Strongly coupled processes of deep inelastic scattering, quasi-fission and fusion are described concurrently with a common set of variables within the Langevin type equations of motion. Shell effects on the multi-dimensional potential energy surface play extremely important role in these reactions. This leads to the two-body (shape isomeric states in fission) and three-body clustering phenomena in heavy nuclear systems. Enhanced yield of the nuclides far from the projectile and target masses was found in the multi-nucleon transfer reactions due to the shell effects. It suggests that the low-energy damped collisions of transactinide nuclei may be used as an alternative way for the production of surviving superheavy long-living neutron-rich nuclei.

Keywords: Damped collisions; fusion; fission; clustering; superheavy elements.

1. Introduction

A new approach was recently proposed \(^{1,2}\) for a unified and simultaneous description of strongly coupled deep inelastic (DI), quasi-fission (QF) and fusion-fission processes of low-energy heavy-ion collisions. The distance between the nuclear centers \(R\) (corresponding to the elongation of a mononucleus), dynamic spheroidal-type surface deformations \(\delta_1\) and \(\delta_2\), mutual in-plane orientations of deformed nuclei \(\varphi_1\) and \(\varphi_2\), and mass asymmetry \(\eta = \frac{A_1 - A_2}{A_1 + A_2}\) are used in this approach as the most relevant variables for description of fusion-fission dynamics. Note that we take into consideration all the degrees of freedom needed for description of all the reaction stages. Thus, in contrast with other models, we need not to split artificially the
whole reaction process into several stages and we may consider concurrently
the strongly coupled DI, QF and CN formation reaction channels within the
same Langevin type equations of motion. At low collision energies the shell
effects play a very important role in dynamics of heavy nuclear systems. In
this paper we concentrate mainly on detailed study of these effects.

2. Adiabatic potential energy

The interaction potential of separated nuclei is calculated rather easily
within the folding procedure with effective nucleon-nucleon interaction or
parameterized, e.g., by the proximity potential. Of course, some uncertainty
remains here, but the height of the Coulomb barrier obtained in these mod-
els coincides with the empirical Bass parametrization within 1 or 2 MeV.
After contact the mechanism of interaction of two colliding nuclei becomes
more complicated. For fast collisions \( \frac{E}{A} \sim \varepsilon_{\text{Fermi}} \) or higher the nucleus-
nucleus potential, \( V_{\text{diab}} \), should reveal a strong repulsion at short distances
protecting the “frozen” nuclei to penetrate each other and form a nuclear
matter with double density (adiabatic conditions, sudden potential). For
slow collisions (near-barrier energies), when nucleons have enough time to
reach equilibrium distribution (adiabatic conditions), the nucleus-nucleus
potential energy, \( V_{\text{adiab}} \), is quite different (Fig. 1). Thus, at energies well
above the Coulomb barrier we need to use a time-dependent potential energy,
which after contact gradually transforms from a diabatic potential

\[ V_{\text{adiab}} = V_{\text{diab}} \]

\[ V_{\text{adiab}} \neq V_{\text{diab}} \]

Fig. 1. Potential energy for \( ^{48}\text{Ca} + ^{248}\text{Cm} \) for diabatic (dashed curve) and adiabatic
(solid curve) conditions (zero deformations of the fragments).
energy into an adiabatic one: \( V = V_{\text{diab}}[1 - f(t)] + V_{\text{adiab}}f(t) \). Here \( t \) is the time of interaction and \( f(t) \) is a smoothing function with parameter \( \tau_{\text{relax}} \sim 10^{-21} \) s, \( f(t = 0) = 0 \), \( f(t \gg \tau_{\text{relax}}) = 1 \).

The calculation of the multidimensional adiabatic potential energy surface for heavy nuclear system remains a very complicated physical problem, which is not yet solved in full. The two-center shell model\(^4\) seems to be most appropriate for calculation of the adiabatic potential energy. However, the simplest version of this model with restricted number of collective coordinates, using standard parametrization of the macroscopic (liquid drop) part of the total energy\(^5\)\(^6\) and overlapping oscillator potentials for a calculation of the single particle states and resulting shell correction, does not reproduce correctly values of the nucleus-nucleus interaction potential for well separated nuclei and at contact point (depending on mass asymmetry). The same holds for the value of the Coulomb barrier and the depth of potential pocket at contact. These shortcomings are overcome in the extended version of the two-center shell model\(^7\). The phenomenological two-core model\(^8\)\(^9\) (based on the two-center shell model idea) was also proposed for a calculation of the multi-dimensional adiabatic potential energy surface in which all the shell effects are included by using experimental nuclear masses of the fragments \( a_1 \) and \( a_2 \) gradually dissolving with increase of a number of the shared nucleons \( \Delta A \), see Fig. 2.

