Fusion Hindrance and Synthesis of Superheavy Elements*

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Abstract—A mechanism for fusion hindrance is clarified, based on the observation that the sticking configuration of projectile and target is located outside of the conditional saddle point. Accordingly, the fusion process is described by two sequential steps of passing over the Coulomb barrier and shape evolution toward the spherical compound nucleus. The latter one is indispensable in massive systems. With the use of a two-step model, excitation functions of fusion reaction are calculated for various combinations of projectiles and targets which lead to superheavy elements. The hindered fusion excitation measured is reproduced precisely without any adjustable parameter. Combined with survival probabilities calculated by the statistical theory of decay, excitation functions for residues of superheavy elements are calculated to compare with the systematic data measured for the cold fusion path. The peak positions and the widths are correctly reproduced, though it is necessary to reduce the shell correction energies of the compound nuclei predicted by the structure calculations in order to reproduce their absolute values. Predictions are made for a few unknown heavier elements. Furthermore, a preliminary attempt toward the shell closure \( N = 184 \) is also presented using a neutron-rich secondary beam.

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1. INTRODUCTION

Experimental efforts [1] have been devoted over several decades to syntheses of the superheavy elements whose existence is predicted by microscopic theories of nuclear structure [2] in terms of the possible existence of a doubly magic nucleus after \(^{208}\text{Pb}\) or a generalized concept of the shell correction energy [3]. Since there is no reliable reaction theory for the synthesis, experiments are based on systematics of the available data so far, taking into account reaction \( Q \) values, etc. Unexpectedly, fusion hindrance was observed and its reaction mechanism has not yet been well understood [4], although it is crucially important for the synthesis. In order to clarify the mechanism and to provide a theoretical framework for calculations of the fusion probability, the present authors et al. have recently proposed a new two-step model for the fusion of massive heavy-ion systems [5]. There, the fusion process is divided into two sequential steps, i.e., an approaching phase for passing over the Coulomb barrier and a formation phase of a spherical compound nucleus. The fusion probability \( P_{\text{fus}} \) is given by the product of a sticking probability \( P_{\text{stick}} \) for the first step and a formation probability \( P_{\text{form}} \) for the second step,

\[
P_{\text{fus}}(E_{\text{c.m.}}) = P_{\text{stick}}(E_{\text{c.m.}}) P_{\text{form}}(E_{\text{c.m.}}),
\]

where \( J \) and \( E_{\text{c.m.}} \) denote the total angular momentum of the system and the incident kinetic energy in the c.m. system.

In both phases, dissipation of the collective energy and its associated fluctuation play an essential role, as explained in the next section.

In addition to the fusion hindrance, another difficulty in the synthesis of the superheavy elements stems from the fragility of the nuclei when their stability is given solely by the so-called shell correction energy because of the absence of fission barrier in the liquid drop model (LDM) for nuclei with fissility very close to 1 [6]. Compound nuclei formed by the fusion reaction are excited, which means that the shells are more or less destroyed. Hence, the shell correction...
energies, which stabilize the nuclei, are diminished. A survival probability $P_{\text{surv}}$ of a compound nucleus against fission decay is calculated from the competition between fission decay, with a barrier depending on excitation energy, and neutron emission, which cools down the compound nucleus and restores shell correction energies. The competition is, as usual, treated by the statistical theory of decay, where absolute values of shell correction energies and their temperature dependence play a decisive role in the determination of survival probability. These factors are properly taken into account through the level density parameter in a statistical code [7]. Residue cross sections are, of course, given by the product of the fusion and the survival probabilities,

$$
\sigma_{\text{res}}(E_{\text{c.m.}}) = \pi \lambda^2 \sum_\mathbf{J} (2J + 1) P^{\mathbf{J}}_{\text{fus}}(E_{\text{c.m.}}) P^{\mathbf{J}}_{\text{surv}}(E^*),
$$

where $\lambda$ denotes the de Broglie wave length divided by $2\pi$, and the excitation energy $E^* = E_{\text{c.m.}} + Q$ shows the reaction $Q$ value.

Examples of excitation functions for residues will be given in Section 3. In Section 4, a discussion will be given on attempts to reach the $N = 184$ closed shell, using a neutron-rich secondary beam.

2. TWO-STEP MODEL OF FUSION OF MASSIVE SYSTEMS

In lighter heavy-ion systems, targets and projectiles are expected to fuse once they pass through the Coulomb barrier and contact each other. But this is not always the case in massive systems with the fissionality of the compound nuclei near 1. This is simply understood from properties of the LDM energy. Figure 1 schematically shows the LDM potential surface as a function of the elongation (distance between two mass centers in a two-center parametrization) and the mass asymmetry parameters. Since the fissionality is nearly equal to 1, the saddle point is near the spherical shape. On the other hand, the contact configuration (dinucleus configuration) with the mass symmetric entrance channel is apparently far from a spherical shape with the lower LDM energy. This means