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PRODUCTION OF NEUTRON-RICH Ca ISOTOPES IN TRANSFER-TYPE REACTIONS

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Пениончкевич Ю. Э., Адамян Г. Г., Антоненко Н. В. E4-2005-141
Получение нейтроноизбыточных изотопов Ca в реакциях передач

Проанализирована возможность получения нейтроноизбыточных изотопов ^{56,58,60}Ca в реакциях передач. Предложены оптимальные условия образования этих изотопов. Энергии связи нейтронов ядер вблизи нейтронной линии стабильности можно оценить, измеряя функции возбуждения.

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Penionzhkevich Yu. E., Adamian G. G., Antonenko N. V. E4-2005-141
Production of Neutron-Rich Ca Isotopes in Transfer-Type Reactions

Possibilities of production of neutron-rich isotopes ^{56,58,60}Ca in transfer-type reactions are analyzed. The optimal conditions for their production are suggested. The neutron separation energies in nuclei near the neutron drip line can be estimated by measuring the excitation functions.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

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The fragmentation reactions at intermediate energies and fragment separators [1–4] are often used now to produce and identify certain exotic nuclei. However, these reactions seem to be not always efficient for synthesizing nuclei which are far from the line of stability. In the fragmentation reactions the excitation energy of fragments is in average rather large, that reduces the probability of survival for weakly-bound nuclei. Due to this, there has also been actively discussed the possibility of reactions of multinucleon transfers for the synthesis of nuclei near the neutron drip line. These reactions have been known for producing exotic nuclei for many years [5–8]. Since the products of multinucleon transfer reactions have wider angular distributions, the experimental efficiency in the collection of exotic nuclei is smaller than in the fragmentation reactions. However, the cross sections for exotic nuclei production can be much larger in the reactions in which the binary mechanism dominates [9] than the cross sections in high-energy fragmentation reactions. In the transfer reactions the total excitation energy is smaller and only binary processes are possible in which the control of excitation energy of the reaction products is simpler. The primary neutron-rich nuclei should be as cold as possible, otherwise they will be transformed into the secondary nuclei with less number of neutrons because of the deexcitation by neutron emission.

In Ref. [10] we demonstrated the possibilities for producing the neutron-rich isotopes of O, Ne, Mg, Si and Ca in some transfer-type reactions. In the present work we will show new results on the production of ^{56,58,60}Ca in the reactions with ^{48}Ca projectile and various targets. The details of the calculations are given in Ref. [10] and only shortly presented in this paper.

The quasifission and fusion as well as transfer-type reactions 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, 11–15]. The cross section $\sigma_{Z,N}$ of the production of primary light nucleus in transfer 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:

$$\sigma_{Z,N} = \sigma_{\rm cap} Y_{Z,N}. \tag{1}$$

We treat only the reactions leading to the 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. The capture cross section is estimated as

$$\sigma_{\rm cap} = \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}} J_{\rm cap}(J_{\rm cap}+1), \tag{2}$$

where μ is the reduced mass for projectile and target. In Eq. (2) we set $J_{\rm cap}=30$ in order to be sure that the exotic nucleus is produced with almost zero angular momentum.

The statistical method for finding $Y_{Z,N}$ uses the DNS potential energy $U(R,Z,N,J)$ calculated as in [10, 13]. There is the pocket in the nucleus–nucleus potential which is situated for pole–pole orientation at the distance $R_m = R_L(1+\sqrt{5/(4\pi)}\beta_L)+R_H(1+\sqrt{5/(4\pi)}\beta_H)+0.5$ fm (β_L and β_H are the deformation parameters of the nuclei with radii R_L and R_H) and keeps the DNS nuclei in contact. The decaying DNS with given Z and N has to escape from this pocket by overcoming the potential barrier $B_{qf}(Z,N) = U(R_b,Z,N,J) - U(R_m,Z,N,J)$ in R at $R_b \approx R_m + 1$ fm.

The quasistationary regime is established quite fast in the DNS, specially along the trajectory in charge (mass) asymmetry corresponding to N/Z equilibrium in the DNS. For this trajectory, $N = N_0(Z)$, i. e. the neutron number follows Z. Therefore, the formation probability for the configuration with Z and $N_0(Z)$ is estimated as

$$P_{Z,N_0}(t_0) \sim \exp\left(-\frac{U(R_m,Z,N_0,J) - U(R_m,Z_i,N_i,J)}{\Theta(Z_i,N_i)}\right). \tag{3}$$

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. Z_i and N_i are related to the DNS in the entrance channel.

The formation of the DNS containing the light neutron-rich nucleus with given Z is considered as a two-step process. The probability $P_{Z,N_0}(t_0)$ is firstly calculated. Then one should calculate the probability $G_{Z,N} = \Lambda^R_{Z,N,N_0} t_0$ of the formation and decay of the DNS with exotic nucleus. Since the DNS with Z and N_0 is in the conditional minimum of potential energy surface, we use the Kramers-type expressions for the quasistationary rate Λ^R_{Z,N,N_0} [10] of decay through the barrier $B_R(Z,N) = U(R_b,Z,N,J) - U(R_m,Z,N_0,J)$ which this DNS should overcome to observe the decay of the DNS with Z and N. As known from the experimental study of deep inelastic collisions, the isotopic distribution follows to the Q_{gg} value [5–7]. Using the expression above for $G_{Z,N}$, we apply the Q_{gg} value to estimate the relative yield of various isotopes of the element with certain Z.

