Microscopic analysis of fusion hindrance in heavy systems

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The interplay between nuclear structures and dynamical effects is crucial for appropriate descriptions of heavy-ion fusion reactions at energies around the Coulomb barrier. Coupled-channels calculations have been widely used to quantitatively describe the entrance channel of fusion reactions in light- and medium-mass systems whose charge product (Z_1Z_2) is less than $1,600$. On the other hand, in heavy systems ($Z_1Z_2 > 1,600$), it is observed that the fusion probability is strongly hindered around the Coulomb barrier, compared with $Z_1Z_2 < 1,600$ systems and with coupled-channels results.1) This is called fusion hindrance, and the extra energy needed to make such systems to fuse is called extra-push energy.2) Quasi-fission process, where a colliding system reseparates to projectile-like and target-like fragments before forming a compound nucleus, is considered to be mostly responsible for this hindrance. For a better description of the reaction mechanism in heavy systems, a dynamical diffusion model using a macroscopic Langevin equation has been developed.3) Moreover, extra-push energies and quasi-fission process have been analyzed using the time-dependent Hartree-Fock (TDHF) model.4)

Recently, we proposed a method to extract nucleus-nucleus potential and one-body energy dissipation from the relative motion of colliding nuclei to nuclear intrinsic excitations in fusion reactions from TDHF time evolutions.5) This method relies on the hypothesis that complex microscopic mean-field evolution of head-on collisions can be accurately reduced to a simple one-dimensional macroscopic evolution that obeys a Newton equation including potential and dissipation terms. In the present report, we apply this method to study the property of potential and energy dissipation in heavy systems and to understand the origins of fusion hindrance.

Figure 1 shows nucleus–nucleus potentials V as a function of relative distance R for the $^{96}\mathrm{Zr} + {}^{124}\mathrm{Sn}$ system ($Z_1Z_2 = 2,000$) obtained with our method for three center-of-mass energies E_{cm}. As a reference, we plot by the filled circles the frozen density potential calculated from the same energy density functionals as in TDHF with the density of colliding nuclei frozen to their ground-state one, meaning that no dynamical effects are included during collision. Note that for the case with $E_{\mathrm{cm}} = 228.4\,\mathrm{MeV}$, the relative velocity $\dot{R}$ becomes almost 0 at $R \sim 11.4\,\mathrm{fm}$, and we stop the extraction of potential at this stage (indicated by the blue filled diamond in Fig. 1). By comparing the obtained potentials in Fig. 1 with those in $Z_1Z_2 < 1,600$ systems in Ref.5), we find two significant differences: (1) Energy dependence of potential, which appears around the Coulomb barrier in $Z_1Z_2 < 1,600$ systems, is less pronounced in heavy systems. (2) While a barrier is observed in the frozen density potential at $R \sim 12.8\,\mathrm{fm}$, there is no barrier in the obtained potentials, and the potentials monotonically increase as R decreases because of dynamical effects. Furthermore, we analyze the origin of the fusion hindrance from the TDHF trajectory with the fusion threshold energy, $E_{\mathrm{cm}} = 228.4\,\mathrm{MeV}$. Extra-push energy by TDHF can be defined as the difference between the fusion threshold energy and the barrier of the frozen density potential. In this system, this is calculated to be 14 MeV. According to our method of extracting potential, the origin of the extra-push energy can be identified from the sum of the total dissipated energy, increase in potential energy, and remaining kinetic energy. In this case at $R \sim 11.4\,\mathrm{fm}$, the total dissipated energy and increase in potential energy are 4.0 MeV and 9.2 MeV, respectively. We conclude from this analysis that the main contribution to the extra-push energy is the increase in extracted potential at $R \lesssim 12.8\,\mathrm{fm}$.

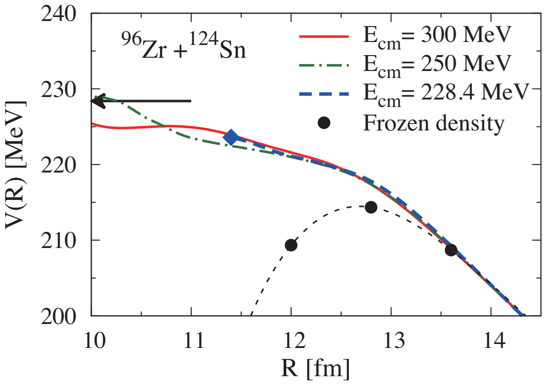

Fig. 1. Nucleus–nucleus potential of the $^{96}\mathrm{Zr} + {}^{124}\mathrm{Sn}$ system extracted from our method with different E_{cm}. Filled circles denote the frozen density potential. The arrow indicates the fusion threshold energy.

References

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