Compound nucleus formation in reactions between massive nuclei: Fusion barrier

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(Received 12 July 1994)

The evaporation residue cross sections σ_{ER} in reactions between massive nuclei have been analyzed within different models of complete fusion. The calculations in the framework of the optical model, the surface friction model, and the macroscopic dynamic model can give the results which are by few orders of magnitude different from experimental data. This takes place due to neglect of the competition between complete fusion and quasifission. A possible mechanism of compound nucleus formation in heavy-ion-induced reactions has been suggested. The analysis of the complete fusion of nuclei on the basis of dinuclear system approach has allowed one to reveal an important feature of the fusion process of massive nuclei, that is, the appearance of the fusion barrier during dinuclear system evolution to a compound nucleus. As a result, the competition between complete fusion and quasifission arises and strongly reduces the cross section of the compound nucleus formation. A model is proposed for calculation of this competition in a massive symmetric dinuclear system. This model is applied for collision energies above the Coulomb barrier. The σ_{ER} values calculated in the framework of dinuclear system approach seem to be close to the experimental data. For illustration the reactions ^{100}Mo+^{100}Mo, ^{110}Pd+^{110}Pd, and ^{124}Sn+^{96}Zr have been considered.

PACS number(s): 25.70.Gh, 25.70.Jj, 24.10.−i

I. INTRODUCTION

The mechanism of compound nucleus formation (CNF) in heavy-ion-induced reactions is of considerable interest. However, its experimental investigation is very difficult since during complete fusion the system does not give signals which allow one to judge this process unambiguously. In experiments, the decay products of an excited compound nucleus are registered; however, they contain no information about the mechanism of CNF. A consistent theoretical analysis of the complete fusion process of two multinucleon interacting systems is a very complicated problem. Therefore, a number of models have been developed for the description of the experimental data. These models are based on simplifying assumptions about the fusion process.

The critical distance model [1], the optical model [2], and the surface friction model [3,4], widely used for the calculation of fusion cross sections, do not consider the mechanism of CNF itself. It is postulated usually that after the capture of a projectile by a target nucleus complete fusion occurs inevitably. One can say sometimes that the process of compound nucleus formation looks like nuclear collapse. The macroscopic dynamic model [5–7] allows one to trace the evolution of the fusion system in time. However, important properties of nuclei such as their nucleon composition and shell structure are not taken into account. In replacing the real atomic nuclei by homogeneous and structureless drops of a hypothetical nuclear liquid, the real process of compound nucleus formation is inevitably distorted.

In [8] a new approach to the analysis of the complete fusion process has been suggested. This approach is based on information about the interaction of two complex nuclei in close contact, which has been obtained in the study of deep inelastic transfer reactions. In the framework of this approach complete fusion of the nuclei is interpreted in the following way. At the capture stage after full dissipation of the collision kinetic energy a dinuclear system (DNS) is formed. The DNS evolves to a compound nucleus by nucleon transfer from a light nucleus to a heavy one. An important peculiarity of the DNS evolution is the retaining of the individuality of nuclei through compound nucleus formation. During the DNS evolution all nucleons of the donor nucleus are transferred shell by shell to the acceptor nucleus. This approach can be called the "DNS approach."

How does one reveal the real mechanism of compound nucleus formation? Our calculations of compound nucleus formation cross sections in the framework of different models have demonstrated that complete fusion of massive nuclei ($A \geq 100$) can be used as a good test of the validity of various complete fusion models.

As an illustration, for the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd the experimental data [9] on evaporation residue cross sections are compared with results calculated in the framework of the standard models: the optical model [2], and the surface friction model [4], and the macroscopic dynamic model [7] (Sec. II). The calculations include the determination of the cross section of compound nucleus formation and an analysis of the competition between various deexcitation channels. The calculated results contain a dramatic discrepancy with the experimental data. For the reaction ^{110}Pd+^{110}Pd the calculated data are several orders of magnitude larger than the experimental data.

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In our opinion, this discrepancy is the result of quasifission of a massive DNS formed in these reactions after full dissipation of the kinetic energy of collision (Sec. III) [10]. In the existing models of complete fusion the competition between complete fusion and quasifission in the initial DNS is not taken into account. On the basis of the DNS approach a model is proposed to calculate the competition between complete fusion and quasifission in a massive symmetric DNS formed at collision energies above the Coulomb barrier. This model seems to be applicable also for the almost symmetric system ^{124}Sn+^{96}Zr (Sec. IV). The evaporation residue cross section $[\sigma_{\rm ER}(E)]$ values calculated for the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd by the proposed model are close to the experimental data (Sec. V). This fact can be considered as an indication of the validity of the interpretation of compound-nucleus-formation mechanism suggested in the DNS approach.

II. CALCULATION OF $\sigma_{\rm ER}(E)$ IN THE FRAMEWORK OF STANDARD MODELS OF COMPLETE FUSION

A. Calculation of the compound-nucleus-formation cross section in the framework of the optical model

The CNF cross section $\sigma_{\rm CN}(E)$ was estimated by one of the variants of the optical model that was used for the description of the experimental data on the synthesis of transuranium elements [2]. The model parameters have been systematized in a wide region of the product of atomic numbers of colliding nuclei Z_1Z_2 by comparing results of the calculation with the experimental data.

The cross section $\sigma_{\rm CN}$ is a part of the total reaction cross section σ_R,

$$\sigma_R = \pi\lambda\!\!\!^{-2}_0 \sum_{l=0}^{\infty}(2l+1)\,T(l, E_{\rm c.m.}). \tag{1}$$

Here $\lambda\!\!\!^{-}_0$ is the de Broglie wavelength of the relative motion of interacting nuclei, $E_{\rm c.m.}$ is the bombarding energy in the center-of-mass system, and T is the penetration coefficient of the lth partial wave through the potential barrier. $T(l, E_{\rm c.m.})$ is approximated by the penetration factor of a parabolic barrier. The potential describing the nucleus-nucleus interaction includes nuclear, Coulomb, and centrifugal potentials,

$$V(R) = V_N + V_C + V_r, \tag{2}$$

$$V_N = V_0 \left\{1 + \exp\left[\frac{R - r_{0v}(A_1^{1/3} + A_2^{1/3})}{d}\right]\right\}^{-1}, \tag{3}$$

$$V_C = \begin{cases} Z_1Z_2e^2/R & \text{if } R > R_C, \\ Z_1Z_2e^2/2R_C(3 - R^2/R_C^2) & \text{if } R \le R_C, \end{cases} \tag{4}$$

$$V_r = \hbar^2 l(l+1)/2\mu R^2, \tag{5}$$

where R is the distance between nuclear centers, $R_C = 1.3(A_1^{1/3} + A_2^{1/3})$ fm, and μ is the reduced mass of the system. The quantities corresponding to the projectile and target nuclei are marked by indices 1 and 2, respectively. The potential parameters V_0, r_{0v}, and d are taken from [2].

