Dynamics of dinuclear system formation and its decay in heavy ion collisions

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Abstract. A variety of phenomena connected with the formation of a dinuclear complex is observed in the heavy ion collisions at low energies. The dinuclear system model allows us to analyze the experimental data and to interpret them by comparison of the partial capture, fusion and evaporation residue cross sections measured for the different reactions leading to the same compound nucleus. The comparison of theoretical and experimental values of the mass and angular distributions of the reaction products gives us a detailed information about reaction mechanism forming the observed yields. The observed very small cross sections of the evaporation residues may be explained by the strong fusion hindrance and/or instability of the heated and rotating compound nucleus and smallness its survival probability. The fusion hindrance arises due to competition between complete fusion and quasifission while the smallness of survival probability is connected with the decrease of the fission barrier at large excitation energy and angular momentum of compound nucleus.

1. Introduction

In the heavy ion collisions at low energies, a variety of phenomena is observed, which are connected with the formation of a dinuclear complex. Deeply inelastic collisions have been studied extensively over a wide range of energies and masses [1]. The multinucleon transfer and energy dissipation mechanisms of these reactions are very similar with the ones of the full momentum transfer (capture) reactions. The difference between deep inelastic collisions and quasifission reactions is determined by the lifetimes of dinuclear system (DNS) formed as intermediate system which consists of interacting nuclei with indestructible cores and excited nucleons in high-lying quantum states. Some of these excited nucleons form the neck or overlap region between constituents of DNS. The nucleon exchange mechanism at dissipation of the relative motion energy of the colliding nuclei was theoretically studied in Ref.[2, 3]. The basic points of those methods were developed to study deep inelastic and quasifission processes which are used to explain the hindrance to complete fusion [4].

The set of the successful experimental results in the synthesis of superheavy elements stimulated great efforts to experimental and theoretical investigations of the fusion-fission processes with massive nuclei. The very small cross sections $\sigma_{ER}$ of the evaporation residues...
observed in the recent experiments [5, 6, 7] may be explained by the strong fusion hindrance
and/or instability of the heated and rotating compound nucleus [8].

The experimental knowledge about fusion-fission reactions at sub- and near-barrier energies
has grown considerably in the last twenty years. The theoretical models are able to reproduce
the main features of such processes, even to make predictions of the cross sections for synthesis
of superheavy elements which are more or less close to the experimental data. But properly
understanding the fusion dynamics for heavy systems requires many more ingredients. The
necessity of more experimental data to disentangle various concurrent effects, is clearly felt. A
full understanding of all steps of the reaction dynamics is very important for the challenging
issue of superheavy element production and new isotopes far from the valley of stability.

Dynamics of complete fusion and role of the entrance channel in formation of the reaction
products in heavy ion collisions are questionable or they have different interpretation still
nowadays. For example, what mechanism of fusion makes the main contribution to formation
of compound nucleus: an increase of the neck between interacting nucleus or multinucleon
transfer at a relatively restricted neck size? How is large the overlap between angular
momentum distributions of dinuclear system and compound nucleus which determine the
angular distribution of reaction products, cross sections of evaporation residue, fusion-fission
and quasifission products? There is an ambiguity in separation of fusion-fission fragments from
the quasifission and fast fission products. Still unclear surely a law of the distribution of the
excitation energy of DNS between its constituent fragments. Therefore, it is interesting to study
the mechanism of deep inelastic and quasifission reactions forming binary fragments accompanied
by neutron and gamma quantum emissions. The analysis of a correlation angular, mass-energy
distributions of the registered fragments and neutron and gamma quantum characteristics allows
us to obtain useful knowledge about complete fusion mechanism.

2. Difference and similarity of quasifission and deep inelastic reactions
An investigation of dissipation dynamics of the deep inelastic and quasifission reactions is useful
to establish relaxation times of different degrees of freedom in heavy ion collisions at low energies.
From an analysis of the experimental data of the mass-angle distributions of the binary reaction
products and gamma-quanta of giant dipole resonances we can conclude that a study of the
DNS stage of these dissipative processes is perspective. Because a sufficient part of the reaction
time of the dissipative processes in heavy ion collisions belongs to this stage, particularly for the
massive system, as well as for the case of colliding nuclei with the nearly equal charge (mass)
numbers. Qualitative difference between deep inelastic and quasifission reactions is that the full
momentum transfer does not take place in the former mechanism while it occurs in the latter
one. The classification of the experimental data of binary products as ones corresponding to the
deep inelastic collision or capture reactions (quasifission and fusion-fission) is based on the mass
distribution characteristics only: projectile-like and target-like products with the total kinetic
energies (TKE) around the Viola systematics [9] are considered as products of deep inelastic
collisions. The authors of Ref. [10] attributed the all events with energy losses larger than 8–15
MeV and with fragments of below 40 mass units to deep inelastic collision at the analysis of the
experimental data of the $^{32}$S+$^{182}$W reaction.

The capture, deep inelastic and complete fusion reaction cross sections are presented in Fig.
1. The difference between capture and complete fusion cross sections is the quasifission cross
section:

$$\sigma_{\text{cap}} = \sigma_{\text{fus}} + \sigma_{\text{qfis}}.$$   (1)

Unfortunately, a possibility of the mixing mass-angle distributions of the quasifission and deep
inelastic reactions is not studied well because the nature of quasifission has been not established
yet.
Figure 1. The experimental data for capture (dot-dashed line), complete fusion (solid line) and deep inelastic collision (dashed line) events for the $^{32}\text{S}+^{182}\text{W}$ reaction [10].

The difference between capture and deep inelastic reactions can be found theoretically from the analysis of the results of dynamical calculations by solving the equations of motion for the radial distance (Eq. 2), angular momentum (Eq. 6) and surface vibrations for quadrupole and octupole multipolarity (Eq. 4) (see Fig. 2) for the $^{48}\text{Ca}+^{208}\text{Pb}$ reaction.

