Possibility of production of neutron-rich isotopes in transfer-type reactions at intermediate energies

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(Received 14 April 2008; published 29 August 2008)

The production cross sections of neutron-rich isotopes of Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, and Ti in the multinucleon transfer reactions ^{48}Ca(64 MeV/nucleon, 140 MeV/nucleon) + ^{181}Ta and ^{48}Ca(142 MeV/nucleon)+^{nat}W are estimated. A good agreement of the calculated results with the available experimental data confirms the mechanism of multinucleon transfer at almost peripheral collisions at intermediate energies. The global trend of production cross section with the charge (mass) number of target in reactions with ^{48}Ca beam is discussed for the future experiments.

DOI: 10.1103/PhysRevC.78.024613 PACS number(s): 25.70.Hi, 24.10.−i, 24.60.−k

Projectile fragmentation at intermediate energies is a well-established method for the production of rare isotopes [1–11]. In addition to the fragmentation reactions the multinucleon transfer reactions are actively discussed to produce exotic nuclei. These binary reactions have been known for producing exotic nuclei for many years [12–19]. In the transfer reactions the excitation energies of the fragments are smaller than in the fragmentation reactions. The control of excitation energy of the reaction products in the binary processes is much simpler. So, the yields of exotic nuclei can be even larger in the transfer reactions than the yields in the high-energy fragmentation reactions in spite of the smaller experimental efficiency in the collection of exotic nuclei in the transfer reactions than in the fragmentation reactions. In Refs. [20] we have shown the possibility to produce the neutron-rich nuclei in the transfer-type reactions at incident energies close to the Coulomb barrier. This process in the ^{238}U(5.5 MeV/nucleon) + ^{48}Ca reaction has been used to produce the odd and even neuron-rich Ca isotopes and study their low-lying states [21].

As shown in Refs. [22,23], in the ^{209}Bi + ^{136}Xe and ^{197}Au + ^{208}Pb reactions at the lower boundary of the Fermi energy domain the total reaction cross section is almost entirely accounted for by binary collisions irrespective of a possible further disassembly of the two highly excited primary partners. The dissipative binary dynamics at these bombarding energies have been also observed in Refs. [24–26]. The observed influence of the target isospin on the final isospin of the projectile-like fragments and broadening of the projectile-like fragments charge distributions with increasing energy dissipation is similar to that encountered in damped reactions at lower bombarding energies of only a few MeV/nucleon above the Coulomb barrier. As clearly shown in Refs. [27–34], the transfer process is a very strong component for the projectile-like products in the peripheral collisions.

The nucleon pickup products have been observed among the products of projectile fragmentation reactions at the bombarding energies above the Fermi energy: ^{48}Ca (55 MeV/nucleon) + ^{181}Ta [1], ^{48}Ca(64 MeV/nucleon) + ^{181}Ta [9], ^{18}O(80 MeV/nucleon) + ^{27}Al, ^{181}Ta [35], ^{112}Sn (63 MeV/nucleon) + ^{nat}Ni [2], ^{86}Kr(70 MeV/nucleon) + ^{27}Al [36], and primary beams of ^{40}Ca, ^{48}Ca, ^{58}Ni, ^{64}Ni at 140 MeV/nucleon on ^{9}Be and ^{181}Ta targets [37]. As shown in Ref. [10], in the collisions of nuclei ^{48}Ca + ^{9}Be,^{nat}W at incident energy 142 MeV/nucleon the yields of the most neutron-rich isotopes of light nuclei tend toward the Q_{gg} systematics [12,14]. Q_{gg} is the difference between the mass excesses of the ground states of the products and reactant nuclei. This allows us to assume the binary character of the interaction contributing to the production of neutron-rich nuclei in the reactions ^{48}Ca + ^{9}Be, ^{nat}W. The larger yields of neutron-rich nuclei with ^{nat}W target than with ^{9}Be target indicates the strong contribution of types of reaction other than fragmentation. In the fragmentation reaction the sequential evaporation of light particles from strongly excited nucleus leads to a somewhat uniform distribution of final products that underlies the semiempirical EPAX systematics based on data from many high-energy experiments [38]. The disagreement of the yields of neutron-rich nuclei with the EPAX formula [38] suitable for the fragmentation supports the assumption about an important role of nucleon transfer binary reaction in the production of the exotic nuclei even at quite high bombarding energy. The mechanism of this reaction seems to be the same like the mechanism of deep inelastic transfer reaction. The collisions should occur with large angular momenta (large impact parameters) to supply small excitation energy in the neutron-rich product. The incident kinetic energy of relative motion is rapidly dissipated into internal energy. However, the dissipation of angular momentum does not almost occur because of the short contact time at high angular momentum and much weaker dissipation rate in comparison with one for the radial motion. In these collisions a short-living dinuclear system (DNS) is probably formed in which the diffusion of nucleons occurs. 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 de-excitation by neutron emission.

