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Possibility of production of neutron-rich Zn and Ge isotopes in multinucleon transfer reactions at low energies

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The production cross sections of new neutron-rich ^{84,86}Zn and ^{90,92}Ge isotopes beyond $N = 50$ are estimated for the first time in the multinucleon transfer reactions ^{48}Ca + ^{238}U and ^{48}Ca + ^{244}Pu. The production of new isotopes in reactions with a ^{48}Ca beam is discussed for future experiments.

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Besides the reactions at intermediate energies [1–7], the multinucleon transfer reactions at low energies are actively discussed to produce exotic nuclei [8–14]. These binary reactions have been known for producing exotic nuclei for many years [15–24]. In Ref. [12] the possibility was shown to produce the neutron-rich nuclei close to the drip line in the transfer-type reactions ^{48}Ca + ^{232}Th, ^{238}U, ^{248}Cm at incident energies close to the Coulomb barrier. The ^{238}U (5.5 MeV/nucleon) + ^{48}Ca reaction was used to produce the odd and even neutron-rich Ca isotopes and study their low-lying states [13]. In Refs. [9–11,14] the neutron-rich nuclei with $A = 50$–80 were studied through multinucleon transfer reactions by bombarding ^{208}Pb and ^{238}U targets with beams ^{48}Ca, ^{58,64}Ni, ^{70}Zn, and ^{82}Se.

The present article deals with the production of neutron-rich Zn and Ge isotopes with neutron number $N > 50$, which are the products of the multinucleon transfer channel of the reactions ^{48}Ca + ^{238}U, ^{244}Pu at low energies. Our purpose is to treat the yield of the neutron-rich nuclei in the production of which the contributions of fast nonequilibrium processes in the entrance channel are expected to be negligible. Note that the actinide-based reactions ^{48}Ca + ^{233,238}U, ^{237}Np, ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, and ^{249}Cf are intensively and successfully used to produce superheavy nuclei and products of the multinucleon transfer process or quasifission, which competes with the complete fusion process [25–28].

As shown in Ref. [12], the diffusive multinucleon transfer-type reactions can be described as an evolution of the dinuclear system (DNS), which is formed in the entrance channel of the reaction after dissipation of the kinetic energy and angular momentum of the relative motion [15,16,29–34]. The dynamics of the process are considered as a diffusion of the DNS in the charge and mass asymmetry coordinates, which are defined here by the charge and neutron numbers Z and N of the light nucleus of the DNS. During the evolution in charge and mass asymmetry coordinates, the excited DNS can decay into two fragments in relative distance R between the centers of the DNS nuclei. So within the DNS model the production of the exotic nucleus is treated as a three-step process. First, the initial DNS with light nucleus (Z_i, N_i) is formed in the peripheral collision for a short time. Second, the DNS with light exotic nucleus (Z, N) is produced by nucleon transfers. Then this DNS separates into two fragments.

The cross section of the production of a primary light nucleus in the diffusive nucleon transfer reaction is written as a sum over all partial waves J

$$\begin{aligned}\sigma_{Z,N}(E_{\text{c.m.}}) &= \sum_J \sigma_{Z,N}(E_{\text{c.m.}}, J),\\ \sigma_{Z,N}(E_{\text{c.m.}}, J) &= \int_0^{\pi/2}\int_0^{\pi/2} d\cos\Theta_1 d\cos\Theta_2 \\ &\quad\times \sigma_c(E_{\text{c.m.}}, J, \Theta_i) Y_{Z,N}(E_{\text{c.m.}}, J, \Theta_i).\end{aligned} \tag{1}$$

