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Microscopic Study on Dynamic Barrier in Fusion Reactions *

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Abstract In this paper we briefly review the fusion process of very heavy nuclear systems and some theoretical models. We propose a microscopic transport dynamic model, i.e. the Improved Quantum Molecular Dynamic model, for describing fusion reactions of heavy systems, in which the dynamical behavior of the fusion barrier in heavy fusion systems has been studied firstly. We find that with the incident energy decreasing the lowest dynamic barrier is obtained which approaches to the adiabatic static barrier and with increase of the incident energy the dynamic barrier goes up to the diabatic static barrier. We also indicate that how the dynamical fusion barrier is correlated with the development of the configuration of fusion partners along the fusion path. Associating the single-particle potentials obtained at different stages of fusion with the Two Center Shell Model, we can study the time evolution of the single particle states of fusion system in configuration space of single particle orbits along the fusion path.

Key words heavy ion fusion process, microscopic transport model, dynamical fusion barrier

1 Fusion process of very heavy nuclei

The formation of compound nuclei by fusion of very heavy nuclei is one of the outstanding problems of low-energy nuclear reactions. Such processes play a key role in the production of superheavy elements [1—3]. The fusion process of very heavy nuclei seems to be subdivided into three steps[4,5]:

1) The capture of two nuclei in an entrance-channel potential well and formation of a common nuclear system of two touching nuclei. The entrance channel is essential for the fusion process, because the population of quasi-bound states near touching is regarded as the first decisive step to fusion. The existence of such capture states crucially depends on the properties of the entrance-channel potential as a function of the distance between centers of mass of fusion partners[6].

2) The formation of a compound nuclear system during shape evolution from two touching nuclear configuration(dinuclear system). The dinuclear system can evolve in time by means of nucleon transfer from the one nucleus to the other one. There are two ways of the system's evolution: the first one leads to complete fusion, the second one to decaying into two nearly equal fragments, that is, the quasifission takes place.

3) The surviving of the excited compound nucleus due to evaporation of neutron and γ-ray emission in competition with fission. The decay properties of the compound system drastically depend on the excitation energy and structure of the compound nucleus as well as the fission barrier height. The schematic picture for the complete fusion process is shown in Fig.1.

2 Theoretical models

In order to describe above fusion process there are several theoretical models. They are the macroscopic dynamical model of Swiatecki (MDM), the dinuclear system concept proposed at Dubna (DNS concept), the fluctuation-dissipation model elaborated by Japanese theoreticians (FDM), the concept of nucleon collectivization of Zagrebaev (CNC).

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The macroscopic dynamic model[7—9] was the first model, which described the whole history of complete fusion of two nuclei beginning from the contact of their surface and ending at the compound nucleus. In the model two important simplifications were used. The first one is that colliding nuclei containing protons, neutrons and having shell structures were substituted by drops of a hypothetical viscose nuclear liquid. The second simplification was that the fusion of two nuclei was considered as a purely dynamic process and was described by classical equations of motion.

In the fluctuation-dissipation model[10—14] the same simplification for nuclei as in the MDM is used, that is, nuclei are considered as drops of viscose nuclear liquid. However, two new important factors have been introduced into the description of the fusion process: a) statistical fluctuations in the interaction of colliding nuclei and, b) shell corrections in the calculation of the potential energy of the nuclear system. These improvements permit one to describe the production cross section of superheavy elements in warm fusion reaction, the mass distribution of fission and quasifission products and so on. However the predictions of the model cause some doubts in some aspects.

The dinuclear system concept is based on the statement "The complete fusion of nuclei and deep inelastic transfer reactions (DITR) are similar nuclear process". Therefore, in DNS model[15—18] the fusion happens in the mass asymmetry coordinate. The DNS remains at the touching configuration and exchanges nucleons until either all nucleons have been transferred from the lighter to the heavier fragment or the DNS decays by quasifission. The DNS model assumes a sudden potential energy surface in the radial coordinate, and adiabatic behavior along the fusion path in the mass asymmetry coordinate. Using this model, the important aspects of the synthesis of heavy and superheavy elements have been analyzed.

