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Investigation of Production Cross Sections for Superheavy Nuclei with $Z = 116 \sim 121$ in Dinuclear System Concept

JIANG Jinge[1], CHAI Qingzhen[1], WANG Bing[1], ZHAO Weijuan[1],
LIU Minliang[2], WANG Hualei[1]

(*1. School of Physics and Engineering, Zhengzhou University, Zhengzhou 450001, China*;
2. Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China)

Abstract: The production cross sections of superheavy elements with $Z = 116 \sim 121$ have been investigated systematically within the dinuclear system (DNS) concept, where the master equation is solved numerically to obtain the fusion probability. The competition between complete fusion and quasifission, which can strongly affect the cross section of the compound nucleus formation, is taken into account. The evaporation residue cross sections σ_{ER} calculated for the hot fusion actinide-based reactions (^{48}Ca+^{245}Cm, ^{48}Ca+^{249}Cf and ^{48}Ca+^{249}Bk) are basically in agreement with the known experimental data within one order of magnitude. Similar calculations for the synthesis of superheavy elements up to $Z = 121$ are performed using the available ^{249}Bk, ^{249}Cf and ^{243}Am as targets and ^{48}Ca, ^{50}Ti and ^{58}Fe as projectiles. Their production cross sections are relatively small, especially for the ^{58}Fe+^{243}Am$\rightarrow^{301}$121 reaction. A systematic analysis indicates that the 3n and 4n channels are respectively the most favorable fusion-evaporation channels in the synthesis of even- and odd-Z superheavy elements.

Key words: dinuclear system model; master equation; superheavy nuclei; evaporation residue cross section

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1 Introduction

Theoretically, the existence of a so-called superheavy nuclear island of stability has been predicted around a proton number $Z = 114$ (also $Z = 120$, 124, or 126, depending on theoretical models and the parametrization employed) and a neutron number $N = 184$ for many years[1–3]. A number of worldwide efforts have been made to synthesize the superheavy nuclei at the well-known laboratories (such as Berkeley, Darmstadt, Dubna, GSI, RIKEN, GANIL and HIRFL)[4–8]. Nevertheless, it is extremely difficult to reach the island because the production cross sections are very small, especially for those nuclei with $Z \geqslant 110$ (some picobarns, or even the part of a picobarn). Between two heavy nuclei to form these superheavy elements, the compound nucleus reaction is then strongly hindered by competing faster processes[9], quasifission and fission. At bombarding energy close to the fusion barrier, the quasifission process ($\lesssim 10^{-20}$ s), an out of equilibrium binary splitting of the composite system, is dominant. And at energy above the fusion barrier, the fission barrier vanishes due to spin effects, leading to fast splitting of the composite system. Theoretical support is thus important to understand the synthesis of very heavy nuclei and many theoretical models have been developed to describe the mechanism behind it.

In particular, the interest in the synthesis of super-

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Biography: JIANG Jinge (1985–), female (Han Nationality), Shangqiu, Henan, Master, working on particle physics and nuclear physics; E-mail: 2005bingxiao@163.com.

Corresponding author: WANG Hualei, E-mail: wanghualei@zzu.edu.cn

heavy nuclei has grown in recent years due to the exciting experimental results[10–17], which indicate the possibility of producing and investigating the nuclei in the superheavy island. Indeed, decay energies and lifetimes of the synthesized nuclides with $Z = 104 \sim 118$ and $N = 162 \sim 177$ demonstrate a considerable increase of the stability of superheavy nuclei with an increasing number of neutrons[18]. So far, 26 new elements beyond uranium (up to element 118) have been synthesized in experiments. However, further experimental progress in the synthesis of superheavy elements with $Z > 118$ is not quite evident, though many theoretical studies are carried out[19–25]. For instance, the tentative experiment aimed at the synthesis of element 120 using the ^{244}Pu(^{58}Fe, xn)$^{302-x}$120 reaction has been conducted by Oganessian et al.[13], but the related α-decay chains were not observed due to the present experimental limit for registration.

