



# Fusion Dynamics of Low-Energy Heavy-Ion Collisions for Production of Superheavy Nuclei

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One of the major motivations for low-energy heavy-ion collision is the synthesis of superheavy nuclei. Based on the following two main aspects, various theoretical and experimental studies have been performed to explore the fusion dynamical process of superheavy nuclei production. The first reason is to elucidate and analyze the synthesis mechanism of superheavy nuclei; the other is to search the favorable incident energy and the best combination of projectile and target to produce new superheavy elements and isotopes of superheavy elements.

**Keywords:** low-energy heavy-ion collisions, superheavy nuclei production, fusion dynamics, transport theory, TDHF model

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## 1. INTRODUCTION

The maximum mass and charge of a nucleus is a long-standing fundamental problem in nuclear physics [1, 2]. Pioneer studies have theoretically predicted the “island of stability” of superheavy nuclei (SHN). The macroscopic-microscopic models predicted  $^{298}\text{Fl}$  to be the double magic nucleus [3–7]. However, results of the self-consistent models showed that the closed shell of  $Z = 114$  becomes weaker, and  $Z = 114$  is replaced by  $Z = 120$  or  $126$  [8–13].

The production process of superheavy nuclei is a very complicated dynamical problem [14]. Many theoretical models have been developed to explain the experimental data. On one hand, the synthesis mechanism of superheavy nuclei needs to be elucidated [15–21]. Different approaches are devoted to calculate and analyze the fusion probability and the distribution of quasifission fragments [15–41]. However, none of them has absolute advantage. On the other hand, in order to produce the new superheavy elements, or isotopes of superheavy elements, the favorable incident energy and the best combination of projectile and target should be evaluated.

The extended nuclear landscape allows us to investigate the nuclear structure of superheavy nuclei and the nuclear reaction mechanism. To search for the optimal condition of synthesis, the influence of the entrance channel [29, 42, 43] and the isospin of heavy colliding nuclei [44–46] on the evaporation residual cross section have been studied systematically in many works. The predictions of the possible way to synthesize the new superheavy elements  $Z = 119$  and  $120$  have also been carried out [17, 47–52].

## 2. EXPERIMENTAL PROGRESS

Producing superheavy nuclei in the laboratory is one of the major motivations of low-energy heavy-ion physics [1, 2, 53–55]. Over the past 30 years, great progress has been achieved for superheavy nuclei production in experimental studies [53–55]. The experimental trends  $\alpha$  decay half-lives, and the evaporation residue cross sections of the superheavy nuclei show

that the stability of superheavy nuclei increases as the neutron number approaches the closed neutron shell closure  $N = 184$ . However, the location of the “island of stability” has not been determined by experiment. Up until now, based on the fusion-evaporation reaction, the superheavy nuclei with charge numbers in the range of  $Z = 104$ – $118$  have been synthesized successfully.

The superheavy elements  $Z = 107 - 112$  was first synthesized by using the cold fusion reactions [1, 53, 54, 56, 57]. The excitation energy range of the formed compound nucleus was 10–18 MeV. The measurement of the evaporation residue cross section decreased dramatically from  $Z = 107$  to  $Z = 113$ . Moreover, the final evaporated residual nuclei were extremely neutron deficient. Experiments of producing superheavy nuclei by cold fusion have been repeated and verified by other laboratories [54, 58, 59].

The  $^{48}\text{Ca}$ -induced hot-fusion reactions were used to synthesize  $Z = 112 - 118$  superheavy nuclei in experiment [54, 55, 60]. From the measurement of evaporation residue cross sections, we found that there was no significant difference from  $Z = 112$ – $118$ , and the values of the evaporation residual cross sections were all in the order of picobarn. Experiments based on hot fusion for synthesizing  $Z = 112$  and  $114$ – $117$  superheavy nuclei have been verified by other laboratories [60].