In the present article we demonstrate the possibilities for producing neutron-rich isotopes in the diffusive nucleon transfer reactions ^{48}Ca + ^{181}Ta at incident energies of 64 MeV/nucleon and 140 MeV/nucleon and ^{48}Ca + ^{nat}W at incident energy of 142 MeV/nucleon discussed for the planned experiments. The comparison of our calculated results with known experimental data would check the nuclear reaction mechanism assumed to be decisive in the production of neutron-rich isotopes at intermediate energies.

The diffusive nucleon transfer reaction can be described as an evolution of the DNS that is formed in the entrance channel of the reaction after dissipation of the kinetic energy of the relative motion [12,13,39–44]. The dynamics of the process is considered 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 in 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, the initial DNS with light nucleus (Z_i, N_i) is formed in the peripheral collision for a short time. Then the DNS with light exotic nucleus (Z, N) is produced by nucleon transfers.

The nucleon transfer reactions at the incident energies about of 70 MeV/nucleon occur in nearly peripheral collisions to avoid high excitation in the DNS and fragmentation. However, the excitation should be enough to form the DNS with the certain exotic nucleus, i.e., to overcome the energy threshold $\Delta B_{Z,N,J}$ for this. The value of $\Delta B_{Z,N,J}$ is defined using the DNS potential energy calculated as in Ref. [42]:

$$U(R, Z, N, J) = B_L + B_H + V(R, Z, N, J), \qquad (1)$$

where B_L and B_H are the mass excesses of the light and heavy fragments, respectively. The nucleus-nucleus potential [42]

$$V(R, Z, N, J) = V_C(R, Z) + V_N(R, Z, N) + V_{\rm rot}(R, Z, N, J) \qquad (2)$$

in Eq. (1) is the sum of the Coulomb potential V_C, the nuclear potential $V_N(R, Z, N)$, and the centrifugal potential $V_{\rm rot}(R, Z, N, J) = \hbar^2 J(J+1)/(2\mu R^2)$ (in the assumption of weak dissipation of angular momentum). At high angular momentum, there is no pocket in the nucleus-nucleus potential and in the calculation one can take $R_m = R_L + R_H + 1$ fm (R_L and R_H are the radii of the DNS nuclei). Note that the value of R_m depends on Z and N. The excitation energy of the initial DNS is $E^*(Z_i, N_i, J) = E_{\rm c.m.} - V(R_m, Z_i, N_i, J)$

The value of $\Delta B_{Z,N,J}$ is calculated as

$$\Delta B_{Z,N,J} = U(R_m, Z, N, J) - U(R_m, Z_i, N_i, J). \qquad (3)$$

With this value the excitation energy of the DNS with exotic nucleus (Z, N) is $E^*(Z, N) = E^*(Z_i, N_i, J) - \Delta B_{Z,N,J}$. Assuming the situation of thermal equilibrium, the excitation energy of the light nucleus with the mass $A_L = Z + N$ in this DNS is $E_L^*(Z, N) = E^*(Z, N) A_L/A_{\rm tot}$, where $A_{\rm tot}$ is the total mass number of the DNS. It is clear that the probability of formation of the DNS with exotic nucleus (Z, N) increases with $E'(Z_i, N_i, J)$. However, the increase of $E^*(Z_i, N_i)$ is possible up to the moment when $E_L^*(Z, N)$ becomes equal to the neutron separation energy $S_n(Z, N)$. Further increase of $E^*(Z_i, N_i, J)$ would lead to the strong loss of neutron-rich nuclei because of the neutron emission.

Taking $E_L^*(Z, N) \approx S_n(Z, N)$, from Eqs. (1)–(3) we find the optimal value of $E^*(Z_i, N_i, J_{Z,N})$ and corresponding angular momentum $J_{N,Z} = R_b(2\mu[E_{\rm c.m.} - V(R_b, Z_i, N_i, J=0) - E^*(Z_i, N_i, J_{Z,N})])^{1/2}$, where R_b is the position of the Coulomb barrier at zero angular momentum. The cross section $\sigma_{Z,N}$ of the production of primary light nucleus in the diffusive nucleon transfer reaction is the product of the capture cross section $\sigma_{\rm cap}$ (the formation of the initial DNS) in the entrance reaction channel and formation probability $Y_{Z,N,J}$ of the DNS configuration with nucleus (Z, N). Only the partial waves with J in the vicinity of $J_{N,Z}$ contribute to $\sigma_{Z,N}$. The collisions with $J < J_{N,Z}$ lead to $E_L^*(Z, N) > S_n(Z, N)$, and the contribution of the collision with $J > J_{N,Z}$ to $\sigma_{Z,N}$ decreases with increasing J because the value of $Y_{Z,N,J}$ decreases. Therefore,

