Production cross sections of the superheavy nucleus 117 based on the dinuclear system model*

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Abstract Within the framework of the dinuclear system model, the capture of two colliding nuclei, and the formation and de-excitation process of a compound nucleus are described by using an empirical coupled channel model, solving the master equation numerically and the statistical evaporation model, respectively. In the process of heavy-ion capture and fusion to synthesize superheavy nuclei, the barrier distribution function is introduced and averaging collision orientations are considered. Based on this model, the production cross sections of the cold fusion system $^{76-82}$Se+^{209}Bi and the hot fusion systems ^{55}Mn+^{238}U, ^{51}V+^{244}Pu, ^{59}Co+^{232}Th, ^{48}Ca+$^{247-249}$Bk and ^{45}Sc+$^{246-248}$Cm are calculated. The isotopic dependence of the largest production cross sections is analyzed briefly, and the optimal projectile-target combination and excitation energy of the 1n-4n evaporation channels are proposed. It is shown that the hot fusion systems ^{48}Ca+$^{247-249}$Bk in the 3n evaporation channels and ^{45}Sc+^{248}Cm in the 2n-4n channels are optimal for synthesizing the superheavy element 117.

Key words superheavy nuclei, dinuclear system model, production cross sections, isotope dependence

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1 Introduction

The synthesis of superheavy elements (SHEs) has been one of the major frontiers in nuclear physics since the 1960s. High intensity beam heavy ion accelerators having been built and put into use provide a powerful tool for the synthesis of superheavy elements in the laboratory. Experimentally, superheavy elements are obtained mostly by evaporation of 1–2 neutrons in cold fusion reactions with ^{208}Pb or ^{209}Bi as targets, or evaporation of 3–5 neutrons in hot fusion reactions with the double magic nucleus ^{48}Ca bombarding actinide nuclei. In recent years, the elements from 107 to 112 were synthesized at GSI in cold fusion reactions[1, 2], the elements 113 to 118 (except 117) were produced at Dubna in hot fusion reactions using the neutron-rich projectile nucleus ^{48}Ca [3–5], and the element 113 was also synthesized by the RIKEN research group in the cold reaction ^{209}Bi (^{70}Zn, n) ^{278}113 [6]. Among the new elements discovered, superheavy nuclei with $Z \leqslant 111$ have already been confirmed and named by the International Union of Pure and Applied Chemistry (IUPAC). Recently the IUPAC has confirmed the recognition of element 112 and has already asked the research group of GSI who synthesized it to propose a name for the new element. To commemorate the famous astronomer Copernicus, they suggested Cn as a name for element 112, and after the proposed name has been thoroughly assessed by IUPAC, the element will receive its official name. For the superheavy element 117, the research team of Dubna in Russia carried out the experiment, but the results have not been announced yet. Furthermore, the synthesis of element 117 has also been supported by the National Basic Research Program of China (Program

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973), so the Institute of Modern Physics (IMP) will launch experiments focused on it this year. Theoretically, various models have also been proposed to describe the formation of superheavy elements. Among these models, the dinuclear system concept (DNSC) has successfully described a series of available experimental data [7–11]. Production cross sections of superheavy elements are quite small, of the order of pb (10^{-12} barn), and they decrease dramatically with increasing atomic number of the synthesized elements [1]. Therefore, not only improving the identification of the detection equipment but also increasing the beam intensity is necessary in these experiments. In theory it is very important to select the optimal combination of target and projectile and the most favorable bombarding energy. For the purpose of guiding the experiment in IMP, we describe in this paper, within the framework of the dinuclear system model, the capture of two colliding nuclei, and the formation and de-excitation process of the compound nucleus by using an empirical coupled channel model, solving the master equation numerically and using a statistical evaporation model, respectively.

This article is organized as follows. In Sec. 2, a brief description of the dinuclear system model will be given. Different fusion reactions aiming for the production of SHE 117 are investigated in Sec. 3. Our work is summarized in Sec. 4.

