Production mechanism of superheavy nuclei in massive fusion reactions*

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Abstract Within the concept of the dinuclear system (DNS), a dynamical model is proposed for describing the formation of superheavy nuclei in complete fusion reactions by incorporating the coupling of the relative motion to the nucleon transfer process. The capture of two heavy colliding nuclei, the formation of the compound nucleus and the de-excitation process are calculated by using an empirical coupled channel model, solving a set of microscopically derived master equations numerically and applying statistical theory, respectively. Fusion-fission reactions and evaporation residue excitation functions of synthesizing superheavy nuclei (SHN) are investigated systematically and compared them with available experimental data. The possible factors that affecting the production cross sections of SHN are discussed in this workshop.

Key words DNS model, master equations, production cross sections

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1 Introduction

The synthesis of very heavy (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 progress with fusion-evaporation reactions[1, 2]. The existence of the superheavy nucleus (SHN) ($Z \geqslant 106$) is due to a strong binding shell effect against the large Coulomb repulsion. However, the shell effect will be reduced with increasing excitation energy of the formed compound nucleus. Combinations with a doubly magic nucleus or nearly magic nucleus are usually chosen due to the larger reaction Q values. Reactions with ^{208}Pb or ^{209}Bi targets are proposed firstly by Yu. Ts. 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 separator SHIP[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]. Superheavy elements $Z = 113-116$, 118 were synthesized at FLNR in Dubna (Russia) with double magic nucleus ^{48}Ca bombarding actinide nuclei[2]. New heavy isotopes ^{259}Db and ^{265}Bh have also been synthesized at HIRFL in Lanzhou[6]. Reasonable understanding on the formation of SHN in massive fusion reactions is still a challenge for theory.

2 Dinuclear system model

The dinuclear system (DNS) is a molecular configuration of two touching nuclei which keep their own individuality[7]. 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. 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 $E_{\rm c.m.}$,

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$$\sigma_{\rm ER}(E_{\rm c.m.}) = \frac{\pi\hbar^2}{2\mu E_{\rm c.m.}}\sum_{J=0}^{J_{\max}}(2J+1)T(E_{\rm c.m.},J) P_{\rm CN}(E_{\rm c.m.},J)W_{\rm sur}(E_{\rm c.m.},J). \quad (1)$$

Here, $T(E_{\rm c.m.},J)$ is the transmission probability of the two colliding nuclei overcoming the Coulomb potential barrier in the entrance channel to form the DNS. The $P_{\rm CN}$ is the probability that the system will evolve from a touching configuration into the compound nucleus in competition with quasi-fission of the DNS and fission of the heavy fragment. 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[8, 9]. We take the maximal angular momentum as $J_{\max}=30$ since the fission barrier of the heavy nucleus disappears at high spin[10].

The level density is very important in the estimation of the survival probability[8] and expressed by the back-shifted Bethe formula[11] with spin cut-off model as

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

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

$$\Delta=\chi\frac{12}{\sqrt{\rm A}} \quad (3)$$

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

$$\sigma^2=T\zeta_{\rm r.b}/\hbar^2, \quad (4)$$

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

$$a(E^*,Z,N)=\tilde{a}(A)[1+E_{\rm sh}(Z,N)f(E^*-\Delta)/(E^*-\Delta)]. \quad (5)$$

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

$$f(E^*)=1-\exp(-\gamma E^*) \quad (6)$$

with $\gamma=\tilde{a}/(\epsilon A^{4/3})$. The parameters are listed in Table 1. In Fig.1 we give the level density parameters of different nuclides at ground state calculated using Eq.(5) and compared with two empirical formula $a(A)=A/8, A/12$.

Table 1. Parameters used in the calculation of the level density.

