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Possibilities of producing superheavy nuclei in multinucleon transfer reactions based on radioactive targets*

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Abstract: The multinucleon transfer (MNT) process has been proposed as a promising approach to produce neutron-rich superheavy nuclei (SHN). MNT reactions based on the radioactive targets ^{249}Cf, ^{254}Es, and ^{257}Fm are investigated within the framework of the improved version of a dinuclear system (DNS-sysu) model. The MNT reaction ^{238}U + ^{238}U was studied extensively as a promising candidate for producing SHN. However, based on the calculated cross-sections, it was found that there is little possibility to produce SHN in the reaction ^{238}U + ^{238}U. In turn, the production of SHN in reactions with radioactive targets is likely.

Keywords: transfer reactions, superheavy nuclei, dinuclear system model

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1 Introduction

Early calculations predicted that the nucleus $Z = 114$ and $N = 184$ is the double magic nucleus and that it is at the center of the island of stability [1–4]. The production of neutron-rich superheavy nuclei (SHN) around the island of stability and superheavy elements with $Z > 118$ is one of the most challenging topics in nuclear physics [5, 6].

Because of the limiting number of combinations for producing neutron-rich SHN in the stable beam-induced fusion reactions, many approaches were proposed in recent years to attain the island of stability. (i) Radioactive beam-induced fusion reactions could be candidates for producing neutron-rich SHN [7–9]. In present facilities, the intensities of radioactive beams are very low [10], which strongly suppresses the production rates. (ii) Stable beam-induced hot fusion reactions in charged particle evaporation channels are also investigated as a possible approach [11]. The disadvantage is that the Coulomb barrier prevents the charged particle evaporation in the cooling process. In our previous study [9], we compared the two approaches. It is shown that the production rates in the radioactive beam-induced reactions are comparable to those in stable beam-induced reactions in the charged particle evaporation channels. (iii) The multinucleon transfer (MNT) process is also suggested for the production of SHN [12–14]. To elucidate the mechanism of the MNT process and produce SHN, the reaction ^{238}U + ^{238}U has been investigated in many studies [15–21]. In Ref. [14], several low-energy collisions of heavy nuclei for producing SHN were studied based on multidimensional Langevin equations. The production of long-lived neutron-rich SHN in collisions of transuranium ions seems likely.

Recently, Wuenschel et al. attempted to produce SHN based on the MNT process [22]. Some promising results were presented. However, no direct evidence indicating that SHN are produced in the collisions of ^{238}U + ^{232}Th is shown. The reason is probably that the charge number of the target is not sufficiently high. The favorable combinations are always essential for producing unknown nuclei [23, 24]. In Ref. [25], one improved version of the DNS model (DNS-sysu) is introduced in detail. The DNS-sysu model can provide a reasonable description of MNT reactions for producing SHN. The reactions based on the ^{238}U target are investigated in Ref. [25]. The production cross-sections decrease strongly with the increasing charge number of products, and the heavy projectiles are favorable for the production of trans-target nuclei. Based on the Langevin-type approach, several ^{238}U induced MNT reactions, including with the target ^{254}Es, are studied in Ref. [26]. It was shown that several actinide nuclei can be produced with the cross-sections larger than 1 μb.

The cross-sections of produced SHN in MNT reactions, based on targets with large charge number, are

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worth estimating. In this study, the MNT reactions based on radioactive targets ^{249}Cf, ^{254}Es, and ^{257}Fm are investigated within the DNS-sysu model. The prospects of the radioactive projectile ^{239}Pu for producing SHN are also investigated. In Section 2, the DNS-sysu model is described briefly. The results and discussion are presented in Section 3. Finally, I summarize the main results in Section 4.

2 Description of the model

In Ref. [25], detailed descriptions on the DNS-sysu model were presented. Here, the brief introductions regarding the model are presented. The master equation in the DNS-sysu model can be written as [25, 27].

$$\begin{aligned}\frac{\mathrm{d}P(Z_1,N_1,\beta_2,t)}{\mathrm{d}t} &= \sum_{Z_1'} W_{Z_1,N_1,\beta_2;Z_1',N_1,\beta_2}(t)[d_{Z_1,N_1,\beta_2}P(Z_1',N_1,\beta_2,t)-d_{Z_1',N_1,\beta_2}P(Z_1,N_1,\beta_2,t)]\\ &+\sum_{N_1'} W_{Z_1,N_1,\beta_2;Z_1,N_1',\beta_2}(t)[d_{Z_1,N_1,\beta_2}P(Z_1,N_1',\beta_2,t)-d_{Z_1,N_1',\beta_2}P(Z_1,N_1,\beta_2,t)]\\ &+\sum_{\beta_2'} W_{Z_1,N_1,\beta_2;Z_1,N_1,\beta_2'}(t)[d_{Z_1,N_1,\beta_2}P(Z_1,N_1,\beta_2',t)-d_{Z_1,N_1,\beta_2'}P(Z_1,N_1,\beta_2,t)]. \qquad (1)\end{aligned}$$

