CLUSTERING PHENOMENA IN SUPERHEAVY NUCLEAR SYSTEMS

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Dynamics of heavy-ion low energy damped collisions is studied within the model based on the Langevin type equations. Shell effects on the multi-dimensional potential energy surface play an important role in these reactions. This leads to several local minima on the fission path of heavy nucleus — so called isomeric states which are nothing else but the two-cluster configurations with magic or semi-magic cores surrounded with a certain number of shared nucleons. In a giant nuclear system (formed, for example, in U + U collision) the three-body clustering configurations may also appear. 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.

1. Introduction
Cluster structure is usually set off against the shell structure of nuclei. However appearance of clusters themselves (compact pieces of nuclear matter) is conditioned just by the shell effects. In light nuclei these clusters are mainly alpha-particles. In heavy nuclear systems tightly packed nuclei (like $^{132}$Sn or $^{208}$Pb) may lead to energetically favorable two (or even three) center configurations. Such configurations play an important role in the fusion-fission processes. Recently a new approach was proposed\textsuperscript{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 mono-nucleus), 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. Our interest in damped collisions of heavy nuclei is conditioned by the necessity to clarify much better than before the dynamics of heavy nuclear systems at low excitation energies and also by a search for new ways for the production of neutron rich superheavy (SH) nuclei and isotopes.
2. Adiabatic Potential Energy and Shape Isomeric States

The interaction potential of separated nuclei may be calculated rather easily within the folding procedure with effective (density dependent) 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 models 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 ($E/A \sim \varepsilon_{\text{Fermi}}$ 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 (diabatic 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. 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 energy into 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, $f(t = 0) = 0$, $f(t >> \tau_{\text{relax}}) = 1$.

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 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 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. This limitation has been overcome recently in the extended version of the two-center shell model which we use here.

Within the two-center shell model the processes of compound nucleus formation (after contact of colliding nuclei), 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 $A_2$ surrounded with a certain amount of shared nucleons $\Delta A = A_{\text{CN}} = A_1 - A_2$. This is extremely important for interpretation of physical meaning of some deep minima on the potential energy surface.

The adiabatic driving potential for formation and decay of superheavy nucleus $^{296}_{116}$ at fixed deformations of both fragments is shown in Fig. 1 as a function of elongation and mass asymmetry and also as a function of charge numbers $Z_1$ and $Z_2$ (minimized over neutron numbers $N_1$ and $N_2$) at $R \leq R_{\text{cont}}$. It is easily to see that the shell structure, clearly revealing itself in the contact of two nuclei
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Fig. 1. Driving potential of nuclear system $^{296}$116 $\to$ $^{48}$Ca+$^{248}$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).

is also retained at $R < R_{\text{cont}}$ (see the deep minima in the regions of $Z_{1,2} \sim 50$ and $Z_{1,2} \sim 82$ in Fig. 1(b)). Following the fission path (dotted curves in Figs. 1(a), (b)) the nuclear system goes through the optimal configurations (with minimal potential energy) and overcomes the multi-humped fission barrier (Fig. 1(c)). These intermediate minima correspond to the shape isomer states. Thus, from the 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.

3. Quasi-Fission and SHE Formation

It is well known that in low-energy collisions of 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 $^{48}$Ca+$^{248}$Cm fusion reaction are shown in Fig. 2 for two different initial orientations of the deformed $^{248}$Cm nucleus.
After overcoming the Coulomb barrier the nuclei become first very deformed (dynamic deformations at contact significantly decreases the Coulomb energy), then the mass asymmetry gradually changes (due to nucleon exchange) 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. 2). 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. 3. 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 dependent 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. 2). However at non-zero 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 [see dark region 4 in Fig. 3(c)].