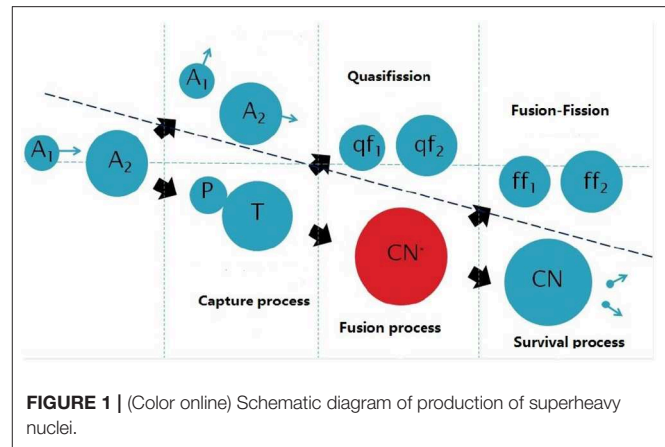
To search for the optimal condition of the superheavy nuclei production, various experiments have been performed to study the entrance channel effect on the evaporation residual cross section [61–65]. Recently, the isospin effect of the target nucleus on the evaporation residue cross section has been explored [66–68]. Some laboratories have also attempted to synthesize the  $Z = 119$  and  $120$  superheavy elements by using hot fusion [69, 70].

Experimentally, the measurement of fusion probability is required to distinguish quasifission between fusion-fission and fast fission [71–76]. The experimental characteristics of the quasifission process are different from the fusion-fission process [77]. Therefore, it is important to distinguish the fusion and quasifission fragments for a better understanding of the fusion mechanism.

### 3. THEORETICAL DESCRIPTION OF FUSION REACTIONS

Theoretically, the synthesis process of superheavy nuclei can be divided into three stages [39]. A schematic diagram for this process is shown in **Figure 1**. The first stage is the capture process, which can be evaluated by the capture cross section. The second stage is that the dinuclear system evolves from the touching configuration to the formation of the compound nucleus, which can be evaluated by the fusion probability. The last stage is where the excited compound nucleus cools down through emitting neutrons or fission, and this can be evaluated by the survival probability. Finally, a very small evaporation residue cross section is obtained for the superheavy nuclei production. The evaporation residue cross section can be expressed as [39],

$$\sigma_{ER}(E_{c.m.}) = \sum_J \sigma_{cap}(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J), \quad (1)$$



**FIGURE 1** | (Color online) Schematic diagram of production of superheavy nuclei.

where  $E_{c.m.}$  is the incident energy in the center-of-mass frame.

#### 3.1. Capture Cross Sections

For the low-energy heavy-ion collision, the capture cross section from the sub-barrier region to above the Coulomb barrier is an important issue for theoretical and experimental studies [78–83]. One of reasons is that the overall uncertainties in predicting superheavy nuclei production are associated with the calculations of capture cross sections [50, 84, 85].

The capture process is closely related to the nuclear structure of the interacting nuclei [86–97]. This is because the nucleus-nucleus potential contains nuclear structure information. To precisely describe the measurements of capture cross sections, the nucleus-nucleus interaction potential is the most important input quantity. In addition, the heavy-ion capture process is intimately linked to nuclear deformation [87, 88]. Thus, the nuclear deformation must be reliable to some extent.

Theoretically, the capture cross section is one of the important components in the synthesis of superheavy nuclei. The capture cross section have been explored extensively [82–84] from light to superheavy by averaging the penetration probability over barrier heights. Most of them have tested a number of experimental data of capture cross sections, however, these experimental data do not contain the capture cross sections of superheavy nuclei [84]. Therefore, it is very important to examine carefully the capture process for the study of the synthesis mechanism of superheavy nuclei.

Usually, the capture cross section  $\sigma_{cap}$  is mainly calculated with an empirical coupled-channel approach for the superheavy nuclei production [17, 44–52]. From a theoretical point of view, one of the powerful methods is to solve coupled-channels equations numerically. This may help us to understand the influence of the couplings between nuclear intrinsic degrees of freedom and the relative motion on capture cross sections.

Recently, the quantum diffusion approach [98–101] has also been used to calculate capture cross sections. This model takes into consideration the influence of fluctuations and dissipation effects on capture cross sections. The nuclear deformation effects and mutual orientations of the colliding nuclei are taken into account through using a double folding potential, and

the influence of two neutrons transfer onto the sub-barrier capture through the change of the deformations of the colliding nuclei [100].

