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# Dynamical Approach for Synthesis of Superheavy Elements

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To success the synthesis of superheavy nuclei $Z > 118$ and approaching the Island of Stability, the estimation of the evaporation residue cross section with high accuracy is indispensable. Though the calculation models include several unknown parameters, the values are chosen to reproduce the experimental data. Here, we use the appropriate values in the statistical model, which are fitted to reproduce the experimental data. Using the same values, we calculate the evaporation residue cross section for $Z = 119$ and 120 using $^{50}$Ti, $^{51}$V and $^{54}$Cr projectiles, and suggest the optimum conditions to produce new elements.

**KEYWORDS:** superheavy elements, dynamical model, fluctuation-dissipation phenomena.

## 1. Introduction

The existence of the Island of Stability in the superheavy mass region has been predicted using the nuclear shell model. Recent experiments on the synthesis of superheavy elements have been focused on the investigation of this region and have succeeded in synthesizing the element till $Z = 118$ [1–3]. At present, attempts to produce elements 119 and 120 are made or planed in several facilities using actinoid targets. In order to produce new nuclei or elements not discovered so far, an accurate prediction of the production cross sections is an important issues in the superheavy elements research.

In the theoretical calculation, the evaporation residue cross section is obtained as the product of the fusion probability forming a compound nucleus and its survival probability in the competition with the fission process. Many theoretical studies on the synthesis of superheavy elements have been published and the evaporation residue cross section corresponding to the above experiments has been estimated [4]. In each model and each stage, a substantial uncertainty is involved. To estimate the evaporation residue cross section correctly, we investigated the parameter dependence of the model calculation, and we tried to reduce the uncertainty of the models. In the previous study, we focus our attention on the parameters of the statistical model [5].

Here, we chose the parameter sets to reproduce the experimental data in the reactions $^{48}$Ca + $^{244}$Pu and $^{48}$Ca + $^{248}$Cm. Using these parameter sets, we estimate the evaporation residue cross section for unknown nuclei, $Z = 119$ and 120 with $^{50}$Ti, $^{51}$V and $^{54}$Cr projectiles, and discuss the possibility to produce new elements.

In Sec. 2, we describe in detail the framework of the model. We discuss the uncertainty of parameters in the models in Sec. 3. In Sec. 4, we present the the evaporation residue cross section for $Z = 119$ and 120 nuclei. Finally, we mention the future work.

## 2. Estimation of evaporation residue cross section

To estimate the evaporation residue cross section, the whole fusion-fission process is divided into the three stages depend on the reaction time scale $t$. The first stage is the approaching process and the capture probability is denoted by $T_l$. The second stage corresponds to the competition between the fusion and quasi-fission processes and the formation probability of forming a compound nucleus in competition with quasi-fission events is denoted by $P_{CN}$ The decay process of the compound process is presented as the third stage and the survival probability of compound nuclei during de-excitation is denoted by $W_{sur}$.

Using these probabilities, the evaporation residue cross section $\sigma_{EV}$ is estimated as

$$\sigma_{EV} = \frac{\pi\hbar^2}{2\mu_0 E_{c.m.}} \sum_{l=0}^{\infty} (2l+1) T_l(E_{CM}, l) P_{CN}(E^*, l) W_{sur}(E^*, l), \tag{1}$$

where $\mu_0$ denotes the reduced mass in the entrance channel. $E_{CM}$ and $E^*$ denote the incident energy in the center-of-mass frame and the excitation energy of the compound nucleus, respectively. $E^*$ is given as $E^* = E_{CM} - Q$ with $Q$ denoting the $Q$-value of the reaction. $T_l(E_{cm}, l)$ is the capture probability of the $l$-th partial wave, which is calculated with the coupled channel model [6]. To estimate $P_{CN}(E^*, l)$, we use the dynamical model and employ the Langevin equation [7, 8]. $W_{sur}(E^*, l)$ is calculated using a statistical model [9, 10].