The concept of nucleon collectivization[19] is that the fusion-fission process takes place in the (A_1, A_2) space, where A_1 and A_2 are two nuclei, surrounded by a certain number of common nucleons ΔA. These nuclei gradually lose (or acquire) their individualities with increasing (or decreasing) the number of collectivized nucleons ΔA. The driving potential in the (A_1, A_2) space can be derived, which allows the calculation of the probability of the compound nucleus formation and the mass distribution of fission fragments in heavy ion fusion reactions.

A wide variety of ideas or models on the complete fusion process testify the fact that the mechanism of the compound nuclear formation is still an unsolved problem[20].

3 Microscopic transport dynamic model

A realistic picture of the mechanism of the compound nucleus formation may be obtained if one takes into account the real structure of colliding nuclei and the quantum-mechanical aspects of their interaction. Based on this consideration, we propose a microscopic transport dynamics model——the improved quantum molecular dynamics (ImQMD) model[21,22]. In the ImQMD model, the one-body phase space distribution function for N-distinguishable particles is given by:

$$f(\boldsymbol{r},\boldsymbol{p}) = \sum_i \frac{1}{(\pi\hbar)^3}\exp\Big[-\frac{(\boldsymbol{r}-\boldsymbol{r}_i)^2}{2\sigma_r^2} - \frac{2\sigma_r^2}{\hbar^2}(\boldsymbol{p}-\boldsymbol{p}_i)^2\Big]. \tag{1}$$

For identical fermions, the effect of the Pauli principle has to be considered[23,24]. In the ImQMD model, the approximate treatment of anti-symmetrization is adopted by means of the phase space occupation constraint method[21,22,25]. The real structure of colliding nuclei is taken into account by the initial condition. The neutron and proton density distribution, binding energy and nuclear radius of initial nuclei are calculated within the relativistic mean field theory. The position of each nucleon in the projectile (or target) is sampled according to the density distribution obtained and the momentum of each wave packet is assigned randomly between zero and local Fermi momentum. Each created nucleus is examined according to the properties of the ground state (the binding energy and the nuclear radius). The propagation of nucleons under the self-consistently generated mean field is governed by Hamiltonian equations of motion:

$$\dot{\boldsymbol{r}}_i = \frac{\partial H}{\partial \boldsymbol{p}_i}, \dot{\boldsymbol{p}}_i = -\frac{\partial H}{\partial \boldsymbol{r}_i}. \tag{2}$$

The Hamiltonian H consists of the kinetic energy and the effective interaction potential energy:

$$H = T + U, \tag{3}$$

$$T = \sum_i \frac{\boldsymbol{p}_i^2}{2m}. \tag{4}$$

The effective interaction potential energy includes the nuclear local interaction potential energy and the Coulomb interaction potential energy:

$$U = U_{\rm loc} + U_{\rm Coul}. \tag{5}$$

and

$$U_{\rm loc} = \int V_{\rm loc}(\rho(\boldsymbol{r}))\,{\rm d}\boldsymbol{r}, \tag{6}$$

where $V_{\rm loc}(\rho(\boldsymbol{r}))$ is potential energy density. The $V_{\rm loc}(\rho(\boldsymbol{r}))$ in the ImQMD model reads[22]

$$V_{\rm loc} = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_{\rm sur}}{2\rho_0}(\nabla\rho)^2 + g_\tau\frac{\rho^{\eta+1}}{\rho_0^{\eta}} + \frac{C_s}{2\rho_0}(\rho^2 - \kappa_s(\nabla\rho)^2)\delta^2, \tag{7}$$

where $\delta = \dfrac{\rho_{\rm n}-\rho_{\rm p}}{\rho_{\rm n}+\rho_{\rm p}}$, $\rho_{\rm n}$, $\rho_{\rm p}$ are the neutron and proton density, respectively. The first three terms in above expression can be obtained from the potential energy functional of Skyrme forces directly. The fifth term is the symmetry potential energy part where both the bulk and the surface symmetry energy are included. In addition, we introduce an extra small correction term $V_\tau = g_\tau\dfrac{\rho^{\eta+1}}{\rho_0^{\eta}}$ in the potential energy functional. The Coulomb energy can be written as the sum of the direct and an exchange contribution, the latter being taken into account in the Slater approximation[26—28]

