Evaporation residues formation channels in heavy ion collisions

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Abstract. Evaporation residues(ER's) formation channels in low energy heavy ion collisions is investigated within di-nuclear system model(DNS) [1] for the reactions $^{20}Ne+^{208}Pb$, $^{25}Mg+^{206}Pb$ and $^{36}S+^{nat}Pt$. The channels which involve cluster emission from excited intermediate system are investigated. The experimental data on velocity distributions of ER's can give a hint about the formation channels and it is in agreement with calculated average velocities for a certain ER's. For the reaction $^{64}Ni+^{164}Dy$, dependence of such cluster emission channels from bombarding energy is predicted.

Keywords: nuclear reactions,evaporation residues,cluster emission
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INTRODUCTION

Study of nuclear reactions induced by heavy ions (HIs) is a topic of interest for last many years. At relatively low bombarding energies and values of impact parameters, HI reaction mechanism can be classified into complete fusion(CF), incomplete fusion(ICF) processes. In case of CF, the projectile is completely absorbed by the target nucleus, forming an excited composite system from which nuclear particles and/or gamma rays may be emitted subsequently. However, in case of ICF, the incident ion is assumed to break up into the fragments in the vicinity of nuclear field of the target nucleus, followed by fusion of one of the fragments with the target nucleus, while the remaining part of projectile goes on moving almost along the beam direction with approximately beam velocity. Theoretical and experimental studies of decay products in heavy ion collisions is very important to establish the role of different reaction mechanisms in producing the final reaction products, also it gives us a very important knowledge about the nuclear processes and structure of the nuclei. The reaction products can be divided into light evaporation particles, complex fragments, fission products and evaporation residues. In low energy nuclear reactions, for the relatively light systems, the evaporation particles and evaporation residues are the main reaction products, while for the heavy systems, fission process is responsible for the main reaction products. For both light and heavy systems, complex fragment emission channel is also always present, with relatively small cross sections comparing to the cross sections for the main reaction products. For the relatively light systems, the detailed investigations of complex fragment emission in complete fusion reactions was carried out both theoretically [2] and experimentally [3]. For the heavy systems, a good example of cluster emission is an observed cluster radioactivity of some heavy nuclei [4]. If the cluster decay is possible from ground state of heavy nuclei, then with increasing excitation energy, it must become more easier. For experimental observation of cluster emission in heavy systems, these clusters should be measured in coincidence with a heavy partners. Also, velocity distributions of heavy partners(or ER's) can give a hint about such processes.

Here we investigate the mechanism of ER's formation in complete fusion reactions induced by HIs and we analyze all possible reaction channels which lead to the final ER's in the reactions $^{20}Ne+^{208}Pb$, $^{25}Mg+^{206}Pb$ and $^{36}S+^{nat}Pt$. Cluster emission is treated under the assumption that light clusters are produced by collective motion of the nuclear system in the charge asymmetry coordinate, with further thermal escape over the Coulomb barrier. Emission barriers for complex fragments are calculated within the DNS model by using the double-folding procedure (with the Skyrme-type density-dependent effective nucleon-nucleon interaction) for the nuclear part of the nucleus-nucleus interaction potential. Both evaporation and binary decay are treated in the same way.

FORMATION AND DECAY OF THE COMPOUND NUCLEUS (CN) AND DINUCLEAR SYSTEM (DNS)

The emission process of complex fragments from the excited intermediate system, formed in heavy ion collisions, involves the motions in charge and mass asymmetry coordinates, which are defined here by the charge and mass (neutron) numbers $Z = Z_1$ and $A = A_1$ ($N = N_1 = A - Z$) of light nucleus of the DNS [1] formed by two touching nuclei, and the motion in the relative distance R between the centers of mass of nuclei. In the decoupled approximation the binary decay consists of two steps: (i) clustering or the formation of asymmetric DNS in the excited state with some probability and (ii) the decay of this DNS by the thermal overcoming the barrier in the nucleus-nucleus potential. The probability of cluster formation is calculated statistically by using the stationary solution of the master equation with respect to the charge and mass asymmetries and depends on the potential energy of the DNS configurations at touching distance and thermodynamical temperature of the system. The probability of the DNS decay in R coordinate is calculated by using the transition state method. This decay process depends on the termodynamical temperature of the DNS and the difference between the potential energies of the DNS configurations at the touching distance and at the barrier position.

