peaks are approximately the same, but the width of these peaks are different: 22 u for the former reaction and 11 u for the latter one. The left panel of Fig. 4 presents the driving potential for the composite system ^{302}120 at scission point. The mass-energy distributions for the reactions ^{58}Fe+^{244}Pu and ^{64}Ni+^{238}U are shown in the right panel of Fig. 4. As in the case of ^{26}Mg+^{248}Cm and ^{36}S+^{238}U the entrance channels are different: $Z_1 Z_2 = 2444$ for the ^{58}Fe+^{244}Pu reaction and 2576 for the ^{64}Ni+^{238}U reaction. The larger Coulomb repulsion in the entrance channel may lead to the faster interaction time and, consequently, transfer of less number of nucleons from one nucleus to another. Nevertheless, the structure of the driving potential is clearly seen in the mass distributions of fission-like fragments formed in the both reactions.

The experimental mass distribution of the fission-like fragments formed in the reaction ^{48}Ca+^{248}Cm at energy close to the Coulomb barrier is presented in the top panel of Fig. 5. The symmetric fragment mass distribution (the open circles in Fig. 5) has been extracted from the experimental mass distribution of the all fission-like fragments using the Gaussian fitting procedure of asymmetric peaks. The driving potential for this composite system at scission point calculated in the frame of the proximity model is also shown in the same figure. As it was mentioned above the

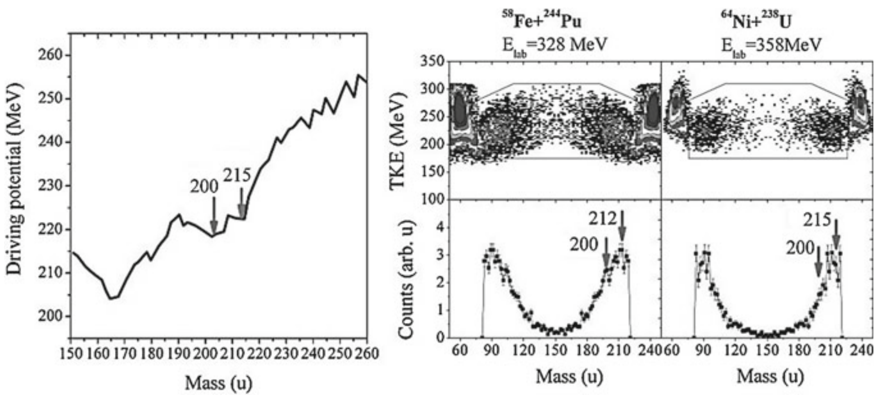

Fig. 4 The driving potential as a function of reaction fragment mass at scission point for the superheavy composite system ^{302}120 (*left* panel). The mass-energy distributions of binary fragments (*top*) and mass distribution for fission-like fragments (*bottom*) for the reactions ^{58}Fe+^{244}Pu and ^{64}Ni+^{238}U at energies of about 1.06 MeV above the Coulomb barrier

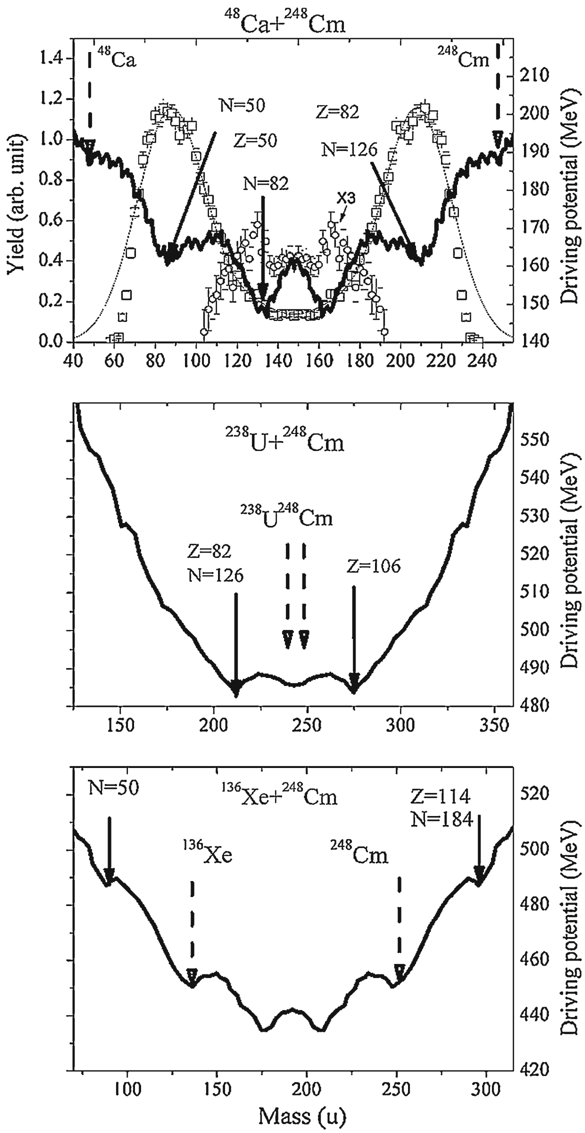

Fig. 5 The driving potentials as a function of reaction fragment mass at scission point for the reactions ^{48}Ca+^{248}Cm, ^{238}U+^{248}Cm and ^{136}Xe+^{248}Cm

maximum fragment yields correspond to the positions of the local minima of the driving potential as in the case of formation of asymmetric fragments, as well as symmetric ones.