Another powerful theoretical tool is to calculate the capture cross section by the time-dependent Hartree Fock (TDHF) method. Recently, the pioneering work of studying capture cross section based on TDHF has been completed for the  $^{40}\text{Ca}+^{238}\text{U}$  reaction [102]. In addition, Umar et al. found that the capture cross sections calculated by TDHF method agreed with the experimental data within 20% [103].

### 3.2. Fusion Dynamics

In order to explain the fusion dynamics process (the second stage), various theoretical approaches and models have been developed. The simplification can be made in different ways, and, as a result, we can obtain different theoretical pictures for the same real nuclear process. Some of the models can be roughly divided into two types. The first type is based on transport equations to describe the fusion dynamics process [15–41]. The second one is based on the time-dependent Hartree Fock method to describe the mainly experimental features in the process of fusion dynamics [104–115].

The first approach is that the multitude of degrees of freedom are decomposed into a dominating collective degree of freedom and other degrees (non-collective) of freedom. Therefore, the dissipative processes are introduced to account for the coupling between the collective motions and the intrinsic motions of the freedom of the system. Many models based on transport equations have been developed, and they assumed that the main characteristics of fusion dynamics process can be described by using the main collective degrees of freedom.

On the one hand, after eliminating the intrinsic motion, a stochastic equation can be derived theoretically. Many models adopted the Langevin forces (Langevin equation) to describe stochastic characteristics of the coupling between collective motions and intrinsic degrees of freedom. One can calculate a bundle of trajectories by solving a stochastic equation [16, 17, 28, 31, 35, 36].

On the other hand, through eliminating the intrinsic degrees of freedom, a diffusion equation can be derived theoretically to describe the distribution of collective degrees of freedom in the phase space [19–21, 27, 29, 29, 30, 32, 41–43, 46, 47, 49, 51, 116, 117]. Diffusion equations (the master equation, Smoluchowski equation, etc.,) may be used to describe the transport process of collective degrees of freedom in phase space.

The second approach is the time-dependent Hartree Fock method. The basic idea of this method is that the mean field produced by all nucleons not only determines the intrinsic motion of a single particle but also describes the evolution characteristics of collective degrees. TDHF calculations may be used to compute the ratio of fusion cross sections to capture cross sections. In addition, the TDHF method may be used to explore the effect of the orientation of the projectile and the target at the contact point, and the role of the nuclear shell structure and tensor force [104–115].

### 3.3. Fusion Mechanism

For the real fusion dynamics process, a theoretical model may be considered as a collection of theoretical assumptions. Up to now, there have been proposed fusion mechanisms that are incompatible with the compound nucleus formation. One assumption is that all the nucleons are immediately collectivized into one superdeformed mononucleus. Then, the dynamic evolution behavior of the superdeformed mononucleus can be described by the equation of motion or transport theory [15–17, 33, 34, 118]. The macroscopic dynamical model is the first model to describe the fusion mechanism based on the idea of forming one superdeformed mononucleus [15]. However, it encountered serious difficulties in attempts to describe evaporation residue cross sections for the synthesis of superheavy nuclei.

As the macroscopic dynamical models, the same approximations are used in the fluctuation-dissipation model [16, 118], the two-step model [17], and the fusion-by-diffusion model [33, 34]. But two significant improvements are taken into account for the description of the fusion-dynamics mechanism: shell effects in the calculation of the potential energy surface of the reaction system and statistical fluctuations in the interaction of colliding nuclei. These improvements permit one to describe the evaporation residue cross section of superheavy nuclei, the mass distribution of quasifission, and fusion-fission products [16, 17, 33, 34, 118, 119].

Another assumption is that two touching nuclei always keeps its own identity with their ground state characteristics and deformations (dinuclear system model) [19–21, 29], fusion is achieved by means of nucleon transfer. However, the real situation is due to strong Coulomb and nuclear interactions between projectile and target; the dinuclear system should be gradually deformed [30, 48]. This assumption has recently been improved upon. The coupling of the deformations evolution of project and target and the nucleon transfer has been studied numerically [120, 121]. The calculated results for the cold and hot fusion reactions by using the dinuclear system model match well with the available experimental data [20, 27, 29, 29, 30, 32, 41–43, 46, 47, 49, 51, 116, 117]. The fusion probability and the distribution of the quasifission fragments can be reasonably described based on the dinuclear system model [120–122].