3. Clusterization and shape–isomeric states

Within the two-center shell model the processes of compound nucleus formation, fission and quasi-fission may be described both in the space of \((R, \eta, \delta_1, \delta_2)\) and in the space \((a_1, \delta_1; a_2, \delta_2)\), because for a given nuclear configuration \((R, \eta, \delta_1, \delta_2)\) we may unambiguously determine the two cores \( a_1 \) and \( a_2 \). This is extremely important for interpretation of physical meaning of some deep minima on the potential energy surface.
Fig. 3. Driving potential of nuclear system $^{296}_{116}$ → $^{48}_{24}$Ca + $^{248}_{92}$Cm. (a) Potential energy in the “elongation – mass asymmetry” space. (b) Topographical landscape of the driving potential on ($z_1, z_2$) plane. Dashed, solid and dotted curves show most probable trajectories of fusion, quasi-fission and regular fission, respectively. Diagonal corresponds to the contact configurations ($\Delta A = 0$). (c) Three-humped barrier calculated along the fission path (dotted curve).

The adiabatic driving potential for formation and decay of superheavy nucleus $^{296}_{116}$ is shown in Fig. 3 as a function of $z_1$ and $z_2$ (minimized over $n_1$ and $n_2$) at $R \leq R_{cont}$ and also as a function of elongation and mass asymmetry at fixed deformations of both fragments. It is easily to see that the shell structure, clearly revealing itself in the contact of two nuclei is also retained at $R < R_{cont}$ (see the deep minima in the regions of $z_{1,2} \sim 50$ and $z_{1,2} \sim 82$ in Fig. 3b). Following the fission path (dotted curves in Fig. 3a,b) the nuclear system goes through the optimal configurations (with minimal potential energy) and overcomes the multi-humped fission barrier (Fig. 3c). These intermediate minima correspond to the shape isomer states. From analysis of the driving potential we may definitely conclude that these isomeric states are nothing else but the two-cluster configurations with magic or semi-magic cores surrounded with a certain amount of shared nucleons.
It is interesting to estimate the adiabatic potential energy for the three-center configuration. Such clusterization may play a role in vicinity of the scission point, where the shared nucleons $\Delta A$ may form a third cluster located between the two heavy cores $a_1$ and $a_2$. Because there are too many degrees of freedom, we calculated the potential energy of a three-body configuration (shown in Fig. 4) only as a function of $Z_1$ and $Z_3$ at fixed deformations ($\delta_1 = \delta_2 = \delta_3 = 0.1$) of the fragments being in contact. The corresponding potential energy (minimized over neutron numbers $N_1$ and $N_3$) is shown in Fig. 5 for $^{248}\text{Cm}$ nucleus. One may see that the potential energy increases with increasing the mass of the third fragment. This means that a ternary fission should be quite unfavorable for transactinide nuclei. However situation may change for heavier nuclear systems (see below).

Fig. 4. Three-body clusterization of a heavy nuclear system

Fig. 5. Landscape of potential energy of a three-body clusterization of $^{248}\text{Cm}$ nucleus
4. Quasi-fission and SHE formation

It is well known that in low-energy collisions of very heavy ions the quasi-fission process dominates hindering formation of compound nucleus. This process is also caused by the shell effects, namely by the deep valleys on potential energy surface. Driving potentials for the $^{48}\text{Ca}+^{248}\text{Cm}$ fusion reaction are shown in Fig. 6 for two different initial orientations of the deformed $^{248}\text{Cm}$ nucleus. After overcoming the Coulomb barrier the fragments become first very deformed, then the mass asymmetry gradually decreases and the system finds itself in the quasi-fission valley with one of the fragments close to the doubly magic nucleus $^{208}\text{Pb}$ (see deep valley at $\eta \approx 0.4$ in Fig. 6). Experimental and calculated energy–mass distributions of the primary reaction products at the near-barrier energy of $E_{\text{c.m.}} = 203$ MeV is shown in Fig. 7. The large yield of the fragments in the region of doubly magic nucleus $^{208}\text{Pb}$ (and complimentary light fragments) is the most pronounced feature of the TKE-mass distribution. Note that a reasonable quantitative description of the QF processes was attained for the first time.

The probability for CN formation in this reaction was found to be very small and depended greatly on the incident energy. Due to a strong dissipation of kinetic energy just the fluctuations (random forces) define the dynamics of the system after the contact of two nuclei. At near barrier collisions, the excitation energy (temperature) of the system is rather low, the fluctuations are weak and the system chooses the most probable path to the exit channel along the quasi-fission valley (see Fig. 6). However at non-zero

![Fig. 6. Driving potentials for the nuclear system formed in $^{48}\text{Ca}+^{248}\text{Cm}$ collision at tip (left) and side (right) orientations of statically deformed $^{248}\text{Cm}$. The solid lines with arrows show schematically (without fluctuations) the projections of the QF trajectories (going to lead and tin valleys) and the path leading to formation of CN.](image-url)
excitation energy there is a chance for the nuclear system to overcome the multi-dimensional inner potential barriers and find itself in the region of the CN configuration. Within the Langevin calculations a great number of events should be tested to find this low probability. For the studied reaction, for example, only several fusion events have been found among more than $10^5$ total tested events [see dark region 4 in Fig. 7(c)].