The quasifission occurs at the full momentum transfer and it belongs to the capture reactions when the system traps into potential well as in Fig. 2(a) and the decay time of DNS, which is formed in this mechanism, is determined by the size of the potential well, by the values of excitation energy $E_{DNS}^*$ and friction coefficients (radial and tangential).

In the deep inelastic reactions, DNS is not trapped into potential well because the DNS momentum decreases up to zero and relative distance between centers of mass of projectile and target nuclei reached the minimum value (see Fig. 2(b). Then the relative distance $R$ increases due to repulsive forces. Although the kinetic energy of the relative motion goes on to be dissipated DNS can overcome the Coulomb barrier from intrinsic part to outside of the potential well and we observed two products after interaction and exchanging nucleons. Therefore, the interaction time of colliding nuclei in deep inelastic collision is small in comparison with the one in capture reactions. The friction coefficients and the size of the potential well plays crucial role in calculations of capture events by solving the following equations [4, 11]:

$$
\mu(R, \alpha_1, \alpha_2) \ddot{R} + \gamma_R(R, \alpha_1, \alpha_2) \dot{R}(t) = F(R),
$$

$$
F(R, \alpha_1, \alpha_2) = - \frac{\partial V(R, \alpha_1, \alpha_2)}{\partial R} - \dot{R} \frac{\partial \mu(R)}{\partial R},
$$

$$
D_{\beta, \beta'}(t) + \gamma_{\beta}(R) \dot{\beta}_i(\alpha_1, \alpha_2, t) = F_{\beta}(R)
$$

$$
F_{\beta}(R) = - \frac{\partial V(\beta_i, \alpha_1, \alpha_2)}{\partial \beta_i}
$$

$$
dL dt = \gamma_{\beta}(R, \alpha_1, \alpha_2) R(t) \left( \dot{R}(t) - \dot{\theta}_1 R_{1\text{eff}} - \dot{\theta}_2 R_{2\text{eff}} \right),
$$
Figure 2. Capture (a) and deep inelastic collision (b) for the $^{48}\text{Ca}+^{208}\text{Pb}$ reaction.

\[ L_0 = J_R(R, \alpha_1, \alpha_2) \dot{\theta} + J_1 \dot{\theta}_1 + J_2 \dot{\theta}_2, \]  
\[ E_{\text{rot}} = \mu(R, \alpha_1, \alpha_2) \dot{R}^2/2 + J_R(R, \alpha_1, \alpha_2) \dot{\theta}^2 + J_1 \dot{\theta}_1^2 + J_2 \dot{\theta}_2^2, \]

where \( R \equiv R(t) \) is the relative motion coordinate; \( \dot{R}(t) \) is the corresponding velocity; \( \alpha_1 \) and \( \alpha_2 \) are the orientation angles between beam direction and axial symmetry axis of the projectile and target, respectively; \( L_0 \) (\( L_0 = l_0 \hbar \)) and \( E_{\text{rot}} \) are defined by initial conditions; \( J_R \) and \( \dot{\theta} \), \( J_1 \) and \( \dot{\theta}_1 \), \( J_2 \) and \( \dot{\theta}_2 \) are moment of inertia and angular velocities of the DNS and its fragments, respectively; \( \gamma_R \) and \( \gamma_\theta \) are the friction coefficients for the relative motion along \( R \) and the tangential motion when two nuclei roll on each other’s surfaces, respectively; \( \omega_\lambda^{(i)} \), \( \gamma_\lambda \) and \( D_\lambda^{(i)} \) are frequency, damping and mass coefficients for the surface vibration multipolarity \( \lambda \), respectively; \( V(R, \alpha_1, \alpha_2) \) is the nucleus-nucleus potential calculated by the double folding procedure [4, 12].

The capture includes complete fusion and quasifission events. The quasifission time is estimated by the formula

\[ \tau_{\text{DNS}}(T_Z) = \frac{\hbar}{\Gamma_{\text{qfiss}}(T_Z)} \]  

if we know the excitation energy \( E_{\text{DNS}}^* \) and quasifission barrier \( B_{qf} \) of the dinuclear system for its decay on fragments with charge numbers \( Z \) and \( Z_{\text{tot}} - Z \), by using the one-dimensional Kramers rate [13, 14, 15]

\[ \Gamma_{\text{qfiss}}(\Theta) = \frac{K_{\text{rot}}^{(\text{DNS})}}{K_{\text{rot}}^{(\text{CN})}} \omega_m \left( \sqrt{\gamma^2/(2\mu_{qf})^2 + \omega_{qf}^2} - \gamma/(2\mu_{qf}) \right) \times \exp \left( -B_{qf}/T_Z \right) / (2\pi\omega_{qf}). \]
Figure 3. Quasifission barrier is a depth of the well in the nucleus-nucleus interaction potential $V(R)$ (a); potential well is replaced by the harmonic oscillator with frequency $\omega_m$ and potential barrier is replaced by the inverted harmonic oscillator with frequency $\omega_b$ which are used to calculate the decay time of DNS into two fragments.

Here the frequency $\omega_m$ and $\omega_b$ are found by the harmonic oscillator approximation to the shape of the nucleus-nucleus potential $V(R)$ for the given DNS configuration $(Z, Z_{tot} - Z)$ on the bottom of its pocket placed at $R_m$ and on the top (quasifission barrier) placed at $R_b$ (see Fig. 3), respectively:

1. $\omega_{m}^2 = \mu_{qf}^{-1} \left| \frac{\partial^2 V(R)}{\partial R^2} \right|_{R=R_m}$,

2. $\omega_{b}^2 = \mu_{qf}^{-1} \left| \frac{\partial^2 V(R)}{\partial R^2} \right|_{R=R_b}$.

