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Theoretical estimation of synthesizing superheavy nuclei using neutron rich targets

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Abstract. The next double magic nucleus after the double magic nucleus lead (^{208}Pb) proton number Z=82 and neutron number N=126 is predicted to be flerovium ^{298}Fl, Z=114 and N=184, and "Island of Stability" around this nucleus is predicted in the nuclear chart. In the synthesis of new elements, it was assumed that the projectile and target nuclei used in the experiments would be stable nuclei. In particular, it was experimentally impossible to use unstable nuclei as target nuclei. Therefore, it was considered difficult to synthesize nuclei on Island of Stability because of the insufficient number of neutrons when it came to fusion between stable nuclei. To approaching Island of Stability, it is necessary to use unstable nuclei with an excess of neutrons. However, until now there has been no method to achieve this. Recently, a new method of colliding unstable nuclei has been planned. It has also been reported that neutron-rich nuclei in the superheavy mass region have lower neutron binding energy than stable nuclei and lower temperature due to neutron emission more quickly, resulting in a high survival probability even at medium and high excitation energies. The goal of this study is to create and analyze neutron emission and mass distribution of fission fragments in the superheavy mass region using the statistical and the dynamical model. In addition, we present the results of calculations using neutron-rich nuclei.

1 Introduction and Background

The next double magic nucleus after the double magic nucleus lead (^{208}Pb) proton number Z=82 and neutron number N=126 is predicted to be flerovium ^{298}Fl, Z=114 and N=184, and "Island of Stability" around this nucleus is predicted in the nuclear chart [1]. In the synthesis of new elements, it was assumed that the projectile and target nuclei used in the experiments would be stable nuclei. In particular, it was experimentally impossible to use unstable nuclei as target nuclei. Therefore, it was considered difficult to synthesize nuclei on Island of Stability because of the insufficient number of neutrons when it came to fusion between stable nuclei. To approaching Island of Stability, it is necessary to use unstable nuclei with an excess of neutrons. However, until now there has been no method to achieve this. Recently, a new method of colliding unstable nuclei has been planned [2]. It has also been reported that neutron-rich nuclei in the superheavy mass region have lower neutron binding energy than stable nuclei and lower temperature due to neutron emission more quickly, resulting in a high survival probability even at medium and high excitation energies [3].

The goal of this study is to create and analyze neutron emission and mass distribution of fission fragments in the superheavy mass region using the statistical and the dynamical model. In addition, we present the results of calculations using neutron-rich nuclei.

2 Theory and Method

There are several ways to parameterize the shape of the amalgamated system. This two-center parameterization [4] is based on three important parameters are: the distance between two centers z, the mass-asymmetry parameter α, and the neck parameter ε. The dimensionless parameter z is defined as follows,

$$z = \frac{z_0}{BR_{CN}} \qquad (1)$$

where z_o denotes the distance between two centers of the potentials, and R_{CN} is the radius of the spherical compound nucleus. B define as $B = (3+\delta)/(3-2\delta)$.

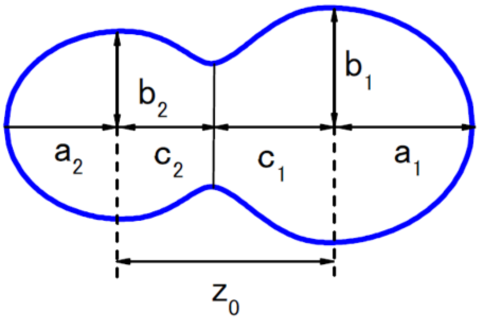

Fig. 1 Nuclear shape the two-center parametrization.

The mass-asymmetry parameter is defined as usual,

$$\alpha = \frac{A_1 - A_2}{A_1 + A_2} \qquad (2)$$

The Langevin equation uses potential energy, friction coefficient, and mass of inertia to derive the probability P_{CN}. When the Langevin equation is solved for a large number of trajectories from the coordinates of the contact point, the majority of trajectories go straight down the potential slope to quasi-fission. However, a very small number of trajectories overcome the potential barrier due to fluctuations caused by random forces and reach the compound nuclear region. The probability of not causing quasi-fission, P_{CN} , can be estimated by solving the Langevin equation many times and calculating what percentage of all trajectories will reach the fusion region. In this study, the multidimensional Langevin equation is used [5].