$$\sigma_{Z,N} = \sigma_{\rm cap} Y_{Z,N,J_{Z,N}} \approx \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}} \Delta J (2J_{N,Z} + 1) Y_{Z,N,J_{Z,N}}, \qquad (4)$$

where μ is the reduced mass for projectile-target combination and ΔJ is angular momentum interval above $J_{N,Z}$ which mainly contribute to the cross section. In our calculation we set $\Delta J = 20$ that corresponds to the change of the impact parameter less than 0.2 fm at the incident energies considered. Only a narrow region of partial waves contribute to transfer cross section, strongly selecting the initial condition.

To estimate $Y_{Z,N,J}$, the simple statistical method is used. The diffusion is important in the DNS evolution. The simultaneous investigation of the diffusion in these collective coordinates allows us to calculate the formation probability $Y_{Z,N,J}$ of the DNS configuration. We assume that the average interaction time of two nuclei is much larger than the transient times in mass and charge asymmetries. We approximate the expression for the formation probability rate $\lambda^{\rm Kr}$ with a Kramers-type formula [42]

$$\lambda^{\rm Kr} = \frac{\omega}{2\pi\omega'}(\{[\Gamma/(2\hbar)]^2 + \omega'^2\}^{1/2} - \Gamma/(2\hbar)) \times \exp\left[-\frac{\Delta B_{Z,N,J_{Z,N}}}{\Theta(Z_i, N_i)}\right],$$

where the temperature $\Theta(Z_i, N_i)$ is calculated by using the Fermi-gas expression $\Theta = \sqrt{E^*/a}$ with the excitation energy $E^*(Z_i, N_i, J_{Z,N})$ of the initial DNS and with the level-density parameter $a = A_{\rm tot}/12\ {\rm MeV}^{-1}$. The frequency $\omega' \approx 2\,{\rm MeV}/\hbar$ of the inverted harmonic oscillator approximate the potential near the final DNS configuration and $\omega \approx 1\ {\rm MeV}/\hbar$ is the frequency of the harmonic oscillator approximating the potential energy surface for the initial DNS [42]. The rate of formation probability is calculated along the most favorable path on the potential energy surface. As was shown in Refs. [42], the friction coefficient $\Gamma = 2$ MeV has the same order of magnitude as the one calculated with other approaches. Then we obtain

$$Y_{Z,N,J_{Z,N}} = \lambda^{\rm Kr} t_0 \approx 0.5 \exp\left[-\frac{\Delta B_{Z,N,J_{Z,N}}}{\Theta(Z_i, N_i)}\right], \qquad (5)$$

where the average interaction time $t_0 = 5\,{\rm MeV}^{-1}\hbar \approx 3 \times 10^{-21}$ s of two nuclei is assumed to be equal to the characteristic time of deep inelastic collisions [12–14,40]. Note that the decay of the DNS from the initial configuration is the dominant

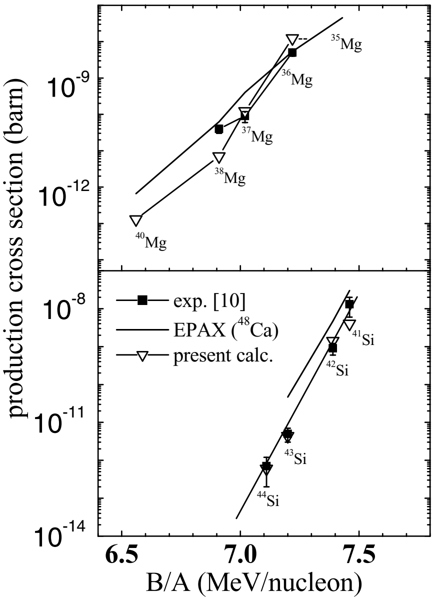

FIG. 1. Production cross sections of Mg and Si isotopes plotted as a function of binding energy per nucleon. The experimental [10] and calculated cross sections for $^{36-38}$Mg and $^{41-44}$Si isotopes in the reaction ^{48}Ca(142 MeV/nucleon) + ^{nat}W are shown by solid squares and open triangles, respectively. Thick solid line is result of fragmentation of ^{48}Ca projectile calculated with the EPAX model.

decay channel here. Using Eq. (3) in (5), we apply the Q_{gg} systematics to estimate the relative yields of various isotopes of the element with Z_i. Indeed, the value of $\Delta B_{Z,N,J_{Z,N}}$ contains the corresponding Q value. As known from the experimental study of deep inelastic collisions, the isotopic distribution follows the Q_{gg} systematics [12,14,22].