In this work, the calculation and analysis are performed for the synthesis of superheavy nuclei with $Z = 116 \sim 121$ using the dinuclear system (DNS) model with the purpose of being helpful in future experiments, especially for the elements $119 \sim 121$. The projectile-target combinations and the optimal beam energies leading to larger cross sections of the synthesis of superheavy elements are presented and analyzed systematically. In order to check the reliability of our approach, we have also evaluated the evaporation residue cross sections of the ^{48}Ca+^{245}Cm, ^{48}Ca+^{249}Cf and ^{48}Ca+^{249}Bk reactions and compared them with the experimental data.

2 The model

The DNS model[24–26], which is based on the information on interactions between nuclei in deep inelastic collisions, is a powerful tool for describing the production of superheavy nuclei and is one of a few models so far which give no contradiction to available experimental data. In general, the evaporation residue cross-section of the compound nucleus can be calculated within the model[24]:

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

where μ and $E_{\mathrm{c.m.}}$ are the reduced mass and the bombarding energy in the center-of-mass system, respectively. $T(E_{\mathrm{c.m.}}, J)$ is the penetration coefficient of the Jth partial wave through the entrance Coulomb barrier, and J_{f} is taken as the value $J_{\mathrm{f}} = 30$ at which the contribution of the corresponding partial wave to $\sigma_{\mathrm{ER}}(E_{\mathrm{c.m.}})$ is usually negligible. The transmission probability $T(E_{\mathrm{c.m.}}, J)$ is calculated by using an empirical coupled channel model[27], where a Gaussian-type function is taken for the barrier distribution. The probability $P_{\mathrm{CN}}(E_{\mathrm{c.m.}}, J)$ of the complete fusion is evaluated by considering the fusion process as a diffusion of DNS. The survival probability $W_{\mathrm{sur}}(E_{\mathrm{c.m.}}, J)$ of the excited compound nucleus can be calculated by the statistical evaporation model, showing the competition between fission and neutron evaporation[27–28].

The formation process of a compound nucleus can not be determined unambiguously since the reaction system does not give signals during complete fusion in experiments. Therefore, compared with different theoretical approaches, the main difference for describing the synthesis of superheavy nuclei is the formation mechanism of a compound nucleus which is still an open question. For instance, the "fusion-by-diffusion" model[20–21] and the concept of nucleon collectivization[30] are used to understand the fusion mechanism. In the DNS model, it is assumed that after full dissipation of the collision kinetic energy a DNS is formed. Then, the system evolves to a compound nucleus by means of nucleon or small cluster transfer from a lighter nucleus to a heavier one in a touching position[26]. The diffusion process is described by the master equation[31–32], instead of the Fokker-Planck equation. The calculation of the driving potential for the nucleon transfer of the DNS includes shell, pairing and even-odd effect corrections, avoiding the harmonic oscillator approximation of the potential energy surface. During the process of the DNS evolution, the competition between fusion and quasi-fission is considered. Based on the fusion probability P_{CN} obtained from the numerical solution of the master equation, together with the calculations of capture probability T and survival probability W_{sur}, as described in Eq. (1), the evaporation residue cross-section σ_{ER} are obtained finally. Certainly, the optimal projectile-target combination and the optimal beam energy to synthesize superheavy nuclei can also be determined by the calculation mentioned above.

3 Results and discussions

To understand the diffusion process of a dinuclear

system, a three-dimensional potential energy surface of the DNS in the ^{48}Ca+^{245}Cm reaction system is shown visually in Fig. 1. The potential energy of the DNS, i.e. the driving potential energy for the nucleon transfer is given by[27, 31]

$$U(R,\eta) = B(A_1) + B(A_2) - [B(A) + V'(J)] + U_{\rm C}(R,\eta) + U_{\rm N}(R,\eta) + V_{\rm rot}(J)\ , \quad (2)$$

where R is the relative distance between the centers of the DNS nuclei and $\eta = (A_1 - A_2)/(A_1 + A_2)$ is the mass asymmetry coordinate. $B(A_1)$, $B(A_2)$, $B(A)$ and $V'(J)$ are the binding energies of the fragments and compound nucleus and the rotational energy of the compound nucleus, respectively. $U_{\rm C}(R,\eta)$, $U_{\rm N}(R,\eta)$, $V_{\rm rot}(J)$ are the nuclear, Coulomb