The nucleus-nucleus potential $V(Z, A, \ell, R)$ includes the Coulomb $V_{\text{Coul}}(Z, A, R)$, nuclear $V_N(Z, A, R)$ and rotational $V_{\text{rot}}(Z, A, R, \ell)$ parts:

$$V(Z, A, \ell, R) = V_{\text{Coul}}(Z, A, R) + V_N(Z, A, R) + V_{\text{rot}}(Z, A, R, \ell),$$

where $R$ is the distance between the centers of the nuclei. Details of the calculation can be found in Refs. [16, 17].

The calculated values of $\hbar\omega_m$ and $\hbar\omega_q$ were equal to 46.52 MeV and 22.37 MeV, respectively. The used value of the friction coefficient $\gamma$ is equal to $8 \cdot 10^{-22}$ MeV fm$^{-2}$s which was found from our calculations; $\mu_q \approx \mu = A_1 \cdot A_2 / A_{CN}$, where $A_1$ and $A_2$ are the mass numbers of the quasifission fragments.

The collective enhancement factor of the rotational motion $K_{\text{rot}}$ to the level density should be included because the dinuclear system is a good rotator. It is calculated by the well known expression [18]:

$$K_{\text{rot}}(E_{DNS}) = \begin{cases} 
(\sigma_{\perp}^2 - 1)f(E_{DNS}) + 1, & \text{if } \sigma_{\perp} > 1 \\
1, & \text{if } \sigma_{\perp} \leq 1
\end{cases}.$$
where \( \sigma_\perp = J_{\text{DNS}} T / \hbar^2 \); 
\( f(E) = (1 + \exp((E - E_{\text{cr}})/d_{\text{cr}})) \); 
\( E_{\text{cr}} = 120 \tilde{\beta}^2 A^{1/3} \) MeV; 
\( d_{\text{cr}} = 1400 \tilde{\beta}^2 A^{2/3} \). \( \tilde{\beta} \) is the effective quadrupole deformation for DNS. We find it from the calculated \( J_{\text{DNS}} \) [19].

DNS can have long lifetime (\( \tau_{\text{DNS}} \)) if it is formed at capture: the value of \( \tau_{\text{DNS}} \) depends on the depth of the potential well (\( B_{d^0} \)), DNS excitation energy (\( E_{\text{DNS}}^* \)) at the given value of angular momentum \( \ell \) and its moment of inertia \( J_{\text{DNS}} \parallel [19] \).

\[
J_{\text{DNS}}^\parallel = J_1 + J_2 + M_1 d_{\parallel}^{(1)2} + M_2 d_{\parallel}^{(2)2},
\]
\[
J_{\text{DNS}}^\perp = J_1 + J_2 + M_1 d_{\perp}^{(1)2} + M_2 d_{\perp}^{(2)2}
\]

where \( d_{\parallel}^{(i)} \) (\( d_{\perp}^{(i)} \)) is the distance between the center of mass of the fragment \( i \) (\( i = 1, 2 \)) and the axis corresponding to the largest (smallest) moment of inertia of DNS.

Due to the shell effects as the quantum states of the neutron and proton systems of the interacting nuclei we have DNS as a molecule of nuclei which don’t fuse immediately. Therefore, the peculiarities of the DNS stage influence the formation of the reaction products with magic proton or neutron numbers. Shell effects are observed as cluster states in the large amplitude collective motions of nuclei. The observed cluster emission, mass-charge distribution of the quasifission fragments and spontaneous asymmetric fission of Th, U and Cf isotopes proved the strong role of shell structure. Reactions of heavy ion collisions and fission (spontaneous and induced) processes can be studied well using the DNS concept.

A characteristic feature of the deep inelastic processes is that the target and projectile identity is largely preserved. In Ref. [20], only for low TKE of the outgoing products (energies below the Coulomb repulsion, \( V_C \), of touching spheres) a small mass drift is found. In these studies, it was difficult to establish the magnitude of such a drift unambiguously, because a relatively small initial mass asymmetry made it difficult to separate drifting projectile- and target-like distributions from the wings of a mass symmetric component.

We would like to stress the importance to distinguish the scattering processes, with no or negligible mass drift, i.e. quasi- and deep inelastic processes, from capture reactions that exhibit a small or large mass drift, usually but not always going to the full mass symmetry configuration and leading to decay into two almost equally large fragments.

The analysis of the mass (charge) distribution of the binary reaction products showed in Refs. [20] and [21, 22] showed that in collisions of nuclei with the magic proton or/and neutron
numbers at the around Coulomb barrier energies charge or mass drift may be small in the capture reactions too. In Ref. [20], an averaged charge number of the projectile-like products $^{86}$Kr+$^{166}$Er was equal to the initial value $< Z_{PLF} > = 36$ up to the total kinetic energy (TKE) loss of 180 MeV. Our theoretical results presented in Fig.5 show that deep inelastic and quasifission reactions products are mixed having the same charge number because the driving potential has a minimum at $Z = 36$ corresponding to projectile charge number. The similar phenomenon was observed in the $^{48}$Ca+$^{208}$Pb reaction [22]. The small drift from the initial charge number of the projectile-like products does not mean that the deep inelastic reactions occurred only. A maximum of the charge distribution can be concentrated at the charge value corresponding to the minimum of the potential energy surface. This phenomenon was reproduced by the DNS model and our results of the charge and mass distributions of the deep inelastic collisions (A) and quasifission (B) fragments are presented in Fig.4.

Understanding the mass drift is basic for investigation of the reaction mechanism. It is relevant to the deep inelastic process and to the capture processes. In capture reactions with heavy nuclei, the direction of the mass drift could influence the probability for the compound nucleus formation: a drift towards asymmetry could favour true compound nucleus formation (with subsequent evaporation of neutrons leading to the observed evaporation residues or fission fragments), whereas a drift towards symmetry could favour quasifission without compound nucleus formation.

