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Formation of Superheavy Nuclei in Massive Fusion Reactions*

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Abstract: Within the concept of the dinuclear system(DNS), by incorporating the coupling of the relative motion to the nucleon transfer process, a dynamical model is proposed for describing the formation of superheavy residue nucleus in massive fusion reactions, in which the capture of two heavy colliding nuclei, the formation of compound nucleus and the de-excitation process are calculated using empirical coupled channel model, solving master equation numerically and statistical theory, respectively. By using the DNS model, the evaporation-residue excitation functions in the ^{48}Ca induced fusion reactions and in the cold fusion reactions are investigated systematically and compared with available experimental data. Optimal evaporation channels and combinations as well as the corresponding excitation energies are proposed. The possible factors that influencing the isotopic dependence of the production cross sections are analyzed. The formation of the superheavy nuclei based on the isotopes U with different projectiles are also investigated.

Key words: DNS model; massive fusion reaction; evaporation-residue excitation function

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1　Introduction

The synthesis of heavy or superheavy nuclei is a very important subject in nuclear physics motivated with respect to the island of stability which is predicted theoretically, and has obtained much experimental results with the fusion-evaporation reactions[1, 2]. The existence of the superheavy nucleus(SHN) ($Z \geqslant 106$) is due to strong binding shell effects against the large Coulomb repulsion. However, the shell effects get reduced with increasing the excitation energy of the formed compound nucleus. Combinations with a doubly magic nucleus or nearly magic nucleus are usually chosen owing to the larger reaction Q values. Reactions with ^{208}Pb or ^{209}Bi targets were first proposed by Oganessian et al. to synthesize SHN[3]. Six new elements with $Z = 107$—112 were synthesized in cold fusion reactions for the first time and investigated at GSI(Darmstadt, Germany) with the heavy-ion accelerator UNILAC and the SHIP separator[1, 4]. Recently, experiments on the synthesis of element 113 in the ^{70}Zn$+^{209}$Bi reaction have been performed successfully at RIKEN (Tokyo, Japan)[5]. However, it is difficult to produce heavier SHN in the cold fusion reactions because of the smaller production cross sections that are lower than 1 pb for $Z > 113$. Other possible ways to produce SHN are very needed to be investigated in experimentally and theoretically. Recently, the superheavy elements $Z=113$—116, 118 were synthe-

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sized at FLNR in Dubna (Russia) with the double. magic nucleus ^{48}Ca bombarding actinide nuclei[6—8]. New heavy isotopes ^{259}Db and ^{265}Bh have also been synthesized at HIRFL in Lanzhou (China)[9]. Further experimental works are necessary in order to testify the new synthesized SHN. A reasonable understanding of the formation of SHN in the massive fusion reactions is still a challenge for theory.

In accordance with the evolution of two heavy colliding nuclei, the dynamical process of the compound nucleus formation and decay is usually divided into three reaction stages, namely the capture process of the colliding system overcoming the Coulomb barrier, the formation of the compound nucleus passing over the inner fusion barrier, and the de-excitation of the excited compound nucleus by neutron emission against fission. The transmission in the capture process depends on the incident energy and relative angular momentum of the colliding nuclei, which is the same as that in the fusion of light and medium mass systems. The complete fusion of the heavy system after capture in competition with quasi-fission is very important to the estimation of the SHN production. The concept of the "extra-push" energy explains the fusion of two heavy colliding nuclei in the macroscopic dynamical model[10, 11]. At present it is still difficult to make an accurate description of the fusion dynamics. After the capture and the subsequent evolution to form the compound nucleus, the thermal compound nucleus will decay by the emission of light particles and γ rays against fission. The three stages will affect the formation of evaporation residues observed in laboratories. The evolution of the whole process of massive heavy-ion collisions is very complicated at near-barrier energies. Most of the theoretical methods on the formation of SHN have a similar viewpoint in the description of the capture and the de-excitation stages, but there are different descriptions of the compound nucleus formation process. There are mainly two sorts of models, depending on whether the compound nucleus is formed along the radial variable (internuclear distance) or by nucleon transfer in a touching configuration which is usually the minimum position of the interaction potential after capture of the colliding nuclei. Several transport models have been established to understand the fusion mechanism of two heavy colliding nuclei leading to SHN formation, such as the macroscopic dynamical model[10, 11], the fluctuation-dissipation model[12], the concept of nucleon collectivization[13] and the dinuclear system(DNS) model[14, 15]. Recently, the improved isospin-dependent quantum molecular dynamics(ImIQMD) model was also proposed to investigate the fusion dynamics of SHN[16, 17]. With these models experimental data can be reproduced to a certain extent, and some new results have been predicted. However, these models differ from each other, and sometimes different physical ideas are used.