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$$\frac{dq_i}{dt} = (m^{-1})_{ij}p_j, \qquad \frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}(m^{-1})_{jk}p_j p_k - \gamma_{ij}(m^{-1})_{jk}p_k + g_{ij}R_j(t), \quad (3)$$

where q_i is deformation coordinate and p_i is momentum of q_i . V is also the potential, and m_{ij} and γ_{ij} are the inertial mass and friction coefficient, R(t) represents a random force fluctuation, and g_{ij} is the strength of the random force. The shape of the nucleus (q_i) was determined by the two-center parameterization using three variables: z_0, which corresponds to the distance between the centers of distance; δ, the degree of deformation of the left and right fragments; and α, the degree of mass asymmetry.

The third stage is a decay process. In this stage, it is important to know the survival probability P_{sur} and it can be calculated by statistical model [6],

$$P_{sur} = \prod_{i=1}^{N} \frac{\Gamma_n^{(i)}}{\Gamma_n^{(i)} + \Gamma_f^{(i)}}. \qquad (4)$$

Γ_n and Γ_f are neutron evaporation width and fission decay width, respectively. From all the probabilities in these 3 stages, we obtain the evaporation residue cross sections σ_{ER}

$$\sigma_{ER} = \frac{\pi\hbar^2}{2\mu_0 E_{cm}} \sum_{l=0}^{\infty}(2l+1)$$

$$\times\, T_l(E_{cm}, l) P_{CN}(E^*, l) P_{suv}(E^*, l). \qquad (5)$$

E_{cm} and E^* denote to the incident energy and excitation energy while μ_0 and l are reduced mass in the entrance channel and angular momentum, respectively.

To calculate σ_{ER} , there are some uncertain parameters in the model in each stage. Here, we focus on the uncertainty in the third stage. In Eq. (4) to obtain the survival probability [6], Γ_n/Γ_f is calculated as follows,

$$\frac{\Gamma_n}{\Gamma_f} = \frac{k_{coll}(gr.st.)}{k_{coll}(saddle)\cdot k_{kramers}} \times A_0 exp\left[2\sqrt{a_n E_n^*} - 2\sqrt{a_f E_f^*}\right]$$

$$E_n^* = E_{int} - B_n \quad , \quad E_f^* = E_{int} - B_f$$

$$k_{kramers} = \frac{\hbar\omega_1}{\sqrt{E_{int}}}\left(\sqrt{1+x^2} - x\right)$$

$$x \equiv \gamma/2\,\omega_1 \qquad (6).$$

$$k_{coll}(\beta_2) = \frac{T}{\hbar^2}J \equiv \sigma_\perp^2$$

$$J = J_0\left[1 + \sqrt{\frac{5}{16\pi}}\beta_2 + \frac{45}{28\pi}\beta_2^2\right]$$

$$J_0 = \frac{2}{5}AmR_{cn}^2$$

$$k_{coll}(\beta_2, E_{int}^*) = (\sigma_\perp^2 - 1)g(\beta_2) + 1 \text{ for } \sigma_\perp^2 > 1$$

$$g(\beta_2) = [1 + \exp((0.15 - \beta_2/\Delta\beta_2)]^{-1} \quad (7)$$

Here, B_n is neutron separation energy. The uncertain parameters include fission barrier height δB_f, friction parameter γ, level density parameters for neutron emission a_n and level density parameter for fission barrier at saddle point a_f in Eq. (6). In the superheavy mass region, it is no determined which values to be used. We need to know the parameter dependence of the survival probability and to see how these uncertainties influence the survival probability and evaporation residue cross section. The collective enhancement factor k_{coll} can be expressed as a function of the quadrupole deformation parameter β_2.