In the classical optical model the CNF cross section is calculated by using the imaginary part of the nucleus-nucleus potential. In [2] the empirical systematic of the ratio $\sigma_{\rm CN}/\sigma_R$ as a function of Z_1Z_2 has been established. This systematics is the result of comparison of the experimental values of $\sigma_{\rm CN}$ and σ_R, obtained in dozens of reactions. The values of $\sigma_{\rm CN}$ in the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd have been found by calculating σ_R and using the empirical systematics of the ratio $\sigma_{\rm CN}/\sigma_R$ presented in [2]. In the calculations of $\sigma_{\rm CN}$ for a heavy system with $Z_1Z_2 > 1500$, the energy displacement between the fusion barrier and interaction barrier should be taken into account. In the present paper this is done according to [2].

B. Calculation of the capture cross section in the framework of the surface friction model

Our calculations are based on one of the recent variants of the surface friction model which takes into account the dynamic deformation of both colliding nuclei [4]. It should be noted that in the framework of this model the capture cross section can be described satisfactorily for such a massive ion as ^{86}Kr.

In this model the capture (fusion) is assumed to take place if the projectile after full dissipation of the kinetic energy is in the potential pocket of $V(R, \alpha)$ (α_i are the deformation parameters). By introducing nuclear friction and solving the system of classical equations of motion, we can obtain the critical angular momentum l_c. All trajectories with $l < l_c$ lead to capture or fusion. In the sharp cutoff approximation the capture (fusion) cross section is determined by the expression

$$\sigma_c = \pi\lambda\!\!\!^{-2}_0 \sum_{l=0}^{l_c}(2l+1) = \pi\lambda\!\!\!^{-2}_0 (l_c+1)^2. \tag{6}$$

In the reactions with relatively light projectiles σ_c is equal to $\sigma_{\rm CN}$. However, in the reactions between massive nuclei where the quasifission (fast fission) takes place the surface friction model can give only σ_c. Nevertheless, we have made the calculations of $\sigma_{\rm ER}$ for the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd assuming that $\sigma_{\rm CN} = \sigma_c$. A comparison of the calculation results with the experimental $\sigma_{\rm ER}$ values gives the scale of quasifission in these reactions.

C. Calculation of the compound-nucleus-formation cross section in the framework of the macroscopic dynamic model

A variant of the macroscopic dynamic model [7] has been used to calculate the CNF cross section in the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd. In this model $\sigma_{\rm CN}$ is determined by the following expression:

$$\sigma_{\rm CN}(E_{\rm c.m.}) = \frac{\pi r_c^2}{E_{\rm c.m.}} \left[\sqrt{\left(\frac{c_1 c_2 + 0.5}{c_2^2}\right)^2 - \left(\frac{c_1^2 + E_B - E_{\rm c.m.}}{c_2^2}\right)} - \left(\frac{c_1 c_2 + 0.5}{c_2^2}\right) \right], \tag{7}$$

where

$$c_1 = k^{1/2}\left[(Z^2/A)_{\rm ef} - (Z^2/A)_{\rm ef}^{\rm thr}\right], \qquad c_2 = \frac{k^{1/2}}{e^2/r_0}\frac{8f^2}{(A_1A_2)^{1/3}},$$

$$k = 2025(A_1A_2)^{1/3}(A_1^{1/3} + A_2^{1/3})^2 32 \left(\frac{3}{\pi}\right)^{2/3} mc^2a^2/(A_1 + A_2),$$

$$r_c = D_1 + D_2 + 1.44 \text{ fm}, \qquad D_i = R_i - 1/R_i,$$

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}, \quad mc^2 = 931 \text{ MeV}, \quad r_0 = 1.224 \text{ fm}.$$

In [7] the following values for parameters are recommended for a better description of the experimental data:

$$f = 3/4, \qquad a = 12, \qquad (Z^2/A)_{\rm ef}^{\rm thr} = 33.$$

In the model [7] the result of massive nuclei collisions depends on a relationship between the kinetic energy of the collision, $E_{\rm c.m.}$, the Coulomb barrier, B_C, and the extra-extra push energy $E_{\rm xx}$. If $E_{\rm c.m.} > B_C + E_{\rm xx}$ during collision the nuclear system takes a more compact shape than the saddle-point one of the compound nucleus; thus complete fusion occurs. In the case of $E_{\rm c.m.} < B_C + E_{\rm xx}$ the nuclei cannot fuse and the system decays via quasi-fission or deep inelastic transfer channel. In the reaction ^{100}Mo+^{100}Mo the $E_{\rm xx}$ value is equal to 1 MeV, and in the reaction ^{110}Pd+^{110}Pd the $E_{\rm xx}$ value is equal to 60 MeV [7]. Since in the second reaction the Bass barrier equals 228 MeV, at $E_{\rm c.m.} > 288$ MeV, the macroscopic dynamic model was expected to be capable of describing $\sigma_{\rm CN}$.

D. Deexcitation of the compound nucleus

In the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd the compound nuclei ^{200}Po and ^{220}U are formed with the excitation energy of dozens of MeV and with a large set of angular momenta. The competition between fission and emission of a light particle determines the part of compound nuclei surviving as evaporation residues.

To describe the decay of the excited nuclei ^{200}Po and ^{220}U, a statistical model based on the Monte Carlo method has been used [11,12]. The angular momenta of compound nuclei formed in the complete fusion reaction have a respective distribution of values of I. The vector **I** is transversal to the ion beam. By means of two random numbers the drawing of the momentum value and its orientation in space are performed. Then for different decay channels of the compound nucleus the maximum of the residual energy is defined in the following way:

$$E_\nu^{\rm res} = E^* - E_r - E_\nu - V_\nu, \qquad E_f^{\rm res} = E^* - E_r - B_f.$$

Here E^* is the excitation energy of the compound nucleus, E_r is its rotational energy, V_ν is the exit Coulomb barrier for a particle of the kind ν ($\nu = n, p, d, t, {}^3$He, α), E_ν is the kinetic energy of the particle, and B_f is the fission barrier. For all $E_\nu^{\rm res} > 0$ the type of emitted particle or γ ray is drawn. For partial widths of the particle ν emission, for the fission and of the γ-quanta emission the following expressions have been used [13]:

$$\Gamma_\nu(E_m^*, I_m) \approx \frac{(2s_\nu + 1)\mu_\nu}{(\pi\hbar)^2\rho_m(U)} \int_{V_\nu}^{U-B_\nu} \sigma_{\rm inv}(E_\nu) \times \rho_d(U - B_\nu - E_\nu) E_\nu dE_\nu, \tag{8}$$

$$\Gamma_f(E_m^*, I_m) \approx [2\pi\rho_m(U)]^{-1} \times \int_0^{U_s - B_f} \rho_s(U_s - B_f - \varepsilon)d\varepsilon, \tag{9}$$

$$\Gamma_\gamma(E_m^*, I_m) \approx \frac{3}{(\pi\hbar c)^2\rho_m(U)} \times \int_0^U \sigma_{\gamma A}(E_\gamma)\rho_d(U - E_\gamma)E_\gamma^2 dE_\gamma, \tag{10}$$

where U is the thermal energy of the mother nucleus, s_ν is the spin of emitted particle, and μ_ν is the reduced mass of the system particle ν plus daughter nucleus. The symbols m and d indicate a mother and a daughter nucleus, respectively. The inverse cross section $\sigma_{\rm inv}$ is calculated within the model [14]:

$$\sigma_{\rm inv} = \begin{cases} \sigma_g c_1(1 + c_2/E_\nu), & \nu = n, \\ \sigma_g c_3(1 - c_4 V_\nu/E_\nu), & \nu = p, d, t, {}^3\text{He}, \alpha. \end{cases} \tag{11}$$

