# Production of unknown transactinides in asymmetry-exit-channel quasifission reactions

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Possibilities of production of new isotopes of superheavy nuclei with charge numbers 104–108 in asymmetry-exit-channel quasifission reactions are studied for the first time. The optimal conditions for the synthesis are suggested in this type of reaction. The products of suggested reactions can fill a gap of unknown isotopes between the isotopes of heaviest nuclei obtained in cold and hot complete fusion reactions.

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## I. INTRODUCTION

The hot actinide-based and cold $^{208}$Pb- and $^{209}$Bi-based complete fusion reactions are intensively used to produce superheavy nuclei [1,2]. However, the synthesis of different isotopes of superheavy nuclei in these reactions is limited by the number of available stable projectiles and targets. There is a large gap of unknown isotopes between the neutron-deficit superheavies obtained in cold fusion and the heaviest isotopes formed in hot fusion. With asymmetry-exit-channel quasifission (AECQ) reactions leading to the nuclei with charge number larger than charge number of the target one can produce the isotopes that cannot be synthesized in complete fusion reactions. The direct production of transactinides in AECQ reactions would also be important for the additional confirmation of superheavy nuclei with charge numbers 112–116 synthesized in $^{48}$Ca-induced complete fusion reactions. The $\alpha$-decay chains of these superheavy nuclei end at the region of unknown isotopes.

In the present article we focus on the production of nuclei with $101 \leqslant Z \leqslant 108$ in the reactions $^{48}$Ca+$^{238}$U, $^{243}$Am, $^{244,246,248}$Cm. The choice of the actinide targets is a natural way to access the superheavy region. The production of heavy actinides has been studied in the transfer-type reactions in bombarding of actinide targets with $^{16,18}$O, $^{20,22}$Ne, and $^{40,44,48}$Ca [3–7]. The heavy products near the target nucleus have been treated in these experiments. The nuclei with $Z > 102$ have not been observed because of small cross sections or short lifetimes to identify the nuclei with the radiochemical method used. Our purpose is to treat the yield of superheavy nuclei far from the target to which the contributions of deep inelastic transfers and fast nonequilibrium processes in the entrance channel [8–10] are expected to be negligible.

## II. MODEL

As shown in Refs. [8–16], the quasifission and fusion as well as transfer-type reactions can be described as an evolution of a dinuclear system (DNS) that is formed in the entrance channel during the capture stage of the reaction after dissipation of the kinetic energy of the collision. The dynamics of these processes is considered as a diffusion of the DNS in the charge and mass asymmetry coordinates, which are defined here by the charge and mass numbers $Z$ and $A$ of the heavy fragment of the DNS. During the evolution in mass and charge asymmetry coordinates, the excited DNS can decay into two fragments via the diffusion in relative distance $R$ between the centers of the DNS nuclei. The reaction products resulting from the decay of the DNS that are more symmetric than the initial (entrance) DNS are usually called quasifission products. The charge, mass, and kinetic energy distributions of the quasifission process were successfully treated with the DNS model in the microscopical transport approach [16]. In the DNS model [12,13] the complete fusion is the transfer of all nucleons of the light nucleus to the heavier one in a touching configuration of the nuclei. The DNS evolution to the compound nucleus competes with the DNS decay. The inner barrier $B^*_{\rm fus}$ of the potential in the coordinates $Z$ or $A$ supplies a hindrance for the fusion in the DNS model, which well reproduces the existing experimental data for the fusion evaporation residue cross sections [12–14].

The formation and decay of the DNS that are more asymmetric than the DNS in the entrance channel, the AECQ reactions, as well as the quasifission are ruled by the same mechanism in the sense that both of them are diffusion processes that use the same relevant collective coordinates: mass and charge asymmetries and relative distance.