The time of decay in R from the initial configuration or from more symmetric configurations mainly determines the time of reaction t_0. If we define the quasistationary rate $\Lambda^R_{Z_i,N_i}$ of decay through the barrier $B_R(Z_i,N_i) = B_{qf}(Z_i,N_i) =$

$U(R_b, Z_i, N_i, J) - U(R_m, Z_i, N_i, J)$ and the rate $\Lambda^{\eta_{\rm sym}}_{Z_i,N_i}$ of symmetrization of the initial DNS through the barrier $B_{\eta_{\rm sym}}$ in the direction to more symmetric configurations, than $t_0 = 1/(\Lambda^R_{Z_i,N_i} + \Lambda^{\eta_{\rm sym}}_{Z_i,N_i})$. Since $B_{\eta_{\rm sym}}(Z_i, N_i) = 0.5 - 1.5$ MeV and $B_{qf}(Z_i, N_i) \geqslant 4$ MeV in the considered reactions, $\Lambda^R_{Z_i,N_i} \ll \Lambda^{\eta_{\rm sym}}_{Z_i,N_i}$ and $t_0 \approx 1/\Lambda^{\eta_{\rm sym}}_{Z_i,N_i}$. Therefore, we can calculate $Y_{Z,N}$ as in Ref. [10]

$$\begin{aligned} Y_{Z,N} = P_{Z,N}G_{Z,N} &\approx 0.5 \exp \times \\ \times \left(- \frac{U(R_m, Z, N_0, J) - U(R_m, Z_i, N_i, J) + B_{\eta_{\rm sym}}(Z_i, N_i)}{\Theta(Z_i, N_i)} \right. &- \left. \frac{B_R(Z, N)}{\Theta(Z, N_0)} \right). \end{aligned} \tag{4}$$

The temperature $\Theta(Z, N_0)$ is calculated for the excitation energy $E^*(Z_i, N_i) - [U(R_m, Z, N_0, J) - U(R_m, Z_i, N_i, J)]$. As follows from Eq. (4), the yields of neutron-rich nuclei with Z and N will be larger if the potential energies of the DNS containing these nuclei are closer to the potential energy of the initial DNS.

The excitation energy of the initial DNS should not exceed the threshold above which the excitation energy of the neutron-rich product is larger than the neutron separation energy. In the DNS formed from the initial DNS by miltinucleon transfers one can assume the thermal equilibrium and define the excitation energy of light nucleus with the mass A_L as $E^*_L(Z, N) = [E^*(Z_i, N_i) - \{U(R_m, Z, N_0, J) - U(R_m, Z_i, N_i, J)\} - B_R(Z, N)]A_L/A_{\rm tot}$. The deviation from the thermal equilibrium is expected only for the DNS decays near the injection point.

The cross section $\sigma_{Z,N}$ for the production of exotic nucleus (Z, N) increases with $E^*(Z_i, N_i)$ up to the moment when $E^*_L(Z, N)$ becomes equal to $S_n(Z, N)$. Further increase of $E^*(Z_i, N_i)$ would lead to the strong loose 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 $S_n(Z, N)$ are taken from the finite range liquid drop model [16]. The solid arrows indicate the values of $E_{\rm c.m.}$ at which $E^*_L(Z, N)$ reaches $S_n(Z, N)$. Since the predictions of $S_n(Z, N)$ have some uncertainties, for ^{56,58,60}Ca we indicate by dashed arrows the values of $E_{\rm c.m.}$ at which $E^*_L(Z, N)$ reaches $0.5S_n(Z, N)$ and continue the excitation function to the right from the solid arrows. One can see that the decrease of $S_n(Z, N)$ by about 2 MeV shifts the arrows to the left by about 10 MeV. The measurement of the excitation functions up to the right side, where they stop suddenly, would be thus useful to estimate $S_n(Z, N)$ for neutron-rich nuclei.

In the ^{48}Ca + ^{197}Au reaction the maximal expected production cross sections for ^{52,54,56,58}Ca are shown in Fig. 2. The values of $E_{\rm c.m.}$ correspond to the condi-