$$U_{\rm Coul} = \frac{1}{2}\int\rho_{\rm p}(\boldsymbol{r})\frac{e^2}{|\boldsymbol{r}-\boldsymbol{r}'|}\rho_{\rm p}(\boldsymbol{r}')\,{\rm d}\boldsymbol{r}\,{\rm d}\boldsymbol{r}' - e^2\frac{3}{4}\left(\frac{3}{\pi}\right)^{1/3}\int\rho_{\rm p}^{4/3}\,{\rm d}\boldsymbol{R}. \tag{8}$$

The parameters in the potential energy density functional are obtained by reproducing the properties of the ground state of a serious finite nuclei, and nuclear matter and the fusion cross section of several selected heavy ion fusion reactions (for details, see Ref. [22]). Within the ImQMD model, we can calculate the nucleus-nucleus interaction potential energy, single-particle potential along the fusion path and the fusion cross section for intermediate heavy reaction system and capture cross section for very heavy reaction system and so on.

4 Dynamic potential barrier

In this section we first study the nucleus-nucleus interaction potential energy $V_{\rm b}(R)$ which is defined by

$$V_{\rm b}(R) = E_{12}(R) - E_1 - E_2. \tag{9}$$

Here R is the distance between centers of mass of projectile and target, which is a function of time. $E_{12}(R)$, E_1 and E_2 are the total energy of the whole system, the energies of projectile (like) and target (like) part, respectively. They are the integration of energy density functional over the whole system, the projectile (like) and the target (like), respectively. The potential energy functional is given by Eq. (7) and for the kinetic energy density functional the Thomas-Fermi approximation is adopted as mentioned in Ref. [29]. Within a microscopic transport theory, such as the ImQMD model, both the static and dynamic potential barriers can be calculated. For the static case, a frozen density is adopted, in this case the density distribution of projectile and target is always assumed to be the same as that at the initial time, and correspondingly the static potential barrier is a diabatic one. For a realistic fusion reaction, the density distribution should evolve with time and the fusion potential barrier experienced is called a dynamic barrier. For a certain reaction system, the reaction dynamics should strongly depend on incident energy (also the impact parameter). So, in general, the dynamical fusion barrier should depend on the incident energy. As an example, we show the fusion barrier for the head on fusion reaction $^{48}{\rm Ca} + {}^{208}{\rm Pb}$ in Fig. 3. The lines with crosses and solid dots denote the proximity potential from Ref. [30] and the static potential, respectively. The thick line with open circles is the results from Strutinsky's macroscopic-microscopic method based on the Two Center Shell Model[31], which provides us with an adiabatic potential barrier. The long-dashed line, short-dashed line, thin line, dot-dashed line and thick line are the dynamic potential barrier when incident energies at center of mass system equal to $E_{\rm cm}$ = 220, 200, 180, 170 and 160MeV, respectively. One can see from the figure that the static barrier is close to the well known proximity potential barrier. We define the maximum value of the dynamic potential barrier experienced in the path of fusion as the height of the dynamic potential barrier. One can see from the figure that when the incident energy is much

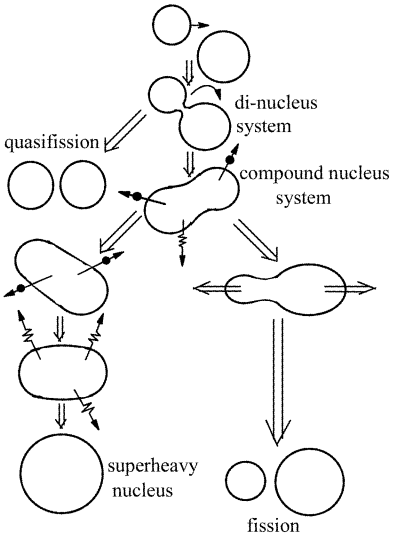

Fig. 1. The schematic description of fusion process for very heavy fusion reaction systems.