The cross section $\sigma_{Z,N}$ of the production of primary heavy nucleus in the AECQ reaction is the product of the capture cross section $\sigma_{\rm cap}$ in the entrance reaction channel and formation-decay probability $Y_{Z,N}$ of the DNS configuration with charge and mass asymmetries given by $Z$ and $N$: $\sigma_{Z,N} = \sigma_{\rm cap} Y_{Z,N}$. Because this nucleus is excited, one should take into account its survival probability $W_{\rm sur}$ in the deexcitation process to obtain the evaporation residue cross section as follows:

$$\sigma_{\rm ER}(Z, N - x) = \sigma_{Z,N} W_{\rm sur}(xn). \quad (1)$$

Here, $x$ is the number of evaporated neutrons from the excited primary heavy nucleus. $W_{\rm sur}(xn)$ is treated as in Ref. [17]. The predicted properties of superheavies are taken from Ref. [18].

Because the actinide targets are deformed, the value of $E^{\rm min}_{\rm c.m.}$, at which the collisions of nuclei at all orientations become possible, is larger than the Coulomb barrier calculated for the spherical nuclei. In the collisions with smaller $E_{\rm c.m.}$ the

 

formation of the DNS is expected to be strongly suppressed. Therefore, we treat $E_{\rm c.m.} \geqslant E^{\rm min}_{\rm c.m.}$, for which the capture cross section is estimated as $\sigma_{\rm cap} = \pi\hbar^2 J_{\rm cap}(J_{\rm cap}+1)/(2\mu E_{\rm c.m.})$, where $\mu$ is the reduced mass for projectile and target. In the AECQ reactions, which occur slightly above the Coulomb barrier, only partial waves with $J \leqslant J_{\rm cap} = 20$ contribute to the production of superheavy nuclei. If in the DNS the total angular momentum is distributed between the nuclei and orbital motion proportionally to the corresponding moments of inertia, for larger $J$ the excited primary heavy nucleus will not survive with respect to fission with valuable probability. For $J_{\rm cap} = 20$, the primary heavy nucleus has angular moment about of 10.

The primary charge and mass yield $Y_{Z,N}$ of the decay fragments can be expressed as in Ref. [16] as follows:

$$Y_{Z,N} = \Lambda^{qf}_{Z,N} \int_0^{t_0} P_{Z,N}(t)\,dt, \tag{2}$$

where $P_{Z,N}$ is the probability of formation of the corresponding DNS configuration and the decay rate $\Lambda^{qf}_{Z,N}$ of this configuration in $R$ is associated with the one-dimensional Kramers rate [19]. The time of reaction $t_0$ is defined as in Ref. [16] from the normalization condition $\sum_{Z,N} Y_{Z,N} = 1$. For $J \leqslant 20$, the value of $P_{Z,N}$ is weakly dependent on $J$ and the factorization (1) is justified.

Using the microscopical method suggested in Ref. [16], one can find $P_{Z,N}(t)$ from the following master equation:

$$\begin{aligned}\frac{d}{dt}P_{Z,N}(t) = {} & \Delta^{(-,0)}_{Z+1,N}P_{Z+1,N}(t) + \Delta^{(+,0)}_{Z-1,N}P_{Z-1,N}(t) \\ & + \Delta^{(0,-)}_{Z,N+1}P_{Z,N+1}(t) + \Delta^{(0,+)}_{Z,N-1}P_{Z,N-1}(t) \\ & - \left(\Delta^{(-,0)}_{Z,N} + \Delta^{(+,0)}_{Z,N} + \Delta^{(0,-)}_{Z,N} + \Delta^{(0,+)}_{Z,N} + \Lambda^{qf}_{Z,N}\right) \\ & \times P_{Z,N}(t),\end{aligned} \tag{3}$$

with initial condition $P_{Z,N}(0) = \delta_{Z,Z_i}\delta_{N,N_i}$ and the microscopically defined transport coefficients for proton ($\Delta^{(\pm,0)}_{Z,N}$) and neutron ($\Delta^{(0,\pm)}_{Z,N}$) transfers between the DNS nuclei. In the reactions considered, the probability of fission of heavy nucleus in the DNS is small enough to be disregarded in Eq. (3). Despite the simplifications made in Ref. [16], the solution of Eq. (3) remains time consumable.

