Dynamical Approach for Synthesis of Superheavy Elements: Fusion Mechanism and Nuclear Structure

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To synthesis of superheavy elements, the shell structure is very important not only in the stability of nuclei, but also the fusion process, especially the cold fusion reaction. We employ the Langevin equation with the microscopic transport coefficients and calculate the fusion cross section for the reaction ^{70}Zn+^{208}Pb $\rightarrow$ ^{278}Cn. In the dynamical process, the effect of nuclear structure is discussed.

Keywords: superheavy elements, langevin equation, nuclear structure.

Introduction

More than 50 years ago, the existence of the Island of Stability in the nuclear chart surrounding the doubly magic superheavy nucleus containing 114 protons and 184 neutrons was predicted [1, 2]. To produce heavier elements with $Z \geq 114$, the cross sections by the cold fusion reaction would be extremely small and hot fusion reactions would have to be used. However, to produce new elements beyond Z =118 and approach to the Island of Stability, we need new idea in the experiments. It is well known that the stability and the decay properties of superheavy nuclei strongly depends on the shell structure. Moreover, it was pointed out that this shell structure also dramatically affects the fusion process [3-8]. Here, we try to clarify the mechanism of the dynamical process and take

advantage of the shell structure in fusion process to synthesize elements beyond $Z = 118$.

According to the macroscopic-microscopic model, the single-particle level diagram for the reaction ^{70}Zn$+$ ^{208}Pb $\rightarrow$ ^{278}Cn was calculated in [7, 8], and it showed that the magic-fragment gap combination 28+82=110 remains far inside the touching point. The original fragment cluster or shell structure is presented during most of the fusion process. In this case, the kinetic energy in the entrance channel does not dissipate into internal energy, and finally the fusion cross section is enhanced. Moreover, in the cold fusion reaction, due to the shell effect, there are so-called cold fusion valley, which leads to fusion. It is expected that the nuclear friction would be small along the valley, too [7, 8]. To describe such aspects, the dynamical studies with "microscopic dissipation model" should be required.

Here, as the microscopic dissipation model, we employ the Langevin equation with the microscopic transport coefficients, friction and mass tensors, which are originated from the single particle levels of the nucleus. The transport coefficients are calculated by the linear response theory [9-11]. We estimate the fusion probability in cold fusion reaction and investigate the effect of it. The dissipative mechanism during the fusion process is discussed.

The paper is organized as follows. In Section 2, we detail the framework of the model. In Section 3, we show the results for fusion cross section by dynamical model. In Section 4, we present a summary of this study and further discussion.

Model

We use the fluctuation-dissipation model and employ Langevin equations [12] to investigate the dynamics of the fusion process. Here, we explain the model, which is generally used.

The nuclear shape is defined by the two-center parametrization [13, 14], which has three deformation parameters, z_0, δ, and α to serve as collective coordinates: z_0 is the distance between two potential centers, while $\alpha = (A_1 - A_2)/(A_1 + A_2)$ is the mass asymmetry of the two fragments, where A_1 and A_2 denote the mass numbers of heavy and light fragments. The symbol δ denotes the deformation of the fragments. The detail of the definition is explained in [10]. We assume in this work that each fragment has the same deformation. In order to reduce the computational time, we employ the coordinate z defined as $z = z_0/(R_{CN}B)$, where R_{CN} denotes the radius of a spherical compound nucleus and B is defined as $B = (3+\delta)/(3-2\delta)$. We use the neck parameter $\epsilon = 1.0$ in fusion process. The three collective coordinates may be abbreviated as q, $q = \{z, \delta, \alpha\}$. The potential energy is defined as a sum of the liquid-drop part V_{LD} and a microscopic part E^0_{shell} [12].

The multidimensional Langevin equations [12] are given as

$$\frac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j,$$

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}\left(m^{-1}\right)_{jk} p_j p_k - \gamma_{ij}\left(m^{-1}\right)_{jk} p_k + g_{ij}R_j(t), \qquad (1)$$

where $i = \{z, \delta, \alpha\}$ and $p_i = m_{ij}dq_j/dt$ is a momentum conjugate to coordinate q_i. The summation is performed over repeated indices. In the Langevin equation, m_{ij} and γ_{ij} are the shape-dependent collective inertia and the friction tensors, respectively, which are called as the transport coefficient. Generally, the wall-and-window one-body dissipation is adopted for the friction tensor [15]. A hydrodynamical inertia tensor is adopted with the Werner-Wheeler approximation for the velocity field [16]. So, in the dynamical model, these the macroscopic transport coefficients have been used generally.