Further improvements of these models have to be made. Here we use a DNS model[15, 18], in which the nucleon transfer is coupled with the relative motion by solving a set of microscopically derived master equations, and a barrier distribution of the colliding system is introduced in the model. We present a new and extended investigation of the production of superheavy nuclei in the ^{48}Ca induced fusion reactions and in other combinations.

In Section 2 we give a simple description on the DNS model. Calculated results of fusion dynamics and SHN production are given in Section 3. In Section 4 conclusions are discussed.

2 DNS Model

The DNS[19] is a molecular configuration of two touching nuclei which keep their own individuality[14]. Such a system has an evolution along two main degrees of freedom: (i) the relative motion of the nuclei in the interaction potential to form the DNS and the decay of the DNS (quasi-fission process) along the R degree of freedom (internuclear motion)；(ii) the transfer of nucleons in the mass asymmetry coordinate $\eta=(A_1-A_2)/(A_1+A_2)$ between two nuclei，which is a diffusion process of the excited systems leading to the compound nucleus formation. Off-diagonal diffusion in the surface (A_1, R) is not considered since we assume the DNS is formed at the minimum position of the interaction potential of two colliding nuclei. In this concept，the evaporation residue cross section is expressed as a sum over partial waves with angular momentum J at the centre-of-mass energy E_{cm}，

$$\sigma_{\mathrm{ER}}(E_{\mathrm{cm}})=\frac{\pi\hbar^2}{2\mu E_{\mathrm{cm}}}\sum_{J=0}^{J_{\max}}(2J+1)T(E_{\mathrm{cm}}, J)\times P_{\mathrm{CN}}(E_{\mathrm{cm}}, J)W_{\mathrm{sur}}(E_{\mathrm{cm}}, J)\ , \tag{1}$$

here，$T(E_{\mathrm{cm}}, J)$ is the transmission probability of the two colliding nuclei overcoming the Coulomb potential barrier in the entrance channel to form the DNS. In the same manner as in the nucleon collectivization model[13]，the transmission probability T is calculated by using the empirical coupled channel model，which can reproduce very well available experimental capture cross sections[13, 15]. The P_{CN} is the probability that the system will evolve from a touching configuration to the compound nucleus in competition with quasi-fission of the DNS，which is described by a set of microscopically derived master equations[15, 18]. The last term is the survival probability of the formed compound nucleus，which can be estimated with the statistical evaporation model by considering the competition between neutron evaporation and fission[15]. We take the maximal angular momentum as $J_{\max}=30$ since the fission barrier of the heavy nucleus disappears at high spin[20].

The survival probability of the excited compound nucleus cooled by the neutron evaporation in competition with fission is expressed as follows：

$$W_{\mathrm{sur}}(E^*_{\mathrm{CN}}, x, J)=P(E^*_{\mathrm{CN}}, x, J)\times\prod_{i=1}^{x}\left(\frac{\Gamma_{\mathrm{n}}(E_i^*, J)}{\Gamma_{\mathrm{n}}(E_i^*, J)+\Gamma_{\mathrm{f}}(E_i^*, J)}\right)_i, \tag{2}$$

where the E^*_{CN}，J is the excitation energy and the spin of the compound nucleus，respectively. The E_i^* is the excitation energy before evaporating the ith neutron，which has the relation

$$E^*_{i+1}=E_i^*-B_i^n-2T_i, \tag{3}$$

with the initial condition $E_1^*=E^*_{\mathrm{CN}}$. The energy B_i^{n} is the separation energy of the ith neutron. The nuclear temperature T_i is given by $E_i^*=aT_i^2-T_i$ with the level density parameter a. $P(E^*_{\mathrm{CN}}, x, J)$ is the realization probability of emitting x neutrons. The widths of neutron evaporation and fission are calculated using the statistical model. The details can be found in Ref.[15]. The level density is expressed by the back-shifted Bethe formula[21] with the spin cut-off model as