The cross section of the charge particle emission from the excited intermediate system is calculated as follows

$$\sigma_{Z,A}(E_{\text{c.m.}}) = \sum_{J=0}^{J_{max}} \sigma_{Z,A}(E_{\text{c.m.}}, J) = \sum_{J=0}^{J_{max}} \sigma_{cap}(E_{\text{c.m.}}, J) P_{CN}(J) W_{Z,A}(E^*_{CN}, J), \qquad (1)$$

where $\sigma_{cap}(E_{c.m.}, J)$ is the partial capture cross section and $W_{Z,A}(E^*_{CN}, J)$ is the emission probability of a given particle from the excited nuclear system. Here, we consider the decay of excited intermediate system as a sequential light particle evaporation, which includes neutrons, protons, deuterons and tritones, and a cluster ($Z \geq 2$) emission.

CN formation and its consequent decay are not necessarily the ultimate results of the evolution of the initial DNS. In addition to contributions from a CN decay, the binary decay component is related to the quasifission (or multinucleon transfer) mechanism. In our model the fragments are produced as binary decay products of the DNS formed during the diffusion process along the mass (charge) asymmetry coordinate with and without stages of CN formation. The dominant reaction mechanism (complete fusion or quasifission) depends on the entrance channel and on the value of the angular momentum deposited into the system. In our model both components are taken into consideration.

Dinuclear system formation

The partial cross section for the formation of a dinuclear system is given as

$$\sigma_c(E_{\text{c.m.}}, J) = \pi\lambda\!\!\!^{-2}(2J+1)P_{\text{cap}}(E_{\text{c.m.}}, J), \tag{2}$$

where $\lambda\!\!\!^{-2} = \hbar^2/(2\mu E_{\text{c.m.}})$ is the reduced de Broglie wavelength and μ the reduced mass. The value of $\sigma_c(E_{\text{c.m.}}, J)$ defines the transition of the colliding nuclei over the Coulomb barrier with the probability $P_{\text{cap}}(E_{c.m.}, J)$ and the formation of initial 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 transition probability is calculated with the Hill-Wheeler formula $P_{\text{cap}}(E_{\text{c.m.}}, J) = (1 + \exp[2\pi(V(R_b, J) - E_{\text{c.m.}})/\hbar\omega(J)])^{-1}$, where the effective nucleus-nucleus potential V is approximated near the Coulomb barrier at $R = R_b$ by the inverted harmonic-oscillator potential with the barrier height $V(R_b, J)$ and the frequency $\omega(J)$.

The total capture section is

$$\sigma_c(E_{\text{c.m.}}) = \sum_{J=0}^{J_{max}} \sigma_{\text{c}}(E_{\text{c.m.}}, J) = \pi\lambda\!\!\!^{-2} \sum_{J=0}^{J_{max}} (2J+1)P_{\text{cap}}(E_{\text{c.m.}}, J), \tag{3}$$

where the maximum value of angular momentum J_{max} in general case is limited by the critical angular momentum J_{cr}, for which potential pocket for the entrance channel disappears. But here, since we are interested on evaporation residues formation channels, we set the maximal angular momentum as $J_{max} = 20\hbar$. For larger angular momentums, the initial DNS formed at the beginning of the reaction, mainly goes towards symmetric configuration and quasifission occur. So, higher angular momentums gives small contribution to ER's cross sections.

The excitation energy of the formed CN is determined as

$$E^*_{CN}(J) = E_{c.m.} + Q - E^{rot}_{12}(J), \tag{4}$$

where Q-value is determined as $Q = B_1 + B_2 - B_{12}$ and the rotational energy E^{rot}_{12} is not available for the internal excitation. Then the temperature of the CN is $T_{CN}(J) = \sqrt{E^*_{CN}(J)/a}$ within the Fermi-gas model. The level density parameter a is taken as $a = 0.114A + 0.162A^{2/3}$ from Ref. [5].