Here, $P(Z_1,N_1,\beta_2,t)$ is the probability distribution function for the fragment 1 with proton number Z_1 and neutron number N_1 at time t. β_2 is the dynamical deformation parameter of the DNS. $W_{Z_1,N_1,\beta_2;Z_1',N_1,\beta_2}$, $W_{Z_1,N_1,\beta_2;Z_1,N_1',\beta_2}$, and $W_{Z_1,N_1,\beta_2;Z_1,N_1,\beta_2'}$ denote the mean transition probabilities from the channels (Z_1, N_1, β_2) to (Z_1', N_1, β_2), (Z_1, N_1, β_2) to (Z_1, N_1', β_2), and (Z_1, N_1, β_2) to (Z_1, N_1, β_2'), respectively. d_{Z_1,N_1,β_2} is the microscopic dimension (the number of channels) corresponding to the macroscopic state (Z_1, N_1, β_2) [28]. For the degrees of freedom of the charge and neutron number, the sum is taken over all possible proton and neutron numbers that fragment 1 may take, however only one nucleon transfer is considered in the model ($Z_1' = Z_1 \pm 1$; $N_1' = N_1 \pm 1$). For β_2, we assume the range $-0.5 \sim 0.5$. The evolution step length is 0.01. The transition probability is related to the local excitation energy [27, 29].

The PES is defined as

$$\begin{aligned}U(Z_1,N_1,\beta_2,R_{\text{cont}}) =& \Delta(Z_1,N_1)+\Delta(Z_2,N_2)\\ &+V_{\text{cont}}(Z_1,N_1,\beta_2,R_{\text{cont}})\\ &+\frac{1}{2}C_1(\beta_2^1-\beta_2^{\text{p}})^2+\frac{1}{2}C_2(\beta_2^2-\beta_2^{\text{t}})^2, \quad (2)\end{aligned}$$

where $\Delta(Z_i,N_i)$ (i = 1, 2) is mass excess of the fragment i. $V_{\text{cont}}(Z_1,N_1,\beta_2,R_{\text{cont}})$ is the effective nucleus-nucleus interaction potential. The last two terms in the right side of the equation are deformation energies. The detailed description of each term is provided in Ref. [25] and the references therein.

The cross-sections of the primary products can be calculated as

$$\begin{aligned}\sigma_{\text{pr}}(Z_1,N_1,E_{\text{c.m.}}) =& \frac{\pi\hbar^2}{2\mu E_{\text{c.m.}}}\sum_{J=0}^{J_{\max}}(2J+1)T_{\text{cap}}(J,E_{\text{c.m.}})\\ &\times\sum_{\beta_2}P(Z_1,N_1,\beta_2,E_{\text{c.m.}}). \quad (3)\end{aligned}$$

Clear signatures were observed for the formation of DNS in heavy collision systems, such as ^{238}U + ^{238}U [30]. For heavy systems without a potential pocket, there is no capture. I consider that the DNS is formed when incident energy is higher than the interaction potential at the contact position. The contact positions are near the relatively flat parts of interaction potential curves [23]. From the diffusion point of view, the strength of diffusion strongly depends on the interaction time, which is reflected from the probability distribution function $P(Z_1,N_1,\beta_2,E_{\text{c.m.}})$. Therefore, it is reasonable to consider T_{cap} as 1.

In the DNS-sysu model, with consideration of the deformation evolution, the excitation energy of primary products can be calculated with following equation [25].

$$\begin{aligned}E^*_{Z_i,N_i,J} =& \frac{Z_i+N_i}{A_{\text{tot}}}\\ &\times\frac{\sum_{\beta_2}[P(Z_i,N_i,\beta_2,J,t=\tau_{\text{int}})E^*_{\text{DNS}}(Z_i,N_i,\beta_2,J,t=\tau_{\text{int}})]}{\sum_{\beta_2}P(Z_i,N_i,\beta_2,t=\tau_{\text{int}})}. \qquad (4)\end{aligned}$$

Here, E^*_{DNS} is the local excitation energy of the system [25].