A new fusion mechanism on compound nucleus formation was proposed by Zagrebaev [18]. The concept of a nucleon collectivization model assumes that two nuclei gradually lose their individualities through increasing the number of collectivized nucleons [18]; the reliability of the theoretical hypothesis needs further demonstration [123]. The nucleon collectivization model allows us to describe reasonably the fusion probability as well as the charge and mass distributions of the quasifission products [124].

### 3.4. Selection of Collective Degree and Calculation of Related Input Quantity in Transport or Diffusion Equations

To theoretically describe fusion dynamics and the mechanism based on transport equations as mentioned above, one needs to assume that several important degrees of freedoms can be

used to describe the main characteristics of fusion dynamics process [15–21]. These important degrees of freedoms include the distance between the nuclear centers, the neutron and proton asymmetries of projectile-target combinations, deformations, and corresponding orientation effects, which influence the dynamics from touching the configuration to the compound nucleus.

Because equations of motion contain time derivatives up to the second order, there are three quantities in each equations of motion. The first quantity is the conservative potential. The second and third are the friction tensor (friction force) and the inertia tensor (inertia parameter), respectively. For the conservative potential, two different approaches have been taken into account to calculate the potential energy surface. The two assumptions of calculating potential energy surface are frozen density or sudden approximation [19–21] and the adiabatic approximation [15–18].

Recently, Diaz-Torres showed that the gradual transition of potential energy surface from the diabatic to the adiabatic should be more realistic for describing the fusion or quasifission [125, 126]. In addition, one needs to consider how the shell structure evolves with excitation energy and deformation. The excitation energy dissipated from kinetic energy of relative motion makes the individual shell structure of nuclei become damped [127–131], and deformation tends to be spherical [132]. Thus, the dynamical potential energy surface has to be further studied. However, a small amount of research work has involved the shell correction energy employed in the fusion process being temperature dependent [133] and the potential energy surface from diabatic approximation to adiabatic approximation to describe the whole dynamic evolution process.

The dissipation tensor arises from the distinction between collective motion and intrinsic motion. The dissipation tensor accounts for the coupling between the collective degrees of freedom and other degrees (non-collective) of freedom. When equations of motion or stochastic equations are used to describe the dynamic process, the friction coefficients are mainly treated by the phenomenological approaches for the description of the fusion dynamics process [16, 124].

The inertial tensor describes the response of the system to small changes in the collective degrees of freedom. The macroscopic approach, macroscopic-microscopic approach, and microscopic approach are used to calculate the inertia tensor of the fission dynamics process [134–137]. However, in the low-energy heavy-ion collisions process, it seems that the proper calculation on inertial parameters has not been paid enough attention compared to the fission dynamics process. In the stochastic equation, the inertia parameter is calculated by the Werner-Wheeler approach [124, 127]. In the diffusion equation, the inertia parameter is treated as a reduced mass of relative motion [138]. From the theoretical point of view, the inertia parameters and friction coefficient of theoretical calculations have to match our understanding of the potential energy surface in the transport equations.

### 3.5. Survival Probabilities

The last important factor is the survival probability of the compound nucleus against fission in the deexcitation process. For exciting compound nuclei, there are two methods to describe the fission process: the statistical approach and the dynamical approach. Based on the statistical model, two different approaches are taken into account for the excitation energy dependent shell structure. The first one is to introduce the influence of excitation energy on the shell structure through the energy level density parameter [139]. The second one is to ensure the excitation energy-dependent shell effect is taken into account by the effective potential energy surface [140].

The uncertainty of survival probability calculation based on statistical model mainly comes from two aspects. On one hand, a number of approximations are adapted in the calculation of survival probability. On the other hand, the survival probabilities for the  $xn$  evaporation channels are very sensitive to the model input. The level densities, fission barriers, neutron-separation energies, as well as the transmission coefficients have to be known with sufficient accuracy. Only systematic calculations based on the same assumptions and parameters can help to confirm the validity and reliability of the theoretical approximations and input quantities [28, 117].

## 4. THE OPTIMUM PROJECTILE-TARGET COMBINATION AND BOMBARDING ENERGY

### 4.1. Influence of Entrance Channel on ERCSSs

Systematic studies of the existing experimental ERCSSs are helpful to reveal reaction mechanisms. In addition, searching the optimal combination of the projectile and target and the range of the favorable beam energy is essential.

