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Production of neutron-rich Ca isotopes in transfer-type reactions

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Abstract. The production cross sections of neutron-rich isotopes ^{52,54,56,58,60}Ca in the diffusive nucleon transfer reactions $^{48}\mathrm{Ca}+{}^{197}\mathrm{Au}$ and $^{48}\mathrm{Ca}+{}^{238}\mathrm{U}$ at incident energies close to the Coulomb barrier are predicted. The global trend of production cross-section with respect to the charge (mass) number of target in reactions with ^{48}Ca beam is analysed for the future experiments.

PACS. 25.70.Hi Transfer reactions – 24.10.-i Nuclear reaction models and methods – 24.60.-k Statistical theory and fluctuations

1 Introduction

The fragmentation reactions at intermediate energies are often used now to produce exotic nuclei [1–4]. However, the excitation energies of the primary products in these reactions are on average rather large, which reduces the survival probability of weakly bound nuclei. The primary neutron-rich nuclei should be as cold as possible, otherwise they will be transformed into the secondary nuclei with a lower number of neutrons because of the de-excitation by neutron emission. So, the fragmentation reactions seem to be not always efficient for the production of nuclides far from the line of stability. The possibility of production of nuclei near the neutron drip line in multinucleon transfer reactions is actively discussed. These binary reactions have been known for producing exotic nuclei for many years [5–10]. In the transfer reactions the excitation energies of the fragments are smaller than in the fragmentation reactions. The control of the excitation energy of the reaction products in the binary processes is much simpler. So, the yields of exotic nuclei can be much larger in transfer reactions than the yields in high-energy fragmentation reactions, in spite of the smaller experimental efficiency in the collection of exotic nuclei in transfer reactions than in fragmentation reactions.

In the present paper we demonstrate for the first time the possibilities for producing neutron-rich isotopes of ^{52,54,56,58,60}Ca in the diffusive nucleon transfer reactions $^{48}\mathrm{Ca}+{}^{197}\mathrm{Au}$, ^{238}U discussed at FLNR (Dubna) and GANIL (Caen) where similar experiments have been planned. Since the production cross-sections of the neutron-rich isotopes ^{56,58,60}Ca are very small, the choice of optimal projectile-target combinations and bombarding energies is important for the experiments. If the production cross-sections were almost independent of the choice of the target, from the experimental point of view the use of the ^{197}Au target would be much easier than the use of actinide targets. One cannot conclude before the presented calculations that the production cross-sections of neutron-rich nuclei in the reaction $^{48}\mathrm{Ca}+{}^{197}\mathrm{Au}$ are much smaller than in the reaction $^{48}\mathrm{Ca}+{}^{238}\mathrm{U}$. Therefore, our final aim is to find the global trend in the production cross-section of exotic nuclei with respect to the charge (mass) number of the target in diffusive nucleon transfer reactions with the ^{48}Ca beam.

2 Model

The diffusive nucleon transfer reaction can be described as an evolution of a dinuclear system (DNS) which is formed in the entrance channel during the capture stage of the reaction after dissipation of the kinetic energy of the collision [5,6,11–17]. The dynamics of the process is 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 DNS light nucleus. During the evolution in charge and mass asymmetry coordinates, the excited DNS can decay into two fragments by diffusion at relative distance R between the centers of the DNS nuclei. The model treats the production of the exotic nucleus as a two-step process. First, from the

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$$Y_{Z,N} \approx 0.5 \exp\left(-\frac{U(R_m,Z,N_0,J)-U(R_m,Z_i,N_i,J)-B_{\eta_{sym}}(Z_i,N_i)}{\Theta(Z_i,N_i)}-\frac{B_R(Z,N)}{\Theta(Z,N_0)}\right), \quad (2)$$

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initial DNS with light nucleus (Z_i, N_i) the DNS with light nucleus (Z, N_0) is produced in the conditional minimum of the (Z, N) surface. Then the barrier penetration to the exotic nucleus (Z, N) is considered. The cross-section $\sigma_{Z,N}$ of the production of the primary light nucleus in the diffusive nucleon transfer reaction is the product of the capture cross-section σ_{cap} in the entrance reaction channel and the formation-decay probability $Y_{Z,N}$ of the DNS configuration with charge and mass asymmetries given by Z and N, respectively:

$$\sigma_{Z,N} = \sigma_{cap} Y_{Z,N} = \frac{\pi\hbar^2}{2\mu E_{c.m.}} J_{cap}(J_{cap}+1) Y_{Z,N}, \quad (1)$$

where μ and $E_{c.m.}$ are the reduced mass for projectile-target combination and the bombarding energy, respectively. In eq. (1) we set $J_{cap} = 30$ in order to be sure that the exotic nucleus is produced with an almost zero angular momentum. We treat only the reactions leading to excitation energies of light neutron-rich nuclei smaller than their neutron separation energies $S_n(Z,N)$. In this case the primary and secondary yields coincide.

