Investigation on the quasifission process by theoretical analysis of experimental data of fissionlike reaction products

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Abstract. The hindrance to complete fusion is a phenomenon presenting in the most part of the capture events in reactions with massive nuclei. This phenomenon is due to the onset of the quasifission process which competes with complete fusion during the evolution of the composed system formed at capture stage. The branching ratio between quasifission and complete fusion strongly depends from different characteristics of reacting nuclei in the entrance channel. The experimental and theoretical investigations of reaction dynamics connected with the formation of composed system is nowadays the main subject of the nuclear reactions. There is ambiguity in establishment of the reaction mechanism leading to the observed binary fissionlike fragments. The correct estimation of the fusion probability is important in planning experiments for the synthesis of superheavy elements. The experimental determination of evaporation residues only is not enough to restore the true reaction dynamics. The experimental observation of fissionlike fragments only cannot assure the correct distinguishing of products of the quasifission, fast fission, and fusion-fission processes which have overlapping in the mass (angular, kinetic energy) distributions of fragments. In this paper we consider a wide set of reactions (with different mass asymmetry and mass symmetry parameters) with the aim to explain the role played by many quantities on the reaction mechanisms. We also present the results of study of the $^{48}$Ca+$^{249}$Bk reaction used to synthesize superheavy nuclei with $Z = 117$ by the determination of the evaporation residue cross sections and the effective fission barriers $< B_t >$ of excited nuclei formed along the de-excitation cascade of the compound nucleus.

1. Introduction
In heavy ion collisions the two reacting nuclei form a rotating nuclear system which in some cases its evolution leads to complete fusion, while in other cases the nuclear system can also re-separate into two fragments different from the initial nuclei in the entrance channel [1–3]. If there is a well in the nucleus-nucleus potential at the first stage of reaction the full momentum transfer can occur (this event is defined as capture) in dependence on the values of relative kinetic energy and friction coefficients [4, 5]. During the evolution of DNS its two nuclei may change their masses $A_1$, $A_2$ and charges $Z_1$, $Z_2$ but with constant total mass $A = A_1 + A_2$ and...
charge $Z = Z_1 + Z_2$. In this context, DNS can evolve into complete fusion (depending on the intrinsic fusion barrier $B_{\text{ifs}}$ which is equal to the difference between the maximum value of the driving potential and its value corresponding to the initial charge asymmetry) through much more its mass asymmetric configurations but also during such an evolution the system can re-separate into two nuclei (quasifission fragments) \cite{4,5}. Being in competition with the complete fusion this process is characterized by the value of the quasifission barrier $B_{qf}$ (the depth of the pocket in the nucleus-nucleus potential). In this case, the quasifission fragments have a mass asymmetry parameter larger than that of nuclei in the entrance channel. On the other hand, it also exists the probability (depending on the characteristics and structures of initial nuclei) that the nuclei constituting the DNS may exchange mass and charge increasing the mass symmetry parameter. In this last case the decay of DNS into two nuclei (depending on the lifetime of DNS and the value of quasifission barrier $B_{qf}$ for such reached couple of nuclei in DNS) lead to fragments with larger mass symmetry parameter than that of nuclei in the entrance channel. Of course, the rates of such different contributions of quasifission are related to the characteristics of the entrance channel (beam energy and kinds of reacting nuclei).

The capture events that survive quasifission populate the complete fusion channel. Consequently, the deformed mononucleus may reach the fully equilibrated statistical shape of the compound nucleus (CN), or if the fission barrier $B_f$ disappears the system immediately decays into two fragments (fast fission process). The latter phenomenon occurs only at high angular momentum $\ell$ for which the fission barrier of the complete fusion system is zero ($B_f(\ell > \ell_f) = 0$). Therefore, the fast fission process is present in reactions only at high angular momentum values ($\ell > \ell_f$) while the quasifission process takes place at all values of $\ell$ contributing to the capture reaction.

Finally, in the last stage of nuclear reaction, the formed CN may de-excite by fission (producing fusion-fission fragments) or by emission of light particles. The reaction products that survive fission are the evaporation residues (ER) \cite{6,7}. The registration of ER is clear evidence of the compound nucleus formation, but generally the determination of ER’s only it is not enough to determine the complete fusion cross section and to understand the dynamics of the de-excitation cascade of CN if the fission fragments are not included into consideration. On the other hands, the registration of the fissionlike fragments and separation of kinds of fragments according to the mechanism of its origin on the basis of some assumptions does not allow for sure correct determination of the fusion-fission rate in the cases of overlapping of the mass fragment distributions of different processes (quasifission, fast fission and fusion-fission).

Moreover, by observing the fission products of various reactions leading to fissile nuclei formed in neutron(or very light particles) - induced reactions on fissile targets, one can conclude that the low excited compound nucleus (at about $E_{\text{CN}}^* < 10$ MeV) decays into very asymmetric fission fragments (near to the shell closure), while the actinide nuclei or compound nuclei formed in heavy ion collisions at intermediate or high excitation energy ($E_{\text{CN}}^* > 15$ MeV) undergo fission by symmetric fragments. Starting from these general observations some researchers put forward the idea that the complete fusion process of two colliding nuclei maybe considered as the inverse process of fission. The authors in the papers \cite{8,9} argued that since the fission of a compound nucleus in heavy ion collisions produces just symmetric fragments, then in the collisions of two symmetric (or almost symmetric) nuclei complete fusion has to be a very probable process. But, unfortunately this is not true. For systems of colliding nuclei heavier than $^{110}$Pa+$^{110}$Pa fusion does not occur absolutely, while for reactions like $^{100}$Mo+$^{100}$Mo, $^{96}$Zr+$^{96}$Zr, $^{96}$Zr+$^{100}$Mo, $^{100}$Mo+$^{110}$Pa or induced by projectiles higher than Zn, Ge, Kr a strong hindrance to fusion appears.

Following the previous reasonings one can affirm that the hypothetical $^{132}$Sn+$^{120}$Cd reaction should lead to the $^{252}$Cf CN since $^{120}$Cd (with $Z=48$ near the shell closure 50) and $^{132}$Sn (with double shell closure $Z=50$ and $N=82$) are produced with highest yields in spontaneous
fission of $^{252}$Cf. But calculation for this reaction does not give meaningful fusion probability ($P_{\text{CN}} < 5 \times 10^{-7}$).