The normalized random force $R_i(t)$ is assumed to be that of white noise, *i.e.*, $\langle R_i(t)\rangle = 0$ and $\langle R_i(t_1)R_j(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$. The strength of the random force g_{ij} is given by Einstein relation $\gamma_{ij}T = \sum_k g_{ij}g_{jk}$. T is the nuclear temperature. The fusion events are determined in our model calculation by identifying the different trajectories in the deformation space.

The approaching phase of heavy-ion collisions is described with the coupled-channels model. After the nuclear contact point, we switch to the dynamical calculation with the Langevin type equation starting at the touching point assuming a nose-to-nose configuration with full kinetic energy [17].
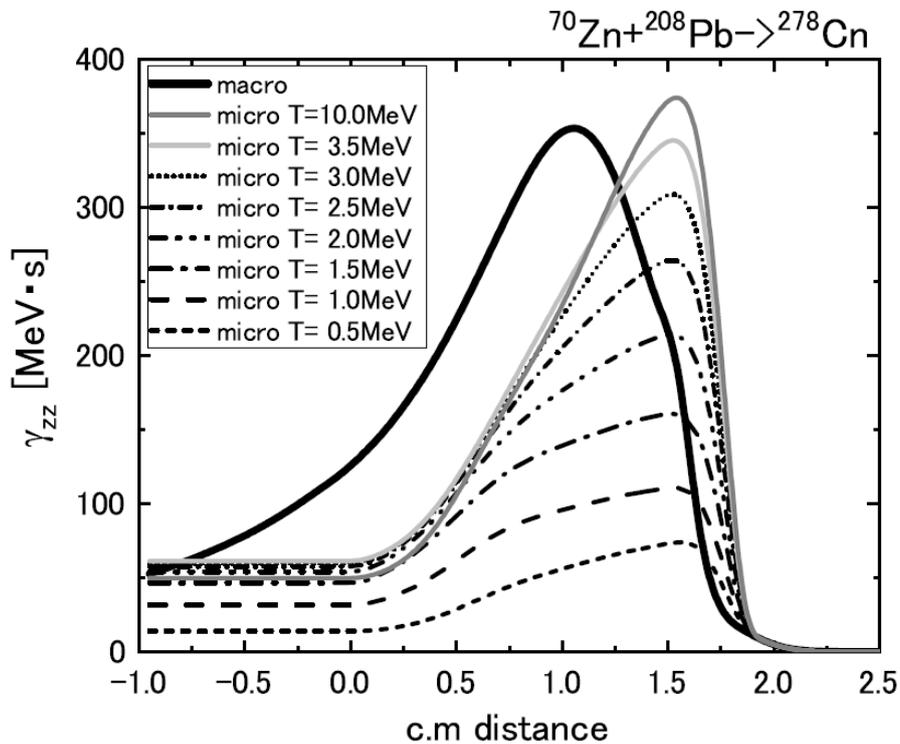

Figure 1. Friction tensors γ_{zz} calculated by the liner response theory for ^{278}Cn, depend on the nuclear temperature T. The black-solid line denotes the friction tensor calculated by macroscopic model.

Fusion probability using microscopic transport coefficients

To calculate the fusion probability, we have used the macroscopic transport coefficients, which do not take into account the nuclear structures. As mentioned in the introduction, to treat cold fusion reaction, we need to introduce the microscopic transport coefficients. It is well-known that the microscopic transport coefficients are calculated by the linear response theory [9-11]. The transport coefficients depend on the nuclear temperature and the friction is smaller than the one-body friction (macroscopic model) at the low temperature.

We try to use the microscopic transport coefficients in the Langevin calculation. More than 20 year ago, such dynamical model has been applied to fission process of ^{216}Th with the Cassini ovaloids [18], and recently it was applied to fission process of ^{236}U, ^{240}Pu etc. at the low excitation energy [19, 20]. Here, to investigate the advantage of nuclear structure in fusion process along the cold fusion valley at the low excitation energy, and clarify the dissipative mechanism to convert from the kinetic energy into the intrinsic energy, we apply the model to the cold fusion reaction.

Figure 1 shows the friction tensor γ_{zz} calculated by the liner response theory for ^{278}Cn, depend on the nuclear temperature T [9-11]. The black-solid line denotes the values of γ_{zz} calculated by the macroscopic model. In the cold fusion reaction, the excitation energy of compound nuclei is about $10 \sim 15$ MeV, which corresponds to about $T \sim 0.5$ MeV. We can see that the magnitude of the microscopic friction tensor is smaller than the macroscopic one at the low temperature.