Here, the average over the orientations of statically deformed interacting nuclei (Θ_i $(i = 1, 2)$ are the orientation angles with respect to the collision axis) is taken into consideration [35]. For the correct description of $\sigma_{Z,N}$, the partial capture cross section σ_c in the entrance channel and the formation-decay probability $Y_{Z,N}$ of the DNS configuration with charge and mass asymmetries given by Z and N should be properly calculated. The value of $\sigma_c(E_{\text{c.m.}}, J, \Theta_i) = \frac{\pi\hbar^2}{2\mu E_{\text{c.m.}}}(2J + 1)T(E_{\text{c.m.}}, J, \Theta_i)$ defines the transition of the colliding nuclei over the Coulomb barrier with the probability T and the formation of the DNS when the kinetic energy $E_{\text{c.m.}}$ and angular momentum J of the relative motion are transformed into the excitation energy and angular momentum of the DNS. The capture (transition) probability $T(E_{\text{c.m.}}, J, \Theta_i) = \{1 + \exp[2\pi(V_J(R_b, Z, N, \Theta_i) - E_{\text{c.m.}})/\hbar\omega_J(Z, N, \Theta_i)]\}^{-1}$ is calculated with the Hill-Wheeler formula. The effective nucleus-nucleus potential [29]

$$\begin{aligned}V_J(R, Z, N, \Theta_i) &= V_N(R, Z, N, \Theta_i) + V_C(R, Z, N, \Theta_i)\\ &\quad + \hbar^2 J(J + 1)/(2\Im),\end{aligned} \tag{2}$$

is calculated as a sum of nuclear V_N, Coulomb V_C, and centrifugal interactions and approximated near the Coulomb barrier at $R = R_b$ by the inverted harmonic-oscillator potential with the barrier height $V_J(R_b, Z, N, \Theta_i)$ and frequency $\omega_J(Z, N, \Theta_i)$. In the entrance channel the moment of inertia is $\Im = \mu R^2$, but after the DNS formation it corresponds to the rigid body limit at sticking condition. The nuclear potential V_N

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is calculated with the double-folding model using a nuclear radius parameter $r_0 = 1.15$ fm and a diffuseness $a = 0.54$ fm for ^{48}Ca and $a = 0.56$ fm for the actinide targets [29]. The quadrupole deformation parameters of actinides are taken from Ref. [36].

The primary charge and mass yields of fragments can be expressed by the product of the formation probability $P_{Z,N}(t)$ of the DNS configuration with charge and mass asymmetries given by Z and N ($A = Z + N$ is the mass number of the nucleus) and of the decay probability of this configuration in R represented by the one-dimensional Kramers rate $\Lambda^{qf}_{Z,N}$ [34]

$$Y_{Z,N} = \Lambda^{qf}_{Z,N} \int_0^{t_0} P_{Z,N}(t)dt. \qquad (3)$$

Here, t_0 is the time of reaction, which is determined as in Ref. [34] from the normalization condition $\sum_{Z,N} Y_{Z,N} = 0.98$. The mass yield of transfer products is defined as follows

$$Y_A = \sum_Z Y_{Z,A-Z}. \qquad (4)$$

Using the macroscopical method suggested in Ref. [34], one can find $P_{Z,N}$ from the solution of the system of master equations

$$\begin{aligned}\frac{d}{dt}P_{Z,N}(t) = {} & \Delta^{(-,0)}_{Z+1,N}P_{Z+1,N}(t) + \Delta^{(+,0)}_{Z-1,N}P_{Z-1,N}(t)\\ & + \Delta^{(0,-)}_{Z,N+1}P_{Z,N+1}(t) + \Delta^{(0,+)}_{Z,N-1}P_{Z,N-1}(t)\\ & - \big(\Delta^{(-,0)}_{Z,N} + \Delta^{(+,0)}_{Z,N} + \Delta^{(0,-)}_{Z,N} + \Delta^{(0,+)}_{Z,N}\\ & + \Lambda^{qf}_{Z,N} + \Lambda^{\text{fis}}_{Z,N}\big)P_{Z,N}(t), \qquad (5)\end{aligned}$$

with initial condition $P_{Z,N}(0) = \delta_{Z,Z_i}\delta_{N,N_i}$ and the transport coefficients that characterize the proton and neutron transfer rates from a heavy to a light nucleus [$\Delta^{(+,0)}_{Z,N}$, $\Delta^{(0,+)}_{Z,N}$] or in the opposite direction [$\Delta^{(-,0)}_{Z,N}$, $\Delta^{(0,-)}_{Z,N}$]. In Eq. (5) we take only the transitions $Z \rightleftharpoons Z \pm 1$ and $N \rightleftharpoons N \pm 1$ into account in the spirit of the independent-particle model. Here, $\Lambda^{\text{fis}}_{Z,N}$ is the fission rate of the DNS heavy nucleus [34]. The solution of the system of master equations (5) with the decay terms and the microscopically calculated transport coefficients ensures a realistic description of the DNS evolution in charge and mass asymmetries [34].