3. Difference between capture and complete fusion for light and massive system
For light or medium-heavy systems, capture inside the Coulomb barrier leads to complete fusion, so that the capture (or barrier-passing) cross section may be equal to the complete fusion cross-

Figure 5. Time dependence of the charge distribution of deep inelastic collision and quasifission products for the $^{86}$Kr + $^{166}$Er reaction.
Figure 6. Potential energy surface calculated for the DNS formed in the $^{96}$Zr$^{+}$124Sn reaction (a); driving potential built by connection of minima of the potential wells for all values of charge asymmetry of DNS (b): $B_{\text{fus}}^{*}$ being considered as the intrinsic fusion barrier for the charge asymmetry $Z = 40$; potential well with depth $B_{\text{qf}}$ which is used as a quasifission barrier (c). The minimum value of the potential well is at $R = R_m$. 

section. According to the DNS concept the hindrance to complete fusion is connected with the presence of quasifission process as a competing channel which leads to formation of binary products without formation of compound nucleus [4, 12]. For the analysis and study of the hindrance to complete fusion we calculate the potential energy surface for DNS formed during interaction of nuclei as a sum of the reaction energy balance ($Q_{\text{gg}} - \text{value}$) and nucleus-nucleus interaction $V(R)$:

$$U_{\text{driv}}(Z_1, R, \ell) = Q_{\text{gg}} + V(R),$$

where $Q_{\text{gg}} = B_1 + B_2 - B_{\text{CN}}$; $B_1$, $B_2$ and $B_{\text{CN}}$ are the binding energies of the constituents of the DNS and compound nucleus, respectively. The values of the binding energies are obtained from [23, 24]. The evolution of DNS with given initial charge numbers of projectile- and target-nucleus ($Z_P$ and $Z_T$) is determined by the potential energy surface. As an example, the potential energy surface calculated for the $^{96}$Zr$^{+}$124Sn reaction is presented in Fig. 6(a). The approaching path of the projectile to the target nucleus occurs along the $R$-axis which is the distance between mass centers of colliding nuclei. Overcoming the Coulomb barrier the system starts to lose its kinetic energy of relative motion due to particle-hole excitation of nucleons and nucleon exchange as it is shown in Fig. 2. In this Section and further we consider capture reactions when the full momentum transfer in heavy ion collision occurred. The evolution of DNS along charge asymmetry takes place along valley on the potential energy surface. The driving potential $U_{\text{driv}}$ is the curve lying on the bottom of this valley. A presence of a hindrance to complete fusion by multinucleon transfer can be found by estimation of the intrinsic fusion barrier $B_{\text{fus}}^{*}$ as the difference between the values of $U_{\text{driv}}$ corresponding to the initial charge asymmetry and
observe hindrance to complete fusion for the colliding energies which can be transformed to hollow at large values of angular momentum. As a result we can

to the CN part there is no hindrance to complete fusion because the maximum value of U

190

values of

light systems the capture and complete fusion cross sections are equal because

P

is equal to zero. To see a dependence of the hindrance to complete fusion on the orbital angular

momentum \( \ell \) we calculate partial fusion cross section as a function of the collision energy \( E_{\text{c.m.}} \):

\[
\sigma^{(\ell)}_{\text{fus}}(E_{\text{c.m.}}) = \sigma^{(\ell)}_{\text{cap}}(E_{\text{c.m.}}) P^{(\ell)}_{\text{CN}}(E_{\text{c.m.}}),
\]

(17)

\( P^{(\ell)}_{\text{CN}} \) is the fusion probability in competition between complete fusion and quasifission. For light systems the capture and complete fusion cross sections are equal because \( P^{(\ell)}_{\text{CN}} = 1 \) for the values of \( \ell \) for which intrinsic fusion barrier \( B^{*}_{\text{fus}} \) is equal to zero. To see a dependence of the fusion probability on the total charge and mass numbers of the colliding nuclei we compare the driving potentials \( U_{\text{driv}}(Z) \) which were calculated by the use of the liquid-drop model to obtain the binding energies \( B_{1}, B_{2}, \) and \( B_{\text{CN}} \) for the four reactions leading to compound nuclei \( ^{120}\text{Sn}, ^{190}\text{W}, ^{236}\text{U} \) and \( ^{252}\text{Cf} \) (see, Fig. 7). One can say that for all reactions leading to the CN \( ^{120}\text{Sn} \) there is no hindrance to complete fusion because the maximum value of \( U_{\text{driv}} \) is in the middle part \( Z_{1} = Z_{2} \). Therefore, there is no intrinsic fusion barrier, \( B^{*}_{\text{fus}} = 0 \). For the reactions leading to the CN \( ^{190}\text{W} \) it is seen that approximately \( B^{*}_{\text{fus}} = 0 \), but there is the plateau at \( 20 < Z < 50 \) which can be transformed to hollow at large values of angular momentum. As a result we can observe hindrance to complete fusion for the colliding energies \( E_{\text{c.m.}} \) at the near and above Coulomb barrier. The dependence of the driving potential on the DNS angular momentum for

Figure 7. Driving potentials calculated for the DNS leading to formation of the compound nuclei \( ^{120}\text{Sn} \) (a), \( ^{190}\text{W} \) (b), \( ^{236}\text{U} \) (c) and \( ^{252}\text{Cf} \) (d).
Figure 8. The dependence of the driving potential on the DNS angular momentum $\ell_{DNS}$ for the reactions leading to the CN $^{190}$W: $\ell = 0$ (solid line), 40 (dashed line), 60 (dotted line), 80 (dot-dashed line), and 100 (double dot-dashed line).

the reactions leading to the CN $^{190}$W is demonstrated in Fig. 8. The increase of $\ell$ leads to the charge symmetric part of the driving potential. Consequently, the intrinsic fusion barrier, i.e. a hindrance to the complete fusion appears for the charge symmetric reactions leading to formation of $^{190}$W at large angular momentum. The increase of the hindrance for the massive system was analyzed in Ref. [25].

