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TOWARDS NEUTRON DRIP LINE VIA
TRANSFER-TYPE REACTIONS

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Получение ядер у нейтронной линии стабильности в реакциях передач

Проведен анализ синтеза нейтроноизбыточных изотопов ^{24,26}O, ^{32}Ne, ^{36,38}Mg, ^{42}Si и ^{56,58,60}Ca в реакциях передачи. Определены оптимальные условия образования этих изотопов. Показано, что измерение функции возбуждения позволяет определить энергии связи экзотических ядер.

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Towards Neutron Drip Line via Transfer-Type Reactions

Possibilities of production of light neutron-rich isotopes ^{24,26}O, ^{32}Ne, ^{36,38}Mg, ^{42}Si and ^{56,58,60}Ca in transfer-type reactions are analyzed. The optimal conditions for their production are suggested. The measurement of the excitation function can allow us to estimate the binding energy of exotic nuclei.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

Successes of accelerator technique and experimental methodologies in the last several years have made it possible to produce light neutron-rich nuclei with $Z \leqslant 30$ close to the nucleon stability line. New phenomena have been discovered that enable us to review our understanding of magic numbers and of the stabilizing role of shell effects. It has been demonstrated that for neutron superrich nuclei there appear new magic numbers with $N = 16$ and $N = 26$ (instead of $N = 20$ and $N = 28$). It turned out that nuclei around these magic numbers are strongly deformed and their stability is determined by the deformation. There has been also discovered a region where two shapes of nuclei (spherical and deformed) coexist (shape-coexistence region). All this imposes certain restrictions on the possibility of predicting the stability of nuclei that are close to the nucleon stability line. Thus, they have not been registered in experiments on direct identification of magic nuclei of ^{28}O and ^{40}Mg, although, in line with some theoretical predictions they should be bound. The very method of synthesizing these nuclei has also turned to be problematic. Since they are rather short-lived (10^{-3} s), fragment separators and fragmentation reactions at intermediate energies are usually used for their identification. But this direct method of nuclei production and identification is not always efficient for synthesizing nuclei that are far from the nucleon stability line. Firstly, the cross section of this nuclei formation is small, secondly, the excitation energy of fragments is rather large, which reduces to minimum the probability of survival for weakly-bound nuclei. Besides, it is impossible to apply the missing-mass method for fragmentation reaction products (it works only for two-body processes) in order to obtain information on the stability of the sought for nucleus. In this connection, there has been actively discussed lately the possibility of multinucleon transfer reactions for the synthesis of nuclei far from the stability line.

Multinucleon transfer reactions have been known for producing exotic nuclei for many years [1–3]. The reactions of fragmentation [4–7] are widely used for this purpose as well because of the larger experimental efficiency in the collection of exotic products. While in the fragmentation reactions the products are focused in forward angles, the products of multinucleon transfer reactions have wider angular distributions. However, in the fragmentation process the control of excitation energy of the produced exotic isotopes is difficult because of large fluctuations and considerable excitation available in the system. 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. One can produce the certain exotic isotope within narrow interval of excitation in the transfer-type reactions which probably have an advantage for producing the nuclei near the neutron drip line. These primary 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. While the excited primary nuclei at the neutron drip line feed the yield of the

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isotopes with less number of neutrons, nothing can feed the yield of the heaviest isotopes. This is opposite to the situation near the proton drip line [8]. The cross sections for exotic nuclei production can be much larger in the reactions in which the binary mechanism dominates [8] than the cross sections in high-energy fragmentation reactions.

The purpose of the present study is to show the possibility of using heavy-ion transfer reactions to produce the neutron-rich isotopes ^{24,26}O, ^{32}Ne, ^{36,38}Mg, ^{42}Si and ^{56,58,60}Ca. As was shown in [1,2,9–13], 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. The dynamics of these processes is considered as a diffusion of the DNS in the charge and mass asymmetry coordinates, which are here defined by the charge and mass numbers Z and A of the light nucleus of the DNS. During the evolution in mass and charge asymmetry coordinates, the excited DNS can decay into the two fragments by diffusion in the relative distance R between the centers of nuclei. The charge, mass and kinetic energy distributions of the transfer reactions and quasifission process were successfully treated with the DNS model in the microscopical transport approach [9, 13]. The quasifission and multinucleon transfer processes are ruled by the same mechanism in the sense that both are diffusion processes in the same relevant collective coordinates: charge (mass) asymmetry and relative distance. The reaction products resulting from the decay of the DNS much more symmetric than the initial (entrance) DNS are usually called quasifission products. The multinucleon transfer reactions are usually related to the smaller changes of charge (mass) asymmetry in the products with respect to the initial DNS. The DNS evolution in charge (mass) asymmetry competes with the DNS decay in R. Here, we consider the multinucleon transfers which transform the initial DNS to the DNS with smaller Z or to the DNS with larger N at fixed Z.