As in Ref. [37], the excitation energy of the initial DNS should be enough to form the DNS with a certain exotic nucleus (i.e., to overcome the energy threshold $\Delta B_{Z,N,J}$ for this). The value of

$$\Delta B_{Z,N,J} = U(R_b, Z, N, J) - U(R_m, Z_i, N_i, J), \qquad (6)$$

is defined using the DNS potential energy calculated as in Ref. [32]

$$U(R, Z, N, J) = B_L + B_H + V_J(R, Z, N, \Theta_i), \qquad (7)$$

where B_L and B_H are the mass excesses of the light and heavy fragments, respectively. Here, the DNS potential energy is calculated at the touching distance $R = R_m \approx R_L[1 + \beta_L Y_{20}(\Theta_L)] + R_H[1 + \beta_H Y_{20}(\Theta_H)] + 0.5$ fm (β_L and β_H are the quadrupole deformation parameters of the nuclei with radii R_L and R_H) and the position of the Coulomb barrier $R = R_b \approx R_m + 1.2$ fm for the systems ^{48}Ca + ^{238}U,^{244}Pu. Note that the values of R_m and R_b depend on the charge and mass asymmetries.

The excitation energy of the initial DNS is $E^*(Z_i, N_i, J) = E_{\text{c.m.}} - V_J(R_m, Z_i, N_i, \Theta_i)$. With this value the excitation energy of the DNS with exotic nucleus (Z, N) is $E^*(Z, N, J) = E^*(Z_i, N_i, J) - \Delta B_{Z,N,J}$. Assuming the situation of thermal equilibrium, the excitation energy of the nucleus with mass $A = Z + N$ in this DNS is $E^*_L(Z, N, J) = E^*(Z, N, J)A/A_{\text{tot}}$, where A_{tot} is the total mass number of the DNS. It is clear that the probability of the formation of the DNS with exotic nucleus (Z, N) increases with $E^*(Z_i, N_i, J)$. However, the increase of $E^*(Z_i, N_i, J)$ is possible up to the moment when $E^*_L(Z, N, J)$ reaches the neutron separation energy $S_n(Z, N)$. The further increase of $E^*(Z_i, N_i, J)$ will lead to the strong loss of neutron-rich nuclei because of the neutron emission. If the primary nucleus is excited, one should take into consideration its survival probability W_{sur} in the deexcitation process to obtain the evaporation residue cross section as follows

$$\sigma^{ER}_{Z,N-x}(E_{\text{c.m.}}) = \sum_J \sigma_{Z,N}(E_{\text{c.m.}}, J)W_{\text{sur}}(E_{\text{c.m.}}, J, x), \qquad (8)$$

where x is the number of evaporated neutrons from the excited primary nucleus. W_{sur} is treated as in Ref. [37] and takes into consideration the competition with other deexcitation channels.

To test our method of calculation of $\sigma^{ER}_{Z,N}(E_{\text{c.m.}})$ and $\sigma_{Z,N}(E_{\text{c.m.}})$, we treat the production of Ti in the multinucleon transfer reactions ^{58}Ni($E_{\text{c.m.}} = 256.8$ MeV)+^{208}Pb [10] and ^{64}Ni($E_{\text{c.m.}} = 307.4$ MeV) + ^{238}U [9] at bombarding energies near the Coulomb barrier. In these reactions the available excitation energies supply two-neutron evaporation from the primary Ti isotopes having the maximal yields. In the ^{58}Ni + ^{208}Pb reaction ^{50}Ti and ^{52}Ti are produced with the cross sections 1 and 0.2 mb [10], respectively, which are consistent with our calculated cross sections 0.6 and 0.35 mb, respectively. In the ^{64}Ni + ^{238}U reaction the experimental [9] and theoretical production cross sections for ^{52}Ti are 0.5 and 1.6 mb, respectively. In the reaction ^{48}Ca($E_{\text{c.m.}} = 204$ MeV) + ^{248}Cm → ^{40}S + (^{254}Fm + $2n$), the calculated $\sigma^{ER}_{Z,N}(E_{\text{c.m.}})$ for ^{254}Fm is about 0.5 μb, which is close to the experimental result presented in Ref. [19]. In the ^{48}Ca($E_{\text{c.m.}} = 274.6$ MeV) + ^{238}U reaction the experimental [14] and calculated ratios of secondary yields $Y(^{62}\text{Fe})/Y(^{58}\text{Cr})$ for the neutron-rich ^{62}Fe and ^{58}Cr isotopes are about 0.2 and 0.3, respectively.