$$\rho(E^*, J)=K_{\mathrm{rot}}K_{\mathrm{vib}}\frac{2J+1}{24\sqrt{2}\sigma^3}a^{-1/4}(E^*-\Delta)^{-5/4}\times\exp[2\sqrt{a(E^*-\Delta)}]\exp\left[-\frac{(J+1/2)^2}{2\sigma^2}\right], \tag{4}$$

where the K_{rot} and K_{vib} are the coefficients of the rotational and vibrational enhancements. The pairing energy is given by

$$\Delta=\chi\frac{12}{\sqrt{A}} \tag{5}$$

in MeV($\chi=-1$，0 and 1 for odd-odd，odd-even and even-even nuclei，respectively). The spin cut-off parameter is calculated by the formula：

$$\sigma^2=\frac{T\zeta_{\mathrm{r.b}}}{\hbar^2}, \tag{6}$$

where the rigid-body moment of inertia has the relation $\zeta_{\mathrm{r.b}}=0.4\,MR^2$ with the mass M and the radius R of the nucleus. The level density parameter is related to the shell correction energy $E_{\mathrm{sh}}(Z, N)$ and the excitation energy E^* of the nucleus as

$$a(E^*, Z, N)=\tilde{a}(A)\frac{1+E_{\mathrm{sh}}(Z, N)f(E^*-\Delta)}{E^*-\Delta}. \tag{7}$$

here，$\tilde{a}(A)=\alpha A+\beta A^{2/3}b_{\mathrm{s}}$ is the asymptotic Fermi-gas value of the level density parameter at high excitation energy. The shell damping factor is given by

$$f(E^{*})=1-\exp(-\gamma E^{*}) \qquad (8)$$

with $\gamma=\tilde{a}/(\varepsilon A^{4/3})$. All the used parameters are listed in Table 1. In Fig. 1 we give the level density parameters of different nuclides at the ground state calculated by using Eq. (7) and compared them with two empirical formulas $a(A)=A/8$, and $A/12$. It can be seen that the strong shell effects appear in the level density.

Table 1　Parameters used in the calculation of the level density

$K_{\rm rot}$	$K_{\rm vib}$	b_s	α	β	ε
1	1	1	0.114	0.098	0.4

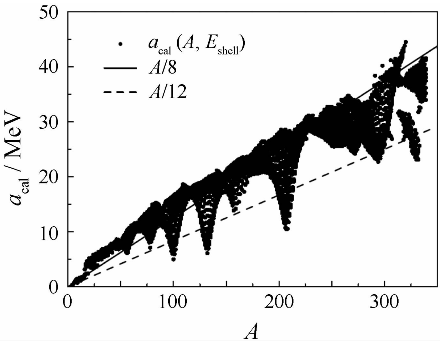

Fig. 1 Calculated values of the level density parameters as a function of the atomic mass.

3　Results and Discussions

3.1　Production cross sections of superheavy nuclei

The evaporation residues observed in laboratories by the cascade of α decay are mainly produced by the complete fusion reactions, in which the fusion dynamics and the structure property of the compound nucleus affects their production. Within the framework of the DNS model, in Fig. 2 we show a comparison of the calculated maximal production cross sections of superheavy elements $Z=102$—120 in the cold fusion reactions by evaporating one neutron, in the ^{48}Ca induced reactions with actinide targets by evaporating three neutrons, and the experimental data[1,2,4,22]. The production cross sections decrease rapidly with increasing the charge number of the synthesized compound nucleus in the cold fusion reactions, such as from 0.2 μb for synthesizing $Z=108$ in the reaction ^{48}Ca+^{208}Pb to 1 pb for $Z=112$ in ^{70}Zn+^{208}Pb, and even below 0.1 pb for synthesizing $Z\geqslant 113$[18]. It seems to be difficult to synthesize superheavy elements $Z\geqslant 113$ in the cold fusion reactions at the present facilities. The calculated results show that the ^{48}Ca induced reactions have smaller production cross sections with ^{232}Th target, but are in favor of synthesizing heavier SHN ($Z\geqslant 113$) with other actinide targets because of the larger cross sections. The experimental data also give such trends. In the DNS concept, the inner fusion barrier increases with reducing mass asymmetry in the cold fusion reactions, which leads to a decrease of the formation probability of the compound nucleus. However, the ^{48}Ca induced reactions have not such increase of the inner fusion barrier for synthesizing heavier SHN. Because of the larger transmission and the higher fusion probability, we obtain larger production cross sections for synthesizing SHN ($Z\geqslant 113$) in the ^{48}Ca induced reactions although these reactions have the smaller survival probability than those in the cold fusion reactions.