Within our approach we estimated a possibility of SH element production in the asymmetric fusion reactions of nuclei heavier than $^{48}$Ca with transuranium targets. Such reactions can be used, in principle, for a synthesis of the elements heavier than 118. Evaporation residue (EvR) cross sections for the fusion reactions $^{50}$Ti+$^{244}$Pu, $^{50}$Ti+$^{243}$Am, $^{54}$Cr+$^{248}$Cm and $^{58}$Fe+$^{244}$Pu are shown in Fig. 8. SH elements beyond 118 may be synthesized also in the fusion reactions of symmetric nuclei (fission-like fragments). However, for such reactions an uncertainty in calculation of the cross sections for CN formation is rather large. Dashed and solid curves in Fig. 8(d) reflect this uncertainty in our estimations of the EvR cross sections in $^{136}$Xe+$^{136}$Xe fusion reaction. If the experiment (performed this
moment in Dubna) will give the EvR cross sections at the level of few pico-barns, then we may really dream about use of neutron-rich accelerated fission fragments for production of SH elements in the region of the “island of stability” (e.g., \( ^{132}\text{Sn}^{\text{+}}\rightarrow^{308}\text{Yb}^{\text{+}}\)).

5. Low–energy damped collisions

Low-energy damped collisions of very heavy transactinide nuclei (e.g., \( ^{238}\text{U}^{\text{+}}\rightarrow^{248}\text{Cm}^{\text{+}}\)) have been also used about thirty years ago for a synthesis of SH elements\(^{11,12}\). The cross sections were found to decrease very rapidly with increasing atomic number of surviving target-like fragments. However, Fm and Md neutron-rich isotopes have been produced at the level of 0.1 \( \mu \text{b} \). Recently it was shown\(^{13}\) that an existence of rather pronounced lead valley on the potential landscape of such giant nuclear systems may lead to the so-called “inverse” (anti-symmetrizing) quasi-fission process, in which one fragment transforms to the doubly magic nucleus \( ^{208}\text{Pb} \), whereas another one transforms to complementary SH element. In spite of rather high excitation energy, this neutron-rich superheavy nucleus may survive in neutron evaporation cascade giving us an alternative way for production of the neutron rich long-living SH elements (see Fig. 9).

Good agreement of the experimental data with our predictions was obtained recently for the near-barrier \( ^{238}\text{U}^{\text{+}}\rightarrow^{238}\text{U} \) damped collisions\(^{14}\). Nevertheless more detailed experiments have to be performed aimed on a study of the shell effects in mass transfer in low-energy collisions of heavy nuclei. For this purpose lighter nuclear systems may be also used. The mass distributions of the primary fragments in the \( ^{160}\text{Gd}^{\text{+}}\rightarrow^{186}\text{W}^{\text{+}}\) reaction calculated with and without the shell corrections to the potential energy are shown in Fig. 10. As can be seen at near barrier collision energies the shell effects may increase by two orders of magnitude the yield of the reaction products even for transfer of twenty nucleons.
Fig. 9. Yield of superheavy nuclei in collisions of $^{238}$U+$^{238}$U (dashed), $^{238}$U+$^{248}$Cm (dotted) and $^{232}$Th+$^{250}$Cf (solid lines) at 800 MeV center-of-mass energy. Solid curves in upper part show isotopic distribution of primary fragments in the Th+Cf reaction.

Fig. 10. Primary fragment mass distribution in the $^{160}$Gd+$^{186}$W reaction at 460 MeV center-of-mass energy calculated with (solid) and without (dashed histogram) shell corrections in potential energy.
Fig. 11. Landscape of potential energy of three-body configurations formed in collision of $^{238}\text{U}+^{238}\text{U}$ (see notations in Fig. 4).

We found also that in low-energy collisions of transactinides the shell effects may lead to formation of three-cluster configurations. In Fig. 11 the landscape of the potential energy surface is shown for a three-body clusterization of the nuclear system formed in collision of $\text{U}+\text{U}$. As can be seen the potential energy has rather deep minimum corresponding to the Pb-Ca-Pb–like configuration (or Hg-Cr-Hg) caused by the N=126 and Z=82 nuclear shells. Existence of this three-body clusterization can be proved.
experimentaly by a coincident detection of the two Pb–like fragments in collisions of transactinides. More flat radial dependence of the potential energy (as compared with a two-body system) is another feature of this three body configuration (see Fig. 12). Decay of U+U–like nuclear system into the three-body configuration may significantly prolong reaction time which could be important for spontaneous positron formation in super-strong electric field 15.

References