Here σ_g is the geometrical cross section and r, c_1, c_2, c_3, c_4 are the parameters taken from [14]. In expression (9) the thermal energy U_s and rotational energy E_r^s are connected at the saddle point by the relation $U_s = E^* - E_r^s$. This form of the width Γ_f takes into account the change of the fission barrier of the rotating nucleus as far as $B_f(I) = B_f(0) - (E_r - E_r^s)$ (see details in [15]). In ex-

pression (10) for the partial width of the electric dipole radiation $\sigma_{\gamma A}$ is the photoabsorbtion cross section (the dipole electric γ transitions dominate in the statistical γ cascade at $U > 1.5$–2.0 MeV; at lower values of U the quadrupole γ transitions plays the crucial role).

To describe the level density as a function of the excitation energy, the well-known expression from [16],

$$\rho(E^*) = \frac{\sqrt{\pi}}{12}\frac{1}{a^{1/4}(E^*)^{5/4}}\exp[S(E^*)], \tag{12}$$

has been used. In (12) the dependence of the nucleus entropy S on the excitation energy E^* is determined by the relation

$$S = 2at \tag{13}$$

by using the connection of the nucleus temperature with its excitation energy:

$$E^* = at^2. \tag{14}$$

The parameter of the level density $a = \pi^2 g_0/6$ is expressed through the density of single-particle states near the Fermi energy $g_0 = f(E_f) = \text{const}$. The decrease of the influence of shell effects on the level density with increasing excitation energy is taken into account by the phenomenological expression [16]

$$a(E^*) = \tilde{a}[1 + f(E^*)\delta W/E^*]. \tag{15}$$

Here $f(x) = 1 - \exp(-\gamma x)$, δW is the shell correction in the nucleus mass formula, $\tilde{a} = A(\alpha + \beta A)$ is the Fermi-gas value of the level density parameter, and A is the mass number of nucleus. The empirical values of the parameters $\alpha = 0.134\ \text{MeV}^{-1}$, $\beta = -1.21 \times 10^{-4}\ \text{MeV}^{-1}$, and $\gamma = 6.1 \times 10^{-2}\text{MeV}^{-1}$ have been obtained from the analysis of the data on the level density with taking into account the contribution of the collective states to the total level density:

$$\rho_{\text{tot}}(E^*) = K_{\text{rot}}K_{\text{vib}}\rho(E^*) \tag{16}$$

(see details in [16]).

After the determination of the deexcitation mode (if fission does not occur) the characteristics of the emitted particles or γ ray, namely, their kinetic energy, orbital momentum, and emission angle, were drawn. For a given particle the simultaneous selection of E_ν, i ($\mathbf{i}$ is the particle orbital momentum) and $\cos(\Theta)$ (Θ is the angle between $\mathbf{I}$ and $\mathbf{i}$) has been performed by using three random numbers. Then by using the fourth random number they are rejected according to the three-dimensional probability density

$$\rho'(E_\nu, i, \cos(\Theta)) \propto i\,\exp\left[2\sqrt{a[E_k^* - E_\nu - \hbar^2(I^2 + i^2)/2j + \hbar^2 Ii\cos(\Theta)/j]}\right]. \tag{17}$$

Here j is the moment of inertia of the compound nucleus. The azimuthal angle of the evaporated particle is drawn in the coordinate system with the axis z parallel to $\mathbf{I}$. The fission process is taken into account by the weight factor

$$F = \prod_{\nu=1}^{x}[1 - \Gamma_f/\Gamma_{\text{tot}}], \tag{18}$$

where Γ_{tot} is the sum of all partial widths and x is the number of steps in the evaporation cascade. This is convenient, in particular, for strongly fissionable nuclei. All the quantities are transformed to the center-of-mass system of interacting nuclei and the characteristics of the residual nucleus are calculated. Then the maximum residual energies of all emission processes and fission channel are calculated for this nucleus. Among the allowed values of E_ν^{res} and $E_f^{\text{res}} > 0$ the next drawing of the deexcitation type is performed. This is done while the condition $E^{\text{res}} > 0$ is satisfied. The gathering of the required statistics for the calculation of different reaction characteristics has provided about 5% calculation accuracy.

The computation of the compound nucleus deexcitation on the basis of the Monte Carlo method is performed for all the considered variants of the CNF cross section calculation (see Secs. II A, II B, and II D). The ratio of the level density parameters, $a_f/a_n = 1$, is used.

The calculated evaporation residue cross sections for the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd are compared in Fig. 1 with the experimental data [9]. A strong discrepancy is observed between the calculated and experimental results. The discrepancy is particularly large for the reaction ^{110}Pd+^{110}Pd when the CNF cross section is calculated within the optical model and the surface friction model. The macroscopic dynamic model gives lower values of σ_{CN}, but the discrepancy between the calculated results and the experimental data is several orders of magnitude. The observed discrepancy cannot be explained in the framework of the standard concepts of the fusion of complex nuclei. Therefore, to investigate the reason for the strong decrease of the evaporation residue cross sections in these reactions, the DNS approach was used.

III. PECULIARITY OF THE COMPLETE FUSION OF MASSIVE NUCLEI: FUSION BARRIER OF A NEW TYPE

According to the DNS approach the first stage of the complete fusion of nuclei ends with the formation of the DNS. The DNS evolution is defined by the potential energy of the system $V(Z, l)$ as a function of the charge asymmetry and the angular momentum. The calculated potential energies of the DNS for the reactions

^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd are presented in Ref. [10]. The liquid-drop mass of nuclei [17] and the nucleus-nucleus potential $V(R) = V_N(R) + V_C(R) + V_r(R)$ have been used to calculate $V(Z,l)$. The calculation has been performed under a simple assumption about the DNS form. The DNS is considered as two spherical overlap nuclei. The distance R between their centers corresponds to the minimum of the potential pocket of $V(R)$. The overlap of nuclei in the DNS is small and we can use the frozen density assumption to calculate the nucleus-nucleus potential. This assumption corresponds to retaining the individuality of the DNS nuclei used in the DNS approach which is used successfully in the description of deep inelastic transfer reactions [24]. The energy scales are normalized to the total energy of the corresponding spherical compound nucleus (see Fig. 1 in Ref. [10]). The isotopic composition of the nuclei forming the DNS is chosen from the condition of N/Z equilibrium in the system.