The production cross sections of neutron-rich isotopes calculated within our approach in the reactions ^{48}Ca + ^{181}Ta,^{nat}W at intermediate incident energies are listed in Table I and in Fig. 1. The comparison of these results with available experimental data has sense only for those neutron-rich isotopes that are mainly produced as primary products of binary reaction. To the yields of lighter isotopes there are contributions of fragmentation process as well as of the de-excitation by neutron emission of heavier primary isotopes. To describe these yields the extension of the present model is necessary.

The predicted values of $S_n(Z,N)$ for unknown nuclei are taken from the finite range liquid drop model [45]. The results correctly reproduce the most of the experimental data. This strongly supports the proposed model. Our calculations clarify that the multinucleon transfer process is the main process that contributes to the total reaction yields of the most exotic nuclei in the intermediate energy region. This means that the observed new isotopes with neutron number larger than the projectile neutron number in reactions ^{48}Ca (55 MeV/nucleon) + ^{181}Ta [1], ^{48}Ca (64 MeV/nucleon) + ^{181}Ta [9], ^{18}O(80 MeV/nucleon) + ^{27}Al, ^{181}Ta [35], ^{112}Sn (63 MeV/nucleon) + ^{nat}Ni [2], ^{86}Kr (70 MeV/nucleon) + ^{27}Al [36], ^{40}Ca, ^{48}Ca, ^{58,64}Ni (140 MeV/nucleon) + ^{9}Be, ^{181}Ta [37], and ^{48}Ca (142 MeV/nucleon) + ^{9}Be, ^{nat}W [10] are most probably the transfer products at large angular momentum

TABLE I. The calculated production cross-sections of nuclide in the indicated reactions are compared with the available experimental data for the reactions ^{48}Ca(142 MeV/nucleon) + ^{nat}W [10], ^{48}Ca (140 MeV/nucleon) + ^{181}Ta [37], and ^{48}Ca(64 MeV/nucleon) + ^{181}Ta [9].

Reaction	E_{lab} (MeV/nucleon)	Nuclide	$\sigma_{Z,N}$ (th.)	$\sigma_{Z,N}$ (exp.)
^{48}Ca + ^{nat}W	142	^{41}Si	4 nb	13^{+6}_{-8} nb
	142	^{42}Si	1.4 nb	$0.9^{+0.3}_{-0.3}$ nb
	142	^{43}Si	4.4 pb	5^{+2}_{-2} pb
	142	^{44}Si	0.6 pb	$0.7^{+0.5}_{-0.5}$ pb
	142	^{46}Si	32 fb	
	142	^{36}Mg	12.4 nb	5^{+1}_{-1} nb
	142	^{37}Mg	123 pb	90^{+30}_{-20} pb
	142	^{38}Mg	7 pb	40^{+10}_{-10} pb
	142	^{40}Mg	0.13 pb	
^{48}Ca + ^{181}Ta	140	^{38}Si	17 μb	∼4 μb
	140	^{40}Si	55.9 nb	∼100 nb
	64	^{42}Si	0.8 nb	
	64	^{44}Si	0.4 pb	
	64	^{46}Si	24 fb	
	64	^{36}Mg	7.1 nb	
	64	^{38}Mg	4 pb	∼35 nb
	64	^{40}Mg	75 fb	
	64	^{41}Al	73 pb	∼8 nb
	64	^{43}Al	40 fb	
	64	^{45}Al	0.1 fb	
	64	^{45}P	54 pb	
	64	^{47}P	0.5 pb	
	64	^{46}S	25 nb	
	64	^{48}S	22 pb	
	64	^{50}S	50 fb	
	64	^{49}Cl	2.2 nb	
	64	^{51}Cl	1.6 pb	
	64	^{53}Cl	2 fb	
	140	^{50}Ar	346 nb	∼150 nb
	64	^{52}Ar	0.82 nb	
	64	^{54}Ar	0.71 pb	
	64	^{54}Ar	0.71 pb	
	64	^{53}K	30.6 nb	
	64	^{55}K	17.3 pb	
	64	^{57}K	0.19 pb	
	64	^{59}K	3 fb	
	64	^{56}Ca	7.9 nb	
	64	^{58}Ca	83 pb	
	64	^{60}Ca	0.16 pb	
	64	^{59}Sc	3.5 nb	
	64	^{61}Sc	28 pb	
	64	^{63}Sc	0.12 pb	
	64	^{60}Ti	136 nb	
	64	^{62}Ti	1.6 nb	
	64	^{64}Ti	15 pb	
	64	^{66}Ti	0.12 pb	