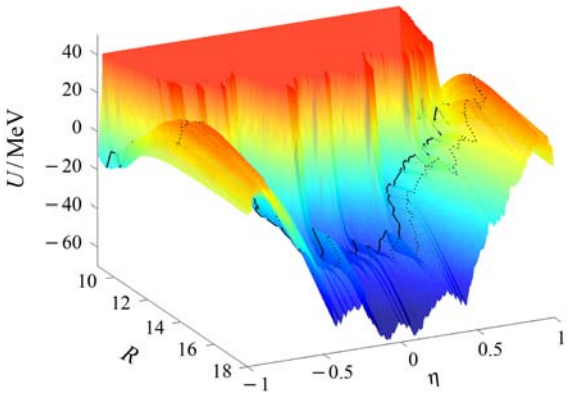

Fig. 1　(color online) Three-dimensional potential energy surface of the DNS in the ^{48}Ca+^{245}Cm → ^{293}116 reaction as a function of the relative distance R between the centers of fragments and the mass asymmetry η for $J = 0$. The solid and dotted curves go along the potential valley and ridge, respectively. The deformations of the DNS nuclei are taken into account.

and centrifugal parts of the nucleus-nucleus potential, respectively. Note that the potential energy surface is calculated at the angular momentum $J = 0$ and is adopted during the whole calculation process due to the similarity for different J. As shown in Refs. [26–28], a initial DNS consisting of two touching frozen nuclei is formed in the entrance channel during the capture stage of the reaction after dissipation of the kinetic energy of the collision. The initial DNS is in the conditional minimum of potential energy surface, as shown in Fig. 1. In the calculation of the potential energy surface, the pole-pole orientation which gives the energy minimum is in favor of nucleon transfer and is adopted for deformed prolate nuclei. The deformations of the DNS nuclei are taken from Ref. [33]. The dynamics of the DNS is considered as a combined diffusion in coordinates R and η. For a given η, there is a potential pocket which keeps the DNS nuclei in contact. The depth of the pocket defines the value of the quasi-fission barrier $B_{\rm qf}(\eta) = U(R_{\rm b},\eta) - U(R_{\rm m},\eta)$ ($R_{\rm b}$, $R_{\rm m}$ indicate the corresponding positions of the potential ridge and valley, respectively). The diffusion in R direction occurs towards the values larger than the sum of the radii of the DNS nuclei and leads to the DNS decay by quasi-fission finally. The complete fusion ($|\eta| = 1$) means the transfer of all nucleons of the light nucleus to the heavier one. Based on the assumption of adiabatic approximation, only the fusion path which goes along the potential valley is considered, as presented by solid curve in Fig. 1. The hindrance in the fusion process by nucleon transfer to form a compound nucleus is the inner fusion barrier $B^*_{\rm fus}$ in the fusion path, as shown in Fig. 2, and $B^*_{\rm fus}$ is defined as the variance of the driving potential at the Bussinaro-Gallone (BG) point and at the entrance position. After the DNS reaches the BG point due to the diffusion process, its potential energy decreases with increasing η and the DNS is driven to form the compound nucleus. From Fig. 2, one also can clearly see that the quasi-fission barrier (the difference of the two curves at a given η) of the DNS increases with the increasing mass asymmetry $|\eta|$, which indicates a more asymmetric DNS configuration may give a relatively smaller quasi-fission probability. After solving the master equation numerically considering the competitive fusion, quasi-fission

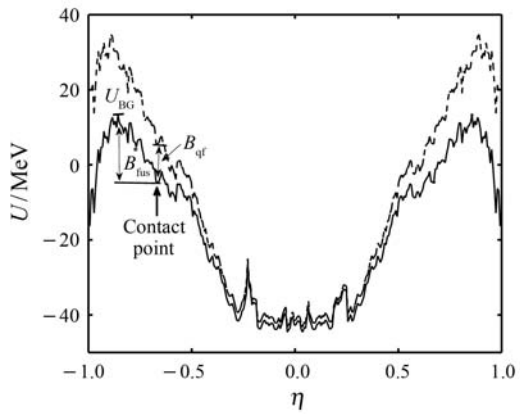

Fig. 2　The driving potential energies of the ^{48}Ca+^{245}Cm system at $R_{\rm m}$ (valley) and at $R_{\rm b}$ (ridge) as functions of η are presented by solid and dotted curves, respectively. The contact point, the inner fusion barrier $B_{\rm fus}$ and the quasi-fission barrier $B_{\rm qf}$ of the initial DNS are indicated.