The total kinetic energy loss (TKEL) for the configuration (Z_1, N_1, β_2) calculated in the DNS-sysu model as shown in Ref. [27] can be written as

$$\text{TKEL} = E_{\text{diss}}+V_{\text{cont}}(Z_{\text{p}},N_{\text{p}},R_{\text{cont}})-V_{\text{cont}}(Z_1,N_1,\beta_2,R_{\text{cont}}). \qquad (5)$$

Here, Z_{p} and N_{p} are the charge number and neutron number of the projectile, which denotes the configuration in the entrance channel. The detailed description of E_{diss} can be seen in Ref. [25].

In the cooling process, the statistical model is applied with the Monte Carlo method [25]. In the ith de-excitation step, the probability of the s event can be written as

$$P_s(E_i^*) = \frac{\Gamma_s(E_i^*)}{\Gamma_{tot}(E_i^*)}, \qquad (6)$$

where, s = n, p, α, γ, and fission. E_i^* is the excitation energy before ith decay step, which can be calculated from the equation $E_{i+1}^* = E_i^* - B_i$. B_i is the separation energy of particle or energy assumed by the γ ray in the ith step. $\Gamma_{tot} = \Gamma_n + \Gamma_f + \Gamma_p + \Gamma_\alpha + \Gamma_\gamma$. Detailed descriptions of the decay width in each decay channel are provided in Ref. [25] and the references therein. Here, I would like to emphasize that the parameters in the DNS-sysu model are usually fixed.

3 Results and discussion

MNT reactions ^{238}U + ^{248}Cm and ^{238}U + ^{238}U for producing trans-target isotopes are compared in Fig. 1. From the available experimental data, the reaction ^{238}U + ^{248}Cm exhibits at least two orders of magnitude larger cross-sections than the ones ^{238}U + ^{238}U. The calculations in the DNS-sysu model are also presented. According to the experiments, the incident energies of $E_{c.m.}$ = 800 and 892 MeV are used in calculations for the reactions ^{238}U + ^{248}Cm and ^{238}U + ^{238}U, respectively. Good agreement with experimental data is noted. The main reason for the increase in cross-sections in the reaction ^{238}U + ^{248}Cm is that ^{248}Cm is heavier than ^{238}U.

The above behavior encouraged me to explore the possibilities of producing SHN in the MNT reactions based on radioactive targets. Figure 2 shows the calculated producted cross-sections of isotopes with $Z = 100-109$ in MNT reactions with the radioactive targets ^{249}Cf, ^{254}Es, and ^{257}Fm. The half-lives of ^{254}Es and ^{257}Fm are hundreds of days. The two projectiles ^{238}U and ^{239}Pu with a different charge number and neutron-proton

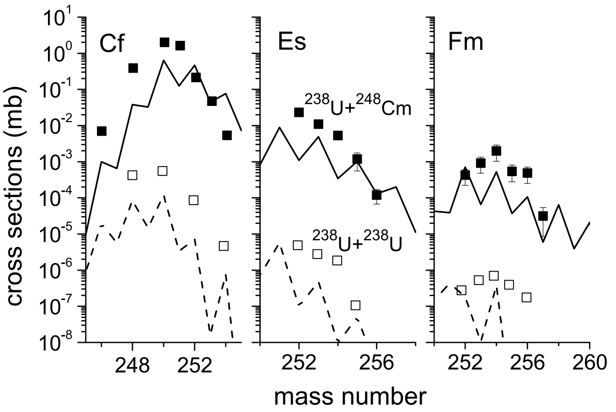

Fig. 1. Yields of isotopes produced in MNT reactions ^{238}U + ^{248}Cm [31] and ^{238}U + ^{238}U [32]. Curves show calculations of DNS-sysu model.