The simple reason resides in the peculiarities of the reaction dynamics. In the spontaneous fission of $^{252}$Cf the average value of angular momentum distribution of the fragments is close to zero, but if we want to reach the $^{252}$Cf compound nucleus, by the hypothetical $^{132}$Sn+$^{120}$Cd reaction (or by the realistic $^{132}$Sn+$^{116}$Cd reaction leading to the $^{248}$Cf CN), the average value of angular momentum distribution of DNS in the entrance channel may be about $<\ell> = 50\hbar$ or higher by increasing the beam energy. The $<\ell>$ value is calculated as

$$<\ell (E_{\text{c.m.}}, \alpha_p, \alpha_T)> = \frac{\sum_{\ell = 0}^{\ell = \ell_d} \ell <\alpha^{(\ell)}_{\text{cap}} \alpha_{\text{cap}},\alpha_{\text{CN}}> (E_{\text{c.m.}})}{\sum_{\ell = 0}^{\ell = \ell_d} <\alpha^{(\ell)}_{\text{cap}} \alpha_{\text{cap}},\alpha_{\text{CN}}> (E_{\text{c.m.}})}. \quad (1)$$

In this case the whole peculiarities of the reaction mechanism in the first stage of reaction should lead almost completely to quasifission (re-separation of nuclei of DNS), while the fusion probability $P_{\text{CN}}$ should be lower than about $10^{-7}$. But also with this low probability of complete fusion, the excited and fast rotating deformed mononucleus undergoes fast fission before the system can reach the compact shape of compound nucleus.

Also in the cases of the explored $^{22}$Ne+$^{250}$Cf (more mass asymmetric system), $^{24}$Mg+$^{248}$Cm, $^{28}$Si+$^{244}$Pu, $^{34}$Si+$^{238}$U, and $^{40}$Ar+$^{232}$Th (less mass asymmetric system) reactions, the $^{272}$Hs compound nuclei formed in the different entrance channels at a defined excitation energy $E_{\text{CN}}^{*}$ have different angular momentum distributions. Therefore, such compound nuclei decay by different rates of reaction products. The fusion-fission fragment mass distributions are peaked around the $^{136}$Xe nucleus with different dispersions and average angular momentum distributions in connection with the various entrance channels. If we calculate the formation probability of the $^{272}$Hs compound nucleus in the mass symmetric $^{136}$Xe+$^{136}$Xe reaction at the same fixed excitation energy $E_{\text{CN}}^{*}$ as in the considered $^{22}$Ne+$^{250}$Cf reaction (where $P_{\text{CN}} \simeq 1$), we do not meaningfully reach such a compound nucleus ($P_{\text{CN}} < 10^{-10}$). The angular momentum distribution for the $^{136}$Xe+$^{136}$Xe collision at the capture stage is completely different and all conditions of reaction dynamics lead to deep inelastic and quasifission products.

In this context, for the $^{136}$Xe+$^{132}$Sn ($P_{\text{CN}} < 10^{-8}$) and $^{132}$Sn+$^{176}$Yb ($P_{\text{CN}} < 5 \times 10^{-11}$) reactions, one can observe the same above-described hindrance to complete fusion.

2. Capture and Deep Inelastic Collision

Our theoretical capture cross section $\sigma_{\text{cap}}$ includes all damped reactions, excluding deep inelastic collisions (DIC). The partial capture cross sections are contributed by the full momentum transfer events corresponding to the trapping into a pocket in the nucleus-nucleus potential after dissipation of the relative kinetic energy. Differently, the DIC events are not characterized by the full momentum transfer and are not trapped in the pocket of the nucleus-nucleus potential. The DIC events are not connected with any pocket of a potential; for example at large values of $\ell$ there is no pocket but the DIC events take place. The partial capture cross section is calculated by the following formula [10, 11].

$$\sigma_{\text{cap}}^\ell (E_{\text{c.m.}}) = \pi \lambda^2 \mathcal{P}_{\text{cap}}^\ell (E_{\text{c.m.}}) \quad (2)$$

where

$$\mathcal{P}_{\text{cap}}^\ell (E_{\text{c.m.}}) = \begin{cases} \text{1}, & \text{if } \ell_{\text{min}} \leq \ell \leq \ell_{d} \text{ and } E_{\text{c.m.}} > V_{\text{Coul}} \\ \text{0}, & \text{if } \ell < \ell_{\text{min}} \text{ or } \ell > \ell_{d} \text{ and } E_{\text{c.m.}} > V_{\text{Coul}} \\ \text{0}, & \text{for all } \ell \text{ if } E_{\text{c.m.}} \leq V_{\text{Coul}}. \end{cases}$$
Figure 1. Capture (a) and deep inelastic collision (b) for the \(^{48}\text{Ca}^{+208}\text{Pb}\) reaction. Dependence of nucleus-nucleus potential (c) on the orbital angular momentum \(\ell\). Illustration of capture path (d) (dot dashed line) into potential well (solid line) as obtained by the numerical solution of the equation of relative motion of colliding nuclei with the initial energy \(E_{\text{c.m.}} = 136.3\ \text{MeV}\) and \(\ell = 0\) for the \(^{32}\text{S}^{+184}\text{W}\) reaction [5].

In the calculation of nucleus-nucleus potential, which includes the Coulombian \(V_{\text{Coul}}(Z, A, R)\), nuclear \(V_n(Z, A, R)\) and rotational \(V_{\text{rot}}(Z, A, R, \ell)\) parts, we take into account the static and dynamic deformations of nuclei at initial stage of interaction, shell structures of nuclei, mass (charge) asymmetry of the interacting nuclei, bombarding energy beam, orbital angular momentum, and orientation angles of the axial symmetry axes of reacting nuclei at initial stage.

In Figs. 1 and 2 we present some examples of capture events with different potential wells and its dependencies on the angular momentum and orientation angles of axes of reacting nuclei;
moreover, in figures we also present the cases of capture and DIC events by changing the beam energies and angular momentum values.

The lifetime of an excited DNS for a given reaction depends on the initial collision energy $E_{c.m.}$ and angular momentum distribution values (see formulae (6)-(8) and Fig.4 of our paper [12]). The nuclei constituting the DNS exchange mass and charge, as well as their shapes. The evolution of DNS depends on its excitation energy, orientation angles of the axial symmetry axes and shell structures of reacting nuclei. Therefore, the DNS during its evolution can evolve to complete fusion (fusion process) or can decay into two fragments (quasifission process). The competition between these two processes is related to the values of intrinsic fusion barrier $B_{fus}^*$ and quasifission barrier $B_{qf}$ [5–7] depending on the peculiarities of reacting nuclei, beam energy and angular momentum distribution.

The mass and angular momentum distributions of quasifission fragments in many cases and conditions can overlap with the mass and angular distributions of fusion-fission fragments, or/and with the ones of the fast fission fragments [10, 13], leading to a real difficulty in the experimental analysis in order to extract the true yields of fragments belonging to various processes (see for example [10, 14] and Fig. 3 of Ref. [15]).
The rotational angle of the dinuclear system forming the $^{58}\text{Cr}+^{144}\text{Ce}$ fragments (by the $^{48}\text{Ca}+^{154}\text{Sm}$) as a function of the orbital angular momentum (a) and (b), and angular distribution of the yield of quasifission fragments (c) and (d).

Usually, in reactions with actinides the maximum of the yield of the quasifission products is observed in the mass region between masses of the projectile-like products and symmetric masses. In the $^{48}\text{Ca}+^{208}\text{Pb}$ reaction, the maximum of the quasifission products is very close to the region of projectilelike and targetlike fragments (see Fig. 4 of Ref. [10], as well as Fig. 1 of Ref. [16] and Fig. 8 of Ref. [17]). This is due to the fact that projectile or/and target are double magic nuclei. As a result the mass distributions of the capture, i.e. quasifission reactions and deep inelastic collisions are mixed. The reaction time of the deep inelastic collisions is much smaller than that of quasifission and fast fission reactions, because the last two reactions take place if capture occurs, i.e. projectile has been trapped into potential well (see Fig. 1).