4. Cold and hot fusion mechanisms in DNS model

Dynamics of complete fusion and role of the entrance channel in formation of heavy ion collision reactions are questionable or/and they have different interpretation still now. For example, what mechanism of fusion makes the main contribution to formation of compound nucleus:

- the increase of the radius of neck between interacting nuclei or multinucleon transfer at relatively restricted neck size?
- peculiarities of angular momentum distribution of DNS and compound nucleus which determine the angular distribution of reaction products, cross sections of evaporation residue, fusion-fission and quasifission products;
- separation of fusion-fission fragments from the quasifission and fast fission products;
- distribution of the excitation energy between different degrees of freedom, as well as between reaction products.

In the DNS concept [26], the evaporation residue cross section at collision energy $E_{c.m.}$ is factorized as follows:

$$\sigma_{ER}(E_{c.m.}) = \sum_{\ell=0}^{\ell_f} \sigma_{\text{fus}}^{(\ell)}(E_{c.m.}) W_{\text{surf}}^{(\ell)}(E_{c.m.}),$$

(18)
Figure 9. An explanation of the difference between “hot” (a) and “cold” (b) fusion on the potential energy surface of DNS for the $^{76}$Ge+$^{208}$Pb reaction. The arrows (c) and (d) show the complete fusion and quasifission directions, respectively.

where $\sigma_{\text{fus}}^{(\ell)}$ is the partial cross section of the complete fusion of the projectile and target nuclei; $W_{\text{sur}}^{(\ell)}$ is the survival probability against fission of the heated and rotating nucleus at each step of the de-excitation cascade by evaporation of neutrons, protons and light particles up to formation of the evaporation residue; $\ell_f$ is the value of CN angular momentum at which its fission barrier disappears: $W_{\text{sur}}^{(\ell)}(E) = 0$ for $\ell > \ell_f$. The decrease of $W_{\text{sur}}$ by increasing the excitation energy is determined by the increase of rate of competition between fission and emission of particles.

At synthesis of the superheavy elements $Z > 114$ the observed cross sections of the evaporation residues are near or less than 1 pb. The smallness of $\sigma_{\text{fus}}$ or/and $W_{\text{sur}}$ in formula (18) leads to small values of the measured cross section $\sigma_{\text{ER}} \sim 1$pb.

The experience of the synthesis of superheavy elements showed that the used reactions can be separated into "cold" and "hot" fusion reactions. In the "cold fusion" reactions the excitation energy the formed compound nucleus $E_{\text{CN}}^*\ell$ is less than 20 MeV [6, 7] while in "hot fusion" reactions $E_{\text{CN}}^*\ell$ is more 25 MeV [5]. In the "cold fusion" reactions the evaporation residue nuclei are formed after emission 1 or 2 neutrons from the heated and rotating compound nucleus. In the "hot fusion" reactions 3 or more neutron emission cascade preceded the evaporation residue formation. The charge asymmetry of the entrance channel determines the type of reaction: "cold fusion" reactions with the $^{208}$Pb and $^{209}$Bi targets used to synthesize superheavy elements Darmstadtium, Roentgenium and Copernicium were more mass symmetric than the "hot fusion" reactions with the $^{48}$Ca projectile on the actinide targets used to synthesize more heaviest elements $Z = 114$–118 in the Flerov Laboratory of the Nuclear Reactions of Joint Institute for Nuclear Research. In Fig.9, the arrow "a" shows the path of the entrance channel leading to the "hot fusion" reactions while the arrow "b" shows the path leading to "cold fusion" reactions. Due to peculiarities of the landscape of the potential energy surface for the massive system,
the excitation energies of DNS and compound nucleus for the symmetric charge numbers (large reaction $Q_{gg}$ values) are smaller in the entrance channel with the $^{208}$Pb target-nucleus (around arrow "b"): $E_{CN}^* = E_{c.m.} + Q_{gg}$. It is seen from the shape of the potential energy surface that the “hot fusion” reaction can not be made “colder” because capture of projectile by target-nucleus becomes impossible by decreasing the beam energy. Note, for this system leading to formation of $^{284}$114, the “cold fusion” reaction $^{76}$Ge+$^{208}$Pb can not be made “warmer” because if we increase the beam energy significantly higher than the Coulomb barrier the system can not be captured due to small size of the potential well in the nucleus-nucleus interaction and restricted value of the friction coefficient for radial motion: we observe only deep inelastic collisions as in Fig. 2(b). One can say that, for the “cold fusion” reaction, the increase of the beam energy enough higher than the Coulomb barrier does not lead to increase the fusion cross section as it is expected from the extra-extra push model [27]. In the “cold fusion” reactions with $^{208}$Pb and $^{209}$Bi targets an increase of the projectile charge number leads to the drastic hindrance to complete fusion as a result of the increase of contributions of the quasifission and deep inelastic collisions. This phenomenon explained the observed smallest cross section in synthesis of superheavy element $Z = 113$ in the $^{64}$Zn+$^{209}$Bi reaction [7].

