Fusion Mechanism in Superheavy Mass Region

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The fusion-fission process for synthesis of superheavy elements is studied on the basis of the fluctuation-dissipation dynamics. Recently at Dubna the experiments on the fission of superheavy nuclei were carried out and they presented the fusion-fission cross section. We calculated the fusion-fission cross section of these systems and compared with these experimental data.

The productions of superheavy elements $Z = 114$ and $Z = 116$ were announced by Dubna group.[1] Also at Dubna the experiments on the fission of superheavy nuclei in the reactions ^{48}Ca + ^{208}Pb, ^{48}Ca + ^{238}U, ^{48}Ca + ^{244}Pu, ^{48}Ca + ^{248}Cm, and ^{58}Fe + ^{248}Cm were carried out.[2] The mass and the total kinetic energy distributions of fission fragments of these reactions were measured. In this paper, we focus on the fusion-fission process and try to reproduce the experimental data by using a fluctuation-dissipation model taking into account the competition between the fusion and quasi-fission. We estimate the fusion-fission cross section $\sigma_{\rm CN}$ as

$$\sigma_{\rm CN} = \frac{\pi\hbar^2}{2\mu_0 E_{\rm cm}} \sum_{l=0}^{\infty} (2l+1) T_l P_{\rm CN} \,, \tag{1}$$

where μ_0 denotes the reduced mass in the entrance channel and $E_{\rm cm}$ denotes the incident energy in center-of-mass frame. T_l is the barrier penetration coefficient of the lth partial wave through the potential barrier. T_l is calculated with parabolic approximation of the combined Coulomb potential and proximity potential. $P_{\rm CN}$ is the probability of forming a compound nucleus in the competition with quasi-fission.

In this work, we employ the Langevin equation.[3] We adopt the three-dimensional nuclear deformation space with the two-center parametrization. As the three collective parameters to be described by the Langevin equation, we treat z_0 (distance between two potential centers), δ (deformation), and α (mass asymmetry of the colliding partner); $\alpha = (A_1 - A_2)/(A_1 + A_2)$, where A_1 and A_2 denote the mass number of target and projectile, respectively. Hydrodynamical inertia tensor is adopted with the Werner-Wheeler approximation for the velocity field, and the wall-and-window one-body dissipation is adopted for the dissipation tensor.

For the purpose of the calibration of our calculation, firstly we analyze the fusion-fission cross section for the ^{48}Ca + ^{208}Pb reaction, where we can utilize the enough data of fusion-fission cross section.[2] The calculation results of the mass distribution of the fission fragments and the excitation function of the fusion-fission cross section give a good agreement with the experimental data beyond the Bass barrier region.[4]

Next, we present the analysis of the ^{48}Ca + ^{244}Pu reaction. We assume that both shapes of the target and the projectile are spherical at touching point of the colliding system. We also take into account the temperature dependent shell correction energy for the potential energy surface.[3,4] For example, at $T = 0$, the potential energy surface in the reaction ^{48}Ca + ^{244}Pu is shown in Figure 1. $z = \delta = \alpha = 0$ corresponds to a spherical compound nucleus. The contact point in the reaction and saddle points are denoted by (+) point and (×) points, respectively. The shadow box denotes the fusion box which is defined as the inside of the fission saddle point, $\{z < 0.6,\ \delta < 0.2,\ |\alpha| < 0.25\}$. We can see

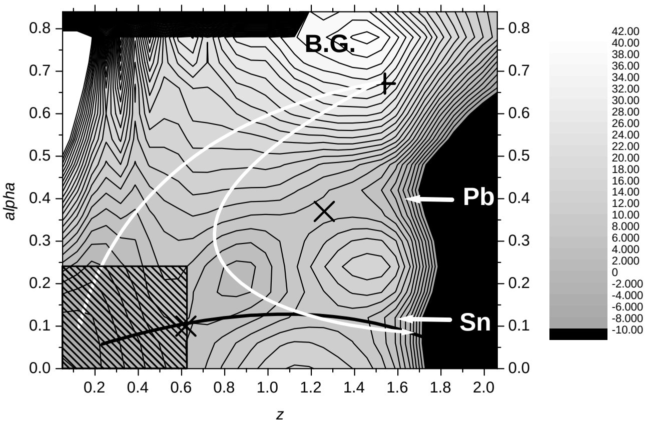

Figure 1. The potential energy surface of liquid drop model with shell correction energy in nuclear deformation space for ^{292}114. The abscissa and the ordinate denote the separation between two potential center and the mass asymmetry, respectively. Symbols are given in text. The arrows indicate the fusion and fission trajectory.