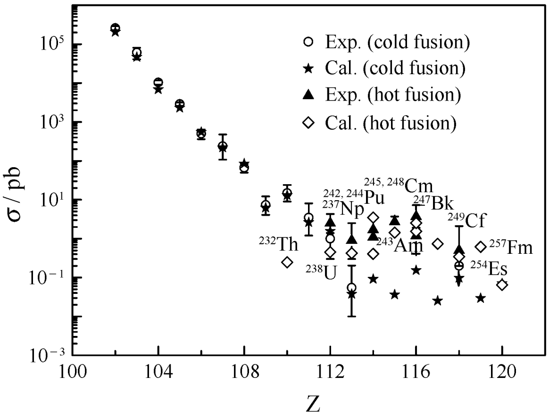

Fig. 2 Maximal production cross sections of superheavy elements $Z=102-120$ in cold fusion reactions based on ^{208}Pb and ^{209}Bi targets with projectile nuclei ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni, ^{70}Zn, ^{76}Ge, ^{82}Se, ^{86}Kr and ^{88}Sr, in ^{48}Ca induced reactions with actinide targets by evaporating 3 neutrons, and in comparison with available experimental data.

It is still a good way to synthesize heavier SHN by using the ^{48}Ca induced reactions. Of course, more experimental data are anticipated to be obtained in the future. However, the actinide targets are difficulty to be handled in experiments synthesizing heavier SHN.

The uranium is the heaviest element existing in the nature. It has a larger mass asymmetry constructed as a target in the fusion reactions with the various neutron-rich light projectiles. The isotope ^{238}U is the neutron-richest nucleus in the U isotopes and often chosen as the target for synthesizing SHN. In Fig. 3 we give evaporation residue excitation functions of the reactions ^{40}Ar, ^{50}Ti, ^{54}Cr, ^{64}Ni+^{238}U in the 2n−5n channels. The results show that the 4n channel in the reaction ^{40}Ar+^{238}U has the larger cross sections with 2.1 pb at an excitation energy 42 MeV. This reaction is being used to synthesize the superheavy nucleus Ds with HIRFL at Institute of Modern Physics in Lanzhou. The reactions ^{50}Ti, ^{54}Cr, ^{64}Ni+^{238}U lead to the cross section smaller than 0.1 pb. Calculations show that the isotopes ^{235}U and ^{238}U are favorable in producing SHN. The cross sections are reduced with increasing the mass numbers of the projectiles. Other reaction mechanisms to synthesize SHN have to be investigated with theoretical models, such as the massive transfer reactions, and the complete fusion reactions induced by weakly bound nuclei. Work in these directions is in progress within the framework of the DNS model.

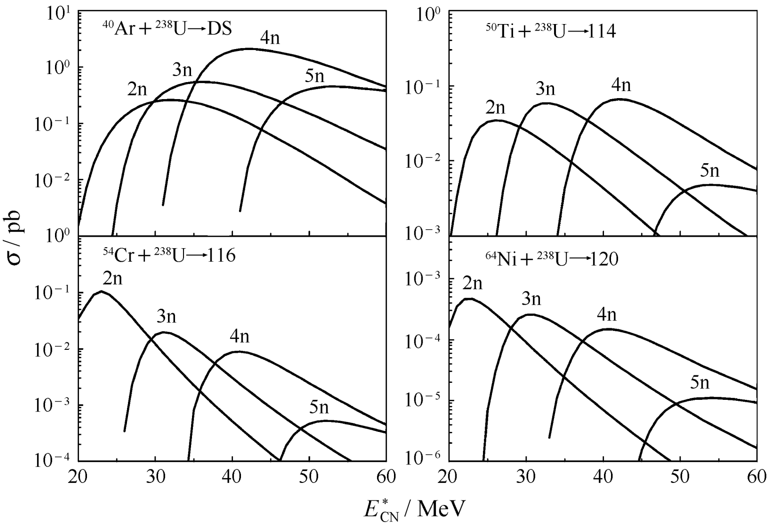

Fig. 3 The evaporation residue excitation functions in the reactions ^{40}Ar, ^{50}Ti, ^{54}Cr, ^{64}Ni+^{238}U.