### Table 1. Comparison of the hindrance to formation of compound nucleus in the “cold” and “hot fusion” reactions used at synthesis of superheavy elements.

| Reactions | $\eta = \frac{A_2 - A_1}{A_1 + A_2}$ | $P_{CN}$ | Reactions | $\eta = \frac{A_2 - A_1}{A_1 + A_2}$ | $P_{CN}$ |
|-----------|---------------------------------|--------|-----------|---------------------------------|--------|
| $^{64}$Ni+$^{208}$Pb$^\dagger$ | 0.529 | $1.4 \times 10^{-7}$ | $^{48}$Ca+$^{244}$Pu$^\ddagger$ | 0.671 | $4.96 \times 10^{-2}$ |
| $^{64}$Ni+$^{209}$Bi$^\dagger$ | 0.531 | $7.0 \times 10^{-8}$ | $^{48}$Ca+$^{243}$Am$^\ddagger$ | 0.670 | $5.02 \times 10^{-2}$ |
| $^{70}$Zn+$^{208}$Pb$^\dagger$ | 0.496 | $2.5 \times 10^{-9}$ | $^{48}$Ca+$^{248}$Cm$^\dagger$ | 0.676 | $1.13 \times 10^{-2}$ |
| $^{70}$Zn+$^{209}$Bi$^\dagger$ | 0.498 | $5.2 \times 10^{-10}$ | $^{48}$Ca+$^{249}$Bk$^\ddagger$ | 0.677 | $5.06 \times 10^{-3}$ |
| $^{76}$Ge+$^{208}$Pb$^\dagger$ | 0.465 | $1.2 \times 10^{-10}$ | $^{48}$Ca+$^{249}$Cf$^\ddagger$ | 0.677 | $7.14 \times 10^{-3}$ |

$^\dagger$The estimations from Ref.[4]
$^\ddagger$The estimations from Ref. [16]
$^\dagger$The estimations from Ref. [28]

In Fig. 10 we presented comparison of the ER cross sections obtained by the DNS model (dot-dashed line) with the experimental data for the synthesis of Roentgenium and Copernicium in the $^{64}$Ni+$^{209}$Bi and $^{70}$Zn+$^{208}$Pb reactions, respectively. The dashed and solid lines in Fig. 10 show the theoretical results for the quasifission and complete fusion excitation functions. The ratio of the complete fusion to capture excitation function ($P_{CN}$) shows how strong the hindrance to complete fusion (see Eq. (17)) due to very small values of fusion cross section in comparison to capture cross section. The event at $E_{CN}^* = 9$ MeV in the $^{70}$Zn+$^{208}$Pb reactions (right panel) was described and published in [4] while the second event at $E_{CN}^* = 12$ MeV was measured after the appearance of the cited paper. One can say that the second event was predicted in [4]. So, we concluded that smallest cross section at synthesis of Copernicium is caused mainly by the huge contribution of the quasifission events that is inherent for the “cold fusion” reactions. This conclusion was deduced from the theoretical analysis which included the realistic nuclear shell effects in calculation of the potential energy surface. The dotted lines in Fig. 10 shows the fission barrier of compound nucleus $B_{fis}$ which is a function of its excitation energy and angular momentum.

The “hot fusion” reactions were favorable for the synthesis of the superheavy elements $Z > 112$: new superheavy elements $Z = 114–118$ have been obtained at the Flerov Laboratory of
Nuclear Reactions of JINR (Dubna, Russia) [5] during the last decade. The ER cross sections in synthesis of superheavy elements $Z = 114$ and $Z = 116$ were confirmed in the recent experiments performed in the Lawrence Berkeley Laboratory [29] and GSI (Darmstadt) [30], respectively. The main reason allowing the experimentalists to succeed in the “hot fusion” reactions or the synthesis of the superheavy elements $Z = 114–118$ is smallness of the intrinsic fusion barrier $B_{\text{fus}}^*$ which decreased the hindrance to complete fusion. But large values of the excitation energy and angular momentum of the compound nucleus formed in the “hot fusion” reactions decrease its survival probability against fission. Therefore, the cross sections of evaporation residues in synthesis of superheavy elements decreases from 3–4 picobarns for $Z = 114$ up to 0.5 pb for $Z = 118$. In Table 1 we compare the hindrance to formation of compound nucleus in the “cold” and “hot fusion” reactions which were used at synthesis of superheavy elements. The difference in the hindrances presented by $R_{\text{CN}} = \sigma_{\text{fus}}/ (\sigma_{\text{fus}} + \sigma_{\text{qfis}})$ in both types of reactions is evidently seen: i) the hindrance to complete fusion is stronger for the “cold fusion” reactions in comparison with “hot fusion” reactions; ii) the hindrance to “cold fusion” reactions increases drastically by increasing of the projectile charge number while it changes slowly in “hot fusion” reactions by increasing the target charge number. This is explained by strong change of the potential energy surface around the charge asymmetry $Z = 82$ than in the region $Z = 20$ for the considered systems.

![Comparison of the ER results obtained by the DNS model (dot-dashed line) with the experimental data for the synthesis of Roentgenium and Copernicium in the $^{64}\text{Ni}^+ + ^{209}\text{Bi}$ (left panel) and $^{70}\text{Zn}^+ + ^{208}\text{Pb}$ (right panel) reactions, respectively. Quasifission and fusion excitation functions are shown by dashed and solid lines, respectively. The dotted line is the fission barrier.](image)

**Figure 10.** Comparison of the ER results obtained by the DNS model (dot-dashed line) with the experimental data for the synthesis of Roentgenium and Copernicium in the $^{64}\text{Ni}^+ + ^{209}\text{Bi}$ (left panel) and $^{70}\text{Zn}^+ + ^{208}\text{Pb}$ (right panel) reactions, respectively. Quasifission and fusion excitation functions are shown by dashed and solid lines, respectively. The dotted line is the fission barrier.

5. **Mixing of mass-angle distributions of the quasifission and fusion-fission products**

The mass (charge) and angular distributions of the reaction products in the heavy ion collisions are the main indicator used to make conclusions about a reaction mechanism. According to the established opinion the products with masses close to the ones of projectile and target nuclei are considered as products formed in deep inelastic reactions; the products with symmetric mass distributions are considered as products of the fusion-fission reactions, i.e. fission products of the heated and rotating compound nucleus formed at complete fusion; the products having intermediate masses between projectilelike and fusion-fission products are considered as quasifission products. The last kind of products appear when proton or neutron numbers in the heavy or light fragment are close to the magic numbers 28, 50, 82 or 126 [31, 32]. So, the symmetric mass distributions from capture reactions can either be the result of compound
nucleus formation followed by fission, or - if the criteria for compound decay are violated - they are ascribed to the quasifission and fast fission channels.