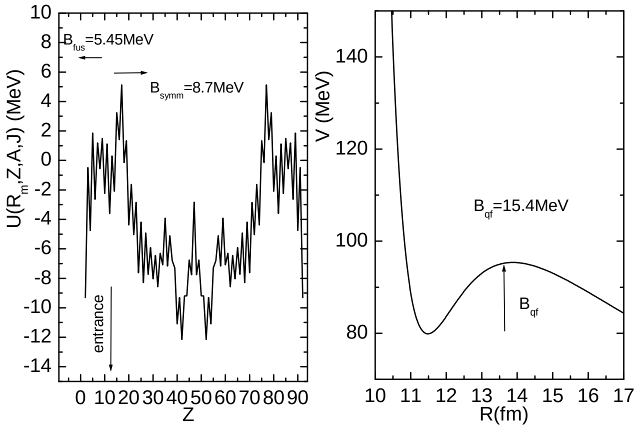

FIGURE 1. Driving potential(left side) and nucleus-nucleus potential(right side) for initial DNS for the $^{25}Mg+^{206}Pb$ reaction. Fusion barrier B_{fus}, barrier for going to symmetric configuration B_{symm} and quasifission barrier B_{qf} are given.

Evolution of dinuclear system and decay

The time evolution of nuclear system in the charge and mass asymmetry coordinates is usually described in the framework of the transport model. In this approach the time dependence of the probability $P_{Z,A}(t)$ to find a system at the moment t in the state with charge Z and mass A asymmetries is calculated by the master equation [6]

$$\begin{aligned}\frac{d}{dt}P_{Z,A}(t) &= \Delta^{(-,0)}_{Z+1,A+1}P_{Z+1,A+1}(t)+\Delta^{(+,0)}_{Z-1,A-1}P_{Z-1,A-1}(t)\\ &+ \Delta^{(0,-)}_{Z,A+1}P_{Z,A+1}(t)+\Delta^{(0,+)}_{Z,A-1}P_{Z,A-1}(t)\\ &- (\Delta^{(-,0)}_{Z,A}+\Delta^{(+,0)}_{Z,A}+\Delta^{(0,-)}_{Z,A}+\Delta^{(0,+)}_{Z,A})P_{Z,A}(t),\end{aligned} \tag{5}$$

with initial condition $P_{Z,A}(0)=\delta_{Z,Z_i=0}\delta_{A,A_i=0}$, i.e. the CN ($Z_i$=0 or 1 and A_i=0 or 1 or 2 or 3) is treated as one of the available asymmetries. The transport coefficients ($\Delta^{(+,0)}_{Z,A}$, $\Delta^{(0,+)}_{Z,A}$) characterize the proton and neutron transfer rates from a heavy to a light nucleus or in opposite direction ($\Delta^{(-,0)}_{Z,A}$, $\Delta^{(0,-)}_{Z,A}$). In Eqs. (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.

For more clear understanding of DNS evolution, we present the most probable path in the potential energy surface to the complete fusion and symmetric DNS configurations. This path corresponds to the minimum of potential energy with respect to mass number A and relative distance coordinate R between DNS nuclei and called as driving potential. In Fig. 1, we present the driving potential for the $^{25}Mg+^{206}Pb$ system and the nucleus-nucleus potential for initial DNS, where the corresponding barriers are pointed. The details of the calculation of potential energy surface(PES) and driving potential can be found in [7, 8].

Thus, the initial DNS evolves by nucleon transfer in three direction: to the complete fusion, to the quasifission from entrance channel and to the symmetric DNS configurations. In the statistical approach, the probability of complete fusion(or overcoming fusion barrier) can be calculated as

$$P_{CN} = \frac{\rho_{fus}}{\rho_{fus} + \rho_{qf} + \rho_{symm}}, \tag{6}$$

where $\rho_{fus}, \rho_{qf}, \rho_{symm}$ are the level densities at the fusion barrier, quasifission barrier for the entrance channel and at the barrier in the way to symmetric DNS. The part of the system, which moves towards symmetric DNS configuration, goes to the quasifission channel. The quasifission barrier for the symmetric DNS is relatively small for heavy systems and the motion in relative distance R coordinate causes quasifission to occur. For the asymmetric DNS configurations, quasifission barrier is relatively high, and the lifetime of such a system is predestined by the time of neutron emission or fission, which can be sufficiently long to reach the mass and charge equilibrium limit in Eq. (5) for the asymmetric DNS and CN configurations behind the fusion barrier. So, the part of the system, which moves towards CN configuration will be localized mainly in that asymmetric DNS(or CN) configuration, for which potential energy surface has deepest minimum and will be statistically distributed among all possible asymmetric DNS and CN configurations. Thus, in the treatment of the formation of asymmetric DNS configurations, the equilibrium limit of the master equation can be imposed so that the probability $P_{Z,A}(E^*_{CN}, J)$ is proportional to the relevant level density ρ. At fixed total energy of the system the level density is proportional to $\exp[-U(R_m, Z, A, J)/T_{CN}]$ [6] and, thus, the DNS formation probability is written in the following way:

$$P_{Z,A}(E^*_{CN}, J) = \frac{\exp[-U(R_m, Z, A, J)/T_{CN}(J)]}{1 + \sum_{Z'=2,A'} \exp[-U(R_m, Z', A', J)/T_{CN}(J)]}, \tag{7}$$

where Z' and A' goes over all charges and masses of DNS configurations, which is behind the fusion barrier.

Since the potential energy of the DNS is determined relatively to the CN potential energy, the local excitation energy of each DNS is

$$E^*_{Z,A}(J) = E^*_{CN}(J) - U(R_m, Z, A, J). \tag{8}$$

If $E^*_{CN}(J) < U(R_m, Z, A, J)$, then the system can not reach the DNS configuration with charge Z and mass A asymmetries and its binary decay is energetically forbidden. To determine the temperature of the DNS, we use the Fermi-gas model expression $T_{Z,A}(J) = \sqrt{E^*_{Z,A}(J)/a}$.

The probability of the thermal penetration of the Coulomb barrier (the decay of the DNS in R into two fragments or the binary decay with $Z \geq 2$) can be written in complete analogy with the fission probability in the transition state formalism (we use here high temperature limit) as

$$P^R_{Z,A} \sim \exp[-B^{qf}_R(Z, A, J)/T_{Z,A}(J)]. \tag{9}$$

The theoretical description of the binary decay and the light particle evaporation processes should be on the same basis and we use the same expression (9) for calculating the probabilities of the neutron, proton, deuteron and tritone emissions. In the calculations the temperature and emission barriers for these particle are the following: $T_{Z=0,A=0}(J) = T_{Z=0,A=1}(J) = T_{Z=1,A=0}(J) = T_{Z=1,A=1}(J) = T_{Z=1,A=1}(J) = T_{CN}(J)$ and $B_R^{qf}(Z = 0, A = 1, J) = B_n$ for the neutron with binding energy B_n, $B_R^{qf}(Z = 1, A = 0, J) = B_p + V_C^{(p)}$ for the proton with binding energy B_p and the Coulomb barrier $V_C^{(p)}$, $B_R^{qf}(Z = 1, A = 1, J) = B_d + V_C^{(d)}$ for the deuteron with binding energy B_d and the Coulomb barrier $V_C^{(d)}$, and $B_R^{qf}(Z = 1, A = 2, J) = B_t + V_C^{(t)}$ for the tritone with binding energy B_t and the Coulomb barrier $V_C^{(t)}$. The Coulomb barriers for outgoing proton, deuteron and tritone are taken as in Ref. [9]

$$V_C^{(i)} = \frac{e^2(Z'-1)}{1.7[(A'-m_i)^{1/3} + m_i^{1/3}]}, \tag{10}$$

where Z' and A' is a charge and mass numbers of nucleus which emits the light charge particle $''i''$ (i=p, d, t) and m_i is the mass number of the light charge particle.

The binary cluster emission process is imagined as a two step process. The system evolves in charge and mass asymmetry coordinates to reach a statistical equilibrium in mass asymmetry coordinate so that the probability of finding the system in each asymmetric DNS configuration and CN configuration depends on the potential energy $U(R_m, Z, A, J)$. After the formation, the excited DNS can decay in R coordinate into the two fragments if the local excitation energy of DNS is enough to overcome the barrier in R. If the system reaches B.G. point, then it goes to the fission channel, since the potential energy decreases towards symmetric DNS configurations. So the fission probability is equal to the probability of reaching B.G. point in driving potential. We note, that such a treatment is only valid if the particle emission barrier and B.G. point height is sufficiently high relatively to local barriers in charge(mass) asymmetry coordinate, otherwise it is a rough approximation.