The nuclear interaction $V_N(R)$ is taken in two variants: "proximity" and "double folding." According to [18] the expression for $V_N(R)$ in the "proximity" variant looks like

$$V_N(R) = -2\pi(\gamma_1+\gamma_2)\bar{R}s_0 \begin{cases} \frac{5}{3}(1+s/s_0)\exp[-1.6s/s_0], & s \geq 0, \\ \frac{5}{3} - s/s_0 - \frac{1}{2}(s/s_0)^2, & s < 0, \end{cases} \tag{19}$$

where $\gamma_i = 0.9517[1 - 1.7826(1 - 2Z_i/A_i)^2]$, $s = R - R_{1p} - R_{2p}$, $R_{ip} = 1.17A_i^{1/3}$ fm, $\bar{R} = R_{1p}R_{2p}/(R_{1p}+R_{2p})$, and $s_0 = 1$ fm. Here s is the distance between the surfaces of interacting spherical nuclei. The expression for $V_N(R)$ in the double-folding form

$$V_N(R) = \int \omega_1(\mathbf{r}_1)\omega_2(\mathbf{R}-\mathbf{r}_2)\mathcal{F}(\mathbf{r}_1-\mathbf{r}_2)d\mathbf{r}_1 d\mathbf{r}_2 \tag{20}$$

is taken from [19]. Here $\omega_i(\mathbf{r}_i)$ are the densities of interacting nuclei and $\mathcal{F}(\mathbf{r}_1-\mathbf{r}_2)$ is the nucleon-nucleon interaction potential. To take into account the repulsive part of the nucleus-nucleus potential, the density-dependent nucleon-nucleon interaction is used [20]. The final expression has the form [19]

$$V_N(R) = C_0\left\{\frac{F_{\rm in}-F_{\rm ex}}{\omega_{00}}\left(\int \omega_1^2(\mathbf{r})\omega_2(\mathbf{r}-\mathbf{R})d\mathbf{r} + \int \omega_1(\mathbf{r})\omega_2^2(\mathbf{r}-\mathbf{R})d\mathbf{r}\right) + F_{\rm ex}\int \omega_1(\mathbf{r})\omega_2(\mathbf{r}-\mathbf{R})d\mathbf{r}\right\}, \tag{21}$$

$$F_{\rm in,ex} = f_{\rm in,ex} + f'_{\rm in,ex}(N_1-Z_1)/A_1(N_2-Z_2)/A_2,$$

where N_i are neutron numbers. The values of the dimensionless parameters f, f' are known from the fit of a large set of the experimental data within the theory of finite Fermi systems [20]: $C_0 = 300$ MeV fm^3, $f_{\rm in} = 0.09$, $f_{\rm ex} = -2.59$, $f'_{\rm in} = 0.42$, and $f'_{\rm ex} = 0.54$. For massive nuclei the expression

$$\omega_i(\mathbf{r}) = \frac{\omega_{00}}{1+\exp[(r-R_{i0})/a_0]} \tag{22}$$

can be used with the parameters ω_{00}=0.17 fm^{-3} and $R_{i0} = r_0A_i^{1/3}$. The position and height of the barrier for many reactions are well described by the values of the parameters $r_0 = 1.08$–1.17 fm and $a_0 = 0.50$–0.55 fm [19]. The same set of parameters has been used to calculate the DNS potential energies for all the reactions considered. For the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd the nucleus-nucleus potentials are presented in Ref. [10]. The double-folding form of $V_N(R)$ has been used there.

A partial overlap of the volumes of interacting nuclei [21] is taken into account in the Coulomb potential. A complete sticking takes place for the DNS evolving to the compound nucleus; therefore the centrifugal potential $V_r(R)$ has the form

$$V_r(R) = \frac{\hbar^2 l(l+1)}{2(j_1+j_2+\mu R^2)}, \tag{23}$$

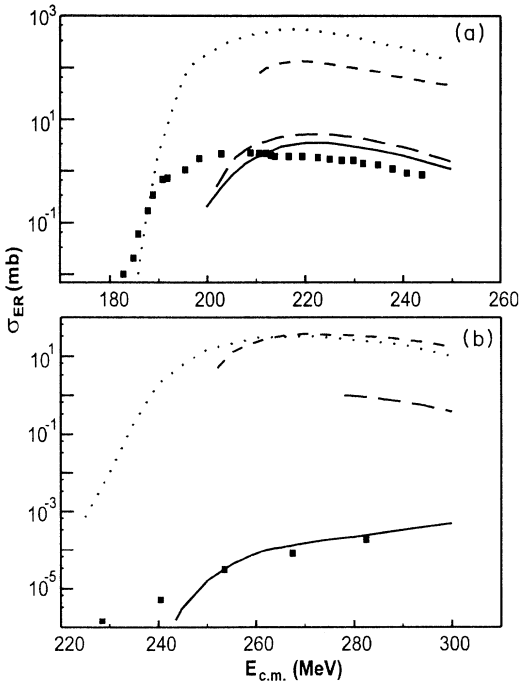

FIG. 1. Evaporation residue cross sections for the reactions ^{100}Mo+^{100}Mo (a) and ^{110}Pd+^{110}Pd (b) as functions of $E_{\rm c.m.}$. The results of calculations in the framework of the optical model, surface friction model, macroscopic dynamic model, and our model are presented by a dotted line, short dashed line, long dashed line, and solid line, respectively. The experimental data are presented by solid squares.

where $j_i = 2mA_iR_i^2/5$ are the rigid-body moments of inertia of the DNS nuclei.

The potential energy of the DNS, $V(Z,l)$, as a function of charge asymmetry and the nucleus-nucleus potential $V(R)$ as a function of R are presented in Fig. 2 schematically. It is seen that for the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd the initial DNS seems to be at the minimum of the potential energy. The DNS is similar to a giant nuclear molecule. As has been emphasized in [8], the existence of the shell structure gives significant stability for nuclei of DNS.

It is clear from Fig. 2 that when going to the compound nucleus the DNS has to overcome the potential barrier that is equal to the difference of the potential energy $V(Z,l)$ at the Businaro-Gallone (BG) point and symmetric configuration. This difference can be called the fusion barrier $B^*_{\rm fus}$. Even at a considerable surplus of the kinetic energy over the entrance barrier the fusion barrier appears when the DNS evolves to the compound nucleus. This is a specific feature of the complete fusion of massive nuclei which can be revealed only within the DNS approach. In further calculations the double-folding potential is used as $V_N(R)$. If we replace it by the proximity potential, the values of $B^*_{\rm fus}$ lower and $\sigma_{\rm CN}$ increase (Fig. 3). Therefore, the total cross section of the fusion of massive nuclei seems to be very sensitive to the potential $V_N(R)$. This fact can be used for a more precise definition of the potential $V_N(R)$.