$^{249}\text{Cf}$ ($T_{1/2} = 351$ y) is the heaviest available target which may be used in experiment. Thus, to get SH elements with $Z > 118$ in fusion reactions we should proceed to heavier than $^{48}\text{Ca}$ projectiles. Strong dependence of the calculated EvR cross sections for the production of SH elements on mass-asymmetry in the entrance channel makes the nearest to $^{48}\text{Ca}$ projectile, $^{50}\text{Ti}$, most promising for further
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Fig. 3. Experimental (a) and calculated (b) TKE-mass distributions of reaction products in collision of $^{48}\text{Ca}+^{248}\text{Cm}$ at $E_{\text{c.m.}} = 203$ MeV. (c) Contributions of DI (1), QF (2,3) and fusion-fission (4) processes into inclusive mass distribution. (d) One of the trajectories in collision of $^{48}\text{Ca}+^{248}\text{Cm}$ leading to QF channel (2).

synthesis of SH nuclei. The calculated excitation functions for synthesis of 117, 119 and 120 SH elements in the fusion reactions of $^{50}\text{Ti}$ with $^{243}\text{Am}$, $^{249}\text{Bk}$ and $^{249}\text{Cf}$ targets are shown in Fig. 4. As can be seen, the estimated EvR cross sections for 117, 119 and 120 SH elements synthesized in the $^{50}\text{Ti}$ induced reactions are quite reachable at available experimental setups.
4. Low-Energy Damped Collisions

The idea to take advantage of the shell effects for the production of SH nuclei in the multi-nucleon transfer processes of low-energy heavy ion collisions was proposed recently in Ref. 10. The shell effects are known to play an important role in fusion of heavy ions with actinide targets driving the nuclear system to the quasi-fission channels (into the deep lead and tin valleys) and, thus, decreasing the fusion probability. On the contrary, in the transfer reactions the same effects may lead to enhanced yield of SH nuclei. It may occur if one of heavy colliding nuclei, say $^{238}$U, gives away nucleons approaching to double magic $^{208}$Pb nucleus, whereas another one, say $^{248}$Cm, accepts these nucleons becoming superheavy in the exit channel — the so called “inverse” (anti-symmetrizing) quasi-fission process.\(^2\)

Here we extended our approach taking into consideration neutron and proton asymmetries separately instead of one mass-asymmetry parameter used before.\(^2\) The potential energy surface of the giant nuclear system formed in collision of $^{238}$U and $^{248}$Cm nuclei is shown in Fig. 5. It is calculated within the two-center shell model for a configuration of two touching nuclei (with fixed value of dynamic deformation $\beta_2 = 0.2$) depending on numbers of transferred protons and neutrons. The initial configuration of $^{238}$U and $^{248}$Cm touching nuclei is shown by the crosses.

In low-energy damped collisions of heavy ions just the potential energy surface regulates to a great extent the evolution of the nuclear system. From Fig. 5 one sees that in the course of nucleon exchange the most probable path of the nuclear system formed by $^{238}$U and $^{248}$Cm goes along the line of stability with formation

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{potential_energy_surface.png}
\caption{Landscape of potential energy surface of the nuclear system formed in collision of $^{238}$U with $^{248}$Cm. Open circles correspond to the most neutron-rich nuclei synthesized in $^{48}$Ca induced fusion reactions while the filled ones show SH nuclei produced in the “cold” fusion with lead target. The dotted line shows the most probable evolution in multi-nucleon transfer process.}
\end{figure}
of SH nuclei which have many more neutrons as compared with those produced in the “cold” and “hot” fusion reactions. Due to fluctuations even more neutron rich isotopes of SH nuclei may be formed in such transfer reactions.

The yield of survived SH elements produced in the low-energy collisions of actinide nuclei is rather low, though the shell effects give us a definite gain as compared to a monotonous exponential decrease of the cross sections with increasing number of transferred nucleons (no shell effects). In Fig. 6 the calculated EvR cross sections for production of SH nuclei in damped collisions of $^{238}$U with $^{248}$Cm at 800 MeV center-of-mass energy are shown along with available experimental data. As can be seen, really much more neutron rich isotopes of SH nuclei might be produced in such reactions.

5. Three-Cluster Configurations of Giant Nuclear System

It is interesting to calculate the adiabatic potential energy also for a three-center configuration. Such clusterization might appear in a 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. 7) only as a
Fig. 7. Landscape of potential energy of three-body configurations formed in collision of $^{238}\text{U} + ^{238}\text{U}$ (see notations in Fig. 7).

function of $Z_1$ and $Z_3$ at fixed deformations ($\delta_1 = \delta_2 = \delta_3 = 0.1$) of the fragments being in contact.

For the giant nuclear systems formed in low-energy collisions of actinide nuclei the shell effects may really lead to formation of three-cluster configurations. In Fig. 7 the landscape of the potential energy surface is shown for a three-body clusterization of the nuclear system formed in collision of U+U. 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 experimentally 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. 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.\(^{11}\)

References