Some work systematically studies the influence of the neutron number of a target or projectile on the evaporation residue cross section [32, 36, 44–46]. Many researchers have found that the fusion probability and survival probability are sensitive to the neutron number of the target or projectile nuclei [32, 36, 44–46]. For  $^{48}\text{Ca}$ -induced hot fusion, the excess neutron of target nucleus is beneficial to the increase of the evaporation residue cross section of the synthesized superheavy nuclei [32, 45, 46].

Using a different combination of projectile and target to produce the same compound nucleus may help us to reveal the effect of the ground-state deformations, the reaction  $Q$  value, the asymmetry of charge and mass of target and projectile, and the Coulomb barrier on the evaporation residual cross section [33, 138, 141]. The results calculated by Liu et al. show that the  $Q$  value of reaction has a significant effect on the capture cross section and fusion probability [142].

### 4.2. The ERCSS of Production Using Radioactive Beams

In order to investigate the possibility of neutron-rich superheavy nuclei production with radioactive beams, some calculations have been made [25, 116, 143, 144]. The evaporation residue

cross section by using radioactive beams are comparable with a stable beam for some superheavy nuclei production [116, 143]. However, the choice of reaction channels is determined by the product of beam intensity and evaporation residue cross section [143].

The intensities of stable beams, in most of the cases, are significantly larger than those of the radioactive beams [143], and the results have shown that the calculated evaporation residue cross section based on stable beam is more favorable for the production of many superheavy nuclei [116, 143]. In addition, due to small evaporation residue cross sections and low radioactive beam intensities, the synthesis of higher charge number superheavy nuclei by using the neutron-rich radioactive beams seems impossible based on today's experimental conditions [116, 143].

### 4.3. Prediction ERCS $Z = 119$ and $120$

By comparing evaporation residue cross sections for production  $Z = 119$  and  $120$ , we found that the calculations from different models were obviously different [17, 47–52, 124]. On one hand, the survival probability of the compound nucleus was very sensitive to the fission barrier. However, the difference in fission barriers of superheavy nuclei calculated by different models was obvious not only due to the absolute values but also the trends with charge number  $Z$  [2, 85]. On the other hand, due to different assumptions, the fusion probability calculated by different models was significantly different for synthesis  $Z = 119$  and  $120$  [84].

According to our calculation and other theoretical predictions, almost all the models that predicted evaporation residue cross sections to produce superheavy new element  $Z = 119$  are generally greater than those in producing  $Z = 120$  [17, 47–52].

## 5. THE FUTURE

The synthesis of SHN in the laboratory has made great progress, and all the elements up to  $Z=118$  have been synthesized successfully. However, the location of the island of stability has not been confirmed in experiments. Although many theoretical approaches were used to study the fusion mechanism, there are still many problems that have not been solved properly.

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In my opinion, the transport theory is the least developed one due to three factors: (i) the neck formation itself and the relationship between dynamic deformation and neck formation should be included to improve the theoretical description of fusion dynamic mechanism; (ii) the gradual transition of the potential energy surface from the diabatic approximation to the adiabatic approximation needs to be further explored; and (iii) the further study of inertia and damping coefficients to match our understanding of the potential energy surface in the transport equations should be performed.

## 6. SUMMARY

The evaporation residue cross section of superheavy nuclei depends on three factors: the capture cross section  $\sigma_{cap}$ , the fusion probability  $P_{CN}$ , and the survival probability  $W_{sur}$ . We found that the reasonable description of the capture cross section near the Coulomb barrier is very important. The coupled channel or TDHF can be better approached to calculate the value, especially for superheavy nuclei calculations.

I think the fusion probability  $P_{CN}$  for producing superheavy nuclei is still not well understood. Not only the magnitude of the fusion probability  $P_{CN}$  but also the dependence of  $P_{CN}$  on the excitation energy and the entrance channel are lacking in clarity. The fusion mechanism must be further studied.

The uncertainty of survival probability calculation based on a statistical model mainly comes from theoretical approximations and input quantities. Systematic calculations based on the same assumptions and parameters can help to confirm the validity and reliability of the theoretical approximations and input quantities.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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**Conflict of Interest:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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