The cross section $\sigma_{Z,N}$ of the production of primary light nucleus in transfer reaction is the product of the capture cross section σ_{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

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

The considered primary light neutron-rich nuclei are mainly deexcited by the neutron or gamma emissions. 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.

If the projectiles and targets are deformed, the value of $E_{\mathrm{c.m.}}^{\mathrm{min}}$, 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 $E_{\mathrm{c.m.}}$

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the formation of the DNS is expected to be suppressed. Therefore, we treat $E_{\text{c.m.}} \geqslant E_{\text{c.m.}}^{\min}$ for which the capture cross section is estimated as

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

where μ is the reduced mass for projectile and target. Indeed, in the considered reactions $E_{\text{c.m.}}$ are always larger than $E_{\text{c.m.}}^{\min}$ to have enough energy for the formation of the DNS with very neutron-rich nucleus. The stability of the light neutron-rich nucleus is expected to be smaller in the excited rotational states than in the ground state. In order to be sure that the exotic nucleus is produced with almost zero angular momentum, only the partial waves with $J \leqslant 30$ should be considered. Here, we assume that the total angular momentum J is distributed in the DNS proportionally to the corresponding moments of inertia. For the calculations of σ_{cap} with (2), we set $J_{\text{cap}} = 30$.

The primary charge and mass yield $Y_{Z,N}$ of decay fragments can be expressed as in [11, 12]

$$Y_{Z,N} = \Lambda_{Z,N}^{qf} \int_0^{t_0} P_{Z,N}(t) dt, \tag{3}$$

where $P_{Z,N}$ is the probability of formation of the corresponding DNS configuration in the multinucleon transfer process and the decay rate of this configuration in R is associated with the one-dimensional Kramers rate [14,15]. The time of reaction t_0 is defined as in [13] from the normalization condition $\sum_{Z,N} Y_{Z,N} = 1$. For $J \leqslant 30$, the value of $P_{Z,N}$ weakly dependents on J and factorization (1) is justified.

Using the microscopical method suggested in Ref. [13], one can find $P_{Z,N}(t)$ from the master equation

$$
\begin{aligned}
\frac{d}{dt} P_{Z,N}(t) &= \Delta_{Z+1,N}^{(-,0)} P_{Z+1,N}(t) + \Delta_{Z-1,N}^{(+,0)} P_{Z-1,N}(t) \\
&+ \Delta_{Z,N+1}^{(0,-)} P_{Z,N+1}(t) + \Delta_{Z,N-1}^{(0,+)} P_{Z,N-1}(t) \\
&- (\Delta_{Z,N}^{(-,0)} + \Delta_{Z,N}^{(+,0)} + \Delta_{Z,N}^{(0,-)} + \Delta_{Z,N}^{(0,+)} + \Lambda_{Z,N}^{qf}) P_{Z,N}(t), \tag{4}
\end{aligned}
$$

with initial condition $P_{Z,N}(0) = \delta_{Z,Z_i} \delta_{N,N_i}$ and the microscopically defined transport coefficients for proton ($\Delta_{Z,N}^{(\pm,0)}$) and neutron ($\Delta_{Z,N}^{(0,\pm)}$) transfers between the DNS nuclei. In order to determine the transport coefficients for the DNS containing the neutron-rich nuclei, one needs the single-particle level schemes for the nuclei from this region. The calculation of these schemes suffers by uncertainties. Therefore, in the present paper we use simple statistical method to calculate $Y_{Z,N}$. As was shown in [16], this method and the method based on

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Eq. (4) lead to close results when the yields of the nuclei not far from the line of stability are treated.