In the middle and bottom panels of Fig. 5 the driving potentials for the composite systems formed in the reactions ^{238}U+^{248}Cm and ^{136}Xe+^{248}Cm calculated in the same approximation are presented, respectively. The dashed arrows indicate the position of the entrance channels, while the solid arrows show the position of the proton and neutron closed shells. It is clearly seen that the local minima in the driving potential exist for all reactions, though in the latest two reactions these minima are located from the outside the entrance channel. Thus, we may expect an increase of the fragment yields in the mass region around these minima. W. Greiner and V. Zagrebaev proposed to call this process "inverse" quasifission in [12]. Notice, that in the case of the reaction ^{238}U+^{248}Cm one of the minima corresponds to doubly magic lead valley and the complementary fragment is a superheavy nucleus around $Z = 106$. In the reaction ^{136}Xe+^{248}Cm both fragments have closed shells: the light fragment is near $N = 50$, the heavy one is close to $Z = 114$ and $N = 184$ (predicted "island of the stability").

The idea of the production of superheavy nuclei in the multi-nucleon transfer reactions in the collision of U+U nuclei (or similar reactions) was already proposed in [13]. In this work it was found that at an incident energy of 7.42 MeV/u (about 22 % above the Coulomb barrier) a direct search for α-decay or fission of superheavy nuclei being produced in a deep inelastic collision resulted in an upper cross section limit of 2 nb. Although the stronger penetration of nuclei leads to enhanced mass transfer, the higher excitation energies involved drastically reduce the survival probability of the nuclei produced. The decrease in collision energy to the Coulomb barrier energy leads to the lower total excitation and consequently to larger cross section of survived superheavy nuclei. According to the calculation of the cross section of survived superheavy nuclei formed in the reaction ^{232}Th+^{250}Cf at 800 MeV center-of-mass energy (near the Coulomb barrier) from [12] there is a real chance for production of the long-lived neutron-rich superheavy nuclei in such reactions.

Figure 6 presents the chart of nuclides in the region of superheavy elements. A large success have been achieved in the synthesis of superheavy elements with $Z = 108$–118 in the reaction of "cold" and "warm" fusion. Even though the "warm" fusion reaction leads to the formation of more neutron-rich nuclei than in the case of "cold" fusion even after the deexcitation process, the isotopes of superheavy elements formed in these ^{48}Ca induced reactions cannot reach the neutron closed shells with $N = 184$ due to the lack of 7–9 neutrons. Moreover, nuclei with $Z > 118$ cannot be synthesized in ^{48}Ca induced reactions since ^{249}Cf is the heaviest target material available for these purposes. From the investigation of the mass-energy distributions of binary reaction fragments obtained in the reactions ^{48}Ca+^{238}U, ^{58}Fe+^{244}Pu and ^{64}Ni+^{238}U [8] it was found that the cross section drops three order of magnitude for the formation of the compound nucleus with $Z = 120$ obtained in the reaction ^{64}Ni+^{238}U compared to the formation of the compound nucleus with $Z = 112$ obtained in the reaction ^{48}Ca+^{238}U at an excitation energy of the compound nucleus of about 45 MeV. This is unfortunately a limiting factor. Furthermore, the relative contribution of the CN-fission from ^{64}Ni+^{238}U is much lower than in the case of ^{58}Fe+^{244}Pu, leading to the formation of the same composite system.

Recently the experiments aimed at the synthesis of isotopes of element Z=120 have been performed using the ^{244}Pu (^{58}Fe, xn)$^{302-x}$120 reaction [14] and ^{238}U(^{64}Ni, xn)$^{302-x}$120 reaction [15]. A cross section limit of 0.4 pb at $E *= 44.7$ MeV for the