2 The dinuclear system (DNS) model

According to the dinuclear system concept [11, 12], the formation process of superheavy elements is divided into three stages: (1) the two reaction partners at large distances, overcoming the Coulomb barrier and reaching the touching point; (2) from sticking to the formation of a compound nucleus; and (3) after the compound nucleus (CN) formation, the compound nucleus surviving fission being cooled down by particle evaporation. Correspondingly, the evaporation residue ($\sigma_{\rm ER}$) is expressed as the product of three factors: the cross section of the projectile being captured by the target ($\sigma_{\rm c}$), the probability of reaching the compound nucleus configuration from the sticking composite nucleus ($P_{\rm CN}$), and the probability of surviving fission ($W_{\rm sur}$),

$$\sigma_{\rm ER}(E_{\rm cm}) = \sum_{J=0}^{J_{\max}} \sigma_{\rm c}(E_{\rm cm},J)\cdot P_{\rm CN}(E_{\rm cm},J) \times W_{\rm sur}(E_{\rm cm},J). \quad (1)$$

So the partial cross sections of capture, fusion and evaporation residue are expressed as [13]

$$\sigma_{\rm c}(E_{\rm cm},J) = \frac{\pi\hbar^2}{2\mu E_{\rm cm}}(2J+1)T(E_{\rm cm},J), \quad (2)$$

$$\sigma_{\rm fus}(E_{\rm cm},J) = \frac{\pi\hbar^2}{2\mu E_{\rm cm}}(2J+1)T(E_{\rm cm},J) \times P_{\rm CN}(E_{\rm cm},J), \quad (3)$$

$$\sigma_{\rm ER}(E_{\rm cm},J) = \frac{\pi\hbar^2}{2\mu E_{\rm cm}}(2J+1)T(E_{\rm cm},J) \times P_{\rm CN}(E_{\rm cm},J)\cdot W_{\rm sur}(E_{\rm cm},J). \quad (4)$$

In the calculation, we take the maximal angular momentum as $J_{\max}=30$ because the fission barrier of heavy nuclei disappears at very high spin [14]. Here, $T(E_{\rm cm},J)$ is the transmission probability which is calculated by using an empirical coupled channel model [12]. Taking the variation of the dynamical deformation of the collision system into account, we express the transmission probability as

$$T(E_{\rm cm},J)=\int f(B)\frac{1}{1+\exp\left\{-\frac{2\pi}{\hbar\omega(J)}\left[E_{\rm cm}-B-\frac{\hbar^2}{2\mu R_{\rm B}^2(J)}J(J+1)\right]\right\}}{\rm d}B. \quad (5)$$

Here, μ and J are the reduced mass and angular momentum of the collision system, respectively, and $\omega(J)$ is the width of the parabolic form at the position of the barrier $R_{\rm B}(J)$. The barrier distribution function is taken to be a Gaussian,

$$f(B)=\begin{cases}\frac{1}{N}\exp\left[-\left(\frac{B-B_{\rm m}}{\Delta_1}\right)^2\right], & B<B_{\rm m}\\ \frac{1}{N}\exp\left[-\left(\frac{B-B_{\rm m}}{\Delta_2}\right)^2\right], & B>B_{\rm m}.\end{cases} \quad (6)$$

In expression (6), $\Delta_2=(B_0-B_{\rm s})/2$, $\Delta_1=\Delta_2-2$, $B_{\rm m}=(B_0+B_{\rm s})/2$, B_0 and $B_{\rm s}$ are the height of the Coulomb barrier at waist-to-waist orientation and the height of the minimum barrier with respect to the variation in the dynamical deformation parameters β_1 and β_2, respectively. N is a normalization constant which is given by expression $\int f(B){\rm d}B=1$.

In accordance with the dinuclear model, the nucleon transfer is a diffusion process which can be described by a master equation. The DNS model also assumes that the two colliding nuclei interact with one another but retain their individuality. So the

evolution of the distribution function $P(A_1,E_1,t)$ for fragment 1 with mass number A_1 and excitation energy E_1 is given by the master equation [15]

$$\frac{\mathrm{d}P(A_1,E_1,t)}{\mathrm{d}t} = \sum_{A_1'} W_{A_1A_1'}[d_{A_1}P(A_1',E_1',t) - d_{A_1'}P(A_1,E_1,t)] - \Lambda^{qf}(\Theta(t))P(A_1,E_1,t). \quad (7)$$