In ref. [11] we suggested a simple statistical method to calculate the formation-decay probability,

see eq. (2) *on top of this page*

using the DNS potential energy U at the touching distance $R = R_m = R_L(1+\sqrt{5/(4\pi)}\beta_L)+R_H(1+\sqrt{5/(4\pi)}\beta_H)+0.5$ fm (β_L and β_H are the deformation parameters of the nuclei with radii R_L and R_H) and the potential barrier in R at $R_b = R_m + 1.2$ fm for the systems ${}^{48+x}$Ca + ${}^{238-x}$U and at $R_b = R_m + 1.4$ fm for the systems ${}^{48+x}$Ca + ${}^{197-x}$Au. The absolute values of R_b and R_m change when one moves away from the stability line, but the difference $R_b - R_m$ remains almost constant [12]. The decaying DNS with given Z and N has to escape from the minimum at $R = R_m$ by overcoming the potential barrier at $R = R_b$. $B_R(Z,N) = U(R_b,Z,N,J) - U(R_m,Z,N_0,J)$ is the barrier which the DNS with Z and N_0 should overcome to observe the decay of the DNS with Z and N. N_0 is neutron number corresponding to the N/Z equilibrium in the DNS at a given Z (the conditional minimum of the potential energy surface). $B_{\eta_{sym}} = (0.5\text{–}1.5)$ MeV is the barrier for the initial DNS in the direction towards more symmetric configurations. The temperature $\Theta(Z_i,N_i)$ is calculated by using the Fermi-gas expression $\Theta = \sqrt{E^*/a}$ with excitation energy of the initial DNS $E^*(Z_i,N_i)$ and with the level-density parameter $a = A_{tot}/12\,\text{MeV}^{-1}$, where A_{tot} is the total mass number of the system. The temperature $\Theta(Z,N_0)$ is calculated for the excitation energy $E^*(Z_i,N_i) - [U(R_m,Z,N_0,J) - U(R_m,Z_i,N_i,J)]$.

Since we consider here only the production of the neutron-rich nuclei with $Z = Z_i$ and $N > N_i$, and the N_i/Z_i ratio in the initial DNS corresponds to the N/Z equilibrium in the DNS, expression (2) for the formation-decay probability is simplified as follows:

$$Y_{Z_i,N} \approx 0.5 \exp\left(-\frac{B_R(Z_i,N)-B_{\eta_{sym}}(Z_i,N_i)}{\Theta(Z_i,N_i)}\right). \quad (3)$$

Thus, the main factor which prohibits the formation-decay is the evolution of the initial DNS to more symmetric configurations in Z with the following decay in R. It should be noted that at the excitation energies under consideration the channel of neutron emission from DNS nuclei can be opened. However, since $B_{\eta_{sym}} \ll S_n$ near the initial DNS and the maximal excitation energy of the initial DNS is about 55 MeV for the binary channel ^{48}Ca + ^{238}U → ^{60}Ca + ^{226}U, the probability of realization of the neutron emission channel is rather small and can be disregarded. The characteristic time of fluctuations in charge (mass) asymmetry is much smaller than the characteristic time of neutron emission. The excitation energy of the DNS containing the neutron-rich nucleus is not sufficient to emit the neutron.

Using eq. (3) for $Y_{Z_i,N}$, we apply the Q_{gg}-systematics to estimate the relative yields of the various isotopes of the element with Z_i. Indeed, the value of B_R contains the Q-value of the reaction. As known from the experimental study of deep inelastic collisions, the isotopic distribution follows the Q_{gg}-systematics [5–7]. The suggested simplified approach is suitable if the initial DNS point in the energy surface is located close to the N/Z equilibrium, which is true for the reactions under consideration. The used two-step picture was substantiated by more detailed master equation calculations [11,17].

3 Results of calculations

In the DNS formed from the initial DNS by diffusive nucleon transfers one can assume the thermal equilibrium and define the excitation energy of the light nucleus with mass $A_L = Z + N$ as $E^*_L(Z,N) = [E^*(Z_i,N_i) - B_R(Z,N)]A_L/A_{tot}$. The deviation from the thermal equilibrium is expected only for the DNS near the injection point. The cross-section $\sigma_{Z,N}$ for the production of the exotic nucleus (Z,N) increases with $E^*(Z_i,N_i)$ up to the moment when $E^*_L(Z,N)$ becomes equal to the neutron separation energy $S_n(Z,N)$. Further increase of $E^*(Z_i,N_i)$ would lead to a strong loss of neutron-rich nuclei because of the neutron emission. The calculated excitation functions for the production of ^{52,54,56,58,60}Ca in the reaction ^{48}Ca + ^{238}U are presented in fig. 1. The production cross-sections for ^{56}Ca are about 5 orders of magnitude larger than the production cross-section for ^{60}Ca. For ^{56,58,60}Ca, the predicted values of $S_n(Z_i,N)$ are taken from the finite-range liquid-drop model [18]. The solid