It is difficult to separate without uncertainty products of these two processes in experiments. To demonstrate importance of this circumstance, the mass distributions of the deep-inelastic and capture reactions were calculated by the method developed on the base of the dinuclear system concept [18, 19]. The results are presented in Fig. 3. The reason of this result can be seen from the driving potential which has a deep valley around initial charge asymmetry due to the nuclear shell effects. Therefore, the sufficient part of the yields of quasifission and deep-inelastic products are mixed in the mass and charge distributions. The difference between them is in their angular distributions which are connected with the lifetime of the formed rotated dinuclear system. The overlap of the maximum of the mass distribution of quasifission with that of the deep inelastic collisions does not mean absent of the contribution of the quasifission process in the total reaction cross section. This explains the strong deviation of the theoretical values of the capture cross section at low energies from the experimental capture cross section which was
determined by the symmetric fragmentation only.

So, the mixing of the mass distributions of the deep inelastic collisions and quasifission processes causes an ambiguous determination of the capture cross section from the experimental mass distributions in case of reactions with magic or double magic nuclei, like to the case of the reaction under discussion. As well as the mixing of the mass distributions of the quasifission, fast fission and fusion-fission reactions makes difficult the estimation of the complete fusion cross section leading to the genuine compound nucleus. Due to the strong dependence of the mass distribution on the peculiarities of nuclear shell structure, the proportion of mixing is changed from one reaction to another reaction. The theoretical study of this problem is useful to establish the reactions and beam energies which are favourable to obtain the maximum cross section of formation of the compound nucleus with the relatively low angular momentum and excitation energy.

We can state that, at the low energies, the products of the symmetric fragmentation are generally formed at usual fission of CN, and therefore they are related to the fusion cross section. At energies \( E_{lab} > 212 \text{ MeV} \) the contribution of the fast fission appears and it increases by the beam energy.

3. Evolution of DNS : competition between Quasifission and Complete Fusion processes

During the lifetime of the excited DNS the composite system evolves by exchanging nucleons between the two nuclei constituting the DNS. For each event, during this stage of reaction, the DNS can reach the shape of a deformed mononucleus (complete fusion) or it can decay into two fragments (quasifission) before to reach the complete fusion stage. In the first case the nuclear system has to reach the statistical equilibrate shape of the CN, but the events which correspond to deformed mononucleus without barrier to provide stability \((B_f=0\) for \( \ell > \ell_f \)), where the \( \ell_f \) is characteristic of each CN with its structure of nucleons) cannot reach the shape of CN because the deformed complete fusion system immediately decays into two fragments (fast fission process).

Therefore, the partial capture cross section is contributed by the following terms:

\[
\sigma^\ell_{cap}(E_{c.m.}; \beta_p, \alpha_T) = \sigma_{qfiss}^\ell(E_{c.m.}; \beta_p, \alpha_T) + \sigma_{fus}^\ell(E_{c.m.}; \beta_p, \alpha_T) + \sigma_{fastfis}^\ell(E_{c.m.}; \beta_p, \alpha_T) \tag{3}
\]

where

\[
\sigma_{fus}^\ell(E_{c.m.}) = \sigma_{cap}^\ell(E_{c.m.}) P_{CN}(E_{c.m.}, \ell), \tag{4}
\]

is the partial fusion cross section and \( P_{CN}(E_{c.m.}, \ell) \) is fusion probability or hindrance factor to complete fusion as a function of \( \ell \). The fusion cross section, for each orientation angles of the symmetry axes of the deformed reacting nuclei, is obtained by formula

\[
\sigma_{fus}(E_{c.m.}; \beta_p, \alpha_T) = \sum_{\ell=0}^{\ell_f} (2\ell + 1)\sigma_{cap}(E_{c.m., \ell}; \beta_p, \alpha_T) P_{CN}(E_{c.m.}, \ell; \beta_p, \alpha_T). \tag{5}
\]

It is clear that the fusion cross section in formula (4) includes the cross sections of evaporation residue and fusion-fission products. Therefore, taking into account the contributions of all configurations, the average value of the fusion cross section is obtained as

\[
< \sigma_{fus}>_{\{\alpha_p, \alpha_T\}}(E_{c.m.}) = \int_0^{\pi/2} \sin \alpha_P \int_0^{\pi/2} \sin \alpha_T \times \sigma_{fus}(E_{c.m.}; \alpha_P, \alpha_T) d\alpha_T d\alpha_P, \tag{6}
\]

for deformed nuclei, or as

\[
< \sigma_{fus}>_{\{\alpha_T\}}(E_{c.m.}) = \int_0^{\pi/2} \sin \alpha_T \times \sigma_{fus}(E_{c.m.}; \alpha_T) d\alpha_T, \tag{7}
\]
for spherical projectile and deformed target.

Obviously, the quasifission cross section is obtained as

$$
\sigma_{qfis}(E_{c.m.}; \beta_P, \alpha_T) = \sum_{\ell_f} (2\ell + 1) \sigma_{cap}(E_{c.m.}, \ell; \beta_P, \alpha_T)(1 - P_{CN}(E_{c.m.}, \ell; \beta_P, \alpha_T)).
$$

Another binary process which leads to the formation of two fragments similar to the ones of fusion-fission or quasifission is the fast fission. The fast fission cross section is calculated by summing the contributions of the partial cross sections related to the range $\ell_f \leq \ell \leq \ell_d$ (for which $B_1 = 0$) leading to the formation of the mononucleus:

$$
\sigma_{fastfis}(E_{c.m.}; \beta_P, \alpha_T) = \sum_{\ell_f} (2\ell + 1) \sigma_{cap}(E_{c.m.}, \ell; \beta_P, \alpha_T) P_{CN}(E_{c.m.}, \ell; \beta_P, \alpha_T).
$$

The fission and the evaporation residue cross sections are calculated by the advanced statistical code [4, 6, 10] that takes into account the damping of the shell correction in the fission barrier as a function of nuclear temperature and orbital angular momentum.