The physical nature of this fusion barrier drastically differs from the extra-extra push of the macroscopic dynamic model [5–7]. The extra-extra push is an additional kinetic energy over the entrance potential barrier which should provide the compact form of fusing nuclei, i.e., a more compact form than the form of the fissile compound nucleus to be reached at the saddle point. Unlike the extra-extra push, the source of energy for getting over the fusion barrier $B^*_{\rm fus}$ is the DNS excitation energy. Namely, the excitation energy allows the system to realize such an endoergic redistribution of the nucleons between the DNS nuclei, after which the system turns out to be at the top of the fusion barrier. These changes of A_i and Z_i can be considered as a large fluctuation in the initial DNS. After reaching the fusion barrier the DNS potential energy begins to decrease with increasing charge asymmetry and the driving forces lead the DNS to a compound nucleus.

At the same time if we look at the nucleus-nucleus potential in the entrance channel $V(R)$ (Fig. 2), we can see the capture of the projectile by the target nucleus into a rather shallow potential pocket. The shallow potential pocket and slight overlap of the two massive nuclei, as a result of strong Coulomb repulsion, can lead to the disintegration of the DNS to two fragments having close masses, i.e., the initial DNS can easily undergo quasifission. The small values of $\sigma_{\rm ER}(E)$, especially in the reaction ^{110}Pd+^{110}Pd, indicate the predominance of the quasifission channel over the complete fusion one. To determine $\sigma_{\rm ER}(E)$, it is necessary to calculate the competition between the channels of complete fusion and quasifission. We propose a simple model of this competition in the initial DNS.

IV. MODEL OF THE COMPETITION BETWEEN COMPLETE FUSION AND QUASIFISSION IN MASSIVE SYMMETRIC DINUCLEAR SYSTEM

In accordance with [8] the fusion process starts after the formation of the DNS. There is competition between the complete fusion and quasifission channels in the ini-

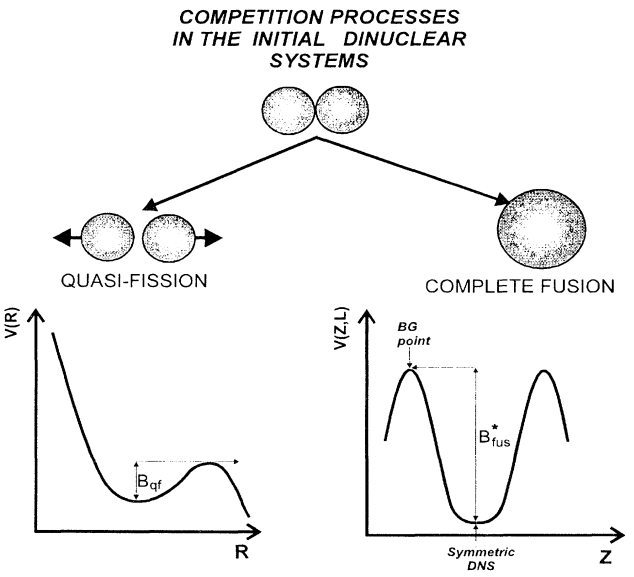

FIG. 2. Schematic presentation of the process of competition between complete fusion and quasifission. Potential energy of the DNS, $V(Z,l)$, as a function of charge asymmetry and nucleus-nucleus potential $V(R)$ as a function of R are presented.

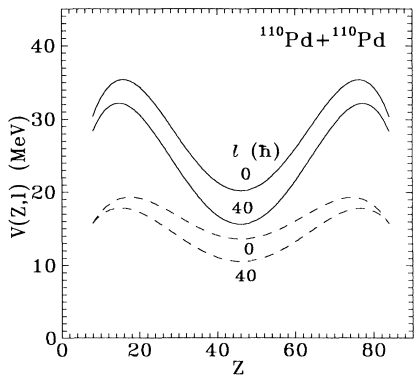

FIG. 3. Potential energy of the DNS as a function of charge asymmetry at $l = 0$ and $40\hbar$ in the case of the reaction ^{110}Pd+^{110}Pd. The nuclear interaction is taken in proximity (dashed lines) and double-folding (solid lines) forms. The energy scales are normalized to the total energy of the corresponding compound nucleus. The sequence $l = 0$, $40\hbar$, 0, $40\hbar$, 0 is assigned as curves from top to bottom.

tial DNS formed by massive nuclei. Therefore, this competition should be taken into account in the calculation of the cross section $\sigma_{\rm CN}(E)$. Unfortunately, the existing models do not allow one to calculate the competition between complete fusion and quasifission in the DNS.

The thermal equilibrium is established in the DNS rather fast, for several units of 10^{-22} s. As the quasifission time is one order of magnitude longer [22] one can try to use the statistical approach to analyze the competition between complete fusion and quasifission. The possibility of using the statistical approach to the DNS decay is indicated by the Q_{gg} systematics of the cross sections of deep inelastic transfer reaction products [23].

We assume that the probability for the initial DNS to evolve via complete fusion or to decay by the quasifission channel is determined by the DNS level densities at the maxima of the fusion and quasifission barriers. A similar approach was used in [24] to describe the charge distribution of deep inelastic transfer reactions. The fusion barrier $B^*_{\rm fus}$ can be calculated from the DNS potential energy $V(Z,l)$ (see Fig. 2). How does one estimate the quasifission barriers? Usually quasifission in asymmetric nuclear systems is considered [25]. These systems evolve towards a symmetric shape with a subsequent decay into two nuclear fragments with close masses. In the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd the initial DNS has a symmetric shape already at the moment of formation. This shape is favorable for decay because of the maximum value of the Coulomb repulsion. The assumption about retaining the individuality of the DNS nuclei [8], its small overlap, and the system position in the minimum potential energy is favorable to use in the analysis of the decay of a massive symmetric DNS in a sudden approximation. In the process of quasifission the DNS should overcome the potential barrier ($B_{\rm QF}$) which coincides with the depth of the pocket of interaction potential $V(R)$ (see Fig. 2).