The statistical method for finding $Y_{Z,N}$ uses the DNS potential energy calculated as in [11]:

$$U(R, Z, N, J) = B_L + B_H + V(R, Z, N, J), \qquad (5)$$

where B_L and B_H are the mass excesses of the light and heavy fragments, respectively, which are taken from [17] for known nuclei and from [18] for unknown nuclei. The nucleus–nucleus potential [11]

$$V(R, Z, N, J) = V_C(R, Z) + V_N(R, Z, N) + V_{\mathrm{rot}}(R, Z, N, J) \qquad (6)$$

in (5) is the sum of the Coulomb potential V_C, the nuclear potential $V_N(R, Z, N)$ and the centrifugal potential $V_{rot}(R, Z, N, J)$. 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 value of $B_{qf}(Z, N)$ coincides with the depth of this pocket and decreases with increasing Z and J. For $J \leqslant 30$, the dependence of $B_{qf}(Z, N)$ is weak and can be disregarded. The decaying DNS with given Z and N has to overcome the potential barrier in R at $R_b = R_m + 1$ fm on the potential energy surface.

One can conclude from the calculations with Eq. (4) that the quasistationary regime is established quite fast in the considered 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

$$P_{Z,N_0}(t_0) \approx C \exp\left(-\frac{U(R_m, Z, N_0, J) - U(R_m, Z_i, N_i, J)}{\Theta(Z_i, N_i)}\right), \qquad (7)$$

where C is normalized constant. 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 $a = A_{\mathrm{tot}}/12$ MeV^{-1}, where A_{tot} is the total mass number of the system.

The formation of the DNS containing the light neutron-rich nucleus with given Z is considered as a two-step process. The formation of the DNS with Z and N_0 is firstly treated. 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} of decay through the barrier $B_R(Z, N) = U(R_b, Z, N, J) - U(R_m, Z, N_0, J)$ which this

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DNS should overcome to observe the decay of the DNS with Z and N:

$$\Lambda^R_{Z,N,N_0} = \kappa_R(Z,N,N_0) \exp\left(-\frac{B_R(Z,N)}{\Theta(Z,N_0)}\right), \quad (8)$$

where pre-exponential factor depends on the friction and stiffness of the potential at the minimum and on the barrier. The temperature $\Theta(Z,N_0)$ is calculated for the excitation energy $E^*(Z_i,N_i) - [U(R_m,Z,N_0,J) - U(R_m,Z_i,N_i,J)]$.

The main factor which restricts the time t_0 of the reaction and prohibits the formation of DNS containing the exotic nuclei is the evolution of the initial DNS to more symmetric configurations and decay of the DNS during this process. Therefore, the time of decay in R from the initial configuration or from more symmetric configurations mainly determines t_0. We use again the Kramers-type expression for 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 $\Lambda^{\eta_{\mathrm{sym}}}_{Z_i,N_i}$ of symmetrization of the initial DNS through the barrier $B_{\eta_{\mathrm{sym}}}$ in the direction to more symmetric configurations:

$$\begin{aligned}
\Lambda^R_{Z_i,N_i} &= \kappa_R(Z_i,N_i) \exp\left(-\frac{B_{qf}(Z_i,N_i)}{\Theta(Z_i,N_i)}\right), \\
\Lambda^{\eta_{\mathrm{sym}}}_{Z_i,N_i} &= \kappa_{\eta_{\mathrm{sym}}}(Z_i,N_i) \exp\left(-\frac{B_{\eta_{\mathrm{sym}}}(Z_i,N_i)}{\Theta(Z_i,N_i)}\right). \quad (9)
\end{aligned}$$

Therefore, $t_0 = 1/(\Lambda^R_{Z_i,N_i} + \Lambda^{\eta_{\mathrm{sym}}}_{Z_i,N_i})$. Since $B_{\eta_{\mathrm{sym}}}(Z_i,N_i) = 0.5 - 1.5$ MeV and $B_{qf}(Z_i,N_i) \geqslant 4$ MeV in the considered reactions, $\Lambda^R_{Z_i,N_i} \ll \Lambda^{\eta_{\mathrm{sym}}}_{Z_i,N_i}$ and $t_0 \approx 1/\Lambda^{\eta_{\mathrm{sym}}}_{Z_i,N_i}$. Therefore, we can calculate $Y_{Z,N}$ as

$$\begin{aligned}
Y_{Z,N} &= P_{Z,N} G_{Z,N} \\
&\approx \kappa \exp\left(-\frac{U(R_m,Z,N_0,J) - U(R_m,Z_i,N_i,J) + B_{\eta_{\mathrm{sym}}}(Z_i,N_i)}{\Theta(Z_i,N_i)} - \right.\\
&\qquad\qquad\qquad\qquad\qquad \left. -\frac{B_R(Z,N)}{\Theta(Z,N_0)}\right), \quad (10)
\end{aligned}$$

where $\kappa = C\kappa_R(Z,N,N_0)/\kappa_{\eta_{\mathrm{sym}}}(Z_i,N_i) \approx 0.5$ from the comparison with the results obtained with Eq. (4) for the formation of different DNS with Z and N_0. For example, Eq. (10) leads to $Y_{Z_i,N_i} \approx 0.05$ that is consistent with our previous results [13]. In the calculation of $Y_{Z,N}$ the uncertainty related to the definition of κ is estimated within the factor of 1.5.