We calculate the fusion cross section in the reaction ^{70}Zn$+^{208}$Pb $\rightarrow$ ^{278}Cn at the low excitation energy. To save a calculation time, we employ the assumption that the deformation of both fragments is the same. In this calculation, ^{70}Zn$+^{208}$Pb, we start the calculation as deformation parameter $\delta = 0.0$, which corresponds to $\beta_2 = 0.0$ deformation [21]. During fusion process, the shell structure of ^{208}Pb strongly remains till the compact shape [7, 8]. So, it seems that the deformation of colliding partner of Pb strongly influences during fusion process and keeps the spherical shape. According to the mass table [22], the deformation in the ground state of ^{70}Zn and ^{208}Pb are $\beta_2 =0.045$ and 0.000, respectively. Therefore, this assumption is not so much crude in cold fusion reaction case.

The fusion cross sections with the macroscopic transport coefficients and microscopic transport coefficients with $T = 0.5$ MeV are denoted by the solid and the dashed lines in Figure 2, respectively. Here, for simplicity, we use the microscopic transport coefficients with $T = 0.5$ MeV everywhere, though the temperature should be changed at each point. It is valid only at low excitation energy region $E^* \sim 10 - 20$ MeV. On the other hand, the fusion cross section with the microscopic transport coefficients in $T = 1.5$ MeV case is denoted by the dashed-dot line in Figure 2. It approaches to the results with the microscopic transport coefficients.

We obtain that the fusion cross section with the microscopic transport coeffi-
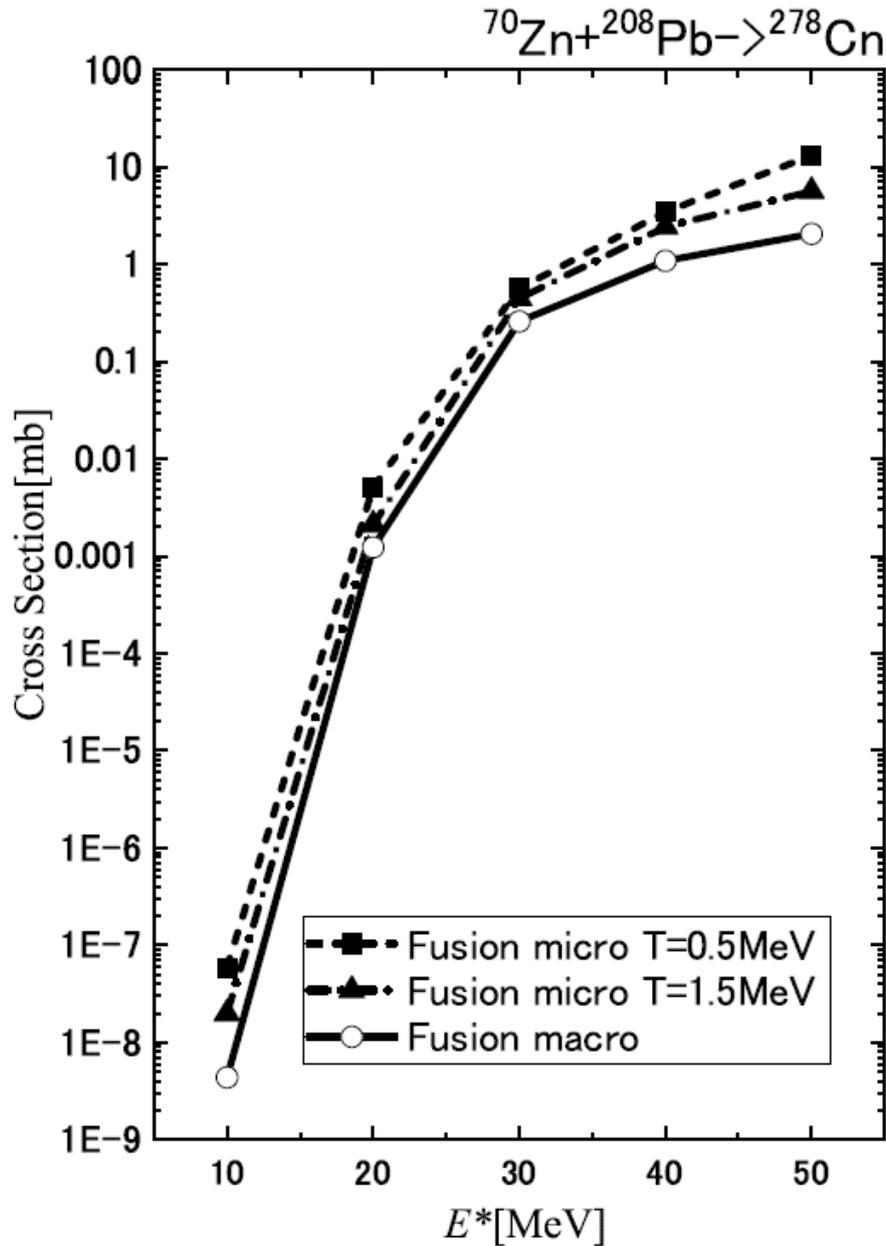
Figure 2. Calculated fusion cross section in the reaction ^{70}Zn+ ^{208}Pb $\rightarrow$ ^{278}Cn, with the macroscopic and microscopic transport coefficients with $T = 0.5$ and 1.5 MeV, which are denoted by the solid, dashed, and dashed-dot lines, respectively.