To describe the DNS level density, one has to use the expression proposed in Ref. [26],

$$\rho_i(E^*_i) = \left[\frac{g^2}{g_1 g_2}\right]^{1/2} \frac{g}{6^{3/4}(2gE^*_i)^{5/4}} \exp\left[2(aE^*_i)^{1/2}\right], \quad (24)$$

where i denotes $B^*_{\rm fus}$ or $B_{\rm QF}$, g_1 and g_2 are densities of single-particle states near the Fermi surface for the two nuclei incorporated in DNS, $2g = g_1 + g_2$, and $a = \pi^2 g/3$. The values of g_1 and g_2 are taken according to the systematics [27]. The excitation energy E^*_i is the difference between the DNS excitation energy in the symmetric configuration $E^* = E_{\rm c.m.} - V(R^*)$ and the value of the corresponding barrier. R^* is the R for the bottom of a pocket in the $V(R)$. Taking into account the above assumption we can get for the probability of complete fusion, $W_{\rm fus}$,

$$W_{\rm fus} = \frac{\rho_{B^*_{\rm fus}}}{\rho_{B^*_{\rm fus}} + \rho_{B_{\rm QF}}}. \quad (25)$$

The ratio $\rho_{B_{\rm QF}}/(\rho_{B^*_{\rm fus}} + \rho_{qf})$ determines the quasifission probability. Therefore, in the general case the fusion cross section can be written in the following form:

$$\sigma_{\rm CN}(E_{\rm c.m.}) = \pi \lambda^2_0 \sum_{l=0}^{l_f} (2l+1) T(l, E_{\rm c.m.}) W_{\rm fus}(l, E_{\rm c.m.}), \quad (26)$$

where l_f is the angular momentum corresponding to the vanishing fission barrier. In our case the last multiplier takes into account the competition between the fusion and quasifissionlike processes. It is supposed that $W_{\rm fus}$=1 in the optical model and in the surface friction model. Usually the fusion of nuclei is considered there when the quasifissionlike channel is negligible. However, in the case of symmetric combination of the massive colliding nuclei quasifission dominates.

The DNS excitation energy is defined by $E_{\rm c.m.}$ and the DNS potential energy. We used the data of Ref. [22] where it was shown that, in contrast to fission in the process of quasifission, light particles do not carry away a considerable portion of the excitation energy of the system.

In classical quasifission models [25] the initial asymmetric DNS evolves to a symmetric form of which it decays into two fragments with close masses. A possibility of the system decay from asymmetric configuration is ignored. Here we followed this traditional concept about quasifission processes. At the same time there is a definite probability of DNS decay from the intermediate configurations during motion to the Businaro-Gallone point. The question is whether this probability is comparable with the quasifission probability from the symmetric configuration. To estimate the quasifission probability from the intermediate configurations, we replaced the δ-functional distribution of Z in the initial DNS by the function proportional to $\exp[-V(Z,l)/t]$ assuming thermal equilibrium in the DNS. For each Z between the symmetric and BG point configurations (Fig. 2) the quasifission probability has been calculated as given above taking into account the weight factors proportional to $\exp[-V(Z,l)/t]$. The DNS configurations close to the symmetric one seem to give the main contribution ($\approx$90%) to quasifission. This allows one to use in the first approximation the traditional statistical model for the analysis of the competition between complete fusion and quasifission in the massive symmetric DNS ignoring quasifission from the intermediate configurations of DNS.

The results of the $\sigma_{\rm CN}(E)$ calculation are presented in Fig. 4. Our data for $\sigma_{\rm CN}(E)$ calculated by standard complete fusion models, namely, the optical [2], surface friction [4], and macroscopic dynamical [7] models are also given in these figures for comparison. As one can see, the formation of the potential barrier $B^*_{\rm fus}$, when the DNS evolves to the compound nucleus, and the competition between complete fusion and quasifission in the initial DNS lead to a sharp decrease of $\sigma_{\rm CN}(E)$ values in reactions between massive nuclei. The position of $B^*_{\rm fus}$ slightly shifts towards larger asymmetry of the DNS with increasing l. To simplify our calculation, we fix the place of $B^*_{\rm fus}$ in the configuration with ^{48}Ca as a light nucleus.

The proposed model has been used also to analyze the competition between complete fusion and quasifission for almost symmetric massive dinuclear systems. In Ref. [28] the cross sections of the reaction channels (HI,xn), where

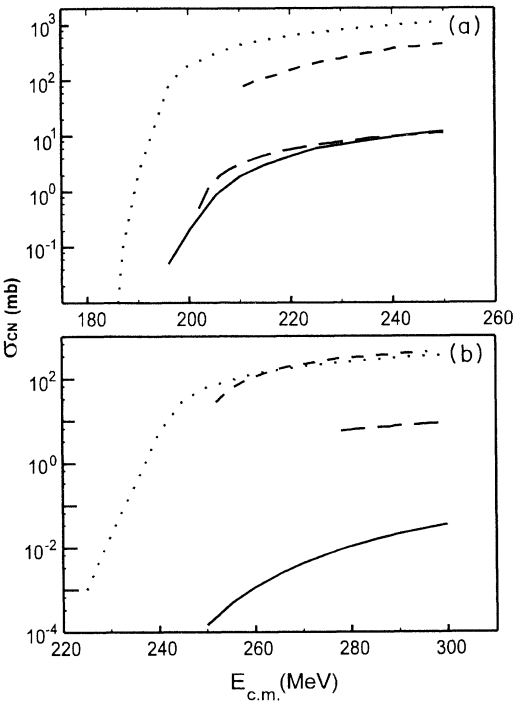

FIG. 4. Compound-nucleus-formation cross sections for the reaction ^{100}Mo+^{100}Mo (a) and ^{110}Pd+^{110}Pd (b), as functions of $E_{c.m.}$. The results of calculation in the framework of the optical model, surface friction model, macroscopic dynamic model, and our model, are presented by a dotted line, short dashed line, long dashed line, and solid line, respectively.

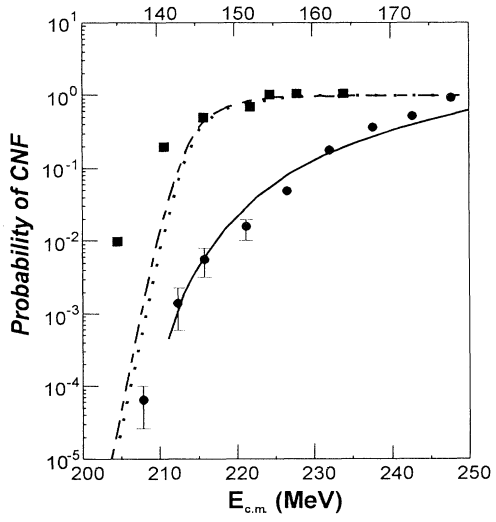

FIG. 5. Probabilities of CNF defined only by the penetration factor of the entrance parabolic barrier are presented by a dotted line and dashed line for the reactions ^{40}Ar+^{180}Hf and ^{124}Sn+^{96}Zr, respectively. For the reaction ^{124}Sn+^{96}Zr the result of calculation in the framework of the DNS approach is presented by a solid line. Probabilities of CNF obtained from the experimental data are presented by solid squares and solid circles for the reactions ^{40}Ar+^{180}Hf and ^{124}Sn+^{96}Zr, respectively. The abscissa for the ^{40}Ar-induced reaction (upper scale) is shifted by the difference of the Coulomb barriers of both reactions.