that the fission fragment of Pb and Sn corresponds to $\alpha \sim 0.4$ and $\alpha \sim 0.12$, respectively, which are indicated in Figure 1. In the calculation, the mean trajectory at $E^* = 33$ MeV goes to quasi-fission at $\alpha \sim 0.4$ passing the outer-saddle point, and the fission fragment Pb is produced. Actually, we can find such Pb fragments in the experimental data at the excitation energy.[2]

At Dubna the experiments on the fission of superheavy nuclei in the reaction ^{48}Ca + ^{244}Pu were carried out and they present the fusion-fission cross section of compound nuclei which is derived from the mass symmetric fission fragments ($A/2 \pm 20$).[2] The subsequent important question is whether all of the mass symmetric fission fragments come from the compound nuclei or

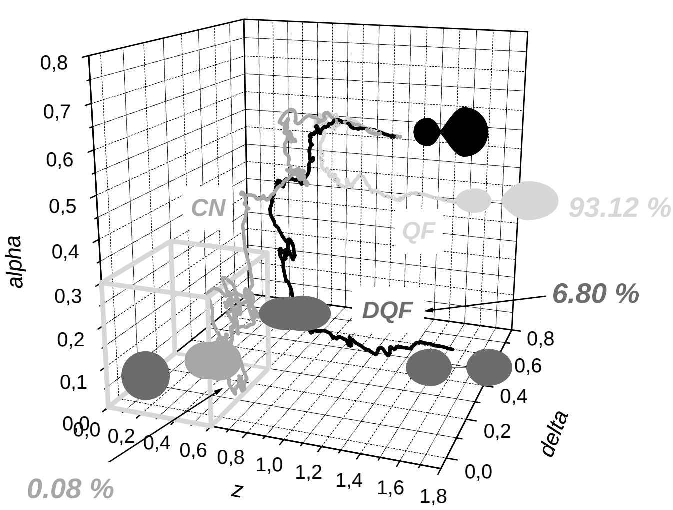

Figure 2. The samples of the trajectory in the three dimensional coordinate space at $E^* = 33$ MeV in the reaction ^{48}Ca + ^{244}Pu.

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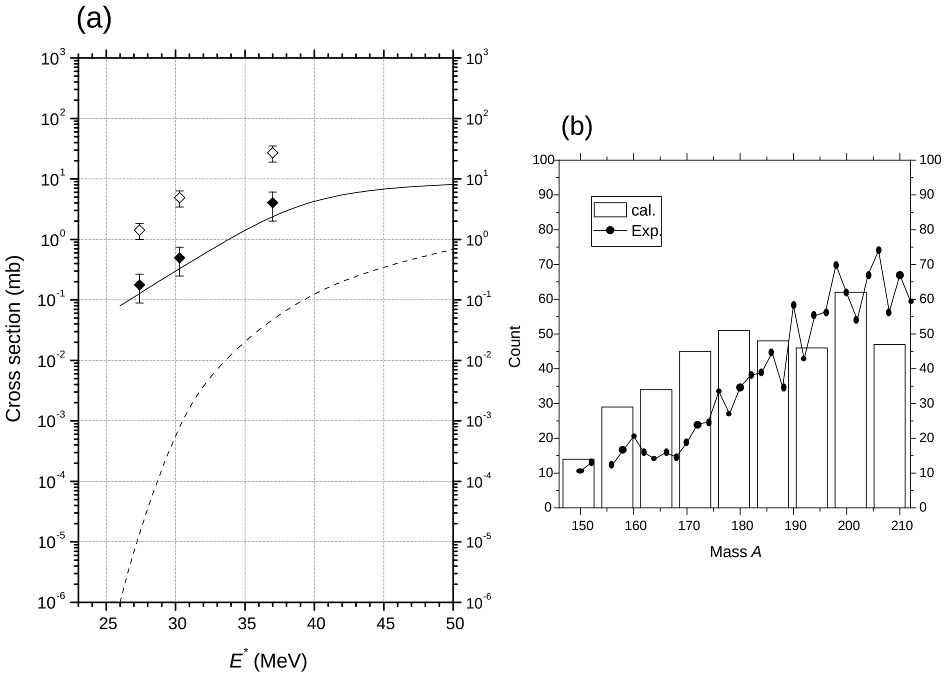

Figure 3. (a) The cross section by the calculation and the experiment in the reactions $^{48}Ca + {}^{244}Pu$. Lines and scatters are given in the text. (b) The mass distribution of the fission fragments in the reaction $^{48}Ca + {}^{244}Pu$. The calculations and experimental data are denoted by the histogram and closed circles, respectively.

not. As the final results of the experiments the mass symmetric fission fragments are detected, but there exists two possibilities where it comes from. One is that the mass symmetric fission fragments come from the compound nuclei and the other is that they come from the quasi-fission. In Figure 1, paths are presented. We try to check them by using three-dimensional trajectory calculation with Langevin equation.