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

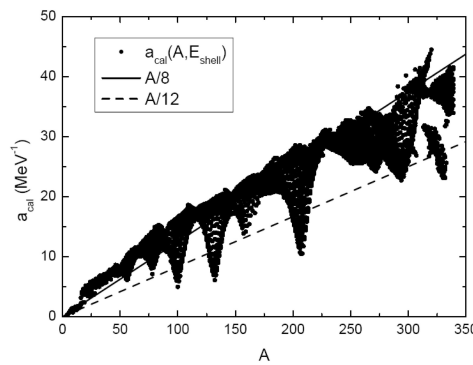

Fig. 1. Calculated values of the level density parameters as a function of the atomic mass.

3 Calculated results and discussions

As a test of the parameters used in the calculation of the level density, we analyzed the fusion-fission reactions for the selected systems ($P_{\rm CN}\sim 1$) as shown in Fig.2. The evaporation residues are mainly determined by the transmission and the survival probabilities. It is clear that the experimental data[12—14] can be reproduced rather well within the error bars. With the same procedure, we calculated the evaporation

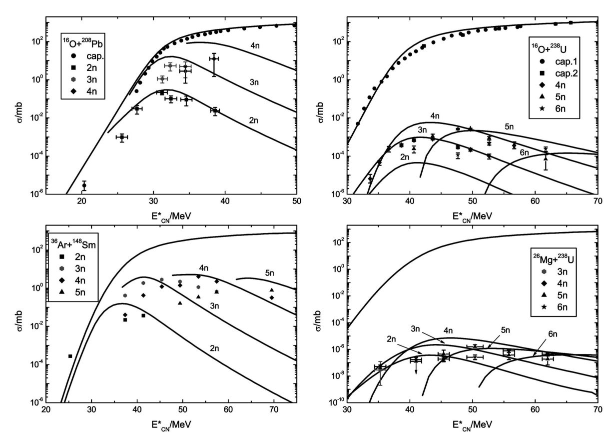

Fig. 2. Comparison of the calculated fusion-fission excitation functions and the available experimental data for the reactions ^{16}O+^{208}Pb, ^{16}O+^{238}U, ^{36}Ar+^{148}Sm and ^{26}Mg+^{238}U.

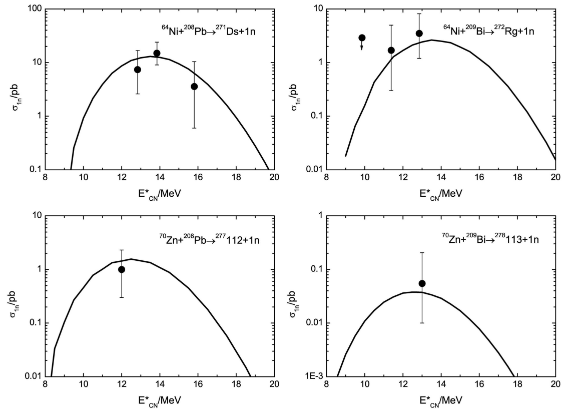

Fig. 3. Calculated evaporation residue excitation functions and compared them with available experimental data.

residue cross sections producing SHN $Z = 110-113$ in cold fusion reactions as shown in Fig.3, and compared them with GSI data for 110-112[1] and RIKEN results[5] for 113. Usually, neutron-rich projectiles are used to synthesize SHN experimentally, such as ^{64}Ni and ^{70}Zn, which can enhance the survival probability $W_{\rm sur}$ in Eq.(1) of the formed compound nucleus due to smaller neutron separation energy. The maximal production cross sections from Ds to 113 are reduced rapidly because the inner fusion barrier is increasing. Within error bars the experimental results can be reproduced very well. When the neutron number of the projectile is increasing, the DNS gets more symmetrical and the fusion probability decreases if the DNS does not consist of more stable nuclei due to a higher 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 larger shell correction energy and neutron separation energy.

4 Conclusions

Within the framework of the DNS model, the fusion-fission reactions and the evaporation residue excitation functions are investigated systematically. The calculated results are in good agreement with available experimental data within error bars.

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