The multinucleon transfer products of the quasifission reactions ^{48}Ca($E_{\text{c.m.}} = 190.2$ MeV) + ^{238}U and ^{48}Ca($E_{\text{c.m.}} = 201$ MeV) + ^{244}Pu at incident energies close to the Coulomb barrier are correctly described within our model. Figures 1 and 2 show the mass yield Y_A as functions of the mass number of the light fragment. The calculated data in Figs. 1 and 2 are related to the primary (before neutron emission) fragments. Therefore, the maxima and minima in the calculated functions Y_A are more pronounced. The postneutron evaporation washes out some peculiarities of these functions. Taking into consideration the experimental uncertainties in the identification of quasifission and fusion-fission products and the measurement of mass, the agreement between the

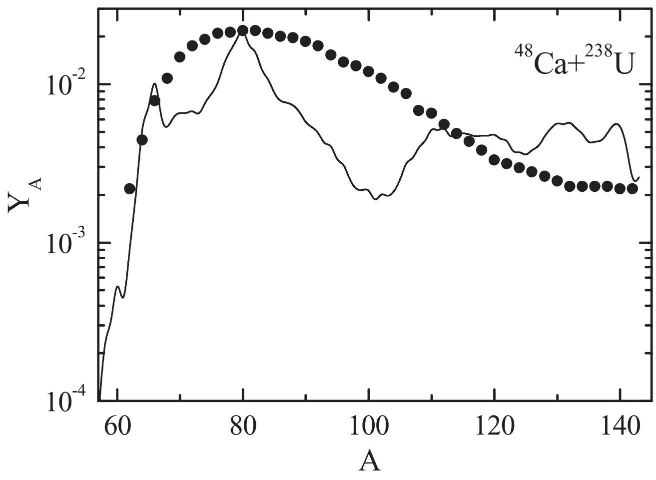

FIG. 1. The calculated (solid lines) mass yield (in relative units) of the quasifission products as a function of the mass number of the light fragment for ^{48}Ca + ^{238}U reaction at bombarding energy $E_{\rm c.m.} = 190.2$ MeV. The experimental data [38] are shown by solid points.

calculated and experimental data [38] is quite good. In the experiment besides the quasifission and fusion-fission, the fission of the heavy nucleus in the DNS with a subsequent fusion of one of the fission fragments with the light nucleus of the DNS and ternary processes with the emission of a light particle are identified as two-body processes of complete momentum transfer. It should be noted that the small oscillations in experimental data are comparable with the accuracy of the measurements [38]. The maximum yield of the quasifission fragments occurs around the nucleus ^{208}Pb for the heavy fragment where the DNS potential energy has a deep minimum. The evolution of the DNS is hindered by this minimum to go to smaller mass asymmetry and correspondingly the decay probability from the configuration with ^{208}Pb is increased. In the reaction $^{48}\mathrm{Ca} + {}^{238}\mathrm{U}$ ($^{48}\mathrm{Ca} + {}^{244}\mathrm{Pu}$), the height of the peak around $A = 80$ is 4.5 (3.5) times larger than the height of the peaks in the symmetric mass region. The main contribution to the symmetric and near symmetric fragmentations comes from the multinucleon transfer process.