Here, $W_{A_1A_1'}$ is the mean transition probability from channel (A_1,E_1) to channel $\left(A_1^{'},E_1^{'}\right)$, and d_{A_1} denotes the microscopic dimension corresponding to the macroscopic state (A_1,E_1) [16]. The sum is taken over all possible mass numbers that fragment 1 may take on (from 0 to $A=A_1+A_2$). The inner excitation energy E_1 is provided by the relative motion dynamics. In Eq. (7), $\Lambda^{qf}(\Theta(t))$ is the quasi-fission rate for the evolution of the DNS along the variable R that can be calculated with the one-dimensional Kramers formula,

$$\Lambda^{qf}(\Theta(t)) = \frac{\omega}{2\pi\omega^{B_{qf}}}\left(\sqrt{\left(\frac{\Gamma}{2\hbar}\right)^2+(\omega^{B_{qf}})^2}-\frac{\Gamma}{2\hbar}\right) \times\exp\left(-\frac{B_{qf}(A_1,A_2)}{\Theta(A_1,E_1,t)}\right). \quad (8)$$

Solving the master equation, Eq. (7), we obtain the formation probability of the compound nucleus at the Coulomb barrier B and angular momentum J, as follows,

$$P_{\mathrm{CN}}(E_{\mathrm{cm}},J,B)=\sum_{A_1=1}^{A_{\mathrm{BG}}}P(A_1,E_1,\tau_{\mathrm{int}}(E_{\mathrm{cm}},J,B)). \quad (9)$$

Here the interaction time τ_{int} is obtained by the deflection function method [17, 18]. The barrier distribution function is used in the calculation of the fusion probability, which can be given by expression (6). However, the dinuclear system varies constantly in the process of nucleon transfer, so it should be noticed that the use of expression (6) in calculating the fusion probability represents a very strong approximation because it is introduced for the entrance channel. We obtain the fusion probability as

$$P_{\mathrm{CN}}(E_{\mathrm{cm}},J)=\int f(B)P_{\mathrm{CN}}(E_{\mathrm{cm}},J,B)\mathrm{d}B. \quad (10)$$

Usually the fission barrier is mainly determined by the microscopic shell correction energy for the proton number $Z>106$ and, as the excitation energy of the compound nucleus increases, it decreases strongly. At our considered excitation energies (greater than the one neutron separation energy), the de-excitation of the excited compound nucleus occurs mainly through fission and the evaporation of neutrons [19]. Therefore, the survival probability of the compound nucleus after emitting x neutrons can be written as

$$W_{\mathrm{sur}}(E^*_{\mathrm{CN}},J)\approx P_{xn}(E^*_{\mathrm{CN}},J) \times\prod_{i=1}^{x}\left(\frac{\Gamma_{\mathrm{n}}(E_i^*,J)}{\Gamma_n(E_i^*,J)+\Gamma_f(E_i^*,J)}\right)_i, \quad (11)$$

where E^*_{CN} and J are the excitation energy and spin of the compound nucleus, respectively. The realization probability $P_{xn}(E^*_{\mathrm{CN}},x,J)$ of an xn channel at a given E^*_{CN} and J, neutron evaporation width Γ_n and fission width Γ_f are estimated with the statistical evaporation theory [12, 20].

3 Results and discussion

3.1 Evaporation-residue excitation functions

As a test of the parameters for the calculation, we calculated the evaporation residue excitation functions of the hot fusion reactions ^{26}Mg+^{248}Cm and ^{48}Ca+^{248}Cm. The results can be seen in Fig. 1. For the light system ^{26}Mg+^{248}Cm (left in Fig. 1), the quasi-fission does not dominate in the sub-barrier

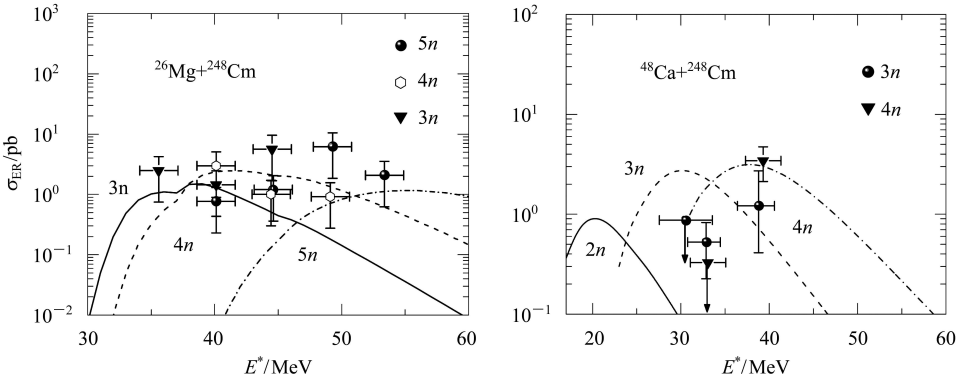

Fig. 1. The fusion-fission excitation functions of the reaction ^{26}Mg(^{248}Cm, 3n–5n)108 and the evaporation residue functions of the reaction ^{48}Ca(^{248}Cm, 2n–4n)116 compared with the available experimental data of Refs. [21, 22].