and fission of heavy fragment in the DNS, one can obtain the fusion probability which is essential in the calculation of the evaporation residue cross section (see Eq. (1)).

The evaporation residue cross sections with even (116 ~ 118) and odd (117 ~ 121) Z in several selected reaction systems are shown in Figs. 3 and 4, respectively. The calculated results for the evaporation residue cross sections in the 2n~5n channels are presented by solid curves as signed in Figs. 3 and 4. The excitation energy of the compound nucleus is obtained by $E^* = E_{\rm c.m.} + Q$, where $E_{\rm c.m.}$ is the incident energy in the center-of-mass system, the Q value is given by $Q = \Delta M_{\rm p} + \Delta M_{\rm T} - \Delta M_{\rm C}$, and the corresponding mass loss obtained from Ref. [33] for projectile, target and compound nucleus, respectively. The available experimental data[18, 34] with error bars are represented by solid diamonds for superheavy nuclei with Z = 116, 117 and 118. One can see that the evaporation residue cross sections $\sigma_{\rm ER}$ calculated for the hot fusion reaction systems

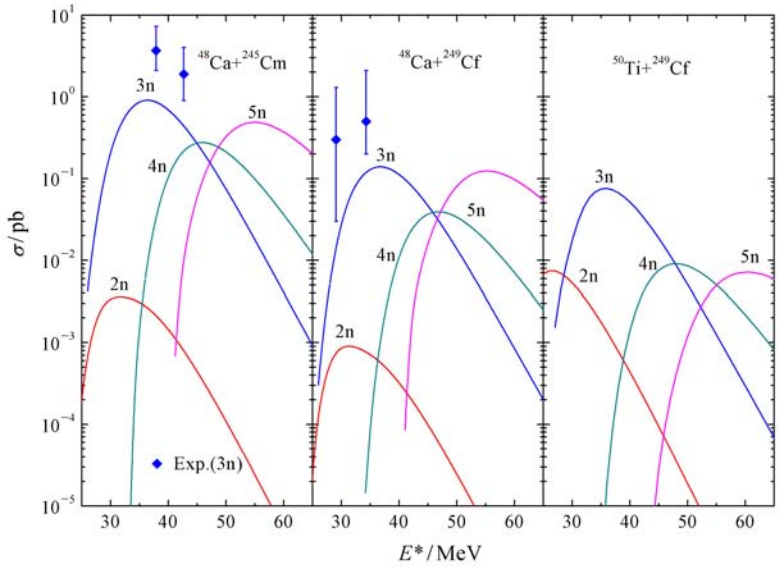

Fig. 3 (color online) Calculated excitation functions for hot fusion in the reactions ^{245}Cm(^{48}Ca, xn)$^{293-x}$116, ^{249}Cf(^{48}Ca, xn)$^{297-x}$118 and ^{249}Cf(^{50}Ti, xn)$^{299-x}$120. The available experimental data[18, 34] are shown by solid diamonds with error bars.