We should remind that quasifission products are formed at decay of DNS without reaching the stage of compound nucleus or one can say without reaching saddle point to arrive to compact shape. The quasifission means that TKE of binary fragments is close to that of fusion-fission products or Viola systematics.

The experimental methods used to estimate the fusion probability depend on the unambiguity of identification of the complete fusion reaction products among the quasifission products. The difficulties arise when the mass (charge) and angular distributions of the quasifission and fusion-fission fragments strongly overlap depending on the reaction dynamics. As a result, the complete fusion cross sections may be overestimated:

$$\sigma_{\text{fus}} = \sigma_{\text{ffis}} + \sigma_{\text{ER}},$$  \hfill (19)

where $\sigma_{\text{ER}}$ is measured by good accuracy while $\sigma_{\text{ffis}}$ may include contribution of the quasifission and fast fission products which are formed at decay of DNS and at decay of the deformed mononucleus-no compound nucleus. We remind the difference between quasifission and fast fission processes:

- quasifission is the decay of DNS which is formed in the capture–full momentum transfer reactions. The angular momentum distribution for the quasifission events can extend from $\ell = 0$ up to $\ell = \ell_d$ where $\ell = \ell_d$ the maximum value of the DNS angular momentum (see Fig. 11, area filled by the horizontal lines). The mass (charge) distribution of quasifission products may be in the wide range from masses (charges) of projectile- and target-like fragments up to symmetric masses mixing with the fusion-fission products;
Figure 12. Two-dimensional TKEmass matrices (upper panels), yields of fragments and their TKE as a function of the fragment mass (middle and bottom panels, respectively) in the $^{48}\text{Ca}+^{154}\text{Sm}$ reaction at the different $E^*_{\text{CN}}$ excitation energies (designated above upper panels). Solid lines in the middle and bottom panels are Gaussian and parabola fits to the mass and TKE distributions, respectively. This figure was copied from Ref. [32].

- fast fission is the decay of the mononucleus which is a non-equilibrated system survived against quasifission but unstable to be formed as compound nucleus due to absence of the fission barrier caused by its fast rotational velocity [33]. Therefore, the partial cross section of fast fission is populated only at large values of the angular momentum $\ell$ (see Fig.11, the area filled by skew-eyed lines).

We tried to analyze reasons for the lack or disappearance of the quasifission feature in the experimental data for the $^{48}\text{Ca}+^{144}\text{Sm}$ and $^{48}\text{Ca}+^{154}\text{Sm}$ reactions presented in the paper [32] as the main conclusion of study. The authors established the fusion suppression and the presence of quasifission for the reactions with the deformed $^{154}\text{Sm}$ target at the beam energies near and below the Coulomb barrier. The contribution of the quasifission fragments with masses in the range $55 < A < 145$ to the total mass distribution of fission fragments decreases, with respect to the contribution of the symmetric compound nucleus-fission, as the $^{48}\text{Ca}$ projectile energy...
Figure 13. Comparison of the results of this work by the DNS model for the capture, complete fusion, quasifission, fast fission and evaporation residue cross sections with the measured data of the fusion-fission and quasifission given in Ref. [32] (panel (a)) and with data of the evaporation residues obtained from Ref. [34] (panel (b)) for the $^{48}$Ca+$^{154}$Sm reaction.

increases (see Fig. 12). The authors did not consider a possibility of the quasifission product yield with masses outside the range $55 < A < 145$. The quasifission products are formed in the ranges $A < 55$ and $A > 145$ too. But those can be mixed with the products of deep inelastic reactions as in the $^{48}$Ca+$^{208}$Pb reaction which was discussed in Section 2. This is a reason why our theoretical results of the capture cross section (long dashed line) overestimated the experimental data (open circles) presented in Ref. [32] at the low energies (see Fig. 13(a)).

The origination of the measured fission-like fragments (stars) at the large bombarding energies is explained by the sum of the quasifission (short dashed line), fusion-fission (dash dotted line) and fast fission (dash-double dotted line) fragments. A cross section of the fast fission channel increases by increasing the bombarding energy due to the increase of the angular momentum of mononucleus. At low energies the contribution of the fusion-fission to the yield of binary fragments is small in comparison with the quasifission contribution. The small calculated fusion-
Figure 14. Mass distribution of quasifission products formed in the $^{48}\text{Ca}+^{154}\text{Sm}$ reaction as a function of time.

The fusion cross section is explained by the large fission barrier ($B_f=12.33$ MeV) for the $^{202}\text{Pb}$ nucleus according to the rotating finite range model by A. J. Sierk [33] and by the additional barrier $B_f^{(\text{micr})} = -\delta W = -(\delta W_{\text{saddle-point}} - \delta W_{\text{gs}}) \approx 8.22$ MeV caused by the nuclear shell structure. We conclude that the experimental fusion-fission data obtained at low energy collisions contain a huge contribution of quasifission fragments with masses $A > 83$ which show an isotropic distribution as presented in Ref. [32]. This is not a new phenomenon and it was discussed as a result of theoretical studies, for example, in our previous papers [11, 35] and in Ref. [36]. The experimental results confirming this conclusion appeared recently in Ref. [37, 38]. The contribution of the mass symmetric products mixed with the fusion-fission products with similar masses increases ambiguity at estimation of fusion cross section by formula (19). This is a reason of increasing the difference our theoretical results and extracted from the experimental data for quasifission.