region, which also means that $P_{\rm CN}$ ~1. The evaporation residues are mainly determined by the capture of the light projectile by the target nucleus and the survival probabilities of the formed compound nucleus. The calculated results agree with the experimental data basically within the error bars. Some differences may come from quasi-fission in the above barrier region and the input quantities, such as the neutron separation energy and shell corrections. In the heavier system ^{48}Ca+^{248}Cm the electrostatic energy of the composite systems formed by two heavy colliding nuclei is very large. Therefore, although the two nuclei may be captured by the nuclear potential, quasi-fission may take place after mass transfer from the heavier nucleus to the lighter one instead of fusing. This can inhibit fusion by several orders of magnitude [14]. As shown in Fig. 1 (right), the experimental data can be reproduced rather well within the error bars.

With the same procedure mentioned above, we analyzed the evaporation residues of the cold fusion reaction ^{82}Se(^{209}Bi, $1n$–$2n$)117 and the hot fusion reaction ^{48}Ca(^{247}Bk, $2n$–$4n$)117. The excitation energy of the compound nucleus is obtained as $E^* = E_{\rm cm} + Q$, where $E_{\rm cm}$ is the incident energy in the center-of-mass system. The Q value is given by $Q = \Delta M_P + \Delta M_T - \Delta M_C$ and the corresponding mass excesses ΔM_i ($i = P$, T, C) are taken from Ref. [23]. From Fig. 2 we see that the maximal production cross sections of the cold fusion system ^{82}Se(^{209}Bi, $1n$–$2n$)117 in the $1n$ channel and the $2n$ channel are 0.047 pb and 0.02 pb occurring at excitation energies of 10 MeV and 23 MeV, respectively. Apparently, the former is nearly 2.5 times larger than the latter. This is mainly due to the fact that the survival probability of the compound nucleus decreases with increasing excitation energy. Similar calculations of the evaporation residue excitation functions were also reported in Refs. [13] and [24]. Our calculations show that the hot fusion reaction ^{48}Ca+^{247}Bk has a maximum value of 1.28 pb for the $3n$ channel at 32 MeV. This is larger than the result of 0.86 pb at 37 MeV for the $3n$ channel calculated with the same model in Ref. [13]. This may be due to our neglect of fission of heavy nuclei in the nucleon transfer process and differences in input quantities. In Ref. [24], the Two-Step Model gives the maximal production cross sections of 0.75 pb for the same reaction in the $3n$ channel corresponding to the excitation energy of 33 MeV, which is in good agreement with our calculated results as well as the value given in Ref. [13].

Since the combined reaction systems consisting of

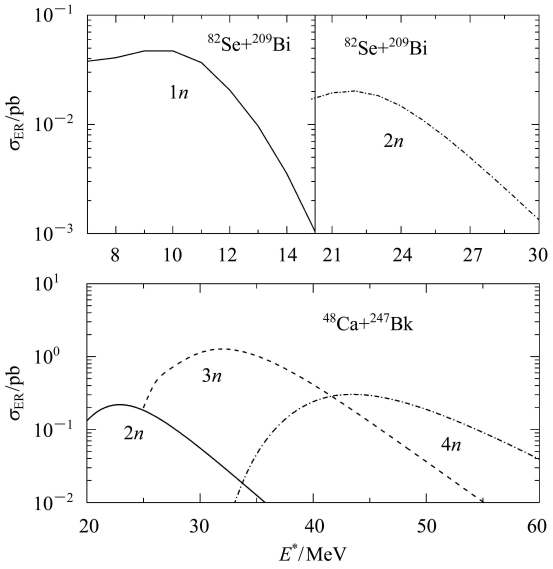

Fig. 2. Production cross sections in the cold reaction ^{82}Se(^{209}Bi, $1n$–$2n$)^{289,290}117 and the hot reaction ^{48}Ca(^{247}Bk, $2n$–$4n$)$^{291-293}$117.