HI denotes heavy ion, have been measured for two reactions leading to the same compound nucleus ^{220}Th: ^{40}Ar+^{180}Hf and ^{124}Sn+^{96}Zr. The standard model of complete fusion was able to describe the experimental data for the first reaction. At the same time, there was a large discrepancy between the calculated and experimental data for the second reaction. From our point of view, the reason for this is quasifission, which is a predominant reaction channel in the second reaction. Indeed, the probability for CNF, which has been determined from the experimental data by using some model assumptions [28], seems to be larger for the reaction ^{40}Ar+^{180}Hf than for the reaction ^{124}Sn+^{96}Zr. The initial DNS formed in the reaction ^{40}Ar+^{180}Hf corresponds approximately to the BG point configuration. In this case $W_{\rm fus} \approx 1$ in (26) and the values of the probability for CNF are described rather well (above barrier) by the penetration factor T of the entrance parabolic barrier (Fig. 5). On the contrary, for the almost symmetric system ^{124}Sn+^{96}Zr the values of $W_{\rm fus}$, which can be much smaller than unity, decrease the probability for CNF. A good description of the experimental data in the framework of the DNS approach is demonstrated for this reaction in Fig. 5. Thus, our model can be applied to almost symmetric systems.

V. CALCULATION OF EVAPORATION RESIDUE CROSS SECTIONS IN THE REACTIONS ^{100}Mo + ^{100}Mo AND ^{110}Pd + ^{110}Pd

Three factors taken into account in calculating the $\sigma_{\rm ER}(E)$ for the reactions ^{100}Mo+^{100}Mo and ^{110}Pd+^{110}Pd are as follows: (i) the capture cross section $\sigma_c(E)$, (ii) the competition between complete fusion and quasifission in the initial DNS, and (iii) the competition between fission and the emission of light particles and γ rays in the compound nucleus deexcitation. The capture cross section $\sigma_c(E)$ has been calculated using an optical model [2]. The competition between complete fusion and quasifission has been calculated in the framework of the proposed model (Sec. IV). The compound nucleus deexcitation has been analyzed in the framework of a statistical model using the Monte Carlo method [11,12].

As is shown in Ref. [29], a considerable part of the excitation energy of the massive compound nucleus is carried away by neutrons before the nucleus reaches the scission point. The independence of prescission neutron multiplicities on the total kinetic energy of the fission fragments indicates that the neutron emission just before and just after scission is not very important in fusion-fission reactions [22]. The survival of the evaporation residues of heavy nuclei at a high excitation energy [30] allows one to assume that the prescission neutron emission takes place mainly before the compound nucleus reaches the saddle point. Therefore, based on the results of Refs. [22,29] we can assume that the excitation energy at the saddle point is about 30–40 MeV. Taking into account the fission of compound nucleus only at $E^* \leq 35$ MeV we obtained a better agreement between the calculated and experimental data. The calculated results seem to be not too different if instead of 35 we take 50 MeV. The

fact that in the reaction ^{110}Pd + ^{110}Pd the intermediate system, before becoming a compound nucleus, emits an α particle [9] has also been taken into account. Because of the dynamic coupling of the DNS modes of motion [19], this emission takes place mainly on the route from the Businaro-Gallone point to a compound nucleus. So it does not influence the competition between fusion and quasifission. The probability of precompound α emission is about 10^{-3} [9] in the reaction ^{110}Pd + ^{110}Pd and has a negligible influence on quasifission, which is the dominant channel of the initial DNS decay. In the reaction ^{100}Mo+^{100}Mo the probability of precompound α emission is considerably smaller than the probability of compound nucleus formation and we can neglect it.

The results of $\sigma_{\rm ER}(E)$ calculations by the developed model are presented in Fig. 1. The optical model used by us to calculate $\sigma_c(E)$ does not take into account the coupling of various fusion channels at $E_{\rm c.m.}$ near the Coulomb barrier. This leads to the disagreement between the calculated and experimental data at low $E_{\rm c.m.}$. Therefore, our model is applicable to describe the experimental values of $\sigma_{\rm ER}(E)$ at the collision energy exceeding the Coulomb barrier.

The drastic disagreement between the experimental data and the results of calculations by the optical and surface friction models is due to the fact that these models do not take into account quasifission processes following massive DNS formation. We presented these calculated results in Figs. 1 and 4 to demonstrate the quasifission role in the fusion of massive nuclei.

The macroscopic dynamic model [7] takes into account many nuclear processes that occur in the entrance channel of the reactions. At $E_{\rm c.m.} > B_C + E_{\rm xx}$ the macroscopic dynamic model was expected to be capable of describing $\sigma_{\rm CN}(E)$. However, the $\sigma_{\rm ER}(E)$ value calculated using this model is about three orders of magnitude larger than the experimental one. From our point of view, this large difference is the result of the absence of the competition between complete fusion and quasifission in the macroscopic dynamic model. Indeed, at $E_{\rm c.m.} > B_C + E_{\rm xx}$ CNF takes place and quasifission is absent. At $E_{\rm c.m.} < B_C + E_{\rm xx}$ quasifission is realized but CNF is not possible. Therefore, the competition between complete fusion and quasifission is not taken into account for a given $E_{\rm c.m.}$.

According to Ref. [7], at energies below $B_C + E_{\rm xx}$ no compound nucleus can be formed at all. However, as one can see from the experimental data (Fig. 1), $\sigma_{\rm ER}(E)$ goes smoothly to energies several dozens of MeV below $B_C + E_{\rm xx}$. In the used variant of the macroscopic dynamical model the fusion barrier fluctuations are not considered. Introduction of these fluctuations [31] allows one to spread $\sigma_{\rm ER}(E)$ to the region $E_{\rm c.m.} < B_C + E_{\rm xx}$. However, the considerable disagreement between the calculated and experimental data remains for a high collision energy. Apparently the reason for the discrepancy lies in the macroscopic approach itself, in which real nuclei possessing a shell structure are replaced by drops of a homogeneous nuclear liquid.

A satisfactory description of $\sigma_{\rm ER}(E)$ by the model of competition between complete fusion and quasifission can be considered as indicative of the realistic interpretation of the mechanism of compound nucleus formation proposed in the DNS approach [8].

Calculations of the evaporation residue cross sections on the basis of the DNS approach allow us to understand the reasons for the sharp decrease of the cross sections in the transition from the reaction ^{100}Mo+^{100}Mo to ^{110}Pd+^{110}Pd. In these reactions the mass and charge of compound nuclei are different only by 10% but the cross sections differ by several orders of magnitude. The dependence of the fusion barrier and quasifission barrier on the angular momentum for both reactions is shown in Figs. 6(a) and 6(b). One can see that the quasifission and fusion barriers change in opposite directions: The quasifission barriers decrease in the transition from the reaction ^{100}Mo+^{100}Mo to the reaction ^{110}Pd+^{110}Pd, and on the contrary the fusion barriers considerably increase.