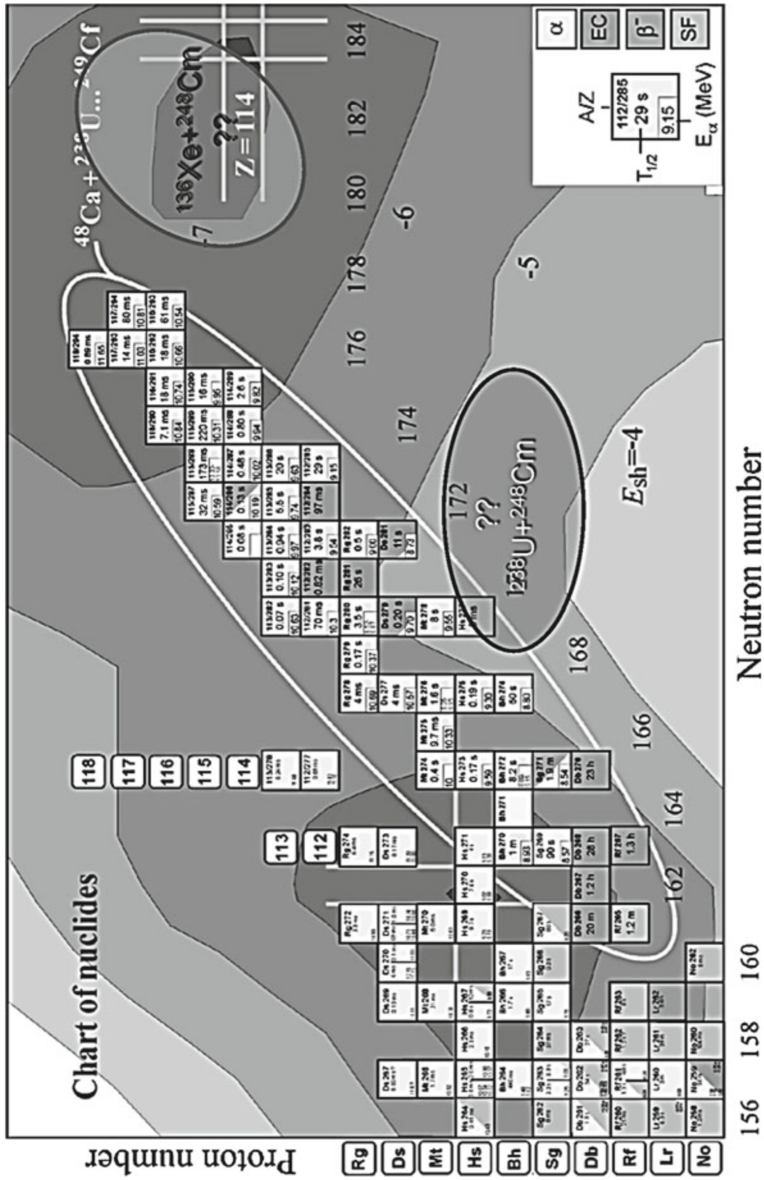

Fig. 6 The chart of nuclides in the region of superheavy elements

former reaction and 0.09 pb at $E^* = 36.4$ MeV for the latter reaction were obtained. In the case of ^{48}Ca induced reactions the evaporation residue cross section for 3n, 4n channels is about a few picobarns even for the heaviest nucleus with $Z = 118$.

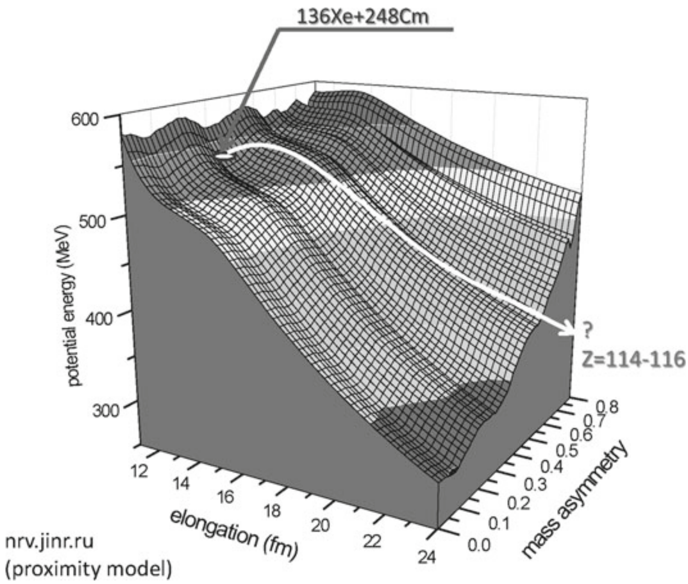

Fig. 7 Driving potential for the nuclear system formed in the ^{136}Xe+^{248}Cm collision. The *solid line* with *arrow* shows schematically the probable trajectory for the formation of fragments with $Z = 114$–116

A possible alternative pathway is represented by the "inverse" quasifission or deep-inelastic reactions in the collision of ^{136}Xe, ^{232}Th and ^{238}U with actinide targets. According to the theoretical expectations the cross section for the survived nuclei formed in such processes is higher than in the reaction of complete fusion. The reaction ^{136}Xe+^{248}Cm can be more interesting due to the fact that the heavy valley of the driving potential for this system corresponds to the nuclei close to the "island of stability", while in the case of the collision of Th and U with actinide targets the heavy valley lies outside the stability line (see Fig. 6). Driving potential as a function of elongation and mass asymmetry for the nuclear system formed in the ^{136}Xe+^{248}Cm collision is shown in Fig. 7. The solid line with arrow shows schematically the possible trajectory for the formation of fragments with $Z = 114$–116. To estimate the formation probabilities of superheavy elements in these reactions the additional investigations are needed.

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