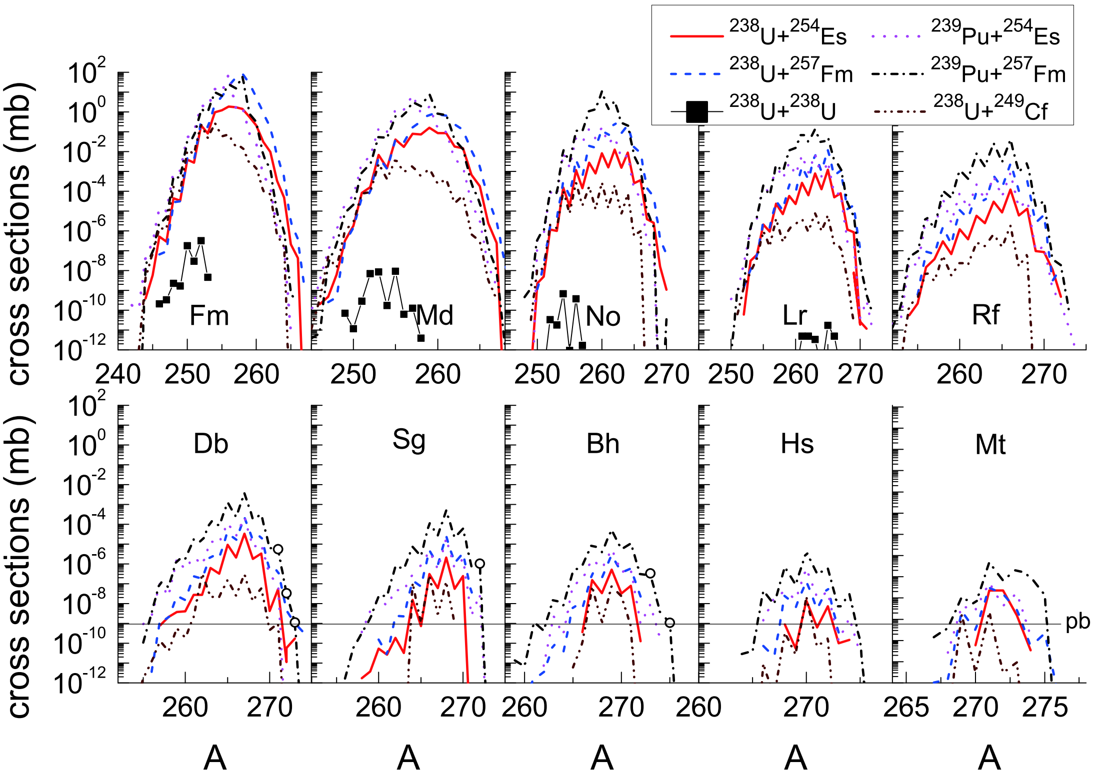

Fig. 2. (color online) Predictions of cross-sections for produced isotopes with Z = 100–109 in MNT reactions ^{238}U + ^{254}Es, ^{238}U + ^{257}Fm, ^{239}Pu + ^{254}Es, ^{239}Pu + ^{257}Fm, ^{238}U + ^{249}Cf, and ^{238}U + ^{238}U, the corresponding incident energies are 962, 970, 982, 991, 950, and 902 MeV, respectively. Circles on curves denote unknown SHN.

ratio are applied. As expected, the produced cross-sections decrease significantly with the increasing charge number of products for all of these reactions. The target effects on produced cross-sections are obvious. Although there is only one proton more in the ^{257}Fm target in comparison to ^{254}Es, the production yields are much higher in the reaction based on the ^{257}Fm target. By comparing the reactions ^{238}U + ^{249}Cf, ^{238}U + ^{254}Es, and ^{238}U + ^{257}Fm, the advantages of cross-sections in the reaction based on the ^{257}Fm target are gradually faded away with an increasing transferred number of protons, which is due to the decrease of the yield contribution from quasi-elastic events.

Moreover, the ^{239}Pu projectile can remarkably enhance the production yields in the neutron-deficient region, because of the high proton richness in ^{239}Pu. However, to produce neutron-rich isotopes, the cross-sections in the ^{239}Pu induced reactions have little advantage over those in the ^{238}U induced reactions. I also show the calculated results of the reaction ^{238}U + ^{238}U. Based on the calculated cross-sections, there is little chance to produce SHN by the ^{238}U + ^{238}U reaction.

Based on the calculated cross-sections, the reaction ^{239}Pu + ^{257}Fm is more likely to produce SHN. As shown in Ref. [14, 25], the production cross-sections of SHN are strongly dependent on the incident energy. Indeed, although in same reaction, to produce different objective nuclei, the optimal incident energies are usually different [33]. Therefore, the incident energies for producing specific nuclei should be chosen carefully. Here, I only estimate the possibilities of producing SHN in MNT reactions. The incident energy of $1.3V_{\text{cont}}$ for each reaction is used. In Fig. 2, the circles denote unknown SHN with cross-sections larger than 1 pb. Several neutron-rich SHN can be produced in the reaction ^{239}Pu + ^{257}Fm. Moreover, to produce Mt isotopes, the calculated cross-sections of several nuclei are above the level of pb. However, the enrichments of radioactive targets ^{254}Es and ^{257}Fm are very low, and they are usually produced in the neutron capture process. Therefore, if sufficient ^{254}Es and ^{257}Fm can be collected to make a target, multinucleon transfer reactions will be encouraging for the production of SHN. In turn, to produce nuclei located at the island of stability, neutron-rich radioactive beams would be promising.

