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Fusion hindrance and extra push in fusion reactions with heavy nuclei

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Abstract. We analyze fusion hindrance phenomena involving heavy nuclei using the microscopic time-dependent Hartree-Fock theory combining with a macroscopic equation of motion with a friction term. We find that a barrier structure disappears in the obtained potentials in heavy systems. We show that main contribution to extra-push energy comes from the increase in dynamical potential.

1. Introduction

Fusion hindrance has been known by observations that fusion reaction at energies around the Coulomb barrier in heavy systems is strongly hindered compared with that in light- and medium-mass systems [1, 2, 3]. This fusion hindrance partially results in extremely low cross sections of the synthesis of superheavy elements. Before these observations, it was pointed out in Ref. [4, 5] that an extra energy (extra-push energy) is needed to fuse in heavy systems whose so-called effective fissility parameters are greater than a certain value, which can approximately correspond to the charge product of projectile and target nuclei being greater than $1600 \sim 1800$. In such heavy systems, quasi-fission (reseparation without forming a compound nucleus after two nuclei touch) is a dominant process and this can be understood by a geometrical consideration of potential energy landscape. For heavy systems, a conditional saddle point on the potential energy landscape appears inside the touching configuration of two nuclei. Therefore, the system needs to overcome the saddle for fusion. Otherwise, the system will reseparate, leading to quasi-fission. Friction leading to energy dissipation from relative motion to internal excitations becomes strong inside the touching configuration because of large overlap of two nuclei.

Previously, the quasi-fission process has been analyzed by a macroscopic dynamical model based on a Langevin equation [6, 7]. Analysis by microscopic reaction theory such as time-dependent Hartree-Fock (TDHF) theory [8, 9, 10, 11] is only a few [11, 12]. The aim of this work is to understand the origin of the fusion hindrance by using a microscopic reaction model, especially focusing on the properties of nucleus–nucleus potential and energy dissipation. In this work, we employ a method of combining the TDHF theory with a macroscopic equation of motion for directly extracting nucleus–nucleus potential and energy dissipation [13, 14].

2. Method

The TDHF theory gives a microscopic self-consistent description through the energy density functional for both static and dynamical properties, which can be applied to nuclei over the

whole nuclear chart. The basic equation for describing time evolution of the dynamics is the so-called TDHF equation for single-particle wave functions $\phi_i(\mathbf{r}, t)$,

$$i\hbar\frac{\partial}{\partial t}\phi_i(\mathbf{r}, t) = \hat{h}[\hat{\rho}]\phi_i(\mathbf{r}, t), \tag{1}$$

where $\hat{h}[\hat{\rho}]$ denotes single-particle Hamiltonian as a functional of one-body density $\hat{\rho}$.

To extract nucleus–nucleus potential and energy dissipation from TDHF evolutions, we use a method of combining microscopic TDHF and macroscopic evolution through a Newton equation, which we proposed in Ref. [13, 14]. This method relies on the assumption that a complicated microscopic mean-field dynamics can be reduced to a one-dimensional macroscopic equation of motion for relative distance R and conjugate momentum P including a friction term,

$$\frac{dR}{dt} = \frac{P}{\mu}, \qquad \frac{dP}{dt} = -\frac{dV}{dR} - \frac{d}{dR}\left(\frac{P^2}{2\mu}\right) - \gamma\frac{dR}{dt}, \tag{2}$$

where μ, V and γ denote the reduced mass, nucleus-nucleus potential and friction coefficient, respectively, as a function of relative distance. The friction term describes dissipation from the relative motion to intrinsic degrees of freedom. We would like to note here that our extracted potential is based on neither sudden nor adiabatic approximation. Our extracted potential and friction automatically contain dynamical effects such as dynamical density evolution. We stop the extraction when the overlap of the projectile and target densities becomes significantly large since our extraction method based on the two-body analysis does not properly work with such a large overlap. To compute TDHF evolutions, we use the three-dimensional TDHF code developed by P. Bonche and coworkers [15]. Details of the computations are in Refs. [13, 14].

3. Result

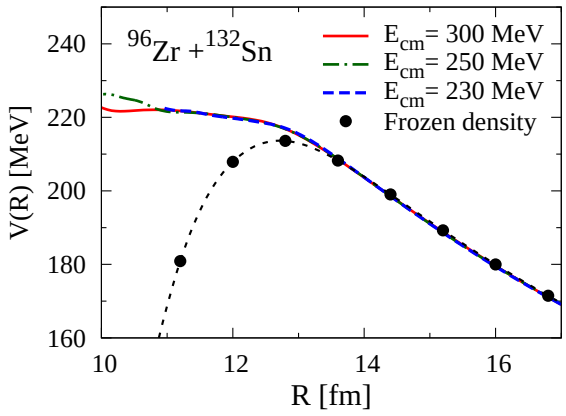

Figure 1. Nucleus–nucleus potential as a function of relative distance for the $^{96}\mathrm{Zr} + {}^{132}\mathrm{Sn}$ system. The lines are the results of our method at different E_{cm} indicated in the figure. The dots are obtained from the frozen density approximation.