## 3. Uncertainty of parameters in the theoretical models

To estimate the evaporation residue cross section, many theoretical models have been developed and applied. The results show rather good agreement with the experimental data. However, for the synthesis of unknown elements, $Z = 119, 120$ etc, the predictions by each model are quite different [4]. Moreover, though the values of the product $P_{CN}W_{sur}$ are the same in most of these predictions, the values of $P_{CN}$ or $W_{sur}$ are different among these models [4].

Inevitably, a substantial uncertainty is involved in each stage. In the first stage, there are few parameters in the coupled channel model. The parameters of the potential (potential depth, diffuseness) and the coupling scheme are not clear for unknown nuclei. In the second stage, the Langevin calculation includes parameters: potential energy (parameters of liquid drop model and shell correction energy), nuclear shape parametrization and the number of the dynamical variables (shape parameters), the transport coefficients (using the macroscopic or microscopic models). The definition of the fusion region is also unclear. In the third stage, the statistical model includes the uncertainty of the fission barrier hight of the compound nucleus, the friction parameter, the level density parameter ($a_f/a_n$), etc. [9, 10]. Moreover, the reaction $Q$-value has also an uncertainty, because the masses of superheavy nuclei are not determined experimentally yet. In order to estimate the evaporation residue cross section correctly, we have to know the parameter dependence of the evaporation residue cross section within the model calculation.

We discussed these uncertainties in the reference [5], especially the parameter dependence of the statistical model in the third stage. The survival probability was calculated by the statistical code `MASADEC`, which was developed by M. Ohta [10] based on the idea in the reference [9]. In the code, the unknown parameters were represented by `ADDS` (the uncertainty of the fission barrier height of the compound nucleus), `FRIC` (the friction parameter), and `fact` (the level density parameter $a_f/a_n$). The values of these parameters were defined in the reference [5].

## 4. Results

### *4.1 Evaporation residue cross section for Fl and Lv*

Under the parameter dependence in the survival probability [5], we obtain the evaporation residue cross section. Figure 1(a) and (b) show the evaporation residue cross section for the reaction $^{48}$Ca + $^{244}$Pu and $^{48}$Ca + $^{248}$Cm, respectively. In this case, we use `ADDS`=1.6, `FRIC`=20.0, and `fact`=1.02. In figures, the capture cross section, fusion cross section and the survival probability are also presented. The maximum values are about $1 \sim 10$ pb at $E^* \sim 30$ MeV, which corresponds to the experimental

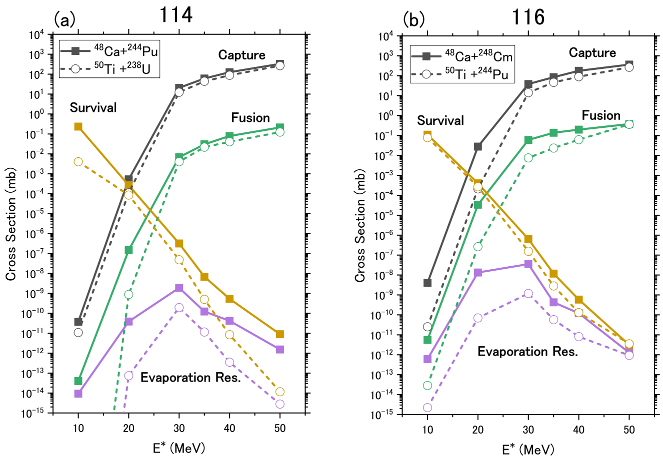


**Fig. 1.** Evaporation residue cross section for (a) Fl in the reactions $^{48}$Ca+$^{244}$Pu and $^{50}$Ti+$^{238}$U, (b) Lv in the reactions $^{48}$Ca+$^{248}$Cm and $^{50}$Ti+$^{244}$Pu. The capture cross section, fusion cross section and survival probability are presented

values [1]. Recently the experiments are performed with $^{50}$Ti projectile instead of $^{48}$Ca projectile to produce more than $Z$ = 118 elements, because the $^{249}$Cf target is available as the heaviest target in the experiment. We calculate the evaporation residue cross section for Fl and Lv using $^{50}$Ti projectiles, in Fig. 1(a) and (b). Due to the larger Coulomb repulsion in the reaction with $^{50}$Ti than that with $^{48}$Ca, the fusion cross section would be smaller. Also, the neutron number of the compound nucleus produced by $^{50}$Ti projectile is smaller than that by $^{48}$Ca projectile, and the survival probability is smaller due to the low fission barrier height and the slow cooling by neutron emissions.

