Origin of fusion hindrance in heavy systems

K. Washiyama[*1]

In fusion reactions in heavy systems whose charge product $Z_P Z_T$ is larger than 1600, it has been observed[1)] that the formation of a compound nucleus is strongly hindered around the Coulomb barrier energy, compared with $Z_P Z_T < 1600$ systems. In such heavy systems, an additional energy is needed to achieve fusion, which is called the extra-push energy.[2)] The most probable reason behind the fusion hindrance phenomenon is the occurrence of the quasi-fission process, which involves reseparation without the formation of a compound nucleus after two nuclei touch each other, in heavy systems. A macroscopic fluctuation–dissipation model using a Langevin equation has been developed[3)] to analyze quasi-fission and fusion dynamics especially in the synthesis of superheavy elements. Recently, the quasi-fission process was analyzed using the microscopic time-dependent Hartree-Fock (TDHF) model.[4)]

The aim of this study is to analyze in detail the origin of fusion hindrance in heavy systems by using the microscopic TDHF model. To this end, we employ our method[5)] to extract nucleus–nucleus potential and one-body energy dissipation from the relative motion of colliding nuclei to internal degrees of freedom in the entrance channel of fusion reactions from TDHF evolutions. We reported in Ref.[6)] that the nucleus–nucleus potential extracted from TDHF in the $^{96}\mathrm{Zr} + {}^{124}\mathrm{Sn}$ system monotonically increases as the relative distance decreases, and that the potential shows no ordinary barrier. In this report, we present results of our systematic study for fusion in heavy systems and discuss a possible origin of fusion hindrance.

First, we perform systematic calculations for estimating the extra-push energy by TDHF for several heavy systems. We define the extra-push energy using TDHF as the difference between the fusion threshold energy and the potential barrier obtained from the frozen density approximation, $E_{\mathrm{extra}} = E_{\mathrm{thres}} - V_{\mathrm{FD}}$. The frozen density potential is estimated while keeping the projectile and target densities frozen to their respective ground-state densities. We confirm that the obtained extra-push energies agree well with those deduced from experimental observations. Then, we extract the nucleus–nucleus potential $V(R)$ and friction coefficient $\gamma(R)$ as a function of the relative distance between two nuclei R for those systems. We find that the property of the extracted potentials is similar to that in the $^{96}\mathrm{Zr} + {}^{124}\mathrm{Sn}$ system,[6)] i.e., monotonic increase and no barrier structure in the potential. Finally, we analyze the fusion hindrance in heavy systems. We extract $V(R)$ and $\gamma(R)$ at the fusion threshold energy. We stop the extraction at R_{min} where the remaining kinetic energy reduces as much as possible in the TDHF simulations. At R_{min}, we can identify the extra-push energy as a sum of the remaining kinetic energy, accumulated dissipation energy estimated from $\gamma(R)$[5)], and increase in potential due to the frozen density barrier, denoted by $\Delta V = V(R_{\mathrm{min}}) - V_{\mathrm{FD}}$. In Fig. 1, the increase in potential ΔV and dissipated energy E_{diss} are plotted for the $^{100}\mathrm{Mo} + {}^{92,100}\mathrm{Mo}$, $^{104}\mathrm{Ru}$, $^{110}\mathrm{Pd}$ (left panel) and $^{96}\mathrm{Zr} + {}^{124,132}\mathrm{Sn}$, $^{136}\mathrm{Xe}$ (right panel) systems. It is clear that the contribution from the increase in potential to the extra-push energy is larger than that from the dissipated energy. From this finding, we conclude that the dynamical increase in potential energy is the main contribution to the extra-push energy.

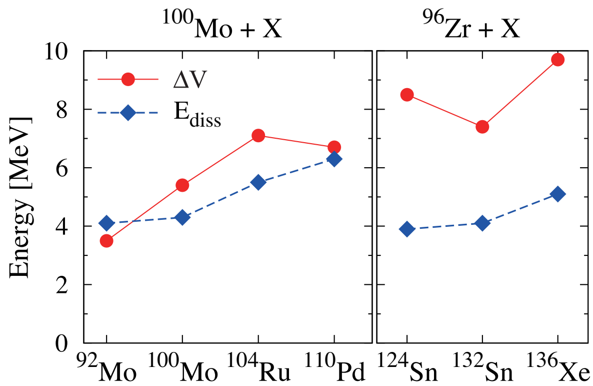

Fig. 1. Increase in potential ΔV (red circle) and accumulated dissipation energy E_{diss} (blue diamond) for the $^{100}\mathrm{Mo} + {}^{92,100}\mathrm{Mo}$, $^{104}\mathrm{Ru}$, $^{110}\mathrm{Pd}$ and $^{96}\mathrm{Zr} + {}^{124,132}\mathrm{Sn}$, $^{136}\mathrm{Xe}$ systems.

References

1) C.-C. Sahm et al.: Nucl. Phys. A **441**, 316 (1985).
2) W. J. Swiatecki: Nucl. Phys. A **376**, 275 (1982).
3) Y. Aritomo, K. Hagino, K. Nishio, and S. Chiba: Phys. Rev. C **85**, 044614 (2012).
4) C. Simenel: Eur. Phys. J. A **48**, 152 (2012); L. Guo and T. Nakatsukasa: EPJ Web Conf. **38**, 09003 (2012); V. E. Oberacker, A. S. Umar, and C. Simenel, Phys. Rev. C **90**, 054605 (2014).
5) K. Washiyama and D. Lacroix: Phys. Rev. C **78**, 024610 (2008); K. Washiyama, D. Lacroix and S. Ayik: Phys. Rev. C **79**, 024609 (2009).
6) K. Washiyama: RIKEN Accel. Prog. Rep. **47**, 67 (2013).

*1 RIKEN Nishina Center