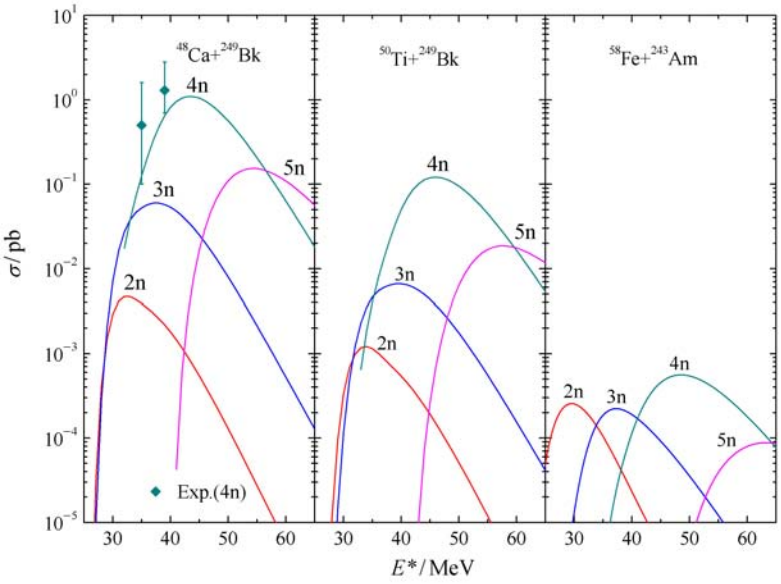

Fig. 4 (color online) The same as in Fig. 3 but for the hot fusion reactions ^{249}Bk(^{48}Ca, xn)$^{297-x}$117, ^{249}Bk(^{50}Ti, xn)$^{299-x}$119 and ^{243}Am(^{58}Fe, xn)$^{301-x}$121. The experimental data are taken from Ref. [14].

^{48}Ca+^{245}Cm, ^{48}Ca+^{249}Cf and ^{48}Ca+^{249}Bk are basically in agreement with the experimental results within one order of magnitude. Especially, it seems that the calculated positions of the maximum production cross sections are in agreement with those from experimental results. The small differences of the maximum positions of the excitation functions between calculations and experiments perhaps come from the beam energy loss due to the blocking of target thickness. The systemic underestimate of calculated σ_{ER} may be mainly related to the predicted nuclear properties (such as masses, fission barriers, neutron separation energies and Q values) which are important for the calculation of B^*_{fus}, W_{sur} and σ_{ER}. As discussed by Adamian et al.[28], the estimated inaccuracy of the calculations of σ_{ER} can be within factor of $2 \sim 5$. Obviously, the differences of σ_{ER} between theories and experiments are almost within the inaccuracy of calculation, as shown in Figs. 3 and 4. This allows us to be confident in our subsequent calculations for $Z = 119 \sim 121$ superheavies. The prediction of their relative production cross sections should be slightly underestimated since the calculations for all reaction systems were carried out with the similar parameters and assumptions. One also sees that the even-Z odd-N and odd-Z even-N compound nuclei have larger evaporation residue cross sections in the 3n and 4n channels, respectively. Moreover, the maximum production sections of the 3n and 4n channels decrease with increasing Z numbers of the compound nuclei, respectively.

The calculated evaporation residue cross sections σ_{ER} at the maxima of excitation functions and the corresponding excitation energies E^* of the compound nuclei are plotted in Fig. 5 for present actinide-based reactions, together with the available experimental data[6, 14, 18]. In the 3n-channel ^{245}Cm(^{48}Ca, 3n)^{290}116, ^{249}Cf(^{48}Ca, 3n)^{294}118 and ^{249}Cf(^{50}Ti, 3n)^{296}120 reactions, we obtain $\sigma_{ER} = 0.85$, 0.14 and 0.076 pb at $E^* = 36.0$, 37.1, and 36.1 MeV, respectively. In the 4n-channel reactions ^{249}Bk(^{48}Ca, 4n)^{293}117, ^{249}Bk(^{50}Ti, 4n)^{295}119 and ^{243}Am(^{58}Fe, 4n)^{297}121, we obtain $\sigma_{ER} = 1.05$, 0.12 pb and 0.56 fb at $E^* = 43.2$, 45.9, and 48.0 MeV, respectively. As expected, the variation of excitation energy E^* between the 3n and 4n evaporation channels of the compound nuclei is ~ 8 MeV (about one neutron separation energy). Our calculations for σ_{ER} agree well with the experimental data within the acceptable inaccuracy. Siwek-Wilczyńska et al.[20] recently suggest the most favorable reaction to synthesize the element $Z = 120$ is ^{50}Ti+^{249}Cf and predict the cross section is only 6 fb for 3n and 4n channels which is smaller than our present result (76 fb). In contrast, our calculation is more consistent with other several predictions with $\sigma_{ER} \approx 20 \sim 200$ fb[21−22, 35]. For the reaction ^{50}Ti+^{249}Bk→119, the present calculations give the maximum production section $\sigma_{ER} = 0.12$ pb in the 4n evaporation channel. This value is slightly smaller than the calculation with $\sigma_{ER} = 0.57$ pb using the fusion-by-diffusion model by Liu et al.[21]. It is worth mentioning that the similar excitation functions are obtained in present work, including both the curve shape and the position of the maximum σ_{ER}. However, our prediction is somewhat larger than the results $\sigma_{ER} \sim 0.035$ and 0.05 pb given by Wang et al.[22] and by Zagrebaev et al.[35], respectively. The different results can be attributed to the dependence of model and parameter. As a further extension of the region of the superheavy elements, we evaluate the production cross sections of element 121 with available ^{58}Fe projectile and ^{243}Am target though the corresponding nucleus, at which the α-decay chain ends, is not identified presently. It shows that the most favorable evaporation channel is the 4n channel and the maximum evaporation residue cross section for the present superheavy nucleus with $Z = 121$ is only 0.56 fb, which is far below the present experimental limit of registration (about 0.1 pb).