(peripheral collisions) to supply the small excitation energy in the primary neutron-rich products. At $J < J_{N,Z}$, the primary neutron-rich nuclei are excited and transformed into the secondary nuclei with less number of neutrons because of the de-excitation by nucleon emission. The yield of these secondary nuclei follows the Q_{gg} systematics as well because of binary character of reaction. Indeed, in Ref. [10] the Q_{gg} systematics fit well the yields of various isotopes.

At more central collision the interacting nuclei are fused by forming the highly excited compound nucleus that undergoes to the sequential fission (fragmentation). So, the value of angular momentum in the entrance channel govern the competition between the fragmentation and massive transfer processes.

Instead of Q_{gg} systematics, a systematics based on the binding energy per nucleon of the neutron-rich isotope is suggested in Ref. [46]. The dependence of the production cross section versus binding energy per nucleon of the neutron-rich Mg or Si isotopes is given in Fig. 1. The overall trend of dependence of cross section as a function of binding energy according to Eq. (5) is good visible. The binding energy of the neutron-rich isotope correlates with Q_{gg} value because the mass excess of the conjugated heavy fragment weakly changes with mass number. The cross sections calculated for very neutron-rich isotopes with the EPAX [38] model in the case of fragmentation of ^{48}Ca projectile (thick solid line) are larger than the experimental and predicted by our model ones. The EPAX model describes well the yields of the isotopes of Mg and Si with $N - Z < 10$. It is apparent that in the binary reaction the projectile must be as close as possible to the region of nuclide to be produced. In this case the smaller number of nucleons has to be transferred.

Because the predicted production cross sections for new exotic isotopes ^{47}P, ^{51,53,55,57}Cl, ^{52,54}Ar, ^{56,58,60}Ca, ^{59,61,63}Sc, and ^{62,64,66}Ti are larger than 0.1 pb, they can be synthesized and detected at present experimental possibilities. The predicted cross sections seem to be optimistic, especially for the isotopes of Ca, Sc, and Ti, in the sense that the predictions are done by assuming the excitation energy of dinuclear system is divided proportionally to the mass numbers of the fragments. In the transfer reactions the excitation energy would be preferentially generated in the primary pickup products with $N + Z > N_i + Z_i$. One should also mention that the production cross section weakly depends on the bombarding energy. For example, in the reaction ^{48}Ca$+^{181}$Ta the cross section at beam energy 64 MeV/nucleon is about of 5% larger than one at 140 MeV/nucleon. This is because of very weak dependence of the ratio $(2J_{N,Z} + 1)/E_{\rm c.m.}$ on $E_{\rm c.m.}$ in the Eq. (4).

One can see that the cross sections in reaction ^{48}Ca$+ ^{\rm nat}$W are larger than the corresponding cross sections in reaction ^{48}Ca$+ ^{181}$Ta. Irradiating the heavier targets by ^{48}Ca beam for producing neutron-rich isotopes, we gain in the Q_{gg} value as well as in the value of $\Delta B_{Z,N,J_{Z,N}}$. Therefore, the heavier targets are preferable for the production of neutron-rich nuclei. For example, replacing ^{181}Ta or $^{\rm nat}$W by ^{232}Th or ^{238}U or ^{248}Cm, one can increase the yield of neutron-rich isotopes. This effect should be taken into consideration in the planned experiments.

The main assumption of the used model is that the reactions at intermediate energies remain binary at high angular momenta. The dynamics of the binary deep inelastic process is considered as the diffusive multinucleon transfer between the interacting nuclei in the peripheral 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 and the narrow interval of the entrance channel angular momenta influence the production cross sections. The calculated results are in a good agreement with the most of available experimental data. From the reaction mechanism point of view, it is surprising and interesting to find that the binary deep inelastic transfer process still accounts for the most part of the production cross section of exotic isotopes in the intermediate energy region. Therefore, transfer reactions provide a very efficient tool for the production of nuclei far from stability. It is crucial for the planning of future experiments with the stable or secondary beams that within multinucleon transfer model the yields of the exotic nuclei near the neutron drip line are accurately predicted in the reactions at intermediate energies.

We thank D.Lacroix for fruitful discussions. This work was supported in part by DFG and RFBR. The IN2P3 (France)-JINR (Dubna) and Polish-JINR (Dubna) Cooperation Programmes are gratefully acknowledged.

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