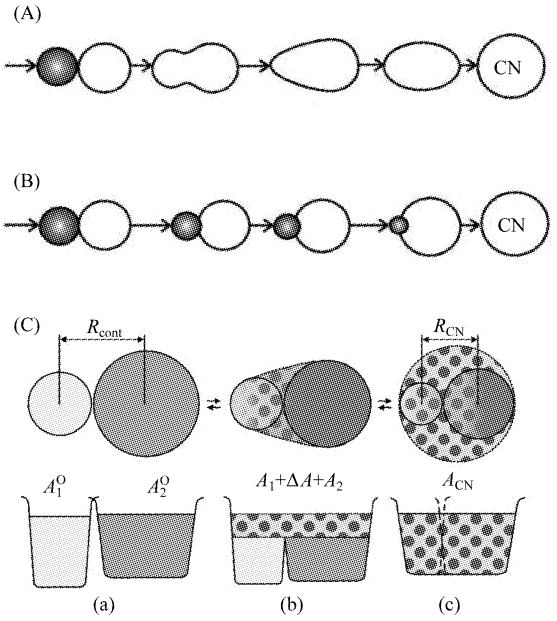

Fig.2. The schematic illustration of the process of the compound nucleus formation in the framework of different approaches. (a) macroscopic dynamic model, (b) dinuclear system model, (c) model of collectivization of nucleons.

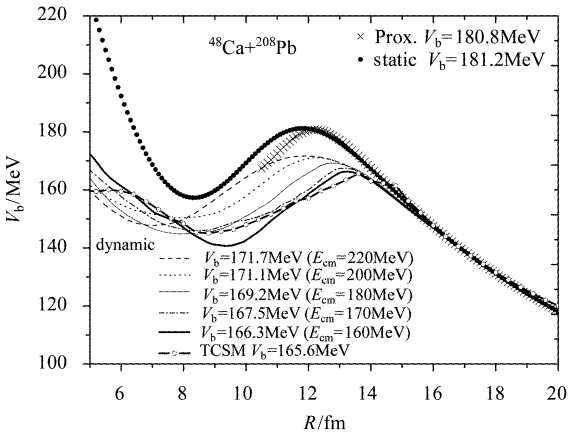

Fig.3. The potential barrier as a function of distance between centers of mass of fragments for head on collisions of $^{48}Ca + ^{208}Pb$. The lines with solid dots and crosses are for the static and proximity potential[30], respectively. The line with open circles is from Strutinsky's macroscopic-microscopic calculation based on the Two Center Shell Model. The other lines from up to down are for dynamic potentials at incident energies of E_{cm} = 220, 200, 180, 170 and 160MeV, respectively.