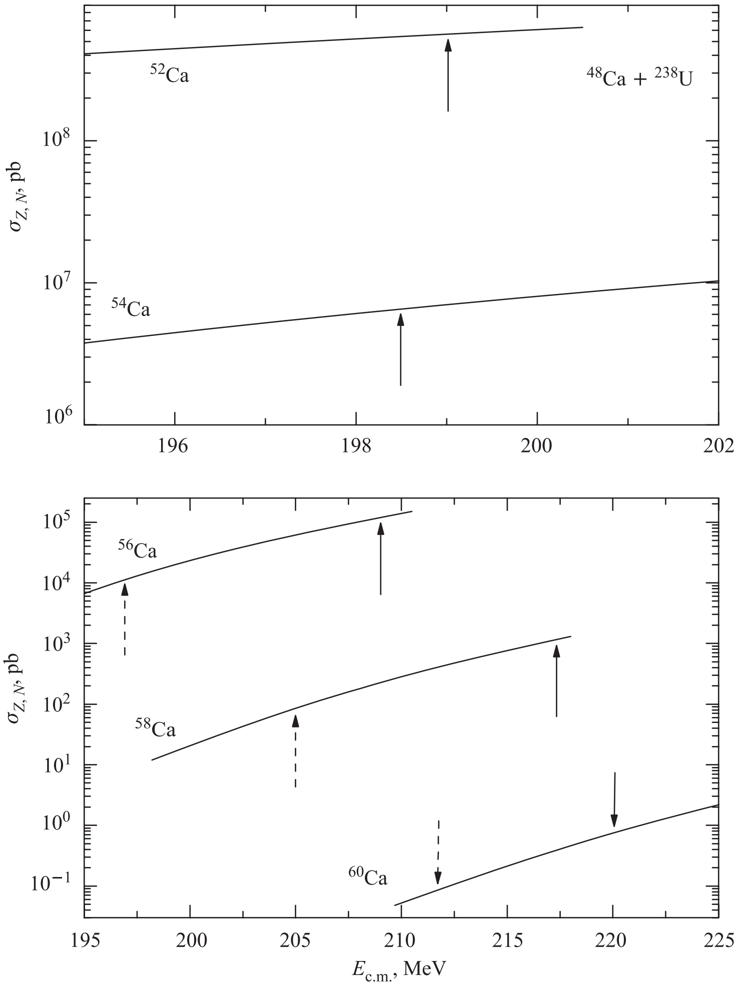

Fig. 1. The excitation functions for producing ^{52,54,56,58,60}Ca in the multinucleon transfer reaction ^{48}Ca + ^{238}U are presented by solid lines. The solid arrows indicate the expected maximal cross sections at $E_{\text{c.m.}}$ corresponding to the thresholds for neutron emission from corresponding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

tions $E^*_L(Z,N) = S_n(Z,N)$ for closed circles and $E^*_L(Z,N) = 0.5S_n(Z,N)$ — 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. Taking heavier target with ^{48}Ca beam for producing neutron-rich isotopes of Ca,

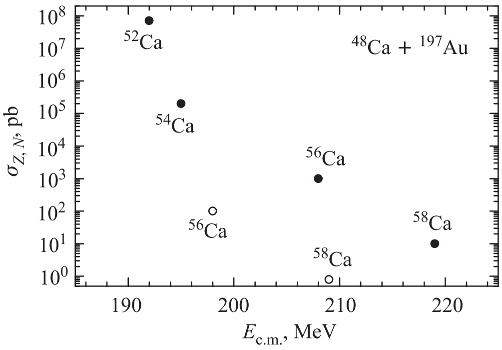

Fig. 2. The expected maximal cross sections for the indicated neutron-rich isotopes of Ca produced in the ^{48}Ca + ^{197}Au reaction at the values of $E_{\mathrm{c.m.}}$ corresponding to the thresholds for neutron emission (closed circles) and to the half of thresholds for neutron emission (open circles)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

we gain in Q value as well as in the value of B_R because of the stronger Coulomb repulsion. As a result, the production cross section grows up (Fig. 3). For ^{56}Ca and ^{58}Ca, this increase of the production cross sections occurs in the similar manner. Replacing ^{124}Sn by ^{248}Cm, one can increase cross section by about 3 orders of magnitude.

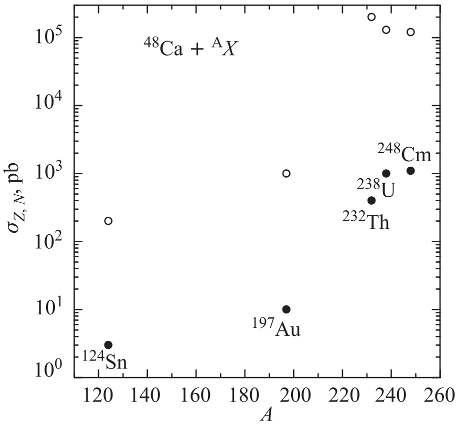

Fig. 3. The expected maximal production cross sections for ^{56}Ca (open circles) and ^{58}Ca (closed circles) in the reactions with ^{48}Ca and indicated targets as functions of the mass of target. The values of $E_{\mathrm{c.m.}}$ in the calculation correspond to the thresholds for neutron emission from ^{56,58}Ca

The production of neutron-rich isotopes of Ca was analyzed in the transfer reactions with ^{48}Ca beam and different targets. The cross sections increase with the mass number of target. This effect is quite strong to be taken into account in the planned experiments. The reactions with actinide targets seem to be preferable. In the multinucleon transfer reactions the production of nuclei near the neutron drip line increases with the available excitation up to the moment when the excitation energy of 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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