The fusion cross section is calculated from the branching ratio $P_{CN}(Z)$ of the decay rates of overflowing the border of the potential well ($B^{(2)}_{qf}$) along $R$ at a given mass asymmetry (decay of DNS in quasifission fragments) over the barriers on mass asymmetry axis $B^{(2)}_{fus}$ for the complete fusion or $B^{(2)}_{sym}$ in opposite direction to the symmetric configuration of DNS (for details see Fig. 4 of Ref. [5]):

$$
P_{CN}^{(Z)}(E^{*}_{DNS}) \approx \frac{\Gamma^{(Z)}_{fus}(B^{*}_{fus}, E^{*}_{DNS})}{\Gamma^{(Z)}_{qf}(B^{*}_{qf}, E^{*}_{DNS}) + \Gamma^{(Z)}_{fus}(B^{*}_{fus}, E^{*}_{DNS}) + \Gamma^{(Z)}_{sym}(B^{*}_{sym}, E^{*}_{DNS})},
$$

where $\Gamma_{fus}$, $\Gamma_{qf}$ and $\Gamma_{sym}$ are corresponding widths determined by the level densities on the barriers $B^{(2)}_{fus}$, $B^{(2)}_{sym}$ and $B^{(2)}_{qf}$ involved in the calculation of $P_{CN}$ are used in the model [7, 20, 21] based on the dinuclear system concept [22]. Here $E^{*}_{DNS}(Z_p, A_p, \ell) = E_{c.m.} - V(Z_p, A_p, \ell, R_m)$ is the excitation energy of dinuclear system in the entrance channel, where $Z_p$ and $A_p$ are charge and mass numbers of the projectile nucleus. $V(Z, A, R_m, \ell)$ is the minimum value of the nucleus-nucleus potential well (for the DNS with charge asymmetry $Z$) and its position on the relative distance between the centers of nuclei is marked as $R = R_m$. The value of $B^{(2)}_{qf}$ for the decay of DNS with the given charge asymmetry of fragments is equal to the depth of the potential well in the nuclear-nuclear interaction. The intrinsic fusion barrier $B^{(2)}_{fus}$ is connected with mass (charge) asymmetry degree of freedom of the dinuclear system and it is determined from the potential energy surface:

$$
U(Z; R, \ell) = U(Z, \ell, \beta_1, \alpha_1; \beta_2, \alpha_2) = B_1 + B_2 + V(Z, \ell, \beta_1, \alpha_1; \beta_2, \alpha_2; R) - (B_{CN} + V_{CN}(\ell)).
$$

Here, $B_1$, $B_2$ and $B_{CN}$ are the binding energies of the nuclei in DNS and the CN, respectively, which were obtained from [23]; the fragment deformation parameters $\beta_i$ are taken from the tables in [23–25] and $\alpha_i$ are the orientation angles of the reacting nuclei relative to the beam direction; $V_{CN}(\ell)$ is the rotational energy of the CN. The distribution of neutrons between two fragments for the given proton numbers $Z$ and $Z_2$ or ratios $A/Z$ and $A_2/Z_2$ for both fragments were determined by minimizing the potential $U(Z; R)$ as a function of $A$ for each $Z$.

The driving potential $U_{dr}(Z) = U(Z, R_m)$ is a curve linking minimums corresponding to each charge asymmetry $Z$ in the valley of the potential energy surface from $Z = 0$ up to $Z = Z_{CN}$ (see Fig. 4 of Ref. [5]). We define the intrinsic fusion barrier for the dinuclear system with
charge asymmetry \( Z \) as 
\[
B_{\text{fus}}(Z, \ell) = U(Z_{\text{max}}, R_\text{m}(Z_{\text{max}}), \ell) - U(Z, R_\text{m}(Z), \ell),
\]
where \( U(Z_{\text{max}}, \ell) \) is a maximum value of potential energy at \( Z = Z_{\text{max}} \) in the valley along the way of complete fusion from the given \( Z \) configuration. The \( B^*_\text{sym}(Z, \ell) \) is defined by the similar way as shown in Fig. 4 c of Ref. [5].

The masses and charges of the projectile and target nuclei are not constant during capture and after formation of the dinuclear system. The intense proton and neutron exchange between constituents of DNS is taken into account by calculation of the complete fusion probability \( P_{\text{CN}} \) as fusion from all populated DNS configurations according to the formula
\[
P_{\text{CN}}(E^*_\text{DNS}(Z, A, \ell); \{\alpha_i\}) = \sum_{Z_{\text{sym}}} \frac{E^*_\text{DNS}(Z, A, \ell)}{E^*_\text{DNS}(Z, A, \ell)} P_{\text{CN}}(E^*_\text{DNS}(Z, A, \ell); \{\alpha_i\})
\]
where \( E^*_\text{DNS}(Z, A, \ell) = E^*_\text{DNS}(Z_P, A_P, \ell) + \Delta Q_{\text{SS}}(Z) \) is the excitation energy of DNS with angular momentum \( \ell \) for a given value of its charge-asymmetry configuration \( Z \) and \( Z_{\text{CN}} - Z; Z_{\text{sym}} = (Z_1 + Z_2)/2; \Delta Q_{\text{SS}}(Z) \) is the change of \( Q_{\text{SS}} \)-value by changing the charge (mass) asymmetry of DNS: \( Y_Z(E^*_\text{DNS}) \) is the probability of population of the \( (Z, Z_{\text{CN}} - Z) \) configuration at \( E^*_\text{DNS} \) and given orientation angles \( \{\alpha_1, \alpha_2\} \). \( Y_Z(E^*_\text{DNS}, \ell, t) \) is the probability of population of the configuration \( (Z, Z_{\text{tot}} - Z) \) at \( E^*_\text{DNS}(Z) \) and \( \ell \). The evolution of \( Y_Z \) is calculated by solving the transport master equation:
\[
\frac{\partial}{\partial t} Y_Z(E^*_Z, \ell, t) = \Delta_{Z+1}^-(E^*_Z, \ell, t) Y_Z(E^*_Z, \ell, t) + \Delta_{Z-1}^+(E^*_Z, \ell, t) Y_Z(E^*_Z, \ell, t) - \Delta_{Z}^-(E^*_Z, \ell, t) Y_Z(E^*_Z, \ell, t), \text{ for } Z = 2, 3, ..., Z_{\text{tot}} - 2.
\]
Here, the transition coefficients of multinucleon transfer are calculated as in [18]
\[
\Delta_{Z}^{\pm}(E^*_Z, \ell, t) = \frac{1}{\Delta t} \sum_{P,T} |g_{PT}^{(Z)}|^2 n_{PT}(z)(1 - n_{PT}(z)) \sin^2(\Delta t (\bar{\varepsilon}_P - \bar{\varepsilon}_T)/2) / (\bar{\varepsilon}_P - \bar{\varepsilon}_T)^2 / 4,
\]
where the matrix elements \( g_{PT} \) describe one-nucleon exchange between the nuclei of DNS, and their values are calculated microscopically using the expression obtained in Ref. [26]. A nonequilibrium distribution of the excitation energy between the fragments was taken into account in calculations of the single-particle occupation numbers \( n_P \) and \( n_T \) as it was done in Ref. [27]; \( \bar{\varepsilon}_P \) and \( \bar{\varepsilon}_T \) are perturbed energies of single-particle states. In Eq. 13, \( \Lambda_{PT}^{1/2} \) is the Kramers rate for the decay probability of the dinuclear system into two fragments with charge numbers \( Z \) and \( Z_{\text{tot}} - Z \) (details in Ref. [28]), and it is proportional to \( \exp(-B_{qf}(Z)/(kT)) \) where \( B_{qf}(Z) \) is the quasifission barrier.