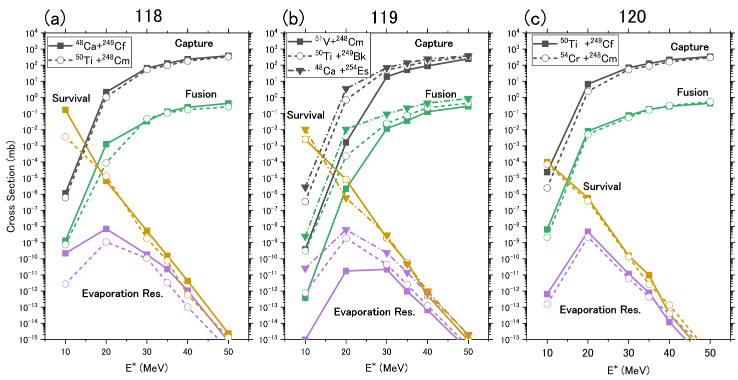


**Fig. 2.** Evaporation residue cross section for (a) Og in the reactions $^{48}$Ca+$^{249}$Cf and $^{50}$Ti+$^{248}$Cm, (b) $Z$ = 119 in the reactions $^{51}$V+$^{248}$Cm, $^{50}$Ti+$^{249}$Bk and $^{48}$Ca+$^{254}$Es and (c) $Z$ = 120 in the reactions $^{50}$Ti+$^{249}$Cf and $^{54}$Ca+$^{248}$Cm. The capture cross section, fusion cross section and survival probability are presented.

*4.2 Evaporation residue cross section for Og, $Z = 119$ and $Z = 120$ nuclei*

Using the same parameters, we calculate the evaporation residue cross section for Og, $Z = 119$ and $Z = 120$ nuclei. The cross sections for Og in the reaction $^{48}$Ca+$^{249}$Cf and $^{50}$Ti+$^{248}$Cm are shown in Fig. 2(a). Figure 2(b) and (c) show the cross sections for $Z = 119$ in the reactions $^{51}$V+$^{248}$Cm, $^{50}$Ti+$^{249}$Bk and $^{48}$Ca+$^{254}$Es, and for $Z = 120$ in the reactions $^{50}$Ti+$^{249}$Cf and $^{54}$Ca+$^{248}$Cm. To produce $Z = 119$, $^{48}$Ca projectile has a large advantage for capture and fusion probability, due to the small Coulomb repulsion. The survival probabilities of these three systems are almost the same. We can say that the more asymmetric combinations are better to obtain the large evaporation residue cross section.

In these calculations, the optimum excitation energies are about 20 MeV. It causes the evaluation of the capture cross section $T_l(E_{cm})$ as discussed in section 3. To calculate the fusion cross section $P_{CN}(E^*, l)$, we have to convert $E_{cm}$ into $E^*$ with the reaction $Q$-value, which includes the mass of superheavy nuclei. Moreover, the Coulomb barriers in these systems are not clear, especially the energy at the barrier top. In this case, the capture cross section will shift in Fig. 2 and the optimum values of excitation energy will change. It is one of the uncertainties of our model.

The estimations of evaporation residue cross section by Zagrebaev et. al were about 25 ∼ 50 fb around $E^* = 40 \sim 45$ MeV for $^{50}$Ti+$^{249}$Bk and $^{50}$Ti+$^{249}$Cf [11]. On the other hands, our estimations are about 1 ∼ 10 pb around $E^* = 20$ MeV. We suggest performing the $2n$ reactions to produce $Z = 119$ and 120 elements, but it strongly depends on the estimation of the capture cross section, especially the energy dependence.

Though they are a rough estimation, it is very important to discuss these results. For the future work, using the more accurate mathematical methods, for example, the covariance function, we try to predict the possibility of synthesis of new elements more accurately.

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