4 Conclusions

The DNS-sysu model has been developed and tested to investigate MNT reactions with the aim of producing SHN. Because of the significant decrease of cross-sections in produced SHN with increasing transferred protons in MNT reactions, it seems unlikely that SHN are produced in the reaction ^{238}U + ^{238}U. Further, the reactions with radioactive targets ^{249}Cf, ^{254}Es, and ^{257}Fm are investigated. The production cross-sections of SHN up to $Z = 109$ can reach tens of pb in the reactions based on the radioactive targets ^{249}Cf, ^{254}Es, and ^{257}Fm. From the point of view of cross-sections, the radioactive combinations with ^{254}Es and ^{257}Fm targets are promising for the production of SHN. However, further experiments should be performed to constrain the theoretical models for better predictions.

References

1 P. Möller and J. R. Nix, J. Phys. G, **20**: 1681 (1994)
2 W. D. Myers and W. J. Swiatecki, Nucl. Phys., **81**: 1-60 (1966)
3 H. Meldner, Ark. Fys., 36: 593(1967). Proceedings of the Lysekil Symposium: Nuclides far off the Stability Line, Aug. 21- 27, 1966, Sweden, https://escholarship.org/uc/item/28q2j00w
4 A. Sobiczewski, F. A. Gareev, and B. N. Kalinkin, Phys. Letts., **22**: 500 (1966)
5 Yu. Oganessian, J. Phys. G: Nucl. Part. Phys., **34**: R165-R242 (2007)
6 S. A. Giuliani, Z. Matheson, W. Nazarewicz et al, Rev. Mod. Phys., **91**: 011001 (2019)
7 W. Loveland, arXiv: 1301.1759v1(2013)
8 X. J. Bao, Y. Gao, J. Q. Li et al, Phys. Rev. C, **91**: 064612 (2015)
9 Z. H. Wu, L. Zhu, F. Li et al, Phys. Rev. C, **97**: 064609 (2018)
10 W. Loveland, Phys. Rev. C, **76**: 014612 (2007)
11 J. Hong, G. G. Adamian, and N. V. Antonenko, Phys. Lett. B,76442 (2007)
12 F. S. Zhang, C. Li, L. Zhu et al, Front. Phys., **13**: 132113 (2018)
13 M. Thoennessen, Rep. Prog. Phys., **76**: 056301 (2013)
14 V. I. Zagrebaev, Yu. Ts. Oganessian, M. G. Itkis et al, Phys. Rev. C, 73, **73**: 031602(R) (0316)
15 K. D. Hildenbrand, H. Freiesleben, F. Pühlhofer et al, Phys. Rev. Lett., **39**: 1065 (1977)
16 J. Tian, X. Wu, K. Zhao et al, Phys. Rev. C, **77**: 064603 (2008)
17 K. Zhao, Z. Li, Y. Zhang et al, Phys. Rev. C, **94**: 024601 (2016)
18 J. V. Kratz, M. Schädel, and H. W. Gäggeler, Phys. Rev. C, **88**: 054615 (2013)
19 Z. Q. Feng, G. M. Jin, and J. Q. Li, Phys. Rev. C, **80**: 067601 (2009)
20 R. Yanez and W. Loveland, Phys. Rev. C, **91**: 044608 (2015)
21 S. Ayik, B. Yilmaz, O. Yilmaz et al, Phys. Rev. C, **96**: 024611 (2017)
22 S. Wuenschel, K. Hagel, M. Barbui et al, Phys. Rev. C, **97**: 064602 (2018)
23 L. Zhu, C. Li, J. Su et al, Phys. Lett. B, **791**: 20-25 (2019)
24 L. Zhu, J. Su, W. J. Xie et al, Phys. Lett. B, **767**: 437 (2017)
25 L. Zhu, arXiv: 1907.09761(2019)
26 V. V. Saiko and A. V. Karpov, Phys. Rev. C, **99**: 014613 (2019)
27 L. Zhu, J. Su, P. W. Wen et al, Phys. Rev. C, **98**: 034609 (2018)
28 W. Nörenberg, Z. Phys. A, **274**: 241-250 (1975)
29 S. Ayik, B. Schürmann, and W. Nörenberg, Z. Phys. A, **277**: 299-310 (1976)
30 S. Heinz, O. Beliuskina et al, Eur. Phys. J. A, **51**: 140 (2015)
31 M. Schädel, W. Brüchle, H. Gäggeler et al, Phys. Rev. Lett., **48**: 852 (1982)
32 M. Schädel, J. V. Kratz, H. Ahrens et al, Phys. Rev. Lett., **41**: 469 (1978)
33 L. Zhu, J. Su, and P. W. Wen, Phys. Rev. C, **95**: 044608 (2017)