Eqs. (13) with the coefficients (14) and initial condition \( Y_Z(E^*_Z, 0) = \delta_{Z,Z_P} \) are solved numerically and the primary mass and charge distributions are found for a given interaction time \( t_{\text{int}} = 5 \times 10^{-21} \) s (see Ref. [29]). In Eq. (12), we use the definition \( Y_Z(E^*_Z, \ell) = Y_Z(E^*_Z, \ell, t_{\text{int}}(\ell)) \). In (14) we use \( \Delta t = 10^{-22} \text{s} << t_{\text{int}} \).

As an example of our calculation of the fusion probability \( P_{\text{CN}} \) versus the angular momentum \( \ell \), we present the results for the \(^{48}\text{Ca}+^{154}\text{Sm}\) reaction at two different \( E^*_{\text{CN}} \) values (see Fig. 6 (a)) and the function \( P_{\text{CN}} \) versus the energy \( E^*_{\text{CM}} - E_B \) for the reaction that lead to different isotopes of thorium (see Fig. 6 (b)). This last figure shows the effect of the entrance channel on the \( P_{\text{CN}} \) fusion probability.

Moreover, Fig. 7 shows the calculation of \( P_{\text{CN}} \) as a function of the energy \( E^*_{\text{CM}} \) for the two close \(^{32}\text{S}+^{182}\text{W}\) and \(^{32}\text{S}+^{184}\text{W}\) reactions for a wide range of excitation energies, in comparison with the calculation reported in Ref. [8]. For these two close reactions we observe two region
Figure 6. (a) The probability $P_{CN}$ of compound nucleus formation as a function of the angular momentum of dinuclear system $\ell$ at energies $E_{c.m.}$ = 138 and 154 MeV, corresponding to the excitation energies of the compound nucleus $E_{CN}^{*}$ = 49 and 63 MeV. (b) The DNS model results for the fusion probability $P_{CN}$ for the $^{16}\text{O}+^{186}\text{W}$, $^{48}\text{Ca}+^{144}\text{Sm}$ and $^{48}\text{Ca}+^{154}\text{Sm}$ reactions as a function of the collision energy relative to the interaction barriers corresponding to each of reactions.

Figure 7. Our theoretical values of the fusion probability $P_{CN}$ for the $^{32}\text{S}+^{184}\text{W}$ reaction as a function of collision energy $E_{c.m.}$, and the one of other authors (Z. & G.) of Ref. [8].

3.1. Compound Nucleus and Fast Fission contributions from the complete fusion formation

In formula (3) the rates among cross sections of the quasifission, fusion-fission, and fast fission processes, which give fragments as reaction products, depend on the masses and charges, shell structure, mass asymmetry of projectile-target nuclei, as well as on the energy and impact parameter of the projectile. As it was noted in Section 1, the formation of quasifission and fast fission products bypasses the stage of the CN formation. The difference between the two mentioned processes is in their dependence on the orbital angular momentum: quasifission is
possible at all angular momenta of collision as fast fission occurs only at $\ell > \ell_f$, where $\ell_f$ is the angular momentum value at which the fission barrier of the compound nucleus disappears. The mass distributions of products of the capture reactions can be mixed by different proportions in different mass regions. To avoid ambiguity, the authors of Ref. [17] referred to the registered products as ones of the symmetric fragmentation (capture) because the genuine fission process is the decay of the compound nucleus into two fragments. The mass distribution of products of the fast fission reactions can be alike to that of the fusion-fission reactions. But the angular distribution of products of the former reaction is more anisotropic than that of the latter reaction due to the difference in their reaction time. In order to estimate the contribution of the fast fission into the calculated capture cross section, we use the value $\ell_f = 58$ obtained in Ref. [17] for the $^{48}\text{Ca} + ^{208}\text{Pb}$ reaction.

In Fig. 8 the results of calculation for the fusion angular momentum distribution of this reaction is presented. One can see that maximum of the partial fusion cross section is around $\ell = 50$. The fast fission contribution for $\ell > \ell_f$ is calculated by formula (11), while the fusion cross section of CN must include the evaporation residues and fusion-fission cross sections only. In our calculation of evaporation residues, the values of the angular momentum $\ell < 58$ were used.

### 3.2. Evaporation Residue

The probability of the formation of a evaporation residue nucleus surviving fission with mass number $A = A_{CN} - (\nu(x) + y(x) + 4k(x))$ and charge number $Z = Z_{CN} - (y(x) + 2k(x))$ from a heated and rotated compound nucleus $^A_{CN}Z_{CN}$ after emissions of $\nu$ neutrons, $y$ protons, and $k \alpha$-particles at the $x$th step of the de-excitation cascade is determined by the formula [6, 10]:

$$
\sigma_{ER(x)}(E_x^*) = \sum_{\ell=0}^{\ell_f} (2\ell + 1)\sigma_{(x-1)}^\ell(E_x^*)W_{sur(x-1)}(E_x^*, \ell),
$$

where $\sigma_{(x-1)}^\ell(E_x^*)$ is the partial cross section of the intermediate nucleus formation at the $(x-1)$th step and $W_{sur(x-1)}(E_x^*, \ell)$ is the survival probability of the $(x-1)$th intermediate nucleus against fission along the de-excitation cascade of CN; $\ell_f$ is the value of angular momentum $\ell$ at which the fission barrier for a compound nucleus disappears completely [30]; $E_x^*$ is the
excitation energy of the nucleus formed at the \( x \)th step of the de-excitation cascade. It is clear that \( \sigma_{\ell}(E_0^*) = \sigma_{fus}^{\ell}(E_{CN}^*) \) at

\[
E_{CN}^* = E_0^* = E_{c.m.} + Q_{gg} - E_{rot},
\]

where \( E_{c.m.}, Q_{gg}, \) and \( E_{rot} \) are the collision energy in the center of mass system, the reaction \( Q_{gg} \) value, and rotational energy of the compound nucleus, respectively. The numbers of the emitted neutrons, protons, \( \alpha \)-particles and \( \gamma \)-quanta, \( \nu(x)n, y(x)p, k(x)\alpha, \) and \( s(x)\gamma, \) respectively, are functions of the step \( x \). The emission branching ratios of these particles depend on the excitation energy \( E_{A}^* \) and angular momentum \( \ell_A \) of the cooling intermediate nucleus.

\[
\begin{align*}
E_{CN}^* & \quad (\text{MeV}) \\
\hline
40 & \quad 0.1 \\
50 & \quad 1 \\
60 & \quad 100 \\
70 & \quad 1000 \\
80 & \quad 10000 \\
90 & \quad 100000 \\
100 & \quad 1000000 \\
\end{align*}
\]

\[
\begin{align*}
E_{c.m.} (\text{MeV}) & \quad 120 \\
140 & \quad 160 \\
180 & \quad 200 \\
\end{align*}
\]

\[
\begin{align*}
\alpha_T & \quad \text{angle} \\
15^\circ & \quad \text{degrees} \\
30^\circ & \quad \text{degrees} \\
45^\circ & \quad \text{degrees} \\
60^\circ & \quad \text{degrees} \\
75^\circ & \quad \text{degrees} \\
90^\circ & \quad \text{degrees} \\
\end{align*}
\]

**Figure 9.** Fusion probability \( P_{CN} \) (a) versus the collision energy \( E_{c.m.} \) for different values of the \( \alpha_T \) angle. Evaporation residue cross sections (b) versus the \( E_{c.m.} \) energy for various orientation angles \( \alpha_T \) of the \( ^{154}\text{Sm} \) target.