So, the emission probability $W_{Z,A}(E^*_{CN}, J)$ of a certain cluster from the excited CN is the product of the DNS formation probability and the DNS decay probability:

$$\begin{aligned} W_{Z,A}(E^*_{CN}, J) &= \frac{P_{Z,A} P^R_{Z,A}}{\sum_{Z',A'} P_{Z',A'} P^R_{Z',A'}} \\ &= \frac{\exp[-U(R_m, Z, A, J)/T_{CN}(J)] \exp[-B_R^{qf}(Z, A, J)/T_{Z,A}(J)]}{\sum_{Z',A'} \exp[-U(R_m, Z', A', J)/T_{CN}(J)] \exp[-B_R^{qf}(Z', A', J)/T_{Z',A'}(J)]}. \end{aligned} \tag{11}$$

Here, $U(R_m, Z, A, J)$=0 for the n, p, d and t-evaporation channels and $\exp[-B_R^{qf}(Z', A', J)/T_{Z',A'}(J)] = 1$ for the B.G. point DNS configuration, since it describes the fission channel. In this sense, the height of B.G. point relatively to CN energy is equal to the fission barrier. Thus, the competition between the evaporation channel, the cluster emission channel and the fission channel is taken into consideration in the very natural way.

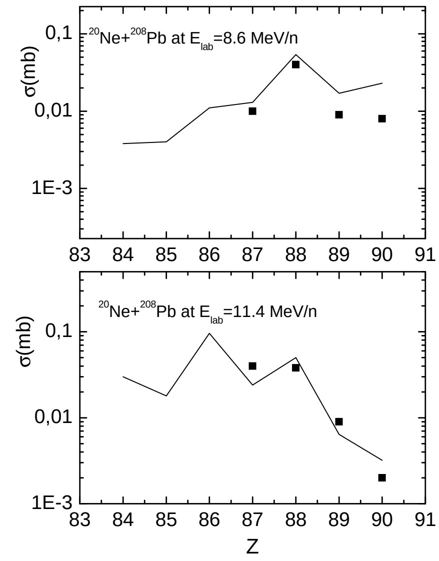

FIGURE 2. Evaporation residues charge distributions in the reaction $^{20}Ne +^{208} Pb$ at bombarding energies $E_{lab} = 8.6 MeV/nucleon$ and $E_{lab} = 11.4 MeV/nucleon$

For the binary decay channel, the excitation energies of the emitted complex fragment and residue nucleus are, respectively,

$$E^*_L(Z,A,J) = [E^*_{Z,A}(J) - B^{qf}_R(Z,A,J)]\frac{A}{A_t},$$
$$E^*_H(Z,A,J) = [E^*_{Z,A}(J) - B^{qf}_R(Z,A,J)]\frac{A_2}{A_t}, \tag{12}$$

where $A_t = A + A_2$ is the total mass number of the DNS and $E^*_{Z,A}(J) - B^{qf}_R(Z,A,J)$ the excitation energy of the DNS at the Coulomb barrier. We assume that the excitation energy and the angular momentum of the DNS is shared between the DNS nuclei proportionally to their mass numbers and moment of inertia, respectively.

CALCULATED RESULTS

In the calculations, we use the formulas (1), (6) and (11) to treat the sequential statistical decay (the evaporation of light particles and/or the binary decay) of the excited intermediate system. The generation of whole cascade of decay channels is performed by the Monte Carlo method. We continue to trace the decay processes until all fragments become cold (the excitation energy of fragments is smaller than its neutron emission threshold). The number n of generation of the events in the Monte Carlo technique was chosen according to the smallest decay probability which is $\sim 1/n$. The generated events were written in output files and then the all decay channels which leads to ER's

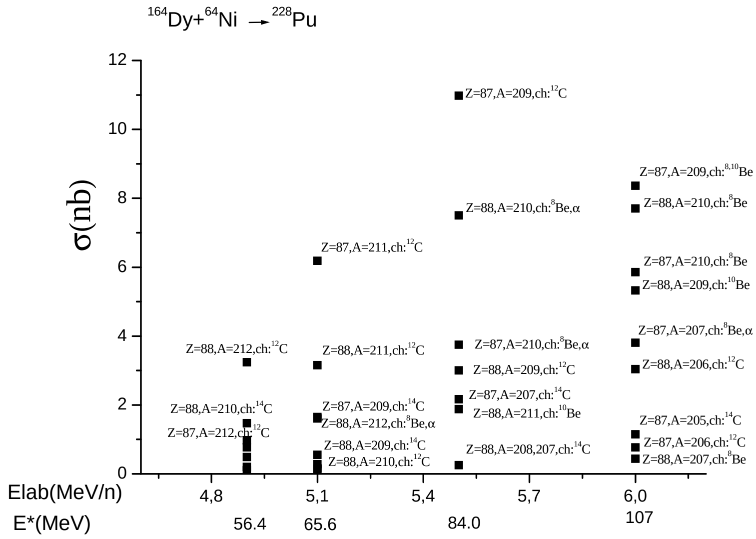

FIGURE 3. Dependence of cluster emission in the $^{64}Ni + ^{164}Dy$ reaction from bombarding(excitation) energy