3 Result and Discussion

Therefore, a mass table is used. Although many mass tables exist, we have adopted Moller's mass table in our calculations [7]. ^{48}Ca+^{238}U survival probabilities and evaporation residue cross sections calculated using Moller's mass table Fig.2 shows the survival probability and evaporation residue cross section of ^{48}Ca+^{238}U calculated using the Moller mass table. This result shows that the survival probability of ^{48}Ca+^{238}U monotonically increases in the excitation energy range above 20 MeV, the evaporation residue cross sections also increase monotonically in the range of excitation energies above 20 MeV.

We investigated the cause of such calculation results. Moller's mass table shows that in the neutron-rich region, a single change in the neutron number causes an inversion of the in Moller's mass table, a reversal of the positions of the ground state and the second pocket can occur. The reason for this is that in Moller's mass table, a reversal of the positions of the ground state and the second pocket can occur with only one change in the neutron number in the neutron-rich region. The deformation degree of the ground state on the mass table changes drastically. As a result, the equation (6) $k_{coll}(gr.st.)$ increases while $k_{coll}(saddle)$ remains constant, resulting in an abnormally large survival probability. Moller's table shows such a tendency, for example, Z =112, N=194-195. This is thought to be the cause of the abnormal value in the calculation of the survival probability. To remedy this

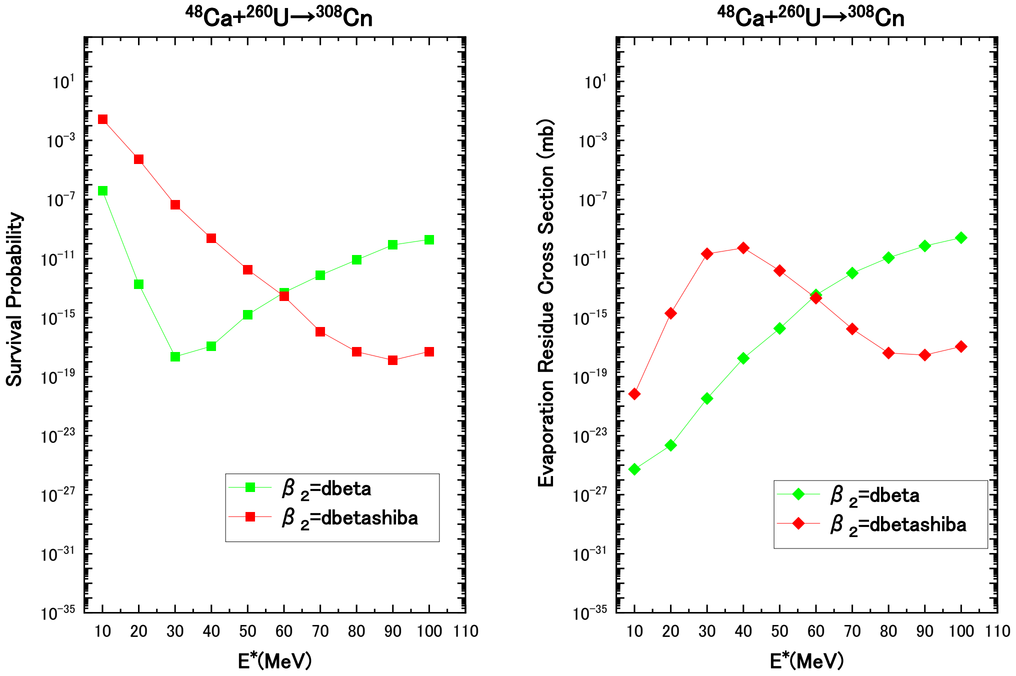

Fig. 2 The evaporation residue cross section and survival probability for ^{48}Ca+^{260}U→^{308}Cn by shiba.dat (dbetashiba is shiba.dat)