The de-excitation cascade, characterized by the emission of the above-mentioned particles, starts from the compound nucleus \( ^{A_{CN}}Z_{CN} \). Its formation probability is the partial cross section of complete fusion \( \sigma_{fus}^{\ell}(E_{CN}^*) \) corresponding to the orbital angular momentum \( \ell \). The fusion cross section is equal to the capture cross section for light systems or light projectile-induced reactions, while for reactions with massive nuclei, it becomes a model-dependent quantity. Concerning estimation of the fusion cross section from the experimental fragments data, its value is sometimes an ambiguous quantity because of difficulties in separating the fusion-fission fragments from the quasifission fragments in the case of overlap of mass and angular distributions.

As an example we present the results of our calculation for the \( ^{48}\text{Ca}+^{154}\text{Sm} \) reaction regarding the fusion probability \( P_{CN} \) (see Fig. 9 (a)) and evaporation residue cross sections \( \sigma_{ER} \) (see Fig. 9 (b)) as a function of the collision energy \( E_{c.m.} \) for different values of the target orientation angles \( \alpha_T \). The dependence of the quasifission-fusion competition during the evolution of the dinuclear system and the sensitivity of the fission-evaporation competition during the de-excitation cascade of the compound nucleus on the values of orientation angle \( \alpha_T \) are demonstrated. The analysis of the dependence of the compound nucleus and evaporation residue formation cross sections on \( \alpha_T \) shows that the observed yield of evaporation residues in the \( ^{48}\text{Ca}+^{154}\text{Sm} \) reaction at the low energies (\( E_{c.m.} < 137 \text{ MeV} \)) is formed in the collisions \( \alpha_T < 45^\circ \). Because the initial beam energy is enough to overcome the corresponding Coulomb barrier for the collisions with these orientation angles \( \alpha_T \). Only in this case it is possible formation of dinuclear system which evolves to compound nucleus or breaks up into two fragments after
multinucleon exchange without formation of the compound nucleus. At larger energies (about $E_{c.m.} = 140–180$ MeV) all orientation angles of the target-nucleus can contribute to $\sigma_{ER}$ and its values are in the 10–100 mb range. At the larger collision energies ($E_{c.m.} > 158$ MeV) the complete fusion still increases but the evaporation residue cross section $\sigma_{ER}$ goes down and its values are in the 1–0.1 mb range due to the strong decrease of the survival probability of the heated compound nucleus along de-excitation cascade. This is connected by the decrease of the fission barrier for a compound nucleus by increasing its excitation energy [3, 4] and angular momentum [30].

Another phenomenon leading to decrease of $\sigma_{ER}$ at higher energy is the fast fission process which is the splitting of the mononucleus into two fragments due to absence of the fission barrier at very high the angular momentum $\ell > \ell_f$.

4. Mass distribution for quasifission and fusion-fission fragments at different energies

To show the evidence of the meaningful overlap of mass distribution of quasifission and fusion-fission process products, and to demonstrate the difficulty in experiments to solve unambiguously the selection of events belonging to true fusion-fission process from the ones of quasifission process, we present in Fig. 10 and discuss the results of investigation on the $^{48}\text{Ca} + ^{248}\text{Cm}$ reaction.

Figure 10. The capture and fusion cross section calculation, in comparison with the experimental data [31, 32], for the $^{48}\text{Ca} + ^{248}\text{Cm}$ reaction leading to the $^{296}_{116}$ superheavy CN. The difference between the fusion cross section and more symmetric fragment yield ($\sqrt{(A_1 + A_2)/2}$ ± 10 amu) at a higher excitation energy is related to the contribution of the quasifission process yielding more symmetric fragments.

In accordance with the above-mentioned considerations, our calculation of the capture cross section (solid line in Fig.10) is in complete agreement with the experimental data [31] for the production of all fragments (full squares), while the fusion cross section (dashed line) is not in agreement with the data (open squares) for the symmetric mass fragments ($\sqrt{(A_1 + A_2)/2}$ ± 20 amu) when a large mass interval of ±20 amu is assumed.

Such disagreement is connected with the contribution of the quasifission process in the range of the more symmetric fragments in which the fusion-fission process also contributes. If it is assumed that the experimental fusion-fission events are in the $\sqrt{(A_1 + A_2)/2}$ ± 10 amu interval (almost close to the $\sqrt{(A_1 + A_2)/2}$ value), the calculated fusion cross sections (the dashed line) will be closer to the new set of the experimental data (open triangles [32] in Fig.10). Indeed, in this case there is an appreciable contribution of the quasifission process (or a contribution which cannot be neglected), in addition to the fusion-fission fragment formation. Therefore, the estimated experimental fusion cross section, connected with the new set of the experimental events of fission fragments, still appears to be a little larger than the calculated fusion excitation...
function at higher excitation energies. A preliminary calculation of the mass distribution of quasifission fragments for a fixed reaction time $t_{\text{reac}}$ of a DNS performed in the framework of the model developed on the basis of the dinuclear system concept [33, 34], indicates that the fragments of the quasifission process also appear in the mass-symmetric region and are mixed with the fragments coming from the fusion-fission process.

5. Study of the reaction dynamics of two close mass asymmetric reactions by the analysis of the fusion-evaporation and fusion-fission processes

![Graphs showing partial quasifission and fusion cross sections](image)

Figure 11. Partial quasifission ((a) and (b) panels) and fusion ((c) and (d) panels) cross sections as a function of the angular momentum $\ell$ for the $^{16}\text{O}+^{184}\text{W}$ (solid line) and $^{19}\text{F}+^{181}\text{Ta}$ (dashed line) reactions. In the panel (a) the beam energies of reactions induced by $^{16}\text{O}$ and $^{19}\text{F}$ are $E_{c.m.}=96.2$ MeV and 95.7 MeV, respectively. These energies correspond to the same excitation energy of CN $E^*_{\text{CN}}=72$ MeV for the both systems shown in the panel (c). Analogously, in the panel (b) the beam energies are $E_{c.m.}=115.2$ MeV and $E_{c.m.}=114.7$ MeV, respectively. The corresponding excitation energy of CN is 91 MeV shown in the panel (d). In (c) and (d), the vertical dashed line at $\ell_f=80\hbar$ separates compound nucleus and fast fission contributions.

There are three main processes causing hindrances to ER formation in reactions with massive nuclei: quasifission, fusion-fission, and fast fission [9]. All of these processes produce binary fragments in different stages of reaction. Moreover, the angular and mass distributions of some parts of their products can overlap [9,35]. Ignoring this mixing may lead to ambiguity at analysis of the experimental data connected with the binary fragments. This problem should be studied carefully.