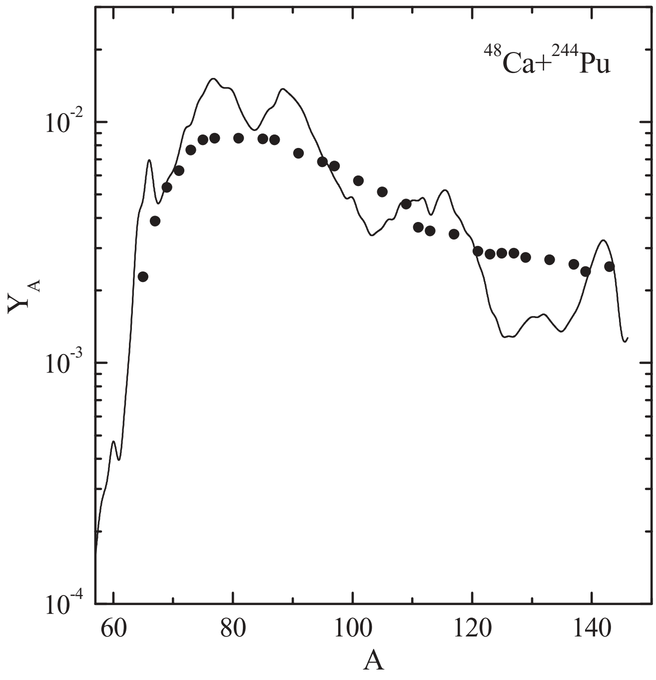

FIG. 2. The same as in Fig. 1, but for ^{48}Ca + ^{244}Pu reaction at bombarding energy $E_{\rm c.m.} = 201$ MeV.

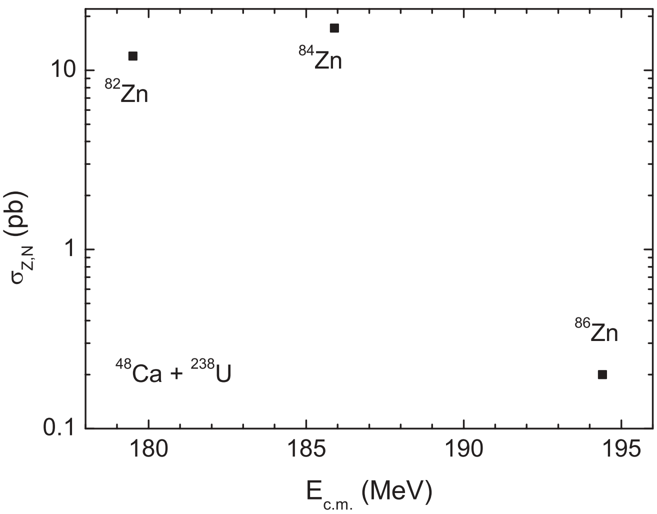

FIG. 3. The expected cross sections for the indicated neutron-rich isotopes of Zn produced in the ^{48}Ca + ^{238}U reaction at values of $E_{\rm c.m.}$ providing the excitations of these isotopes are equal to the corresponding thresholds for the neutron emission.

As shown previously, the suggested method is suitable for predicting the mass and charge yields and the production cross sections for the products of multinucleon transfer reactions. The calculated production cross sections of neutron-rich isotopes in the reactions $^{48}\mathrm{Ca} + {}^{238}\mathrm{U}$, ^{244}Pu at incident energies near the Coulomb barrier are presented in Figs. 3 through 5. We treat only the reactions leading to excitation energies of light neutron-rich nuclei equal to or smaller than their neutron separation energies $[E^*_L(Z, N, J) \leqslant S_n(Z, N)]$. In this case $W_{\rm sur} = 1$ and the primary and secondary yields coincide. In Figs. 1 and 2 the values of $E_{\rm c.m.}$ provide the condition $E^*_L(Z, N, J) = S_n(Z, N)$. The predicted values of $S_n(Z, N)$ for unknown nuclei are taken from the finite-range liquid-drop model [39]. If $E^*_L(Z, N, J) > S_n(Z, N)$, the primary neutron-rich nuclei are transformed into the secondary nuclei with less numbers of neutrons because of the deexcitation by neutron emission. The DNS evolution in the reactions treated can be schematically presented in the following way: $^{48}\mathrm{Ca} + {}^{238}\mathrm{U} \rightarrow {}^{78,80}\mathrm{Zn} + {}^{208,206}\mathrm{Pb} \rightarrow {}^{82,84,86}\mathrm{Zn} + {}^{204,202,200}\mathrm{Pb}$ and $^{48}\mathrm{Ca} + {}^{244}\mathrm{Pu} \rightarrow {}^{84,82}\mathrm{Ge} + {}^{208,210}\mathrm{Pb} \rightarrow {}^{86,88,90,92}\mathrm{Ge} + {}^{206,204,202,200}\mathrm{Pb}$. The system initially moves to the deep minimum of the potential energy surface (energetically favorable), which is caused by the shell effects around the DNS with magic heavy ^{208}Pb and light ^{80}Zn or ^{82}Ge nuclei; then from this minimum it reaches the DNS with exotic light nucleus by fluctuations in mass