The suggested simplified approach is suitable if the initial DNS point in the reaction is located 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 mainly contribute to the production of nuclei near the injection point and our statistical approach underestimates their yields.

In the present paper we consider such multinucleon transfers which transform the initial DNS to smaller Z and/or to larger N. For larger yields of neutron-rich nuclei with Z and N, the potential energies of the DNS containing these nuclei should be closer to the potential energy of the initial DNS. This is the main criteria to select the projectile and target. 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. As was mentioned above, the nuclei produced near the neutron drip line should be quite cold to avoid their loose in the deexcitation process.

The exotic nuclei as well as any nuclei far from the entrance channel of the reaction are the result of multinucleon transfers between the projectile-like and target-like parts of the DNS. Thus, we can assume that the thermal equilibrium in the DNS containing the exotic nucleus or in the DNS which is quite far from the initial DNS in the space (N, Z). Indeed, for the formation of these DNS one needs quite a long time $t_0 \approx 10^{-20}$ s at $J \leqslant 30$. This allows us to assume the same temperature in the DNS nuclei and to define the excitation energy of light nucleus with the mass A_L as $E_L^*(Z, N) = [E^*(Z_i, N_i) - \{U(R_m, Z, N_0, J) - U(R_m, Z_i, N_i, J)\} - B_R(Z, N)]A_L/A_{\text{tot}}$. The deviation from the thermal equilibrium is expected only for the DNS decays near the injection point where the temperature of heavy nucleus is smaller than the temperature of light nucleus. Thus, assuming the thermal equilibrium in the DNS, we can underestimate the excitation of light primary nucleus and predict upper limit for $E^*(Z_i, N_i)$. Note that the partition of excitation energy in the DNS weakly influences $Y_{Z,N}$. Since in our calculations of the DNS potential energy the deformations of the nuclei [19] are close to their values in the ground states, the excitation energies of the DNS nuclei remain almost without changes after the DNS decays.

In order to test our method of calculation of $\sigma_{Z,N}$, we treat the production of Ti in the multinucleon transfer reactions ^{58}Ni+^{208}Pb ($E_{\text{c.m.}} = 256.8$ MeV) and ^{64}Ni+^{238}U ($E_{\text{c.m.}} = 307.4$ MeV) [20, 21]. The excitation energies available in these reactions 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 [20], respectively, which are consistent with our calculated cross sections of 0.6 and 0.35 mb, respectively. In the ^{64}Ni+^{238}U reaction the experimental [21] and theoretical cross sections for ^{52}Ti are 0.5 and 1.6 mb, respectively. Therefore, the suggested method is suitable for prediction of the cross sections for the products of multinucleon transfer reactions.

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Since the value of $Y_{Z,N}$ increases with $E^*(Z_i, N_i)$, the cross section $\sigma_{Z,N}$ for the production of exotic nucleus (Z, N) increases as well 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. Therefore, the excitation functions for the production of nuclei near the neutron drip line stop suddenly on the right side. The measurement of the excitation functions would be thus useful to estimate $S_n(Z, N)$ for neutron-rich nuclei. The calculated excitation functions for the production of ^{56,58,60}Ca in the reactions ^{48}Ca+^{124}Sn, ^{232}Th and ^{248}Cm are presented in Figs. 1 and 2. The arrows indicate the values of $E_{\text{c.m.}}$ at which $E_L^*(Z, N)$ reaches $S_n(Z, N)$ taken from finite range liquid drop model [18]. Since the predictions of $S_n(Z, N)$ have some uncertainties, we slightly continue the excitation function to the right from the arrows. If the predicted value of $S_n(Z, N)$ would be smaller by δ, the arrows in Figs. 1 and 2 are shifted to the left on $\delta A_{\text{tot}}/A_L$.