The ER formation process is often considered as the third stage of the three-stage process. The first stage is capture–formation of the DNS after full momentum transfer into the deformation energy of nuclei, their excitation energy, and rotational energy from the initial relative motion of the colliding heavy ions in the center-of-mass system. Capture takes place if the initial energy of the projectile in the center-of-mass system is enough to overcome the interaction barrier (Coulomb barrier + rotational energy of the entrance channel) [20]. The study of the dynamics of heavy ion collisions at energies near the Coulomb barrier shows that
Figure 12. Comparison of the experimental values of the evaporation residue cross sections normalized with respect to the capture cross sections for the $^{16}$O+$^{184}$W (solid circles) [41] and $^{19}$F+$^{181}$Ta systems (solid squares) [41] with the corresponding theoretical results (dashed and solid lines, respectively) as a function of the excitation energy $E_{CN}^*$ of CN (left axis). Theoretical results of the sum of the quasifission and fast fission cross sections (normalized with respect of the fusion cross sections) for the $^{16}$O+$^{184}$W (dot dashed line) and $^{19}$F+$^{181}$Ta (dot-dot dashed line) systems are presented versus $E_{CN}^*$ and compared on the right axis.

Complete fusion does not occur immediately in collisions of massive nuclei [4,9,21,36,37]. After formation of the DNS, the quasifission process competes with the formation of CN. Quasifission occurs when the DNS prefers to break down into fragments instead of being transformed into a fully equilibrated CN. The number of events contributing to quasifission increases drastically by increasing the sum of the Coulomb interaction and rotational energy in the entrance channel [1, 7, 9].

Another reason for the decreasing yield of ER with increasing excitation energies is the usual fission of a heated and rotating CN that was formed in competition with quasifission. The stability of a massive CN decreases due to the decrease in the fission barrier by increasing its excitation energy $E_{CN}^*$ and angular momentum $\ell$ [38–40]. The theoretical values of the quasifission partial cross sections for the $^{19}$F+$^{181}$Ta and $^{16}$O+$^{184}$W reactions are presented in the left panels of Fig. 11. It is seen from these figures that the quasifission takes place at all values of $\ell$ leading to capture. The angular momentum distributions of CN formed in these reactions at the excitation energies $E_{CN}^*$ = 72 and 91 MeV are presented in the right panels of Fig. 11. The spin distributions of CN formed in each of these reactions differ mainly by the probability but not by the values of the angular momentum ranges. This means that the number of CN formed in both reactions under discussion are different, but they have a similar range of the angular momentum $\ell$. The vertical dotted lines at $\ell_f = 80\hbar$ in these panels separates the complete fusion ($\ell_f < 80\hbar$) and fast fission ($\ell_f \geq 80\hbar$) regions of the angular momentum.

The quasifission and fast fission processes produce binary fragments which can overlap with those of the fusion-fission channel and the amount of mixed detected fragments depends on the mass asymmetry of entrance channel, as well as on the shell structure of the reaction fragments being formed. The suggestion for the experimental studies of the difference between characteristics of the fusion-fission, quasifission and fast fission products can be made when their mass (charge), kinetic energy and angular distributions are explored in detail by dynamical calculations allowing to obtain the relaxation times of these processes. Therefore, the correct estimation of the CN formation probability in the reactions with massive nuclei is a difficult task for both experimentalists and theorists. Different assumptions about the fusion process are
Figure 13. Spin distribution of evaporation residue cross sections as a function of the angular momentum $\ell$. The upper part is for the $^{16}\text{O}+^{184}\text{W}$ reaction, the lower part is for $^{19}\text{F}+^{181}\text{Ta}$ reaction, both at two $E_{CN}^*$ energies: approximately 62-63 MeV and 80-81 MeV.

used in different theoretical models which can give different cross sections. The experimental methods used to estimate the fusion probability depend on an unambiguous identification of the complete fusion 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 [9].

We confirm that the compared ratios of the cross sections between evaporation residues and complete fusion $\sigma_{ER}/\sigma_{fus}$ for the $^{16}\text{O}+^{184}\text{W}$ and $^{19}\text{F}+^{181}\text{Ta}$ reactions discussed in [41] are not free from the above-mentioned ambiguity in the determination of the fusion cross section $\sigma_{fus}$. Theoretical values of the fusion cross section include only evaporation residues and fusion-fission cross sections

$$\sigma_{fus} = \sigma_{ER} + \sigma_{ff}. \quad (17)$$

The experimental values of fusion cross section reconstructed from the detected fissionlike fragments and evaporation residues [41]:

$$\sigma_{fus}^{(exp)} = \sigma_{ff} + \sigma_{qf} + \sigma_{fast fis} + \sigma_{ER}, \quad (18)$$

where $\sigma_{ff}$, $\sigma_{qf}$, and $\sigma_{fast fis}$ are the contributions of fusion-fission, quasifission and fast fission processes, respectively, and $\sigma_{ER}$ is the ER contribution. According to the statement of the authors of Ref. [41], the complete fusion cross sections are obtained by adding fission cross sections [42] to the measured data of the evaporation residue cross sections [43]. Therefore, we can state that the definition of the experimental fusion cross section is similar with the definition of capture [9]: $\sigma_{fus}^{(exp)} = \sigma_{cap}$.
In Ref. [42], the complete fusion cross section is derived from a statistical model where only neutron evaporation and fission are included. We think that the fission data from Ref. [42] contain quasifission fragments and, at larger beam energies, also fast fission contributions, which appear as hindrances to complete fusion. This argument is confirmed by our results obtained in the framework of the DNS model. We calculate the total ER and fusion-fission excitation functions in the framework of the advanced statistical model [38–40].

6. Study for the synthesis of the $^{297}$117 element by the $^{48}$Ca+$^{249}$Bk reaction

By using the above-mentioned method we calculated the capture, quasifission, fast fission and fusion (formation of CN) cross sections for the $^{48}$Ca induced reaction on the $^{249}$Bk target (see Fig. 14 (b)). In the $E_{c.m.} < 200$ MeV energy range the fusion cross section is about three orders of magnitude lower than that of quasifission (which is close to the capture cross section in the whole explored energy range), and it is about one order of magnitude lower than the one of fast fission. At higher $E_{c.m.}$ energies, the fusion cross section is about two orders of magnitude lower than that of quasifission, while it is about five times lower than the one of fast fission. In this reaction the quasifission is the completely dominant process in comparison to complete fusion, and the fast fission is also a strongly relevant process in comparison to the fusion formation (CN). In this case, fast fission process takes place starting from the $\ell_f$ value equal to 30 $\hbar$.