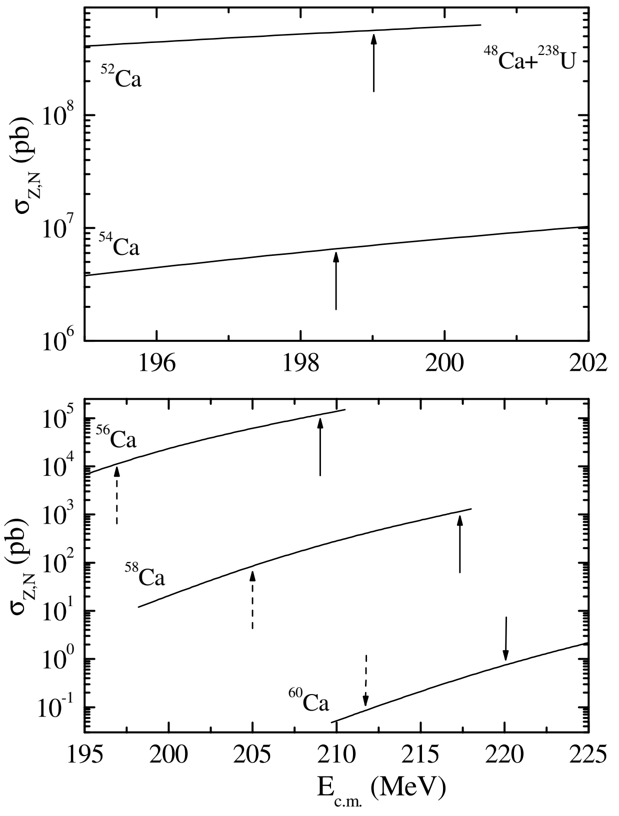

Fig. 1. The excitation functions for producing ^{52,54,56,58,60}Ca in the multinucleon transfer reaction $^{48}\mathrm{Ca}+{}^{238}\mathrm{U}$ are presented by solid lines. The solid arrows indicate the expected maximal cross-sections at $E_{c.m.}$ corresponding to the thresholds for neutron emission from the corresponding Ca isotopes. For ^{56,58,60}Ca, the dashed arrows indicate the expected cross-sections at $E_{c.m.}$ corresponding to half the thresholds for neutron emission.

arrows indicate the values of $E_{c.m.}$ at which $E^*_L(Z_i,N)$ reaches $S_n(Z_i,N)$. Since the predictions of $S_n(Z_i,N)$ have some uncertainties, for ^{56,58,60}Ca we indicate by dashed arrows the values of $E_{c.m.}$ at which $E^*_L(Z_i,N)$ reaches $0.5S_n(Z_i,N)$ and continue the excitation function to the right from the solid arrows. One can see that the decrease of $S_n(Z_i,N)$ by about 2 MeV shifts the arrows to the left of about 10 MeV. The measurement of the excitation functions up to the right sides, where they strongly drop down, would be thus useful to estimate the neutron binding energies in the neutron-rich nuclei.

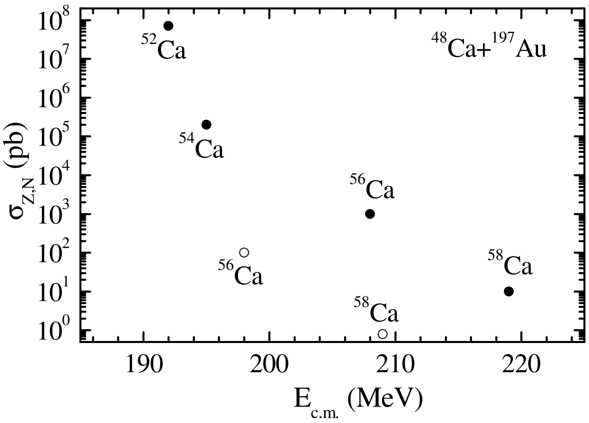

Fig. 2. The expected maximal cross-sections for the indicated neutron-rich isotopes of Ca produced in the $^{48}\mathrm{Ca}+{}^{197}\mathrm{Au}$ reaction at values of $E_{c.m.}$ corresponding to the thresholds for neutron emission (closed circles) and to half the thresholds for neutron emission (open circles) from corresponding Ca isotopes.

