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Influence of neutron excess of projectile on multinucleon transfer reactions

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ABSTRACT

In order to study the influence of neutron excess of projectile on multinucleon transfer process, the reaction systems ^{64}Ni + ^{208}Pb and ^{136}Xe + ^{208}Pb are investigated within the dinuclear system (DNS) model, where dynamic deformation as well as temperature are taken into account consistently on the potential energy surface of the system. The calculated transfer cross sections can well reproduce the experimental data. By comparing the obtained results of the two reaction systems involved above, we found that the fragment distribution of the transfer reaction induced by ^{136}Xe ($N/Z = 1.51$) appears to extend out to larger neutron numbers than that induced by ^{64}Ni ($N/Z = 1.28$). It is found that the radioactive projectiles ^{140}Xe ($N/Z = 1.59$) and ^{144}Xe ($N/Z = 1.67$) with much larger neutron excess in comparison to the stable beam ^{136}Xe ($N/Z = 1.51$) are favorable to produce neutron-rich nuclei with lighter and slightly more charged than the original ^{208}Pb target.

To expand the nuclear landscape, multinucleon transfer reactions are provided an important way to produce new neutron-rich nuclei [1–4] that have not yet been produced in complete fusion reactions because of the lack of sufficiently neutron-rich projectile-target combinations. Several experimental results show that the multinucleon transfer (MNT) reaction is a good candidate to produce heavy neutron-rich nuclei [5–18]. To understand multinucleon transfer processes, several theoretical approaches have been developed [19–29].

All transport models in these approaches [19,20,22,23,26,29] arise from the same physical mechanism, namely the transfer of nucleons on the potential energy surface between the colliding nuclei. The calculation of potential energy surface is extremely important in nuclear physics [30]. The potential energy surface for a nucleus can be determined the ground state deformation [31]. As the excitation energy is raised that the total energy is expected to be distributed between the intrinsic motion and the collective motion for heavy-ion collisions and fission dynamics process [32,33]. The higher probability is at the ground state deformation, but there exists also a finite probability for other deformations due to excitation energy [34]. Therefore, temperature effects in the potential energy surface are widely discussed in the publications [33,35–37].

It is well known that the shell damping is due to excitation energy [38–40]. Thus, not only the microscopic but also the macroscopic features, like the deformation, are functions of excitation energy (temperature). In addition, the liquid drop energy contributions such as volume, symmetry, surface and Coulomb energy are dependent on excitation energy [41]. Therefore, one should include the dependence of shell damping as well as liquid drop energy on the temperature when driving potential is calculated. In Langevin-type approaches, it is usually done by introducing thermodynamic functionals (free energy or entropy) instead of the bare potential energy [35,36]. Another approach assumes that the potential energy should be temperature-dependent itself [33]. The latter approach is adopted in present work.

The multinucleon transfer reaction is described by the DNS model with the four-variable master equation [29]. The aim of this letter is to study the influence of neutron excess of projectile on multinucleon transfer reactions. The influence of projectile N/Z ratio on the production of heavy neutron rich nuclei through the comparison between ^{64}Ni + ^{208}Pb and ^{136}Xe + ^{208}Pb reactions, and the evolves of transfer cross sections as the increasing projectile neutron number compared to ^{136}Xe, will be discussed. The cross

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section of the production primary fragments in the multinucleon transfer reaction can be written as a sum over all partial waves J

$$\sigma^{pri}_{Z_1,N_1}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m.}, J) Y_{Z_1,N_1}(E_{c.m.}, J), \tag{1}$$

where the primary charge and mass yields of fragments $Y_{Z_1,N_1}(E_{c.m.}, J)$ are related to the product of the formation probability $P(Z_1, N_1, \beta_1, \beta_2, \varepsilon_1, t)$ for fragment 1 of the DNS configuration with Z_1, N_1, β_1 and β_2 and with excitation energy ε_1 at time t and of the decay probability of this configuration in R represented by the one-dimensional Kramers rate $\Lambda^{qf}(Z_1, N_1, \varepsilon, \beta_1, \beta_2)$ [42]. The primary charge and mass yields of fragments $Y_{Z_1,N_1}(E_{c.m.}, J)$ at the angular momentum J is given by

$$\begin{aligned} &Y_{Z_1,N_1}(E_{c.m.}, J) \\ &= \int_0^{\tau_{int}} \sum_0^{\beta_1^{max}} \sum_0^{\beta_2^{max}} \Lambda^{qf}(Z_1, N_1, \varepsilon, \beta_1, \beta_2) \\ &\quad \times P(Z_1, N_1, \beta_1, \beta_2, \varepsilon_1, t) \rho(\beta_1) \rho(\beta_2) \Delta\beta_1 \Delta\beta_2 dt. \end{aligned} \tag{2}$$

The time evolution of the probability distribution function $P(Z_1, N_1, \beta_1, \beta_2, \varepsilon_1, t)$ is described by the four-variable master equations (MEs) in the corresponding potential energy surface [29]. The interaction time $\tau_{\rm int}$ in the dissipative process of two colliding nuclei is determined by using the deflection function method [43,44].