At the large energy $E_{\text{c.m.}}=154$ MeV ($E_{\text{CN}}=63$ MeV) the experimental values of the quasifission cross section are much lower than that of the fusion-fission cross section [32]. According to our theoretical result a sufficient part of the quasifission fragments shows the behaviour of the fusion-fission fragments: the mass distribution can reach the mass symmetric region and their angular distribution can be isotropic due to the possibility that the dinuclear system can rotate by large angles for large values of its angular momentum [39]. The authors of Ref. [32] did not exclude such a behaviour of the quasifission fragments. It is difficult to separate the quasifission fragments from the fusion-fission fragments when both, their mass and angle distributions, overlap in the region of symmetric masses. So, ignoring the quasifission products mixed with deep inelastic collisions and consideration of the all mass symmetric products as fusion-fission products are reasons of difference between the theoretical (dotted line in Fig. 13(a)) and experimental (up filled triangle in Fig. 13(a)) values of quasifission cross sections.

At low energies the projectile-like quasifission fragments with $A < 70$ give a large contribution to the cross section for the considered $^{48}\text{Ca}+^{154}\text{Sm}$ reaction since the excitation energy of the
DNS is too small to shift the maximum of the mass distribution to more mass symmetric configurations of DNS. The observed quasifission feature at low energies is connected with the peculiarities of the shell structure of the interacting nuclei. The increase in the beam energy leads to a decrease of the shell effects and the yield of the quasifission fragments near the asymmetric shoulders decreases because the main contribution of quasifission moves to the mass symmetric range. As it is seen from Fig. 14 that the yield of products with the masses in the range 85 < A < 125 appears at times \( t > 8.5 \cdot 10^{-21} \) s. The evaporation residue and fusion-fission excitation function were calculated by the advanced statistical model [40, 41]. In this model, the partial fusion cross sections obtained by the DNS model were used as input data.

**Figure 15.** Two-dimensional TKEmass matrices (upper panels), yields of fragments and their TKE as a function of the fragment mass (middle and bottom panels, respectively) in the \(^{48}\text{Ca}+^{144}\text{Sm}\) reaction at the different \( E_{CN} \) excitation energies (designated above upper panels). Solid lines in the middle and bottom panels are Gaussian and parabola fits to the mass and TKE distributions, respectively. This figure was copied from Ref. [32].

**Figure 16.** The mass distribution of quasifission products formed in the \(^{48}\text{Ca}+^{144}\text{Sm}\) reaction as a function of time.

Due to large fission barrier of the compound nucleus \(^{202}\text{Pb}\) fission probability is very small and the yield of the evaporation residues after neutron emission cascade dominates. Therefore, our theoretical fission excitation function (dot-dashed line) presented in Fig. 14(a) is sufficiently lower than the experimental data (down open triangles). As we have discussed above the latter data included a contribution of the quasifission events. It is important to note that the evaporation residue excitation function (thick dotted line in Fig. 14(b)) is in good agreement with the experimental data (solid squares in Fig. 14(b)) which is the unambiguous physical
quantity obtained from Ref. [34]. This fact confirms the correctness of our partial fusion cross sections.

The difficulties in identification of the quasifission products are connected with absence of the appropriate knowledge about reaction mechanism and complete analysis of the yield of quasifission and accompanying particles. The assumption about possibility to observe the yield of quasifission products only in the mass range corresponding to the middle between projectile-like and fusion-fission products is not completely true: if there is no sufficient yield of reaction products in this intermediate region it does not mean that there is no yield of the quasifission products. For example, the authors of Ref. [32] came to the same conclusion about the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction where they did not observe the characteristic peak of the quasifission products in the mass distribution (see Fig. 15). Our theoretical results of the charge and mass distributions showed that there are two reasons of a lack of the usual quasifission peak: (i) one part of the mass distribution of the quasifission fragments is in the mass range of projectile-like products $48 < A < 60$; (ii) another part of the quasifission fragments is mixed with the fusion-fission fragments and has similar isotropic distributions. The isotope $^{144}\text{Sm}$ is a magic nucleus with the neutron number $N=82$. Therefore, the concentration of the asymmetric mode of the quasifission fragments in the mass range $48 < A < 60$ is explained by the effect of the shell structure of the double magic projectile-nucleus $^{48}\text{Ca}$ and magic target-nucleus $^{144}\text{Sm}$ on the mass distribution of the reaction fragments. As a result, the mass distributions of the products of deep-inelastic collisions and asymmetric quasifission overlap in this mass range. This case is similar to the $^{48}\text{Ca}+^{208}\text{Pb}$ reaction where the presence of the quasifission feature was doubtful. But our investigation showed that due to the collision of the double magic $^{48}\text{Ca}$ and $^{208}\text{Pb}$ nuclei the mass distribution of the quasifission fragments is concentrated around the initial masses (see Fig. 2) because the potential energy surface has a local minimum in this region. In Fig. 16, we present the time dependence of the mass distribution of quasifission products of the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction. One can see that the mass numbers of the quasifission products are concentrated in the mass range $80 < A < 110$ which overlaps completely with the mass range of fusion-fission products. In different from the $^{48}\text{Ca}+^{154}\text{Sm}$ reaction, in the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction no yield of the quasifission products were found in the intermediate mass range where quasifission was used to be observed.

The lack of quasifission events in the experimental studies of the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction or disappearance of quasifission events by increasing the beam energy are connected with the measurement and analysis of the experimental data. More advanced experiments at different beam energy and reaction charge asymmetry must be performed by registration in coincidence of the fission-like products, neutrons and gamma-quanta. The results of such experiments should be analysed by study the different correlation functions of the observed quantities to distinguish quasifission feature in the case that the mass-angle distributions of the quasifission and fusion-fission fragments strongly overlap in the mass symmetric region. We should know the information about the angular momentum and excitation energy of the system going to fission (compound nucleus or DNS) additionally to the mass, angle and kinetic energy distributions of the fission fragments and accompanying them neutrons. The theoretical models must be enough perfect and they should have as possible a small amount of free parameters to make unambiguous conclusions about reaction mechanism after the good description of the observed experimental data which are interpreted without additional assumptions.

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