double magic or near double magic nuclei have a larger Q value, which can reduce the excitation energy of the compound nucleus so that the fusion probability and survival probability increases, they are often used to synthesize superheavy elements. Because most of the combined reaction systems are not stable, and because the experiments for the synthesis of SHEs demand a longer time measurement, currently the more stable projectile and target nuclei are the main selection for synthesizing superheavy nuclei. Here we have chosen several groups of combined projectile-target systems with longer half-lives to calculate their excitation functions. The corresponding results are shown in Fig. 3 and Table 1. As a whole, our

Table 1. The maximal production cross sections in the $2n$–$4n$ evaporation channels for the hot reactions ^{45}Sc+^{248}Cm, ^{51}V+^{244}Pu, ^{55}Mn+^{238}U and ^{59}Co+^{232}Th.

reactions	channels	E^*/MeV	$\sigma_{\rm ER}$/pb
^{45}Sc+^{248}Cm	$2n$	26	2.432
^{45}Sc+^{248}Cm	$3n$	36	2.552
^{45}Sc+^{248}Cm	$4n$	46	3.250
^{51}V+^{244}Pu	$2n$	24	0.318
^{51}V+^{244}Pu	$3n$	32	1.029
^{51}V+^{244}Pu	$4n$	43	0.330
^{55}Mn+^{238}U	$2n$	23	0.084
^{55}Mn+^{238}U	$3n$	34	0.216
^{55}Mn+^{238}U	$4n$	47	0.039
^{59}Co+^{232}Th	$2n$	24	0.084
^{59}Co+^{232}Th	$3n$	35	0.112
^{59}Co+^{232}Th	$4n$	47	0.0139

calculated results are consistent with the results in Ref. [13], and both demonstrate that reaction ^{45}Sc (^{248}Cm, $2n$–$4n$)117 in the $2n$–$4n$ channels has larger production cross sections compared to the others, which is appropriate for synthesizing the SHE 117.

3.2 Isotopic dependence of the production cross sections

To find optimal projectile-target combinations, the study of the dependence of the production cross sections of SHEs on the isotopic compositions is very important and will be of great reference value for the further synthesis of superheavy nuclei. We show the dependence of the maximum values of the evaporation residue cross sections on the isotopic targets $^{246–248}$Cm for the $3n$–$4n$ channels and $^{247–249}$Bk in the $3n$ channel as well as for the isotopic projectiles $^{76–82}$Se in the $1n$ channel in Fig. 4. The calculated results indicate that the production cross sections are not simply increasing with the neutron number of the projectile or target nucleus. Odd-even effects of the production cross sections can be seen in the two evaporation channels. This mainly comes from the contribution of the survival probability, which in turn is very much influenced by the neutron separation

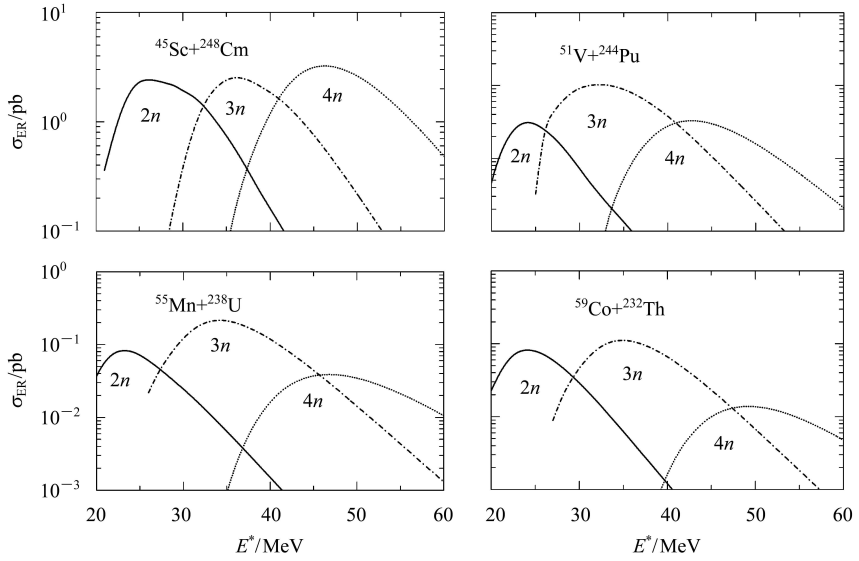

Fig. 3. The calculated excitation functions for the hot reactions ^{45}Sc+^{248}Cm, ^{51}V+^{244}Pu, ^{55}Mn+^{238}U and ^{59}Co+^{232}Th in $2n$–$4n$ evaporation channels.