cients in $T = 0.5$ MeV is enhanced by one order of magnitude, in comparison with the case using the macroscopic transport coefficients. It is clearly shown the shell effects in the fusion process.

Figure 3 shows the time evolution of the kinetic energy in the reaction ^{70}Zn+ ^{208}Pb $\rightarrow$ ^{278}Cn. The black and the gray lines denote the results of the sample trajectories with the microscopic transport coefficients with $T = 0.5$ MeV and macroscopic one, respectively, with the same seed of the random numbers. Because of the smaller values of the microscopic friction tensor, the dissipative speed is slower than that in the macroscopic case. We can see that the dynamics of fusion process in $t \leq 1.5 \times 10^{-21}$ s is very important. The fusion probability is affected significantly till this time.

In this paper, we discussed the nuclear structure effects during fusion process within the dynamical model. At low temperatures, as other quantum effects, the importance of the memory effect (Markovian process) was pointed out in [23]. In the next step, we have to take into account the effect, too.
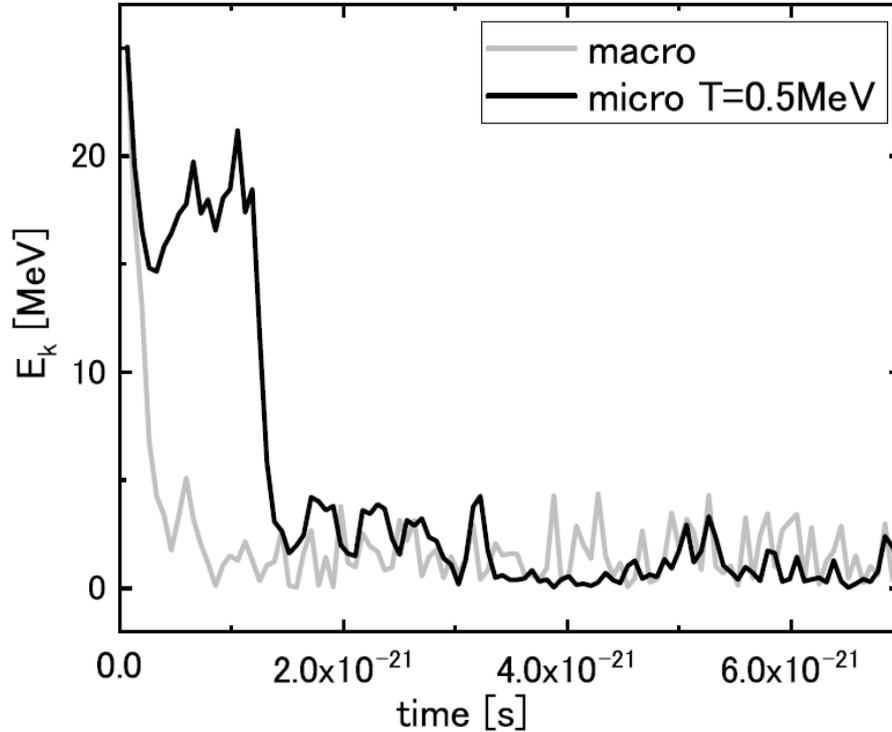

Figure 3. Time evolution of the kinetic energy in the reaction ^{70}Zn+^{208}Pb $\rightarrow$ ^{278}Cn. The black and the gray lines denote the results of the sample trajectories with the microscopic transport coefficients with $T = 0.5$ MeV and macroscopic one, respectively, with the same seed of the random numbers.

Conclusion

In this study, we investigate the effect of nuclear structure in the cold fusion reaction using the dynamical model. In Langevin equations, instead of the macroscopic transport coefficients, the microscopic one is introduced. The fusion cross section ^{70}Zn+^{208}Pb $\rightarrow$ ^{278}Cn is enhanced by one order of magnitude at the low excitation energy, in comparison with the case using the macroscopic transport coefficients. In the future, we plan to calculate the evaporation residue cross section in cold fusion reaction and compare with the experimental data.

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