We suggest here the simpler statistical method to find $Y_{Z,N}$ using the DNS potential energy calculated as in Ref. [12]:

$$U(R, Z, N, J) = B_L + B_H + V(R, Z, N, J), \tag{4}$$

where $B_L$ and $B_H$ are the mass excesses of the light and heavy fragments, respectively. The nucleus-nucleus potential [12] $V(R, Z, N, J) = V_C(R, Z) + V_N(R, Z, N) + V_{\rm rot}(R, Z, N, J)$ in Eq. (4) is the sum of the Coulomb potential $V_C$, the nuclear potential $V_N(R, Z, N)$, and the centrifugal potential $V_{\rm rot}(R, Z, N, J)$. There is the pocket in the nucleus-nucleus potential that is situated for pole-pole orientation at the distance $R_m(Z, N) = R_L(1 + \sqrt{5/(4\pi)}\beta_L) + R_H(1 + \sqrt{5/(4\pi)}\beta_H) + 0.5$ fm ($\beta_L$ and $\beta_H$ are the deformation parameters of the nuclei with radii $R_L$ and $R_H$) and keeps the DNS nuclei in contact. The depth of this pocket defines the value of $B_{qf}(Z, N) = U(R_b, Z, N, J) - U(R_m, Z, N, J)$ of the quasifission barrier, which increases with $Z$ when the DNS becomes more asymmetric. The decaying DNS with given $Z$ and $N$ has to overcome the potential barrier in $R$ at $R_b(Z, N) = R_m(Z, N) + 1$ fm. Here, we deal with the decay of DNS before it reaches, via nucleon transfers, the inner fusion barrier (Bussinaro-Gallone point) at $Z \approx Z_{\rm tot} - 8$ ($Z_{\rm tot}$ is the total charge number of the system) in the reactions considered. The initial DNS is in the conditional minimum of potential energy surface. To produce from it the decaying DNS with $Z$ and $N$, one should overcome the barrier $B_R(Z, N) = U(R_b, Z, N, J) - U(R_m, Z_i, N_i, J)$. For each $Z$, the minimization of $U$ with respect to $N$ results in the DNS corresponding to the minimal value of $B_R(Z, N)$. The decays of these DNS mainly yield the products of the AECQ reactions. As follows from the calculations with Eq. (3), the quasistationary regime is established quite quickly in the DNS and one can use the Kramers-type expressions for the flow rate $\Lambda^R_{Z,N}$ over the barrier $B_R(Z, N)$ and for the flow rate $\Lambda^{\eta_{\rm sym}}_{Z_i,N_i}$ over the barrier $B_{\eta_{\rm sym}}(Z_i, N_i)$, prohibiting the motion of the initial DNS in charge (mass) asymmetry to more symmetric configurations. Therefore,

$$Y_{Z,N} = \Lambda^R_{Z,N} t_0. \tag{5}$$

The decay of the initial DNS in $R$ as well as its evolution to more symmetric configurations ($Z < Z_i$) with consequence decay in $R$ mainly define the reaction time $t_0 = 1/(\Lambda^R_{Z_i,N_i} + \Lambda^{\eta_{\rm sym}}_{Z_i,N_i})$, where $\Lambda^R_{Z_i,N_i} = \Lambda^{qf}_{Z_i,N_i}$. Because $B_{\eta_{\rm sym}}(Z_i, N_i) =$ 0.5–1 MeV and $B_R(Z_i, N_i) = B_{qf}(Z_i, N_i) =$ 3–4 MeV in the $^{48}$Ca-induced actinide-based fusion reactions, $\Lambda^R_{Z_i,N_i} \ll \Lambda^{\eta_{\rm sym}}_{Z_i,N_i}$ and $t_0 \approx 1/\Lambda^{\eta_{\rm sym}}_{Z_i,N_i}$ [14]. Substituting $t_0$ into Eq. (5) and estimating the ratio of preexponential factors in the expressions for the flow rates as 0.5, for the reactions considered we obtain the following:

$$Y_{Z,N} \approx 0.5 \exp\left(-\frac{B_R(Z, N) - B_{\eta_{\rm sym}}(Z_i, N_i)}{\Theta(Z_i, N_i)}\right). \tag{6}$$