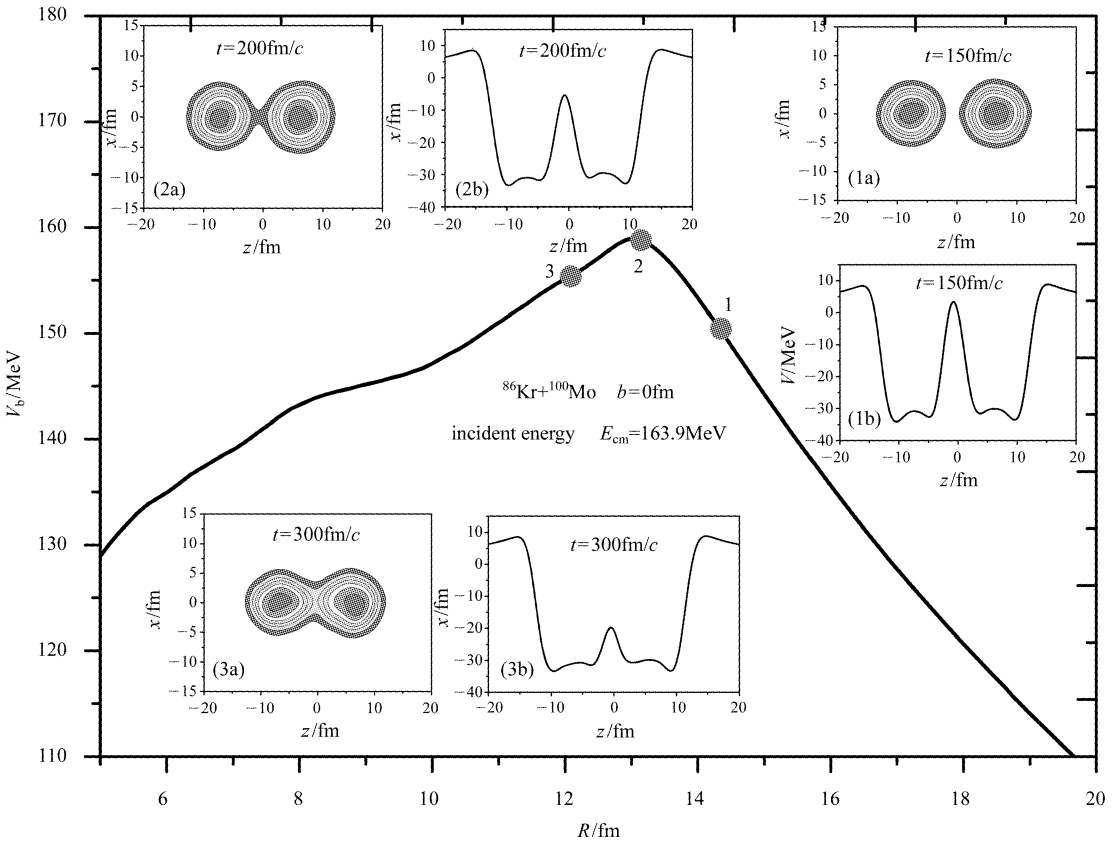

Fig.4. The fusion path for a head on collision of $^{86}Kr + ^{100}Mo$ at the energy 10MeV below the Coulomb barrier. Subfigures 1a, 2a, 3a are for contour plots of the density distributions, and 1b, 2b, 3b are for corresponding single-particle potentials.

higher than the static barrier, for example, when E_{cm} = 220MeV, the height of dynamic barrier reaches 171.7 MeV which is close to the hight of the static barrier $V_b(R)$ = 181.2 MeV; with incident energy decreasing, for example, when E_{cm} = 180MeV, the height of dynamic barrier is reduced to $V_b(R) \sim 169$MeV. As the incident energy goes down to much below the static barrier, for instance, when E_{cm} = 160MeV, the dynamic barrier further decreases to $V_b(R)$ = 166.3 MeV which approaches to the adiabatic barrier ($V_b(R)$ = 165.6 MeV). Thus we can associate the up- and low-limit of the dynamic potential barrier with the two edges of the barrier distribution. Furthermore, one can see from the figure that there exists a local minimum in each dynamic potential barrier, that is, the so-called capture pocket(CP) like shape, which implies that there still exists possibility of reseparation after passing over the entrance barrier. We have calculated the potential barriers for systems of $^{131}I + ^{131}I$, $^{54}Cr + ^{208}Pb$, $^{32}S + ^{230}Th$ and $^{12}C + ^{250}Fm$ which can form the same compound nuclei ^{262}Sg and found that the height of the barrier, the location and the shape of the CP are rather different. But as soon as the energy dependence of the dynamic potential barrier is concerned, the behavior shown for heavy system of $^{48}Ca + ^{208}Pb$ is quite general.