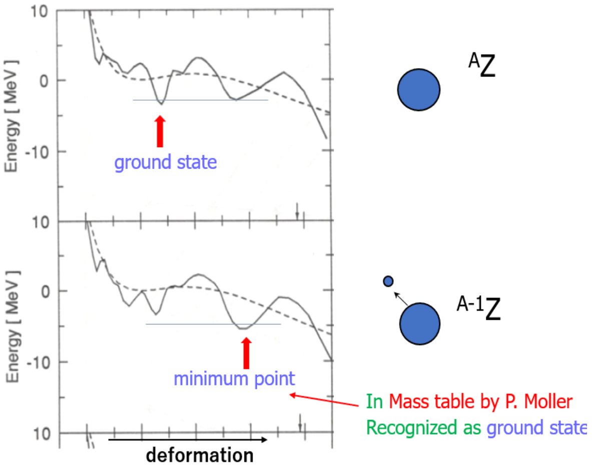

Fig.3 Ground state and minimum point

problem, a potential diagram of the deformation space was created, the ground state was visually confirmed from the diagram, the position of the ground state *(β_2)* was checked for continuity, and the mass table was modified (Figs 3 and 4). As a result, in the new mass table (new mass table is named shiba.dat), the sharp increase in the neutron-rich region with respect to β_2 was eliminated and continuity was maintained.

Fig.2 shows that in the mass table before modification, the survival probability increases as the excitation energy increases. However, after the modification, the monotonicity decrease problem was improved. The evaporation residue cross section also increased monotonically with excitation energy before the modification. But after the modification, it decreased at higher excitation energies.

We changed the upper limit of neutron emission from 10 times to 20 times in our calculations.

Next, ^{286}Cn, we fixed at neutron separation energy (sep1=4.87) and β_2 was varied in Fig.5.

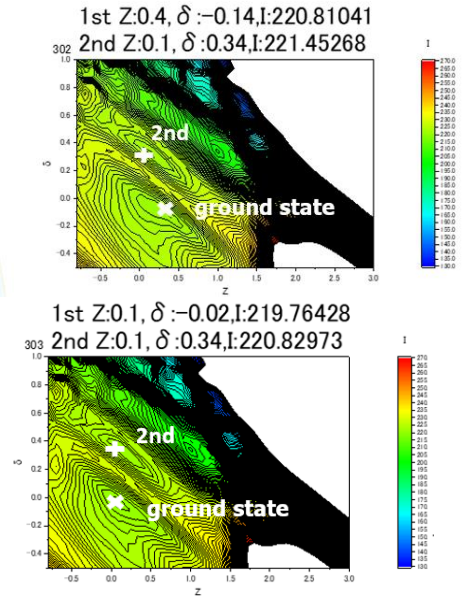

Fig.4 Two-center shell model

β_2= +22 is the result of calculating ^{286}Cn to match ^{308}Cn. The results confirm the improvement in survival probability. For fixed β_2= 0.22, the survival probability was found to be abnormal. When fixed to β_2= 0, the survival probability showed improvement. When β_2 of collective enhancement is fixed at β_2 =0.22 and β_2 = 0, the survival probability is confirmed to be abnormal. Four results indicate the possible impact of collective enhancement.

Our code used Moller's mass table, but a problem was identified with neutron-rich nuclei, so we modified the mass table to improve the survival probability and evaporation residue cross section. To evaluate the survival probability of unknown neutron-rich nuclei, it is necessary to understand the scope of application and improve the existing models rather than applying them as they are.

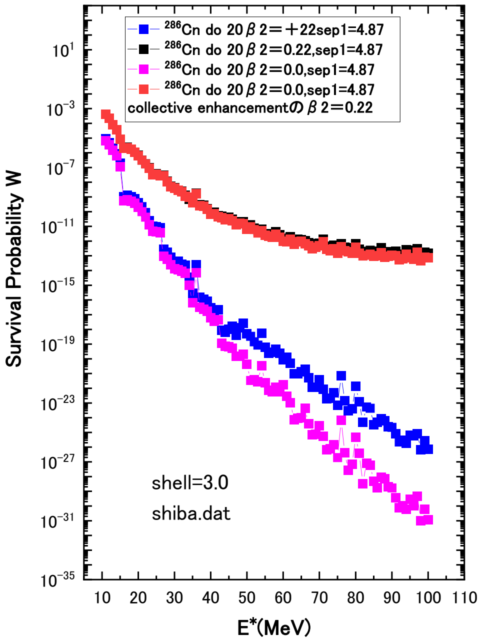

Fig.5 The calculation results of survival probability for ^{48}Ca+^{238}U→^{286}Cn (^{286}Cn do 20 means 20 times the upper limit of the number of neutrons in ^{286}Cn.)

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