The effects of collision orientation and energy dependence in multinucleon transfer reactions

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Abstract. Multinucleon transfer (MNT) reaction\textsuperscript{136}Xe+\textsuperscript{208}Pb near Coulomb barrier energies are investigated within the dinuclear system (DNS) model. It is found that the collision orientation has an important influence on the mass distributions attributed to the depth of pocket in the driving potential. The calculation results of the isotopic production show that the energy dependence in neutron-deficient side is more sensitive than that in neutron-rich side. The production of the $N = 126$ isotones are calculated by GRAZING model, DNS+GEMINI model, and ImQMD+GEMINI model, respectively. It demonstrates that MNT reaction is a promising way to produce neutron-rich isotopes in the region of the neutron shell closure $N = 126$.

1. Introduction

The synthesis of unknown heavy neutron-rich nuclei in MNT reactions has becomes the focus of attention in nuclear physics recently [1–6]. The discovery of these nuclei is particularly important in understanding the r-process in nuclear astrophysics. Projectile fragmentation is an important method to produce new neutron-rich isotopes in the atomic number range of $Z < 92$ in the past several decades, but the production cross sections is quite small [7]. In recent years, experimental research on MNT reactions have been performed at available facilities by different groups. For example, reaction of $^{136}\text{Xe}+^{208}\text{Pb}$ was carried out at the Flerov Laboratory of Nuclear Reactions in Dubna in 2012 and at the Gammasphere facility of Argonne National Laboratory in 2015 to produce the neutron-rich $N = 126$ nuclei [8, 9]. Meanwhile, reaction of $^{136}\text{Xe}+^{198}\text{Pt}$ at the energy above the Coulomb barrier was performed by Watanabe group at GANIL in Caen [10]. It demonstrates that MNT reactions have obvious advantages in the production of new heavy neutron-rich isotopes around $N = 126$ shell [3].

To understand the MNT progress in heavy-ion collisions, several theoretical models have been proposed. The phenomenological models such as the DNS model [6, 11] and GRAZING code [12, 13] have been developed and used by different groups for predicting the production cross sections of heavy neutron-rich nuclei. In addition, some microscopic dynamics models such as the time-dependent Hartree-Fock (TDHF) model [14] and improved quantum molecular dynamics (ImQMD) model [4, 5] have been successful used to describe the nucleon transport
and energy dissipation during the heavy-ion collisions. In this work, we investigate the influence of the collision orientation and energy dependence in MNT reaction of $^{136}$Xe+$^{208}$Pb within the framework of the DNS model.

The article is organized as follows. In section 2, a brief description of the theoretical models. The results and discussion are presented in section 3, and conclusions are given in section 4.

2. Brief description of the DNS model

In the DNS model, the evolution of the colliding partner is a diffusion process along mass asymmetry and relative distance degrees of freedom. The potential energy surface (PES) of the DNS is given by

$$U(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta_2, J) = U_{LD}(Z_1, N_1) + U_{LD}(Z_2, N_2) - U_{LD}(Z, N) - V_{rot}(J) + V_{CN}(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta_2, J).$$  (1)

Here $U_{LD}(Z_1, N_1)$, $U_{LD}(Z_2, N_2)$ and $U_{LD}(Z, N)$ are the binding energies of two deformed nuclei and CN, respectively. $V_{rot}(J)$ is the rotation energy of the CN. $V_{CN}(Z_1, N_1, Z_2, N_2, R, \beta_1, \beta_2, \theta_1, \theta_2, J)$ is the interaction potential of two fragments. Detail description of $V_{CN}$ see Ref. [15]. Within the PES, the distribution probability of a fragment is obtained by solving the follow master equation [6, 11, 15]:

$$\frac{dP(Z_1, N_1, E_1, t)}{dt} = \sum_{Z'_1} W_{Z_1,N_1;Z'_1,N_1}(t)\{d_{Z_1,N_1}P(Z'_1, N_1, E'_1, t) - d_{Z'_1,N_1}P(Z_1, N_1, E_1, t)\} + \sum_{N'_1} W_{Z_1,N_1;Z_1,N'_1}(t)\{d_{Z_1,N_1}P(Z_1, N'_1, E'_1, t) - d_{Z_1,N'_1}P(Z_1, N_1, E_1, t)\} - [\Lambda_{fI}(\Theta(t)) + \Lambda_{fis}(\Theta(t))]P(Z_1, N_1, E_1, t).$$  (2)

The production cross section of a primary fragment with charge number $Z$ and mass number $A$ are calculated as follows:

$$\sigma_{tr}^{DNS}(Z, A, E) = \frac{\pi \hbar^2}{2\mu E} \sum_l (2l + 1) \times P_c(E, l) P_{tr}^{DNS}(Z, A, E),$$  (3)

where $\mu$ is the reduced mass of the system and $E_{c.m.}$ is the incident energy at the center of mass frame. $P_c$ is capture probability and $P_{tr}^{DNS}(Z, A, E)$ is the production probability of a fragment. The code GEMINI is used to treat the excited primary fragments in the subsequent de-excitation processes.