The shell corrections for the odd-odd and odd-even nuclei in the 292-297 mass region of the 117 element were obtained from the static fission barrier $B_f$ (for $\ell=0$) calculated by Sobiczewski [44], which correspond to the realistic values of shell corrections, as an extension of the results presented in the paper of Kowal et al. [45] for the even-even superheavy nuclei. We calculated the average effective fission barriers and evaporation residue cross sections for all nuclei along the de-excitation cascade of the $^{297}$117 compound nucleus by using such values of shell corrections (for $\ell=0$) and taking into account their fade-out (see Refs. [4,6,10,46] and references therein) as a function of the temperature and angular momentum. In Fig. 14(b), we compare the individual excitation functions of the evaporation residue for emission of neutron only along the cascade of

![Figure 14](image-url)
Figure 15. The effective fission barrier $< B_f >$ as a function of the excitation energy for the $^{48}\text{Ca}^{+249}\text{Bk}\rightarrow^{297}\text{117}$ reaction leading to $^{297}\text{117}$ compound nucleus.

The effective fission barrier $< B_f >$ values for different neutron number of excited nuclei when they are formed with a defined excitation energy $E^*$ (for example 17, 25, 33 MeV). Of course, such conditions for the intermediate nuclei are reached starting from different excitation energy values of $E^*_{\text{CN}}$. In details, to form the nuclei with masses $A$ of 297, 296, 295, 294 and 293 u at the same excitation energy, for example $E^*=25$ MeV, it is necessary to start from CN with excitation energy of 25.0, 33.5, 41.7, 51.6 and 60.8 MeV, respectively. The changing of the $< B_f >$ values along the rows are related to the structure effects of nuclei by changing the neutron number. Such changes of $< B_f >$ are similar for the three presented cases of excitation energies. Instead, the $< B_f >$ values along a column show the change of the effective fission barrier for a defined intermediate nucleus by changing its excitation energy $E^*$. For all intermediate nuclei with different neutron number, the changes have the same trend by changing the excitation energy $E^*$. It is clear that the $< B_f >$ value decreases increasing $E^*$.

| $E^*$(MeV) | $A=297$ | $A=296$ | $A=295$ | $A=294$ | $A=293$ | $A=292$ |
|-----------|----------|----------|----------|----------|----------|----------|
|           | N=180    | N=179    | N=175    | N=177    | N=176    | N=175    |
| 17        | ....     | 4.2      | 4.3      | 3.8      | 3.6      | 3.3      |
| 25        | 1.9      | 2.9      | 3.0      | 2.6      | 2.4      | ....     |
| 33        | 0.8      | 1.7      | 1.8      | 1.6      | ....     | ....     |

Table 1. Effective fission barrier $< B_f >$ for the $^{48}\text{Ca}^{+249}\text{Bk}\rightarrow^{297}\text{117}$ reaction leading to intermediate excited nuclei with masses $A=297, 296, 295, 294, 293$ and 292, at excitation energies of nuclei $E^*=17, 25$ and 33 MeV.
7. Conclusions

In a large number of capture reactions with massive nuclei the quasifission process with its peculiarities is the main subject for the understanding of the reaction dynamics. Therefore, by using beams of $^{124}$Sn and $^{132}$Sn (neutron-rich) in collisions with targets heavier than $^{92}$Zr, and for reactions with the Coulomb parameter $z = \frac{Z_1 \times Z_2}{A_1^{1/3} + A_2^{1/3}}$ (connected with the intense Coulomb repulsion between reacting nuclei) higher than 200, for which the quasifission yield is at least two orders of magnitude higher than the complete fusion yield (and then the fusion probability $P_{CN}$ is lower than about $10^{-2}$, as for example for the reactions listed in Table 2), are produced intense yields of quasifission fragments. Therefore, all above-mentioned reactions are excellent reactions for the study of the quasifission process. For the last reaction ($^{238}$U+$^{248}$Cm) in Table 2 the $P_{CN}$ value is not reported because for this reaction capture cross section does not exist.

Moreover, at energies higher than the Coulomb barrier, the fast fission gives a relevant contribution to decay of the complete fusion system into two fragments. For these reactions contribution of the complete fusion cross section to the capture cross section is very small. In such a context the ER cross section is very small, or in many cases is lower than the limit (about 0.2 pb) of the present possibility of the experimental setup. Therefore, before to plan new long beam-time and expensive experiments it is necessary to estimate, by a hopeful analysis of the reaction dynamics, the quasifission and complete fusion cross sections, and then the fast fission and CN cross sections because only the fusion-fission and fusion-evaporation yields contribute to the CN cross section. Only for the two above-mentioned reactions ($^{92}$Zr+$^{132}$Sn, $^{86}$Kr+$^{136}$Xe) it is possible to observe evaporation residues. For all other reactions listed in Table 2 it is not possible to observe meaningful fusion-fission contributions and least of all evaporation residues. The ratios of fusion-fission fragment to quasifission fragment yields for the all other mentioned reactions are much lower than $10^{-3}$ and therefore it is impossible to separate the fragments of fusion-fission process from the fragments of the huge amount of quasifission process. Our theoretical model is a powerful predictive method of calculation of reaction products and also to describe the processes of the reaction dynamics. Moreover, also for reactions leading to synthesis of superheavy elements our model is able to calculate the effective fission barriers along the various steps of the de-excitation cascade of the compound nucleus at various excitation energy and number of neutrons of intermediate excited nuclear systems.

| Reaction       | $Z_{tot}$ | $z = \frac{Z_1 \times Z_2}{A_1^{1/3} + A_2^{1/3}}$ | $P_{CN}$   |
|----------------|----------|-----------------------------------------------|------------|
| $^{86}$Kr+$^{136}$Xe | 90       | 204                                           | $\sim 4 \times 10^{-2}$ |
| $^{92}$Zr+$^{132}$Sn | 90       | 209                                           | $\sim 5 \times 10^{-2}$ |
| $^{136}$Xe+$^{132}$Sn | 108      | 284                                           | $< 10^{-4}$ |
| $^{64}$Ni+$^{208}$Pb | 110      | 232                                           | $< 10^{-5}$ |
| $^{208}$Pb+$^{70}$Ge | 114      | 262                                           | $< 10^{-7}$ |
| $^{139}$La+$^{139,140}$La | 114 | 306, 317                                      | $< 10^{-10}$ |
| $^{86}$Kr+$^{208}$Pb | 118      | 286                                           | $< 10^{-4}$ |
| $^{238}$U+$^{58}$Ni | 120      | 256                                           | $< 10^{-6}$ |
| $^{132}$Sn+$^{174}$Yb | 120      | 327                                           | $< 10^{-10}$ |
| $^{238}$U+$^{70}$Ge | 124      | 286                                           | $< 10^{-7}$ |
| $^{58}$Fe+$^{238}$U | 124      | 251                                           | $< 10^{-3}$ |
| $^{132}$Sn+$^{186}$W | 124      | 343                                           | $< 10^{-11}$ |
| $^{132}$Sn+$^{208}$Pb | 132      | 373                                           | $< 10^{-13}$ |
| $^{160}$Gd+$^{186}$W | 138      | 431                                           | $< 10^{-16}$ |
| $^{132}$Sn+$^{243}$Cf | 148      | 430                                           | $< 10^{-15}$ |
| $^{238}$U+$^{248}$Cm | 188      | 707                                           | - - - -    |

Table 2. Reactions, total $Z$ of the system, $z$ parameter of the Coulomb repulsion, and fusion probability $P_{CN}$ are reported.
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