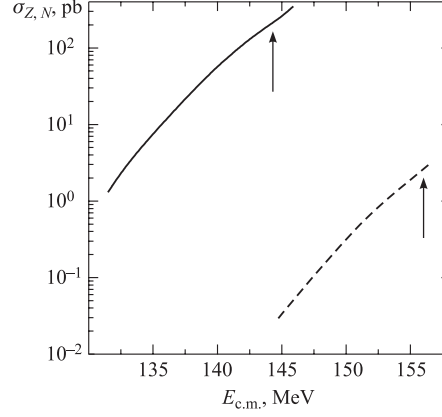
Fig. 1. The excitation functions for producing ^{56,58}Ca in the multinucleon transfer reaction ^{48}Ca+^{124}Sn are presented by solid and dashed lines, respectively. The arrow indicates the expected maximal cross sections at $E_{\text{c.m.}}$ corresponding to the thresholds for neutron emission from ^{56,58}Ca
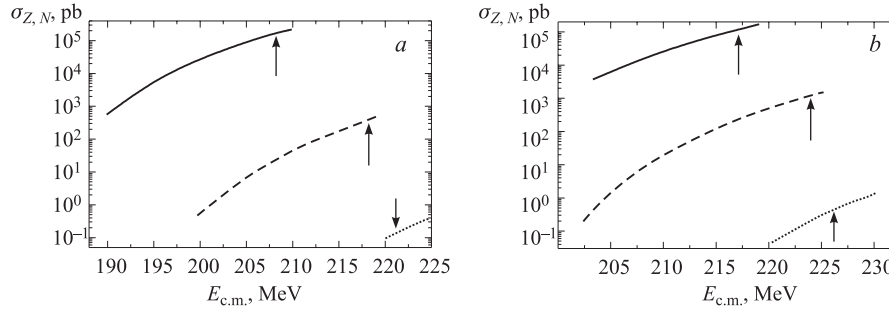
The excitation functions are quite steep on the left side. In order to produce the neutron-rich isotopes of Ca, one can use the reactions ^{48}Ca+^{232}Th and ^{248}Cm. These reactions are more favorable than the reaction ^{48}Ca+^{124}Sn.

Fig. 2. The same as in Fig. 1, but for the production of ^{56,58,60}Ca in the reactions ^{48}Ca+^{232}Th (a), ^{248}Cm (b). The calculated results for ^{56,58,60}Ca are presented by solid, dashed and dotted lines, respectively

In the reactions with ^{48}Ca projectile the maximal expected cross sections for other neutron-rich nuclei are shown in Fig. 3. The values of $E_{\text{c.m.}}$ correspond to the condition $E_L^*(Z,N) = S_n(Z,N)$. One can see that ^{26}O is produced better with ^{124}Sn target, and ^{36,38}Mg — with ^{232}Th target. The reactions with ^{232}Th and ^{248}Cm targets are useful for producing ^{42}Si. In the ^{48}Ca+^{124}Sn reaction at $E_{\text{c.m.}} = 161$ MeV the cross section for ^{28}O is about 1 fb.
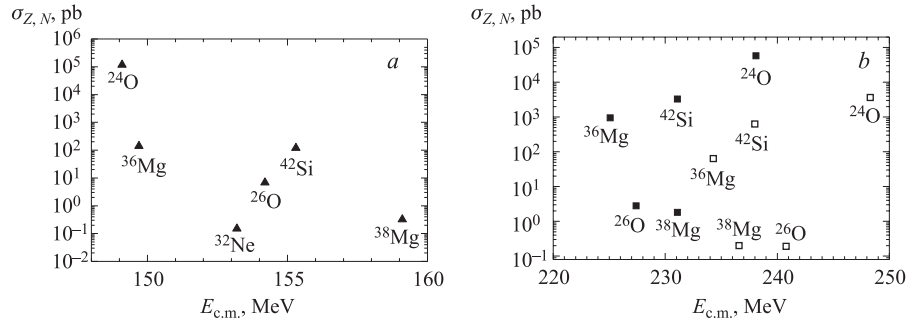
Fig. 3. The expected maximal cross sections for the indicated neutron-rich nuclei produced in the reactions ^{48}Ca+^{124}Sn (▲), ^{232}Th (■), ^{248}Cm (□) at corresponding values of $E_{\text{c.m.}}$

The possibility of production of the nuclei near the neutron drip line in the multinucleon transfer reactions was demonstrated. The suggested method of calculation supplies us with the maximal expected cross sections for the neutron-rich nuclei and with the excitation functions. 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. The choice of projectile-target combination should correspond to the minimal Q value for the certain multinucleon transfer. With present experimental possibilities one can detect the neutron-rich nuclei ^{26}O, ^{32}Ne, ^{36,38}Mg, ^{42}Si and ^{56,58,60}Ca in the considered reactions.

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