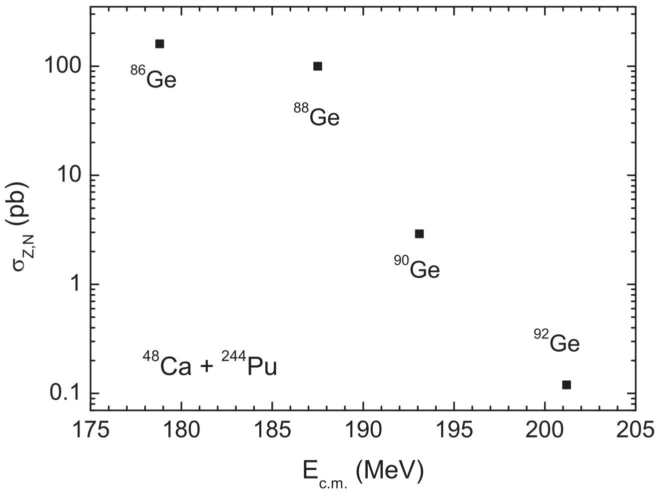

FIG. 4. The same as in Fig. 3, but for the indicated neutron-rich isotopes of Ge produced in the ^{48}Ca + ^{244}Pu reaction.

asymmetry. For low excitation energy, the evolution of the dinuclear system toward symmetry is hindered by this minimum.

The production cross section for ^{82}Zn (^{86}Ge) is about 2 (3) orders of magnitude larger than the production cross section for ^{86}Zn (^{92}Ge) (Figs. 3 and 4). Although $P_{30,52} \gg P_{30,54}$ ($P_{32,54} \gg P_{32,56}$), the cross sections of production of ^{82}Zn (^{86}Ge) and ^{84}Zn (^{88}Ge) are comparable because, in the case of ^{82}Zn (^{86}Ge), the optimal bombarding energy is considerably below the Coulomb barrier for the spherical nuclei and correspondingly $\sigma_c[^{82}\text{Zn}\ (^{86}\text{Ge})] \ll \sigma_c[^{84}\text{Zn}\ (^{88}\text{Ge})]$. At $E_{\text{c.m.}}$ smaller than the value of this barrier, only the collisions at certain mutual orientations lead to the capture. Since the yields of ^{82}Zn and ^{86}Ge isotopes as primary products is suppressed by the capture process, the production of these isotopes as secondary products at higher bombarding energies seems to be possible. However, the formation of the DNS with heavier isotopes of Zn or Ge occurs with smaller probability. Therefore, the productions of ^{82}Zn and ^{86}Ge as secondary products and as primary products seem to be with comparable cross sections.

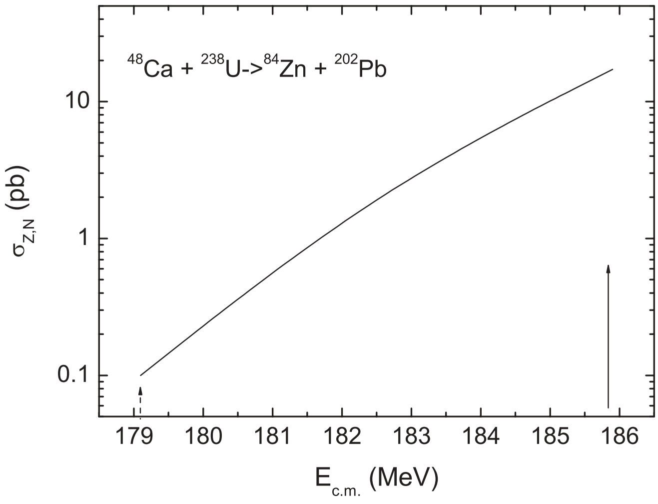

FIG. 5. The excitation function for producing ^{84}Zn in the multinucleon transfer reaction ^{48}Ca + ^{238}U. The solid (dashed) arrow indicates the expected cross section at the value of $E_{\text{c.m.}}$ providing the excitation of ^{84}Zn is equal to the threshold (half of the threshold) for the neutron emission.