The exchange with valence nucleons between the nuclei of the DNS increases the nuclear attraction [33]. This leads usually to an increase of the capture cross section but the fusion barrier $B^*_{\rm fus}$ is changed slightly. Therefore, all the peculiarities of the fusion process of massive nuclei seem to be conserved.

The deformation of the DNS nuclei under the influence of Coulomb forces slightly changes $B^*_{\rm fus}$ as well. This influence of the deformation has been estimated. It was supposed that in the symmetric DNS the nuclei look like

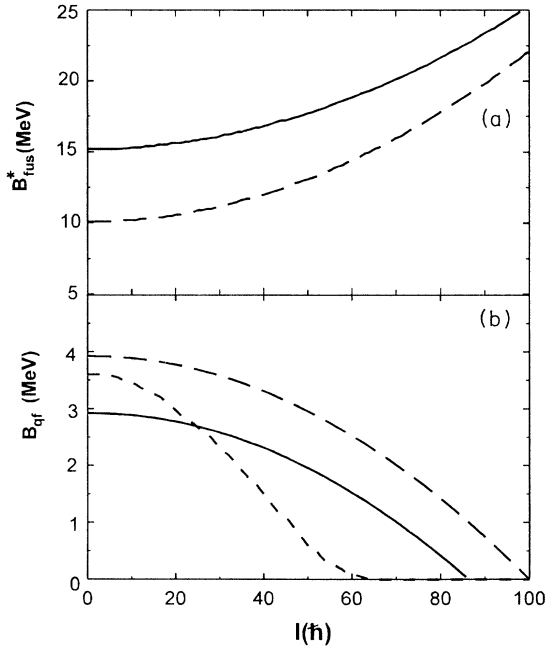

FIG. 6. (a) Dependence of the fusion barrier $B^*_{\rm fus}$ on the angular momentum for the system ^{100}Mo+^{100}Mo (long dashed line) and for the system ^{110}Pd+^{110}Pd (solid line). (b) Dependence of the quasifission barrier $B_{\rm QF}$ on the angular momentum for the system ^{100}Mo+^{100}Mo (long dashed line) and for the system ^{110}Pd+^{110}Pd (solid line). Fission barrier for the compound nucleus ^{220}U according [32] is presented by a short dashed line.

rotating prolate ellipsoids with a collinear-located large axis. In both the reactions on the fusion barriers the light nucleus of the DNS was ^{48}Ca while the heavy nuclei were ^{152}Er and ^{172}Hf (if the particle evaporation is neglected). For this configuration the deformation is introduced only for heavy nuclei of the DNS. The surface of the deformed nucleus is described by the expression

$$R_{id} = fR_i[1 + \beta Y_{20}(\theta, \varphi)], \tag{27}$$

$$f = \left[\left(1 + \beta\sqrt{\frac{5}{4\pi}}\right)\left(1 - \beta\sqrt{\frac{5}{16\pi}}\right)^2\right]^{-1/3}.$$

The factor f is introduced for volume conservation. Calculations of $B^*_{\rm fus}$ were performed with $V_N(R)$ in the "proximity" form. In (19) $\bar{R}$ has been modified according to [34]. The potential of the Coulomb interaction, $V_C(R)$, was calculated following [34] as well. In $V(Z, l)$ the corresponding changes have been done in the components describing the surface and the Coulomb energies. For the symmetric configuration of the DNS the value $\beta = 0.2$ was taken, and for the BG point, $\beta = 0.4$, which is in accordance with the data on the deformation in symmetric and asymmetric fission [35]. By our estimations the deformation of the DNS nuclei increases $B^*_{\rm fus}$ nearly by 2 MeV for the reaction ^{110}Pd+^{110}Pd and by 1 MeV for the reaction ^{100}Mo+^{100}Mo.

VI. CONCLUSION

In this paper the cross sections of the evaporation residues in the reactions between massive nuclei are analyzed in the framework of different models of complete fusion. This analysis allows us to estimate the validity of the CNF mechanism suggested in different models.

The determination of the evaporation residue cross sections includes the calculation of the CNF cross section and the competition between fission and emission of light particles, γ rays at the compound nucleus deexcitation. The CNF cross sections have been calculated in the framework of standard models of complete fusion, and the deexcitation of a compound nucleus has been calculated using the Monte Carlo method.

The results obtained, calculated by the optical model, the model with surface friction, and the macroscopic dynamic model, seem to be in sharp contradiction with the experimental data. Especially, for the reaction ^{110}Pd+^{110}Pd the calculated evaporation residue cross sections exceed the experimental value by several orders of magnitude.

The analysis of complete fusion in massive symmetric and almost symmetric systems on the basis of the DNS approach revealed an important specific feature of this process: the appearance of the fusion barrier, after the capture during the DNS evolution to a compound nucleus. This barrier is, in principle, different from the extra-extra push energy of the macroscopic dynamical model. As a result, the competition between the channels of quasifission and complete fusion arises and strongly reduces the CNF cross section.

On the basis of the DNS approach a model of the competition between complete fusion and quasifission in a massive symmetric DNS has been developed which includes the fusion and quasifission barriers as main elements.

The calculations of the evaporation residues cross sections in the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd+^{110}Pd on the basis of this model give satisfactory agreement with the experimental data, which can be considered as evidence of the validity of the concept of the CNF mechanism developed in the DNS approach.

ACKNOWLEDGMENTS

The authors (N.V.A. and A.K.N.) are grateful to the International Science Foundation for financial support under Grant No. RFJ-000.

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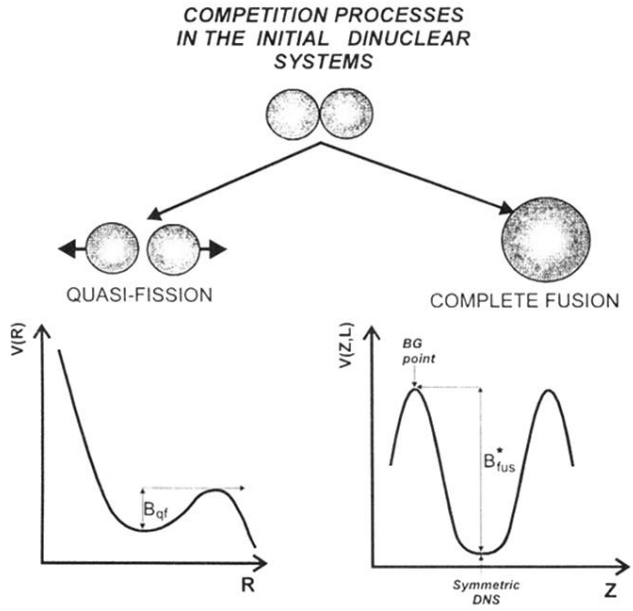

FIG. 2. Schematic presentation of the process of competition between complete fusion and quasifission. Potential energy of the DNS, $V(Z,l)$, as a function of charge asymmetry and nucleus-nucleus potential $V(R)$ as a function of R are presented.