were analyzed. The average values of ER's velocities is calculated from kinematics, namely from the energy conservation and momentum conservation laws, with taking into account possible particle evaporation along with binary decay.

To check the validity of our model for heavy systems, we compare the calculated charge distributions for evaporation residue products for the reaction $^{20}Ne + ^{208}Pb$ at bombarding energies $E_{lab} = 8.6 MeV/nucleon$ and $E_{lab} = 11.4 MeV/nucleon$. The excitation energy of CN is $E_{ex} = 98.8 MeV$ and $E_{ex} = 150 MeV$, respectively. In Fig. 2 the calculated ER's cross sections

$$\sigma_Z(E_{\mathrm{c.m.}}) = \sum_A \sigma_{Z,A}(E_{\mathrm{c.m.}}) \tag{13}$$

are in good agreement with the experimental data [10]. The experimental behavior of the charge distributions are reproduced for both bombarding energies. The odd-even effects are visible in the charge distributions for ER's. This fact indicates the influence of shell structure of the DNS nuclei on the evolution and decay of the system. Thus, the presented model is able to reproduce experimental ER's cross section both in shape and quantity.

The evaporation residues formation channels for the reaction $^{20}Ne + ^{208}Pb$ at bombarding energies $E_{lab} = 8.6 MeV/nucleon$ and $E_{lab} = 11.4 MeV/nucleon$ are tabulated in Table 1. The contribution for total cross section from each channel is given as in percentage. From the table, one can say which residual nuclei are formed with a cluster emission. The same analysis was performed for the reaction $^{25}Mg + ^{206}Pb$ at $E_{lab} = 5.9 MeV/nucleon$ and $E_{lab} = 8.7 MeV/nucleon$, for which the experimental study was done recently in GSI with velocity filter SHIP [11]. The cross sections and velocity distributions of residual nuclei have been measured.Only reaction residues leaving

TABLE 1. The competition between ER-channels in $^{20}Ne+^{208}Pb$ at E = 8.6MeV/A(first two column) and E = 11.4MeV/A(last two column).

	COMPETITION CHANNELS	**Rate (percent)**	**COMPETITION CHANNELS**	**Rate (percent)**
	6n,2p,^{14}C	37	12n,4α	10
Po	8n,α,^{12}C	18	(12-11)n,α,$^{12,14}C$	15
	8n,^{18}O	18	10n,2p,α,^{8}Be	10
	6n,2p,3α	18	11n,2p,3α	50
	6n,2p,α,^{8}Be	9	10n,4p,2α	15
	8n,1p,$^{12,14}C$	42	(13-12)n,1p,$^{12,14}C$	10
At	7n,1p,3α	50	12n,1p,3α	20
	7n,1p,α,^{8}Be	8	12n,1p,α,^{8}Be	6
			11n,3p,2α	55
			11n,2p,$^{3,2}H$,2α	5
			11n,5p,α	4
	(10-9)n, $^{12,14}C$	12	14n, ^{12}C	1
Rn	8n, 3α	40	13n, 3α	4
	8n,^{8}Be,α	10	13n,2p,^{8}Be	5
	8n,^{8}Be,2p	4	12n,2p,2α	45
	8n,2p,2α	32	12n,1p,$^{3,2}H$, 2α	5
	6n,2p,2 $^{3,2}H$,α	2	12n,4p,α	35
			11n,3p,$^{3,2}H$,α	5
	7n,2p,$^{3,2}H$,α	10	(14-13)n,3p,α	57
Fr	8n,1p,2α	90	13n,1p,2α	16
			14n,5p	20
			11n,4p,$^{3,2}H$	7
	10n,2α	37	14n,2α	5
Ra	9n,2p,α	63	(15-14)n,2p,α	52
			14n,4p	40
			13n,3p,$^{3,2}H$	3