The temperature $\Theta(Z_i, N_i)$ is calculated by using the Fermi-gas expression $\Theta = \sqrt{E^*/a}$ with the excitation energy $E^*(Z_i, N_i)$ of the initial DNS and with the level-density parameter $a = A_{\rm tot}/12$ MeV$^{-1}$, where $A_{\rm tot}$ is the total mass number of the system.

The suggested simplistic approach is suitable if the initial DNS is close to the $N/Z$ equilibrium that is true for the reactions considered. If the injection point is considerably displaced from the $N/Z$ equilibrium, the dynamical effects contribute mainly to the production of nuclei near the injection point and our statistical approach underestimates their yields.

The reactions with the transfer of many nucleons occurs during quite a long time, up to $t_0 \approx 10^{-20}$ s at $J \leqslant 20$. This allows us to assume the same temperature in the DNS nuclei and to define the excitation energy of primary heavy nucleus proportionally to its mass $A_H$: $E^*_H(Z, N) = [E^*(Z_i, N_i) - B_R(Z, N)]A_H/A_{\rm tot}$. The deviation from the thermal equilibrium is expected only for the DNS near the injection point where the temperature of heavy nucleus is smaller than the temperature of light nucleus [3–7]. Thus, assuming the thermal equilibrium in the DNS, we can overestimate the excitation of heavy primary nucleus and predict the low limits of $W_{\rm sur}$ and

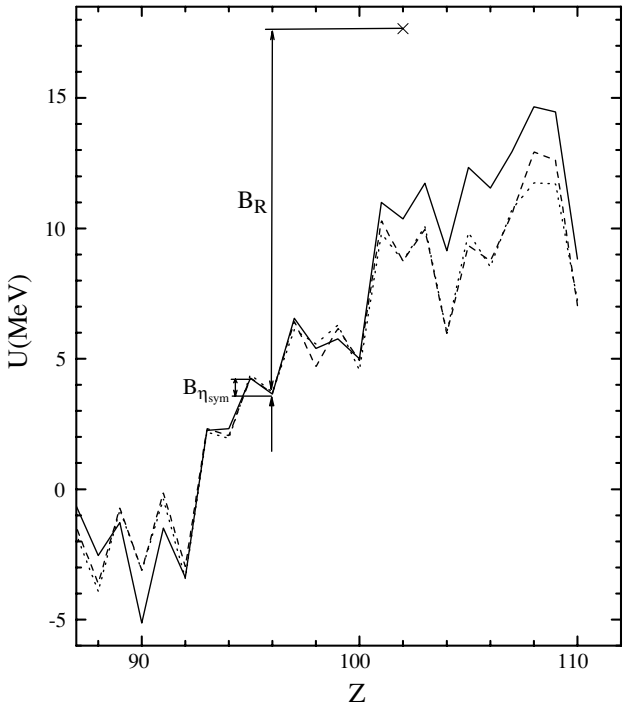


FIG. 1. The DNS potential energies at $R_m$ and $J = 0$ as functions of $Z$ of heavy nucleus are presented by dotted, dashed, and solid curves for the reactions $^{48}$Ca+$^{244,246,248}$Cm, respectively. The arrow indicates the initial DNS. For the $^{48}$Ca+$^{248}$Cm reaction, the barriers $B_{\eta_{\rm sym}}(Z_i = 20, N_i = 48)$ and $B_R(Z = 102, N = 160)$ are indicated. The $\times$ notates $U(R_b, Z = 102, N = 160, J = 0)$. The potential energies refer to the energies of corresponding compound nuclei.