3. Results and Discussion

In Fig. 1, the driving potential as a function of mass number in reaction $^{136}$Xe+$^{208}$Pb at different collision orientations are presented. In this work, the orientation of the light fragment $\theta_1$ is set to be $0^\circ$. It is shown that the collision orientation of two fragments has an important influence on the depth of the pocket in the driving potential. One can see that the driving potential increases with the increasing of the collision orientation $\theta_2$. In fact, the driving potential has a very important influence on the transfer of the nucleons.
Figure 1. The driving potential as a function of mass number in reaction $^{136}$Xe$^{208}$Pb at different collision orientations.

Mass distributions of primary and secondary fragments in reaction $^{136}$Xe$^{208}$Pb at $E_{c.m.} = 450$ MeV at different collision orientations are shown in Fig. 2. The solid and dashed lines denoted the mass distributions of primary and secondary fragments, respectively. The black, blue, olive indicate the different collision orientation. The red circles represent the available experimental data from Argonne National Laboratory [9]. From Fig. 2, one can see that the mass distributions of both primary and secondary fragments are influenced by the collision orientations. Note that the yields of the fragments in the region of $150 \leq A \leq 190$ decrease with the increase of the collision orientation of $\theta_2$ due to the higher potential in the driving potential as shown in Fig. 1.

Figure 2. Orientation effects on the mass distributions of primary and secondary fragments in reaction $^{136}$Xe$^{208}$Pb at $E_{c.m.} = 450$ MeV and compared with the available experimental data from Argonne [9].

Fig. 3 shows the final isotopic production cross sections from Pt to At for reaction
Figure 3. The isotopic production cross sections from Pt to At for reaction $^{136}\text{Xe}+^{208}\text{Pb}$ at $E_{\text{c.m.}} = 1.06, 1.10,$ and $1.14 V_C$. Here $V_C$ is the Coulomb barrier. The experimental data (solid circle) are from Ref. [9].

$^{136}\text{Xe}+^{208}\text{Pb}$ at different energies. It is notable that the energy dependence in neutron-deficient side is more sensitive than that in neutron-rich side. One important reason is that higher beam energy leads to the higher local excitation energy which makes the primary fragments easy to obtain more excitation energy. Then the excited fragments in neutron-rich side will de-excite by evaporating more neutrons. In consequence, the final isotopic distributions shift from neutron-rich side to neutron-deficient side. In addition, higher incident energy can improve the transfer probability of nucleons within the same PES. However, higher beam energy leads to the higher local excitation energy which leads to the smaller survival probability of primary fragments, especially for extremely neutron-rich nuclei. It is obvious that the mass distributions near the projectile-like fragments reduce rapidly. This is because there is a steeply rise in the driving potential when $^{136}\text{Xe}$ transfer nucleons to $^{208}\text{Pb}$.

In Fig. 4, the production cross sections of the $N = 126$ isotones in reaction $^{136}\text{Xe}+^{208}\text{Pb}$ at $E_{\text{c.m.}} = 450$ MeV are calculated by GRAZING model, DNS+GEMINI model, and ImQMD+GEMINI model, respectively. A comparison of the theoretical calculations with the experimental measurements [9] is also shown. One can see that GRAZING model is suitable for the transfer of just a few nucleons. ImQMD+GEMINI model is successful in description of a large number of nucleons transfer. For DNS+GEMINI model, the calculation results are consistent with the experimental data near the peak. The neutron-rich nuclei $^{204}\text{Pt}$, $^{205}\text{Au}$, $^{206}\text{Hg}$, $^{207}\text{TI}$ can be produced with quite high cross sections in this reaction. It demonstrates
Figure 4. The production cross sections of the $N = 126$ isotones as a function of the atomic number in reaction $^{136}\text{Xe} + ^{208}\text{Pb}$ at $E_{c.m.} = 450$ MeV. The solid, dashed, and dash-dotted lines indicate the calculation results from GRAZING model, DNS+GEMINI model, and ImQMD+GEMINI model, respectively. The solid circles denote the available experimental data from Argonne [9].

that the MNT reaction is a promising way to produce neutron-rich isotopes in the region of the neutron shell closure $N = 126$.

4. Conclusions
The influence of the collision orientation and energy dependence in MNT reaction of $^{136}\text{Xe} + ^{208}\text{Pb}$ is studied by using the DNS model. The collision orientation has an important influence on the mass distributions due to the depth of the pocket in the driving potential. The isotopic production cross sections are predicted at $E_{c.m.} = 1.06, 1.10,$ and $1.14 \text{ V}_c$ and compared with the available experimental data. We find that the energy dependence in neutron-deficient side is more sensitive than that in neutron-rich side. The MNT reaction is regarded as a promising method to produce neutron-rich isotopes in the region of the neutron shell closure $N = 126$.

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