As shown in Fig. 5, it can be seen that the calculated evaporation residue cross sections decrease by more than three orders of magnitude with increasing Z number of

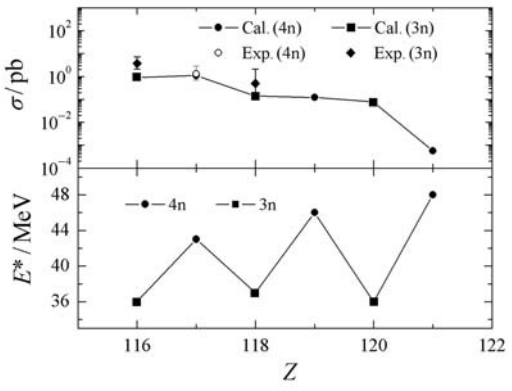

Fig. 5　Maximal production cross sections and the optimal excitation energies in the synthesis of superheavy elements with $Z = 116 \sim 121$, and compared with the experimental data from Refs. [14, 18, 34].

compound nuclei from 116 to 121. The evaporation residue cross sections, as mentioned in the model section, are determined by the competition among the three reaction stages which are related to the capture, fusion and survival probabilities, respectively. Since the main aim of the present work is focused on the fusion process, we show the dependence of fusion probabilities of even and odd Z compound nuclei formed in our selected reaction systems on excitation energy in Fig. 6. The similar analysis of the capture and survival probabilities has been widely discussed elsewhere and is not presented here. As one can see from Fig. 6, there is an increase trend of the fusion probabilities with increasing excitation energy. However, the decrease trend of $\sigma_{\rm ER}$ with increasing charge number Z of the compound nuclei can not be well understood from the fusion probability $P_{\rm CN}$ except in the reaction ^{58}Fe+^{243}Am. There is even a conflict between the changing trend of $\sigma_{\rm ER}$ and $P_{\rm CN}$, for instance, it is not expected that the $P_{\rm CN}$ of the compound nucleus (^{50}Ti+^{249}Cf) with $Z = 120$ is larger than that of the one (^{48}Ca+^{249}Cf) with $Z = 118$ at their optimal excitation energies. Therefore, it is believed that the capture and/or survival probabilities will play an important role in the inversion of $\sigma_{\rm ER}$. In general, the capture probability decreases with increasing Z number of the sum of projectile and target nuclei due to the large Coulomb barrier. For the hot-fusion reaction with high excitation energy, the survival probability strongly affects the production cross section $\sigma_{\rm ER}$, especially for the maximum position of the excitation function, since the capture and fusion probabilities depend weakly on excitation energy relatively.