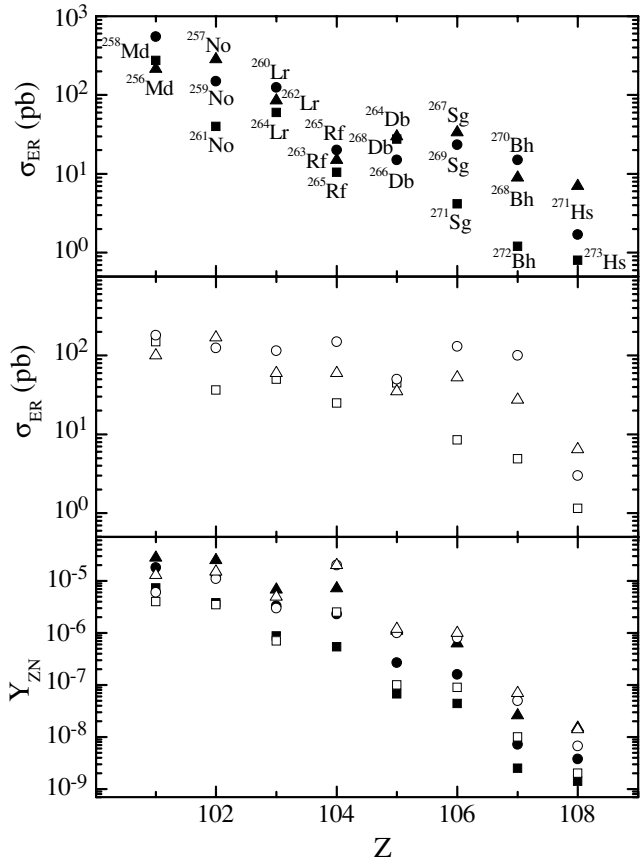


FIG. 2. The calculated primary yields $Y_{Z,N}$ (lower part) and evaporation residue cross sections $\sigma_{\rm ER}$ (middle and upper parts) are shown by triangles, circles, and squares for the reactions $^{48}$Ca+$^{244,246,248}$Cm ($E_{\rm c.m.} = 207$, 205.5, and 204 MeV), respectively. The heavy fragments after $1n$ evaporation are indicated in the upper part of the figure. The results obtained with Eqs. (2) and (3) and with Eq. (6) are indicated by closed and open symbols, respectively.

$\sigma_{\rm ER}$. Note that the partition of excitation energy in the DNS weakly influences $Y_{Z,N}$. Because in our calculations of the DNS potential energy the deformations of the nuclei are close to their values for the ground states, the excitation energies of the DNS nuclei remain almost without changes after the DNS decays.

### III. RESULTS AND DISCUSSION

The DNS potential energies at $R_m$ as functions of $Z$ of heavy fragment are shown in Fig. 1 for the reactions $^{48}$Ca+$^{244,246,248}$Cm. The deformations of the DNS nuclei are taken from Ref. [20]. The minimization with respect to $N/Z$ ratio is applied for each $Z$. Indeed, these isotopes are expected to have the largest yields. For $102 < Z < 110$, the potential energy decreases with total number of neutrons of the DNS and the larger primary yield of superheavy nuclei is expected in the reactions with $^{244,246}$Cm rather than with $^{248}$Cm. This is demonstrated in Fig. 2, where the primary yields of the most probable isotopes of heavy nuclei are calculated with Eqs. (2) and (3) and with Eq. (6). Similar results are obtained with these two methods. For $Z \geqslant 104$, the simplified approach can give $Y_{Z,N}$ larger within factor of 5. Because there are no experimental data to be compared with the calculated results presented in Fig. 2, it is difficult to give preference to one of the methods. In the reaction $^{48}$Ca+$^{248}$Cm $\rightarrow$ $^{40}$S+($^{254}$Fm+$2n$), the calculated $\sigma_{\rm ER}$ for $^{254}$Fm is about 0.5 $\mu$b in two approaches, which is close to the experimental result presented in Refs. [5–7] where the yields of nuclei above Fm were not measured. We note that the calculation of $Y_{Z,N}$ with Eq. (6) is technically much simpler.