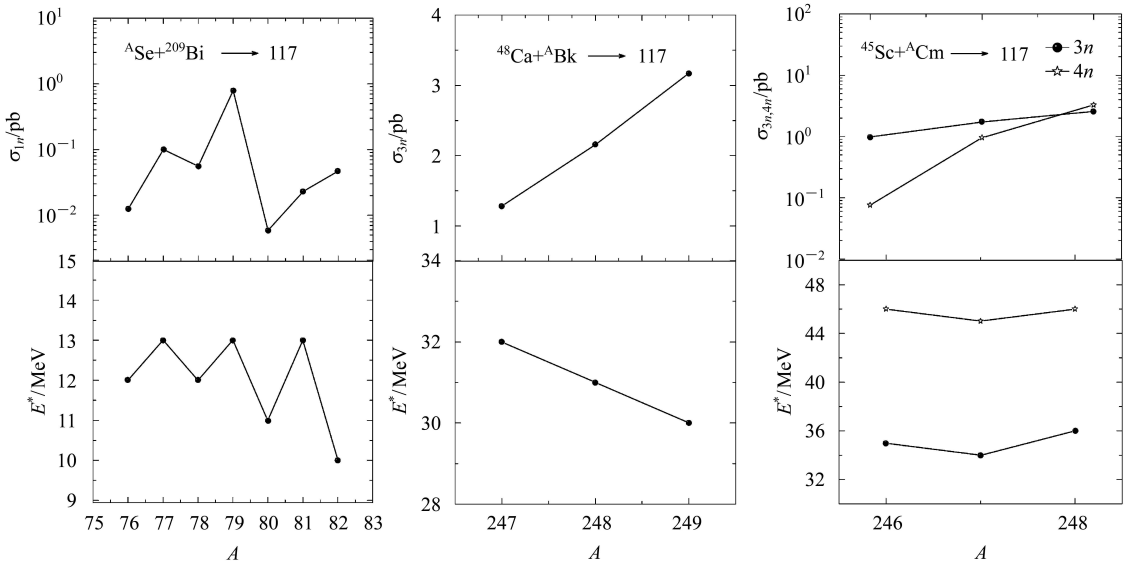

Fig. 4. Isotopic dependence of the calculated maximal production cross sections for the cold reaction ^{A}Se(^{209}Bi, $1n$)117 and the hot reactions ^{48}Ca(^{A}Bk, $3n$)117, ^{45}Sc(^{A}Cm, $3n$–$4n$)117.

energy and shell correction energy. Comparing the data from Fig. 4 and Table 1, we find that the maximum production cross sections of the combinations ^{48}Ca ($^{247-249}$Bk, $2n$–$4n$)117 in the $3n$ channel are 1.28 pb, 2.16 and 3.17 pb, respectively. Similar results have been obtained in Ref. [25]. The cross sections of these reactions are much larger than those of the other selected combinations, except the reaction system ^{45}Sc+^{248}Cm in the $2n$–$4n$ channels. The corresponding excitation energies are 32, 31 and 30 MeV, respectively. Therefore, it is also a good way to use the hot reaction ^{48}Ca($^{247-249}$Bk, $2n$–$4n$)117 in the $3n$ channel for the synthesis of SHE 117.

4 Summary

Using the DNS model we investigated the production of the superheavy nucleus 117 in fusion-evaporation reactions. The production cross sections of the cold fusion system $^{76-82}$Se+^{209}Bi and the hot fusion systems ^{55}Mn+^{238}U, ^{51}V+^{244}Pu, ^{48}Ca+$^{247-249}$Bk, ^{59}Co+^{232}Th and ^{45}Sc+$^{246-248}$Cm have been calculated. We briefly analyzed the isotopic dependence of the largest production cross sections and the optimal projectile-target combination and excitation energy of the $1n$–$4n$ evaporation channels were proposed. It was shown that the hot fusion systems, ^{48}Ca+$^{247-249}$Bk in the $3n$ evaporation channels and ^{45}Sc+^{248}Cm in the $2n$–$4n$ channels, are optimal for synthesizing the superheavy element 117.

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