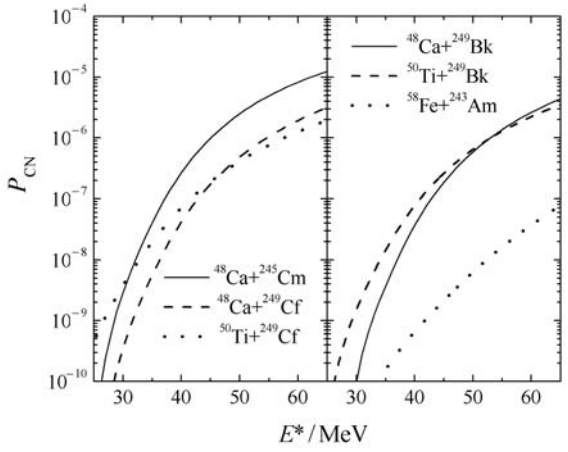

Fig. 6 Dependence of fusion probabilities of even (left part) and odd (right part) Z compound nuclei formed in the present reaction systems on excitation energy.

Compared to other reaction systems, the fast fall-off of $\sigma_{\rm ER}$ in the ^{58}Fe+^{243}Am reaction may be caused to a great extent by the strong decrease of $P_{\rm CN}$. The mass asymmetry $|\eta| = 0.61$ of this reaction system is lower than those of considered other systems with $|\eta| \sim 0.665 \sim 0.676$, which may indicate a large inner fusion barrier $B^*_{\rm fus}$ hindering the complete fusion. Further experimental extension of the region of superheavy element seems to be mainly limited by the number of available projectiles and targets and awaits the intensive radioactive ion beams.

4 Summary

In conclusion, the production cross sections of superheavy elements with $Z = 116 \sim 121$ in 2~5n evaporation channels are investigated systematically by means of several selected reactions within the framework of the DNS model, where the formation of a compound nucleus is described by the master equation. The three-dimensional potential energy surface governed the diffusion process of the DNS is analyzed visually, showing the competition between complete fusion and quasi-fission processes. Available experimental data for superheavy nuclei with $Z = 116 \sim 118$ formed in actinide-based reactions can be basically reproduced within one order of magnitude. The evaporation residue cross sections for the new isotopes of superheavy elements with $Z = 119 \sim 121$ are calculated in the hot fusion reactions with the available projectiles and targets. It is shown that the even-Z odd-N and odd-Z even-N compound nuclei will give larger production cross sections for the 3n and 4n evaporation channels, respectively. Except for the reaction ^{58}Fe+^{243}Am→121, the selected other ones all give the maximum production cross sections above or close to the level of the present experimental possibilities.

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基于双核模型对 $Z = 116 \sim 121$ 超重核产生截面的研究

蒋金鸽[1]，柴清祯[1]，王 兵[1]，赵维娟[1]，柳敏良[2]，王华磊[1]

(1. 郑州大学物理工程学院，河南 郑州 450001;
2. 中国科学院近代物理研究所，甘肃 兰州 730000)

摘要： 在双核模型的理论框架下系统研究了超重元素 $Z = 116 \sim 121$ 的蒸发剩余截面，计算过程中核子扩散由主方程描述，同时考虑了全熔合与准裂变的竞争。计算基本再现了利用热熔合反应 $^{48}Ca+^{245}Cm$，$^{48}Ca+^{249}Cf$ 和 $^{48}Ca+^{249}Bk$ 产生 116 ~ 118 号同位素的合成截面。同样，分别以 ^{249}Bk，^{249}Cf 和 ^{243}Am 为靶，以 ^{48}Ca，^{50}Ti 和 ^{58}Fe 为炮弹，计算了 $Z = 119 \sim 121$ 号同位素的生成截面。结果表明，这些超重核的生成截面随着质子数的增大进一步变小。例如，利用 $^{58}Fe+^{243}Am$ 反应合成 121 号同位素的最大蒸发剩余截面仅在 fb 量级。基于对选择的几个反应系统的系统分析，发现双核系统在熔合蒸发过程中偶 Z 奇 N 和奇 Z 偶 N 复合核分别有强的 3n 和 4n 蒸发道。

关键词： 双核模型；主方程；超重核；蒸发剩余截面

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通信作者： 王华磊，E-mail: wanghualei@zzu.edu.cn