According to statistical mechanics, the character that the shape of the nucleus tends to be spherical at high excitation energy should be included [34]. In order to consider consistently the influence of temperature effects and dynamical deformation on the potential energy surface, the β_1 and β_2 are considered as two discrete variables. Thus the more real potential energy surface where the DNS evolves with the temperature effects is modified to

$$\begin{aligned} &U(N_1, Z_1, N_2, Z_2, R, \beta_1, \beta_2) \\ &= U_C(Z_1, Z_2, R, \beta_1, \beta_2) + U_N(N_1, Z_1, N_2, Z_2, R, \beta_1, \beta_2) \\ &\quad + B^1_{LD}(N_1, Z_1, \varepsilon^*_1) \prod_{k\geq 2}(1 + b_k \beta_k^2) \\ &\quad + E^1_{shell}(N_1, Z_1, \beta) \exp(-\gamma_D \varepsilon^*_1) \\ &\quad + B^2_{LD}(N_2, Z_2, \varepsilon^*_2) \prod_{k\geq 2}(1 + b_k \beta_k^2) \\ &\quad + E^2_{shell}(N_2, Z_2, \beta) \exp(-\gamma_D \varepsilon^*_2) \\ &\quad - B_{CN}, \end{aligned} \tag{3}$$

where ε^*_i is allocated from the local energy of the DNS, according to the mass number A_i, and the damping factor means the speed of washing out the shell correction against the excitation energy. In present work $\gamma_D^{-1} = 20$ MeV is adopted and is in accordance with the general 18–25 MeV [38,39]. The Coulomb and nuclear interaction are addressed in detail in Ref. [45,46]. The deformation dependent binding energy is calculated by macroscopic–microscopic model [47].

The production cross sections of the final fragments in transfer reactions can be written as

$$\sigma_{Z_1,N_1}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m.}, J) Y_{Z_1,N_1}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J) \tag{4}$$

The code GEMINI is used to treat the sequential statistical evaporation of excited fragments. Subsequent deexcitation cascades of the excited fragments via emission of light particles (neutron, proton, and α) and gamma-rays competing with the fission process are taken into account, which lead to the final mass distribution of the reaction products. The details of the GEMINI are given in Ref. [48].

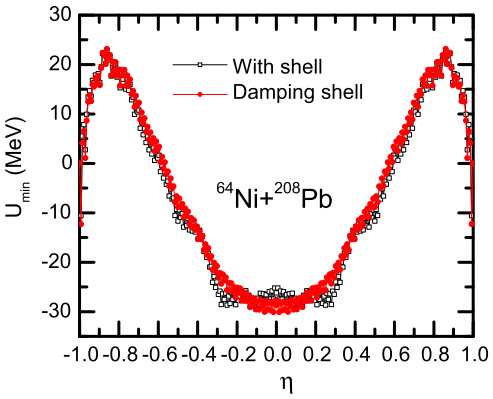

Fig. 1. The potential energy surface for the reaction ^{64}Ni + ^{208}Pb as a function of mass asymmetry η.

Influence of the nuclear structure on the multinucleon transfer process can be included in potential energy surface. The calculation of the driving potential (potential energy surface) for the ^{64}Ni + ^{208}Pb system depends on the Z_1, N_1, and the fragment deformations β_1, β_2. It turns out that there is a valley (the minimum) in the two variable driving potential at fixed the β_1, β_2 [49]. The driving potential along the valley can be described as a function of the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$, and is displayed in Fig. 1, where the open squares show the driving potential that calculated by using deformation dependent binding energies. The fluctuation of the driving potential as a function of the asymmetry η arise from the shell and even-odd effects. The driving potential calculated by formula (3) becomes relatively smooth as shown the red dots in the Fig. 1 when the temperature is taken into account. As it is related to the local excitation energy, the change of the driving potential will directly affect the transition probability and the microscopic dimensions.

In order to verify our ability in calculating the transfer cross section by using the Eq. (4), the production cross sections of isotopes in the multinucleon transfer reactions ^{64}Ni + ^{208}Pb and ^{136}Xe + ^{208}Pb at bombarding energy $E_{c.m.} = 267.64$ MeV and $E_{c.m.} = 450$ MeV are studied, respectively. The change of the proton number of the target-like fragment (TLF) deviating from ^{208}Pb as a function of the neutron number of the TLF are shown in Fig. 2. The black and blue lines are distributions of final fragments with and without temperature effects, respectively. The positive (negative) number of transferred nucleons denotes the proton number of nucleons added to (removed from) the target. It can be seen from the right panels of Fig. 2, the transfer cross sections of one to four proton pickup channels [$(+1p)$, $(+2p)$, $(+3p)$ and $(+4p)$] are reproduced reasonably when the dynamic deformation as well as the temperature effects are considered consistently in the potential energy surface. The production cross sections of the projectile-like fragment deviating from the ^{64}Ni (top) and ^{136}Xe (bottom) as a function of neutron number of the PLF are also shown in Fig. 3, respectively. The calculated results are in also better agreement with the experimental data when considering the temperature effect on the potential energy surface.

One can see from the left panels of Fig. 2 for one- to four-proton [$(-1p)$, $(-2p)$, $(-3p)$ and $(-4p)$] stripping channels and from the right panels of Fig. 3 for one- to four-proton [$(+1p)$, $(+2p)$, $(+3p)$ and $(+4p)$] pick up channels for the reaction ^{64}Ni +