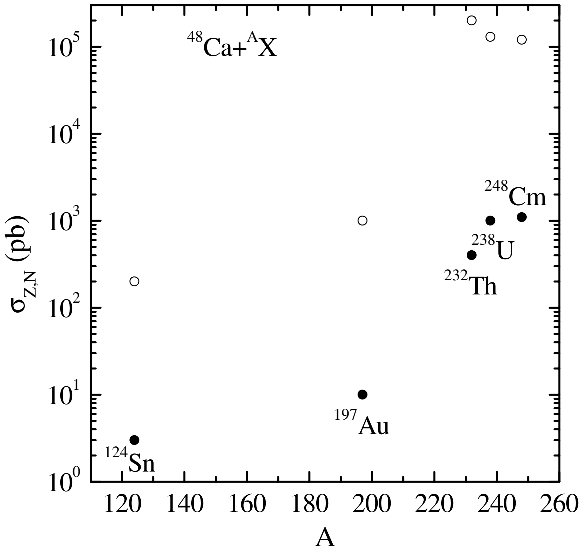

Fig. 3. The expected maximal production cross-sections for ^{56}Ca (open circles) and ^{58}Ca (closed circles) in reactions with ^{48}Ca and indicated targets as functions of the target mass. The values of $E_{c.m.}$ in the calculation correspond to the thresholds for neutron emission from ^{56,58}Ca. The results for the targets ^{124}Sn, ^{232}Th and ^{248}Cm are taken from ref. [11].

In the $^{48}\mathrm{Ca}+{}^{197}\mathrm{Au}$ reaction the maximal expected production cross-sections for ^{52,54,56,58}Ca are shown in fig. 2. The values of $E_{c.m.}$ correspond to the conditions $E^*_L(Z_i,N)=S_n(Z_i,N)$ for closed circles and $E^*_L(Z_i,N)=0.5S_n(Z_i,N)$ for open circles. One can see that the cross-sections in fig. 2 are more than one order of magnitude smaller than the corresponding cross-sections in fig. 1. Irradiating the heavier targets by a ^{48}Ca beam for producing neutron-rich isotopes of Ca, we gain in the Q-value as well as in the value of B_R. Therefore, the heavier targets are preferable for the production of neutron-rich nuclei (fig. 3). For example, replacing ^{124}Sn by ^{238}U, one can increase the yield of neutron-rich Ca by about 3 orders of magnitude. To illustrate the effects from the entry points (Q_{gg}-systematics) and the barrier penetration, we give the following examples. For the binary channels $^{48}\mathrm{Ca}+{}^{238}\mathrm{U}\rightarrow{}^{56}\mathrm{Ca}+{}^{230}\mathrm{U}$ ($^{48}\mathrm{Ca}+{}^{238}\mathrm{U}\rightarrow{}^{58}\mathrm{Ca}+{}^{228}\mathrm{U}$) and $^{48}\mathrm{Ca}+{}^{197}\mathrm{Au}\rightarrow{}^{56}\mathrm{Ca}+{}^{189}\mathrm{Au}$ ($^{48}\mathrm{Ca}+{}^{238}\mathrm{U}\rightarrow{}^{58}\mathrm{Ca}+{}^{187}\mathrm{Au}$), $Q_{gg}=15.7\,\mathrm{MeV}$, $B_R=18.7\,\mathrm{MeV}$ ($Q_{gg}=24.2\,\mathrm{MeV}$, $B_R=26.7\,\mathrm{MeV}$) and $Q_{gg}=29.0\,\mathrm{MeV}$, $B_R=27.9\,\mathrm{MeV}$ ($Q_{gg}=40.4\,\mathrm{MeV}$, $B_R=38.4\,\mathrm{MeV}$), respectively. One can see that Q_{gg} mainly contributes to the value of B_R.

4 Summary

The results of our calculations show that the production cross-sections of the neutron-rich nuclei ^{52,54,56,58,60}Ca in the ^{48}Ca + ^{197}Au reaction are much smaller than in the ^{48}Ca + ^{238}U reaction. Combining these new results with our previous calculations of the diffusive nucleon transfer reactions ^{48}Ca + ^{124}Sn, ^{232}Th, ^{248}Cm in ref. [11], one can conclude that the production cross-sections of the neutron-rich isotopes of Ca increase with the charge (mass) number of the target in the transfer reactions with the ^{48}Ca beam. This effect is quite strong and should be taken into consideration in the planned experiments. The reactions with actinide targets seem to be preferable. In the diffusive nucleon transfer reactions the production of nucleus near the neutron drip line increases with the value of $E_{c.m.}$ up to the moment when the excitation energy of this exotic nucleus reaches the threshold for neutron emission. Therefore, one can estimate the neutron separation energies for the unknown isotopes by measuring their excitation functions.

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