The dependence of the production cross section of the neutron-rich ^{84}Zn isotope versus $E_{\text{c.m.}}$ is presented in Fig. 5. The overall trend of the dependence of the cross section on the neutron separation energy is easily visible. The solid arrow indicates the value of $E_{\text{c.m.}}$ at which the value of $E_L^*(Z, N, J)$ reaches $S_n(Z, N) = 3.99$ MeV. Since the predictions of $S_n(Z, N)$ have some uncertainties, we indicate by the dashed arrow the value of $E_{\text{c.m.}}$ at which the value of $E_L^*(Z, N, J)$ reaches $0.5S_n(Z, N)$. One can see that the decrease of the neutron binding energy by 2 MeV leads to the shift of $E_{\text{c.m.}}$ by about 7 MeV and the decrease of the production cross section by about 2 orders of magnitude. This decrease of $\sigma_{Z,N}$ is mostly due to the strong decrease of the capture cross section with decreasing $E_{\text{c.m.}}$ below the spherical Coulomb barrier. The measurement of the excitation function will be useful for estimating $S_n(Z, N)$ in the neutron-rich nuclei since, at $E_L^*(Z, N, J) > S_n(Z, N)$, the excitation function strongly drops down.

In our calculations the theoretically predicted [39] binding energies and neutron separation energies are used for neutron-rich nuclei. The uncertainties of these predictions mainly contribute to the uncertainty of our results. We assume that the excitation energy of DNS is shared between the DNS nuclei proportionally to their mass numbers. Since the isotopes of interest are formed from the projectile by the acceptance of nucleons, they can be slightly more excited than in the limit of thermal equilibrium. Taking into consideration these facts, we estimate the uncertainty within a factor of 3 to 5 in the calculated cross sections. If the neutron-rich isotope is close to the region of known nuclei, then the predictions for it have less uncertainties and the cross section is estimated with higher accuracy.

In the present article we demonstrate the possibilities for producing neutron-rich isotopes ^{82,84,86}Zn and ^{86,88,90,92}Ge in the reactions ^{48}Ca + ^{238}U, ^{244}Pu at incident energies near the Coulomb barrier. Note that ^{84,86}Zn and ^{90,92}Ge isotopes were not observed yet in the experiments. The dynamics of the binary reaction is considered as the diffusive multinucleon transfer between the interacting nuclei in the collisions when the excitation energy of the produced exotic isotope is lower than the threshold for the neutron emission. The calculated results indicate that the Q_{gg} values influence the production cross sections because of the binary character of the reaction. Indeed, the value of $\Delta B_{Z,N,J}$ contains the Q_{gg} value. The predicted cross sections are on the level (0.1–160) pb. The current experimental technology allows us to reach the cross section of 1 pb in about one week of beam time. Therefore, the multinucleon transfer reaction at low energies provides an efficient tool for producing nuclei far from stability and may be a fruitful method for reaching the neutron drip line. The production of the isotopes treated can be supplementary information in the experiments on the production of superheavy nuclei, which run for a long time with the same reactions. The multinucleon transfer reactions can provide detailed information about the dynamics of a dinuclear system in the mass and charge asymmetry degrees of freedom.

Due to the large neutron excess and smaller losses because of the quasifission near the entrance channel, the use of the ^{48}Ca projectile is more preferable than the use of heavier projectiles to reach the neutron-rich region of nuclide in the actinide-based reactions. One can also produce new heavy neutron-rich isotopes of nuclei with $Z = 66$–82 as complementary fragments in the actinide-based multinucleon transfer reactions with a ^{48}Ca beam.

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