5 Configuration in fusion path

For further investigating the fusion dynamics, let us study the configuration along the fusion path in the fusion potential energy surface. As an example, in Fig.4 we illustrate fusion path for the head on fusion reaction of $^{86}Kr + ^{100}Mo$ at the energy 10MeV below the barrier. In the figure, we plot the dynamical barrier V_b as a function of the distance between the centers of mass of projectile and target. Simultaneously, in subfigures we plot the contour plots of density distributions as well as the corresponding single-particle potentials at 3 typical times, i.e., before, at, and after reaching the highest value of the dynamic barrier along the fusion path. The single-particle potential is calculated by

$$V_{sp}(\boldsymbol{r}) = \int \rho(\boldsymbol{r}')\, V(\boldsymbol{r} - \boldsymbol{r}')\, d^3r' , \qquad (10)$$

with $\rho(\boldsymbol{r})$ being the density distribution of the system and $V(\boldsymbol{r} - \boldsymbol{r}')$ the effective nucleon-nucleon interaction. Subfigures (1a) and (1b) are the contour plot of the density distribution and the corresponding single-particle potential at point 1 of the fusion path. One can see from these two figures that at this point the fusion partners are not in touch [see sub-figure (1a)], and there is a high enough inner potential barrier which prevents nucleons from moving from the projectile to the target, or vice versa [see sub-figure (1b)]. At the time, corresponding to point 2, the dynamic potential reaches a maximum value. The contour plot of density distribution [sub-figure (2a)] shows that the fusion partners are at a touching configuration, a neck starts to grow and, following this, the inner potential barrier in the potential well is reduced, allowing a few nucleons to move from projectile to a target, or vice versa [see sub-figure (2b)]. At the time corresponding to point 3, the dynamical barrier is reduced considerably. Sub-figures (3a) and (3b) show that the neck develops considerably at this time and, consequently, the inner potential barrier in the potential well is reduced substantially, and nucleon transfer between the projectile and target becomes much easer than before. This means that a pre-compound nucleus start to formed. From this study we have learned that how the dynamical fusion barrier is correlated with the development of the configuration of fusion partner along the fusion path. Associating the single-particle potentials obtained at different stages of fusion with the Two Center Shell Model[31], we can study the time evolution of the single particle states of fusion system in configuration space of single particle orbits along the fusion path, by which one can study the collectivization of nucleons[19] quantitatively. This kind of work is in progress.

6 Summary

In this paper we schematically describe the fusion process of very heavy nuclear systems and briefly review the main theoretical models. We propose an improved quantum molecular dynamics model for describing fusion reaction of heavy systems, in which the dynamical behavior of the fusion barrier has been studied firstly. In our approach the fusion barrier calculated with the frozen density identical to the initial density of the system is called the static barrier. The real barrier encountered in the fusion process is the dynamic barrier. Our results show that the dynamical barrier strongly depends on the incident energy. The height of dynamic barrier decreases with decrease of the incident energy, and finally approaches a low limit which is close to the adiabatic barrier calculated by Strutinsky's macroscopic-microscopic method. With increase of the incident energy the dynamic barrier increases and its

up-limit closes to diabatic static barrier. In this paper we also show how the dynamical fusion barrier is correlated with the development of the configuration of fusion partners along the fusion path. Associating the single-particle potentials obtained at different stages of fusion with the Two Center Shell Model[31], we can study the time evolution of the single particle states of fusion system in configuration space of single particle orbits along the fusion path, by which one can study the collectivization of nucleons[19] quantitatively.

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重核融合反应动力学位垒的微观研究*

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摘要　在简要评述重核融合过程中几种主要理论模型的基础上,提出了微观输运动力学模型,即改进的量子分子动力学模型.在这个模型的框架内,我们研究了重核融合位垒的动力学行为.我们发现,随入射能量的减少,可以得到最低的动力学位垒,它趋近于绝热静态位垒.而随入射能量的增加,动力学位垒增加,最后趋近于非绝热静态位垒,这给出了位垒分布的两个边缘.在微观输运动力学模型基础上,我们还研究了在融合路径上,动力学位垒与融合体系微观构型的关系.考虑到融合过程不同时刻的单粒子位势与双中心壳模型位势的相似性,我们可以很好的研究融合过程中,在构型空间里单粒子态及相关量的时间演化行为.

关键词　重离子融合过程　微观输运模型　动力学位垒

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