Figure 2 shows the samples of the trajectory in the three dimensional coordinate space at $E^* = 33$ MeV. Nuclear shapes at each points are shown in Figure 2. The probability of mass asymmetric fission fragments occupies 93.12%, which corresponds to quasi-fission process (QF). The trajectories which go to mass symmetric fission region occupy 6.8% of all trajectories. However, almost all trajectories of mass symmetric fission process do not enter the fusion box. They go to the direction of the large deformation of fragments. We call such trajectories as *"deep quasi-fission process"* (DQF).[4] That is to say, the deep quasi-fission process contributes to the yield of the mass symmetric fission fragments.[4,5] In fact, at $E^* = 33$ MeV, only 0.08% of all trajectories can enter to the spherical region or fusion box, which is denoted by CN in Figure 2.

Figure 3(a) shows the cross section by the calculation and the experiment in the reactions $^{48}Ca + {}^{244}Pu$. The open and closed diamonds denote the capture cross section $\sigma_{\rm cap}$ and the cross section $\sigma_{A/2\pm20}$ which derived by the yield of the mass symmetric fission fragments with $A/2 \pm 20$ in the experiments, respectively.[2] The $\sigma_{A/2\pm20}$ by the calculation is denoted by the solid line. It presents very good agreement with the experimental data. The calculated fusion-fission cross section $\sigma_{\rm CN}$ is denoted by the dashed line. It is calculated by the trajectory crossing the three-dimensional fusion box mentioned above. The fusion-fission cross section $\sigma_{\rm CN}$ by the calculation is one or two order magnitude smaller than the cross section $\sigma_{A/2\pm20}$. We see that the cross section $\sigma_{A/2\pm20}$ includes the deep quasi-fission events. Such an information is very important to estimate the evaporation residue cross section.

Furthermore we try to calculate other systems, the reactions $^{48}Ca + {}^{238}U$ and $^{48}Ca + {}^{248}Cm$. Also in these case, the calculation for the cross section $\sigma_{A/2\pm20}$ agrees with experimental data well. And we can see that the calculation for the fusion-fission cross section $\sigma_{\rm CN}$ also is one or two order magnitude smaller than the cross section $\sigma_{A/2\pm20}$.[4] Figure 3(b) shows the mass distribution of the fission fragments in the reaction $^{48}Ca + {}^{244}Pu$. The calculation result shows that mass asymmetric fission fragments are dominant, which agree with the experimental data.

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References

(1) Yu. Ts. Oganessian, A. V. Yeremin, A. G. Popeko, S. L. Bogomolov, G. V. Buklanov, M. L. Chelnokov, V. I. Chepigin, B. N. Gikal, V. A. Gorshov, G. G. Gulbekian, M. G. Itkis, A. P. Kabachenko, A. Yu. Lavrentev, O. N. Malyshev, J. Rohac, R. N. Sagaidak, S. Hofmann, S. Saro, G. Giardina, and K. Morita, Nature **400**, 242 (1999); Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Labanov, F. Sh. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Yu. S. Tsyganov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukov, G. V. Buklanov, K. Subotic, M. G. Itkis, K. J. Moody, J. F. Wild, N. L. Stoyer, M. A. Stoyer, and R. W. Lougheed, Phys. Rev. Lett. **83**, 3154 (1999).

(2) M. G. Itkis, Yu. Ts. Oganessian, A. A. Bogatchev, I. M. Itkis, M. Jandel, J. Kliman, G. N. Kniajeva, N. A. Kondratiev, I. V. Korzukov, E. M. Kozulin, L. Krupa, I. V. Pokrovski, V. A. Ponomarenko, E. V. Prokhorova, A. Ya. Rusanov, V. M. Voskresenski, F. Hanappe, B. Benoit, T. Materna, N. Rowley, L. Stuttge, G. Giardina, and K. J. Moody, *Proceedings of the International Workshop on Fusion Dynamics at the Extremes*, edited by Yu. Ts. Oganessian and V. I. Zagrebaev (World Scientific, Singapore, 2001), p. 93.

(3) Y. Aritomo, T. Wada, M. Ohta, and Y. Abe, *Proceedings of the International Workshop on Fusion Dynamics at the Extremes*, edited by Yu. Ts. Oganessian and V. I. Zagrebaev (World Scientific, Singapore, 2001), p. 123.

(4) Y. Aritomo (submitted to Phys. Rev. C).

(5) V. I. Zagrebaev, Y. Aritomo, M. G. Itkis, Yu. Ts. Oganessian, and M. Ohta, Phys. Rev. C **65**, 014607 (2002).