3.2 Isotopic dependence of the production cross sections

Recent experimental data show that the production cross sections of the SHN depend on the target isotope in the ^{48}Ca induced fusion reactions. For example, the maximal cross section in the 3n channel is $3.7\pm^{3.6}_{1.8}$ pb for the reaction ^{48}Ca+^{245}Cm at the excitation energy 37.9 MeV; however, it is 1.2 pb for the reaction ^{48}Ca+^{248}Cm although the later is a neutron-rich target[8, 23]. The isotopic trends of the production cross sections were also observed and investigated in cold fusion reactions[18, 24]. In Fig. 4 we give the isotopic dependence of the production cross sections to synthesize the same SHN in the cold fusion and in the ^{48}Ca induced reactions. It is shown that the isotopes ^{79}Se based on ^{208}Pb and ^{245,247}Cm in the 3n channels, ^{248}Cm in the 4n channel, and ^{250}Cm are suitable to produce the element $Z=116$. The ^{48}Ca induced reactions give larger production cross sections than the cold fusion reactions. The corresponding excitation energies are also given in the figures. In the DNS model, the isotopic trends of the production cross sections are mainly determined by both the fusion and survival probabilities. Of course, the transmission probability of two colliding nuclei can also be affected since the isotopes have initial quadrupole deformations. When the neutron number of the target increases, the DNS gets more asymmetrical and the fusion probability increases if the DNS does not consist of more stable nuclei (such as magic nuclei) because of a smaller inner fusion barrier. A smaller neutron separation energy and a larger shell correction lead to a larger survival probability. The compound nucleus with closed neutron shells has a larger shell correction energy and a larger neutron separation energy. The neutron-rich actinide target has larger fusion and survival probabilities due to the larger asymmetric initial combinations and smaller neutron separation energies. But such actinide isotopes are usually unstable with short half-lives. With the establishment of the high intensity radioactive-beam facilities, the neutron-rich SHN may be synthesized experimentally, which approaches the island of stability.

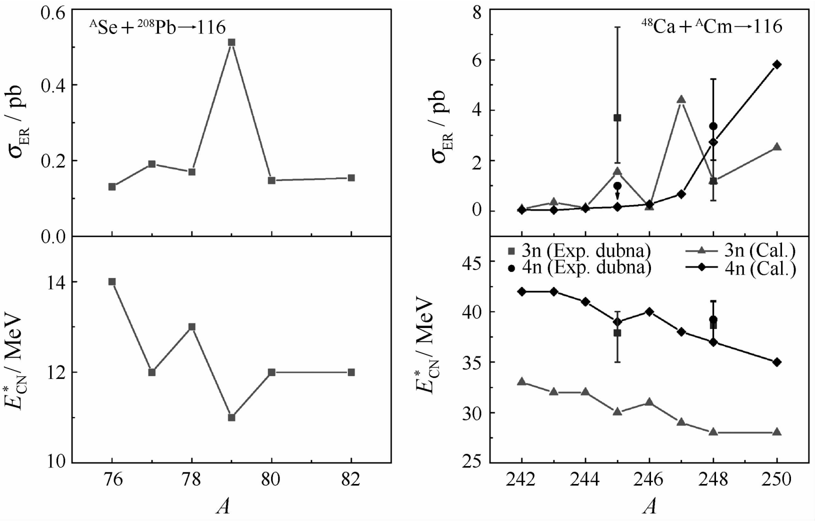

Fig. 4　Isotopic dependence of the calculated maximal production cross sections in cold fusion reactions and in ^{48}Ca induced reactions leading to the synthesis of superheavy elements $Z=116$, and compared with the experimental data.

4　Conclusions

Using the DNS model, we systematically investigated the production of superheavy residues in fusion-evaporation reactions, in which the nucleon transfer leading to the formation of the superheavy compound nucleus is described with a set of microscopically derived master equations that are solved numerically and include the quasi-fission of the DNS and the fission of the heavy fragments. The maximal production cross sections in the cold fusion and in the ^{48}Ca induced reactions are compared. The calculated results are in good agreement with the available experimental data within the error bars. Isotopic trends in the production of superheavy element $Z=116$ are analyzed for the two reaction types. The evaporation residue excitation functions of the reactions ^{40}Ar, ^{50}Ti, ^{54}Cr, ^{64}Ni+^{238}U in the 2n—5n channels are also studied.

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