First, we show extracted nucleus–nucleus potentials. Figure 1 shows potentials extracted at different center-of-mass energies E_{cm} for the $^{96}\mathrm{Zr} + {}^{132}\mathrm{Sn}$ system. As a reference, we plot by the filled circles the frozen density potential that is calculated from the same energy density functionals as in TDHF with the projectile and target densities frozen to their ground-state one. Comparing with the frozen density potential, we find an increase in extracted potential at all the energies used here at $R < 13$ fm. In Fig. 2, we investigate in detail the property of extracted potentials for the $^{96}\mathrm{Zr} + {}^{124}\mathrm{Sn}$ system by comparing with those in the $^{40}\mathrm{Ca} + {}^{40}\mathrm{Ca}$ system. We find two significant differences: (1) For the $^{96}\mathrm{Zr} + {}^{124,132}\mathrm{Sn}$ systems, no potential

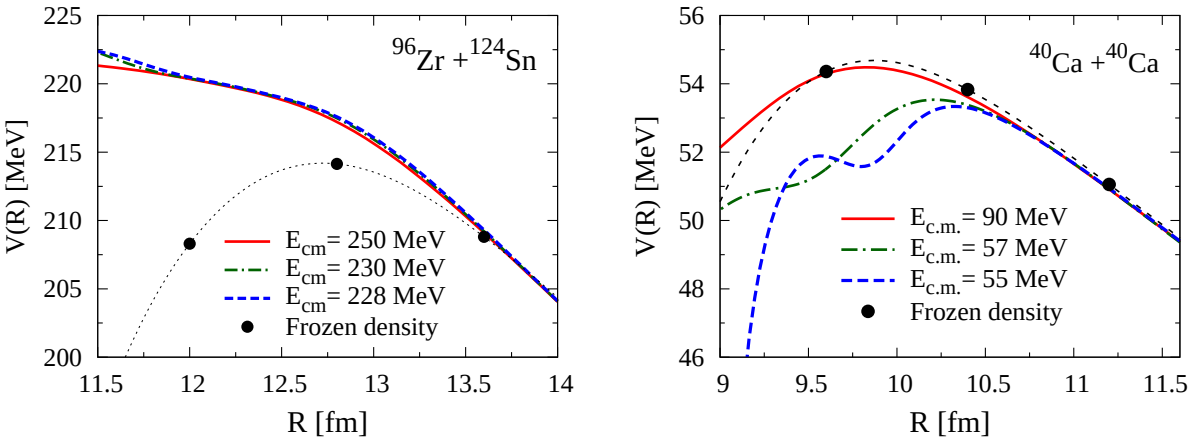

Figure 2. Left panel: Zoom around the frozen density barrier for nucleus–nucleus potentials extracted for the $^{96}\mathrm{Zr} + {}^{124}\mathrm{Sn}$ system. Right panel: Same as in the left panel but for the $^{40}\mathrm{Ca} + {}^{40}\mathrm{Ca}$ system.

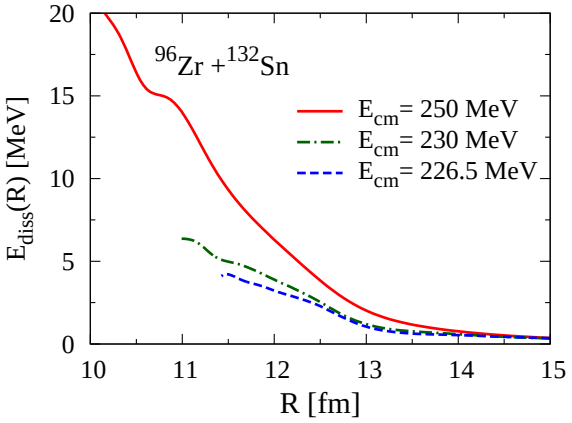

Figure 3. Dissipated energy calculated in Eq. (3) for the $^{96}\mathrm{Zr} + {}^{132}\mathrm{Sn}$ system. The lines are the results of our method at different E_{cm} indicated in the panel

barrier is observed in the potentials extracted at any E_{cm} and the potentials monotonically increase as R decreases. For the $^{40}\mathrm{Ca} + {}^{40}\mathrm{Ca}$ system, a barrier is observed as usual. (2) Energy dependence of potential appears in the $^{40}\mathrm{Ca} + {}^{40}\mathrm{Ca}$ system, while it is not significant in the $^{96}\mathrm{Zr} + {}^{124,132}\mathrm{Sn}$ systems around the frozen density barrier at $R \sim 12.8\,\mathrm{fm}$.