the target at angles of up to 2° with respect to the beam direction are accepted by the entrance aperture of SHIP. It corresponds to the fact, that the measured velocity distributions correspond to the light particle emission channels and/or the cluster emission channel in which cluster were emitted in opposite or along the direction to the beam direction. When cluster is emitted in opposite(along) direction, from kinematics we get the velocity of residue nucleus which is larger(smaller) than compound nucleus velocity. We note here, that in our calculations, the contributions from compound nucleus, quasifission process and multinucleon transfer are not separated, since our model treat these processes in the same basis, so the results here represent contributions from all of these processes. Velocity distributions which is presented in [11] are in a very good agreement with our estimations from the kinematics of cluster decay. It is very important

TABLE 2. The competition between ER-channels in $^{25}Mg+^{206}Pb$ at E = 8.7MeV/n(E^* = 118MeV).

ER	COMPETITION CHANNELS	Rate (percent)	ER	COMPETITION CHANNELS	Rate (percent)
	n,$Ne^{20,22}$	30		n,3α	40
Po	n,1p,F^{19}	10		n,2p,2α	40
	n,2α,$^{12,14}C$	30	Ra	n,4p,α	10
	n,α,$O^{16,18}$	15		n,α,$^{8,10}Be$	5
	n,5α	10		n,$^{12,14}C$	5
	n,3α,$^{8,10}Be$	5			
	n,1p,α,$^{12,14}C$	34		n,3p,α	90
At	n,1p,4α,	34	Ac	n,1p,2α	5
	n,1p,2α,$^{8,10}Be$	10		n,2p,Li^7	5
	n,1p,$O^{16,18}$	17			
	n,2p,N^{15}	5			
	n,$O^{16,18}$	5		n,2α	5
Rn	n,4α	15	Th	n,2p,α	85
	n,α,$^{12,14}C$	15		n,4p	5
	n,2α,$^{8,10}Be$	5			
	n,2p,3α	60			
	n,1p,$^{12,14}C$	5			
Fr	n,1p,α,$^{8,10}Be$	10			
	n,3p,2α	15			
	n,1p,3α	70			

support for our suggested mechanism of evaporation residue formation, since with other mechanisms than cluster decay, the residual nuclei will have very similar velocity to the compound nucleus velocity. One more possibility is incomplete fusion(ICF), where it takes place not full momentum transfer, thus the residual nuclei will have smaller velocities. But at this bombarding energies, the contribution from ICF process expected to be very small. The competition channels for the case of $E_{lab} = 8.7MeV/nucleon$ is presented in Table 2. In Fig. 3 we presented the dependence of cluster emission channels in the reaction $^{64}Ni+^{164}Dy$, which leads to the evaporation residues Fr,Ra, from bombarding energy. The residual nuclei and the emitted clusters are written for each bombarding energy. The cross sections are rather small comparing with the reaction $^{20}Ne+^{208}Pb$ at bombarding energy $E_{lab} = 8.6MeV/nucleon$. It is so, because complete fusion probability(or probability of overcoming fusion barrier) P_CN in equation (1), is smaller for the reaction $^{64}Ni+^{164}Dy$ then for more asymmetric reaction $^{20}Ne+^{208}Pb$. The optimal bombarding energy to observe the cluster emission from heavy nuclei depends on the excitation energy of intermediate system formed during the collision. For the $^{64}Ni+^{164}Dy$ reaction, the optimal excitation energy is around 90 MeV, and it corresponds to the bombarding energy $5.5-5.6$MeV/nucleon.

SUMMARY

Cluster decay of the excited intermediate system formed in heavy ion collisions is described in the framework of dinuclear system concept. The mechanism of cluster emission is treated under the assumption that the light clusters are produced by a collective motion of the nuclear system in the charge asymmetry coordinate with further thermal penetration through the Coulomb barrier. The emission barriers for complex fragments are calculated by using the double-folding formalism for the nuclear part of the nucleus-nucleus interaction potential. The competition between the evaporation channel and binary decay channel is taken into consideration in a unique way. Our approach describes well the experimental production cross sections for evaporation residues. Performed analysis of all possible channels leading to evaporation residues are very helpful for the interpretation of experimental observations. The measured velocity distributions are in good agreement with the suggested mechanism of cluster decay.

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