In Fig. 2 the excitation energies of primary heavy nuclei correspond to $E_{\rm c.m.} = 204-207$ MeV, close to $E^{\rm min}_{\rm c.m.}$. In this case $E^*_H(Z, N)$ are related to the maxima or to the right sides of excitation functions for one neutron emission. For example, for $^{262}$No and $^{274}$Hs $E^*_H = 16\,[W_{\rm sur}(1n) = 2.4 \times 10^{-4}]$ and 11 MeV $[W_{\rm sur}(1n) = 1.6 \times 10^{-2}]$, respectively. Although $Y_{Z,N}$ decreases by about 3 orders of magnitude with increasing $Z$ from 102 to 108, the evaporation residue cross section decreases only by about 30 times because of the increase of $W_{\rm sur}$ with $Z$. The experimental data [7] as well as our treatment indicate the preference of a projectile/target combination with a smaller number of neutrons to produce superheavy nuclei. If one increases $E_{\rm c.m.}$, the larger values of $Y_{Z,N}$ are overcompensated by smaller values of $W_{\rm sur}$ and thus $\sigma_{\rm ER}$ become smaller. One can see that with the AECQ reactions on actinide targets, the unknown isotopes of superheavy nuclei can be produced with suitable cross sections. In Fig. 2 the nuclei $^{261}$No and $^{264}$Lr, and all nuclei with $Z > 103$, were not yet

produced in complete fusion reactions. Therefore, the AECQ leads to the superheavies with mass numbers that are between those produced in the cold and hot fusion reactions [1,2].

The probability of transfer of large number of nucleons from projectile to target correlates with the dependence of the DNS potential energy on $Z$. For example, in the $^{48}$Ca+$^{238}$U ($E_{\mathrm{c.m.}} = 196.5$ MeV) reaction the slightly smaller value of $B_R(Z = 102, N = 160)$ as compared with the $^{48}$Ca+$^{248}$Cm reaction leads to larger $Y_{Z=102,N=160}$ and larger $\sigma_{\mathrm{ER}} \approx 70$ pb for $^{261}$No. Although in the $^{48}$Ca+$^{243}$Am ($E_{\mathrm{c.m.}} = 202$ MeV) reaction the $\sigma_{\mathrm{ER}}$ for Rf and Db are similar to those in the reactions $^{48}$Ca+$^{246,244}$Cm, the cross sections for Sg and Bh are smaller. In the reaction with $^{243}$Am the nuclei Sg and Bh are farther in $Z$ from the target and the $N/Z$ ratio in the system is slightly larger.

If in the actinide-based reactions a projectile other than $^{48}$Ca is used, the AECQ mostly yields the isotopes of superheavies that were already produced with larger cross sections in various complete fusion reactions. In the lead-based reactions the cross sections are expected to be smaller than in the actinide-based reactions because of a larger number of nucleons to be transferred. For example, in the $^{70}$Ge+$^{208}$Pb reaction the $\sigma_{\mathrm{ER}}$ is already about 1 pb for $^{250}$No in the $0n$ evaporation channel.

## IV. SUMMARY

In the reactions $^{48}$Ca+$^{238}$U, $^{243}$Am, $^{244,246,248}$Cm one can produce the new isotopes of superheavies with $Z =$ 104–108, which are not reachable in the hot and cold complete fusion reactions with the stable projectiles and targets. The production of these isotopes is also important for the experimental identification of superheavy nuclei. For example, for the reaction $^{243}$Am($^{48}$Ca,xn)$^{291-x}$115 $\alpha$-decay chains end at $^{267,268}$Db [1], which can be directly obtained in AECQ reactions $^{48}$Ca+$^{246,248}$Cm. Note that the methods elaborated for describing AECQ are suitable for the analysis of production of various exotic nuclei, for example, of neutron-rich light nuclei.

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