In Fig. 3, we show dissipated energy for the $^{96}\mathrm{Zr} + {}^{132}\mathrm{Sn}$ system. We calculate the dissipated energy through the friction coefficient by

$$E_{\mathrm{diss}}[R(t)] = \int_0^t dt' \gamma[R(t')] \left(\frac{dR}{dt}\right)^2, \tag{3}$$

at time t when we stop the extraction of the friction coefficient. In all the cases, the dissipated energy monotonically increases as nuclei approach to each other.

Finally, we analyze the origin of the fusion hindrance. We first define the extra-push energy E_{extra} of TDHF as the difference between the fusion threshold energy E_{thres} and the frozen density potential barrier V_{FD}, $E_{\mathrm{extra}} = E_{\mathrm{thres}} - V_{\mathrm{FD}}$. The fusion threshold energy is determined as the lowest energy for a reaction with the system remaining a compact shape for a sufficiently long time ($\sim 1200\,\mathrm{fm}/c$) after touching. For the analysis of the extra-push energy, we extract potential and energy dissipation from TDHF trajectories at E_{thres}, in which remaining kinetic

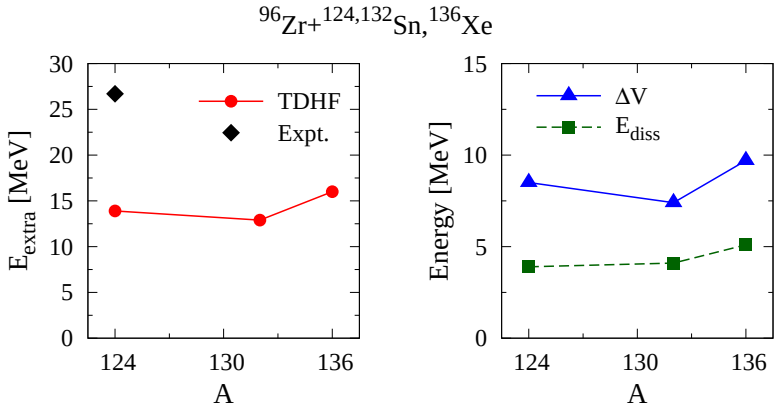

Figure 4. Left panel: Extra-push energies extracted from our TDHF method (solid circles) and from experimental data (triangle) [2] for the ^{96}Zr + ^{124,132}Sn, ^{136}Xe systems. Right panel: increase in potential and dissipated energy extracted from our TDHF method.

energy is smallest at the relative distance where we stop extracting potential. At this relative distance, denoted by $R_{\rm stop}$, we can identify the extra-push energy as the sum of the dissipated energy $E_{\rm diss}(R_{\rm stop})$ in Eq. (3) and the increase in potential ΔV at $R_{\rm stop}$ from the frozen density potential barrier, $\Delta V = V(R_{\rm stop}) - V_{\rm FD}$. The results are summarized in Fig. 4. It is clear that the contribution from the increase in potential ΔV is larger than the dissipated energy $E_{\rm diss}$ for the ^{96}Zr + ^{124,132}Sn, ^{136}Xe systems. From this finding, we conclude by our microscopic analysis that main contribution to the extra-push energy is from the dynamical increase in potential.

4. Summary

We have discussed the origin of the fusion hindrance by using microscopic TDHF combining with a macroscopic equation of motion for extracting dynamical nucleus–nucleus potential and energy dissipation. Dynamical increase in potentials extracted in heavy systems appears, which is different from that in light- and medium-mass systems. We analyze extra-push energies and find that main contribution to the extra-push energy is from the dynamical increase in potential.

Acknowledgments

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References

[1] Gaggeler H *et al.* 1984 *Z. Phys. A* **316** 291
[2] Sahm C C *et al.* 1985 *Nucl. Phys. A* **441** 316
[3] Schmidt K H and Morawek W 1991 *Rep. Prog. Phys.* **54** 949
[4] Swiatecki W J 1981 *Phys. Scripta* **24** 113; 1982 *Nucl. Phys. A* **376** 275
[5] Bjornholm S and Swiatecki W J 1982 *Nucl. Phys. A* **391** 471
[6] Zagrebaev V and Greiner W 2005 *J. Phys. G* **31** 825
[7] Aritomo Y, Hagino K, Nishio K and Chiba S 2012 *Phys. Rev. C* **85** 044614
[8] Bonche P, Koonin S E and Negele J W 1976 *Phys. Rev. C* **13** 1226
[9] Flocard H, Koonin S E and Weiss M S 1978 *Phys. Rev. C* **17** 1682
[10] Negele J W 1982 *Rev. Mod. Phys.* **54** 913
[11] Simenel C 2012 *Eur. Phys. J. A* **48** 152
[12] Guo L and Nakatsukasa T 2012 *EPJ Web Conf.* **38** 09003
[13] Washiyama K and Lacroix D 2008 *Phys. Rev. C* **78** 024610
[14] Washiyama K, Lacroix D and Ayik S 2009 *Phys. Rev. C* **79** 024609
[15] Kim K H, Otsuka T and Bonche P 1997 *J. Phys. G* **23** 1267