CHIN.PHYS.LETT. Vol. 20, No. 9 (2003) 1466

Development of the Neck in Fusion Reactions ^{40}Ca+^{90,96}Zr *

WANG Ning(王宁)[1], WU Xi-Zhen(吴锡真)[1,2], LI Zhu-Xia(李祝霞)[1,2,3]
[1]*China Institute of Atomic Energy, PO Box 275(18), Beijing 102413*
[2]*Nuclear Theory Centre of National Laboratory of Heavy Ion Accelerator, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 7300000*
[3]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080*

(Received 10 March 2003)

The neck dynamics and nucleon transfer through the neck in fusion reactions ^{40}Ca+^{90,96}Zr are studied by applying the improved quantum molecular dynamics model. A special attention is paid to the dynamic behaviour of the neck development at touching point and to the contribution of excess neutrons in a neutron-rich target (or projectile) to neck formation and nucleon transfer.

PACS: 25. 70. −z, 24. 10. −i

Studies of synthesis of superheavy elements have greatly stimulated an investigation on fusion process of heavy systems at a low energy.[1−5] The fusion process of heavy nuclei at low incident energies is very complicated, because it involves the deformation of the projectile and target, neck formation and nucleon transfer between the composite systems as well as dissipation. The neck development plays an essential role in this complicated process. The phenomenological study on the neck dynamics in the fission process was performed for a quite long time.[6,7] Encouraged by the synthesis of superheavy nuclei recently, the dynamical study of fusion process has attracted much attention, and several models have appeared in recent years.[8,9] One of them is called the macroscopic dynamic model. According to this model,[8] a strongly deformed mononucleus is formed during the collision of heavy systems. This means that the neck develops rather fast in the fusion process. Another model for describing the fusion process is called the di-nuclear system model,[9] which assumes that the united system is formed by a series of nucleon or small cluster transfers from a light nucleus to a heavier one in a touching configuration. According to this model, the neck development is strongly hindered in the touching configuration. These two controversial models can provide information of the fusion cross section of superheavy systems. However, a clear understanding of the fusion mechanism microscopically is still much less. To study fusion mechanism microscopically, the quantum molecular dynamics model could be very useful. Since the fusion process of heavy system is extremely complicated, as the first step to attack the goal, we attempt to study the fusion process of intermediate heavy systems at present. In this Letter, we concentrate our attention on the neck dynamics and mass transfer between the composite systems.

In the study, we employ our improved quantum molecular dynamics (ImQMD) model.[10,11] For the reader's convenience we briefly introduce the effective interaction potential energy of the model, which includes the nuclear local interaction potential energy and Coulomb interaction potential energy. The nuclear local interaction potential energy reads

$$U_{\rm loc} = \frac{\alpha}{2}\sum_i \Big\langle \frac{\rho}{\rho_0}\Big\rangle_i + \frac{\beta}{3}\sum_i \Big\langle \frac{\rho}{\rho_0}\Big\rangle_i^2 + \frac{C_s}{2}\int \frac{(\rho_p-\rho_n)^2}{\rho_0}{\rm d}^3\boldsymbol{r} + \int \frac{g_0}{2}(\nabla\rho)^2{\rm d}^3\boldsymbol{r}, \qquad (1)$$

where

$$\langle\rho\rangle_i = \sum_{j\neq i}\rho_{ij}, \quad \rho_{ij} = \frac{1}{(4\pi\sigma_r^2)^{3/2}}\exp\Big[-\frac{(\boldsymbol{r}_i-\boldsymbol{r}_j)^2}{4\sigma_r^2}\Big].$$

The third term on the right-hand side of Eq. (1) is the symmetry potential energy, and the gradient term in $U_{\rm loc}$ is to account for the surface energy and to correct the second term of formulae (1).[10,11] Because in this work we are going to study the isospin effect on the fusion dynamics in neutron-rich nuclear fusion reactions, we pay a special attention to the symmetry potential term. Therefore, we make a more careful treatment on the symmetry potential term, namely, in addition to the volume symmetry potential term, we further introduce a surface symmetry potential term according to the finite-range liquid-drop model,[12] which reads

$$U_{\text{sur-sym}} = \frac{C_sC_k}{2\rho_0}\sum_{i,j\neq i} s_i s_j \rho_{ij}\nabla_i^2\rho_{ij}, \qquad (2)$$

where s_i is +1 for proton and −1 for neutron, and C_k is the strength parameter for the surface symmetry term. The parameters used in this work are listed in Table 1. Considering the fact that for a finite system the nucleons are localized in a finite region corresponding to the size of the system, the width of wavepackets representing nucleons in the system

---

* Supported by the National Natural Science Foundation of China under Grant Nos 10175093, 10175089, 10235020, and 10235030, the Science Foundation of Chinese Nuclear Industry, and the Major State Basic Research Development Programme under Grant No G20000774.

should have a relation with the size of the system. As the same as in Ref. [10], we adopt a system size dependent wavepacket width $\sigma_r = 0.16N^{1/3} + 0.49$, where N is the number of nucleons bound in the system. In order to overcome the difficulty in describing the Fermionic nature of an N-body system with the QMD model, we implement the phase space constraint into the model,[13] which can effectively retain the Pauli principle in the QMD model.

Table 1. Parameters used in the calculations.

α(GeV)	β(GeV)	ρ_0(fm^{-3})	g_0(GeV fm^5)	C_s(GeV)	C_k(fm^5)
−0.124	00.71	0.165	0.96	0.032	1.0

By using our model, the ground state properties including the binding energies, root-mean-square radii, density distributions, momentum distributions as well as their time evolution for selected nuclei from ^{6}Li to ^{208}Pb have been described well with a set of parameters. The experimental data of the fusion cross sections for ^{40}Ca+^{90,96}Zr have been reproduced well as shown in Fig. 1.[10] In addition, the dynamic lowering of the Coulomb barrier in neutron rich nuclei and its influence on the fusion cross section were discussed in Ref. [11]. Based on the studies mentioned above, it is natural to extend this model to study the neck dynamics, which is important for understanding the fusion mechanism. In order to give an intuitive picture of the fusion process, we show the contour plots of the time development of density distributions in Figs. 2(a)–2(d) and the time evolution of distributions of protons and neutrons in coordinate space in Figs. 2(e)–2(h), for fusion reaction of ^{40}Ca+^{90}Zr at impact parameter $b = 6$ fm and incident energy $E_{\rm c.m.} = 108$ MeV (10 MeV above the Coulomb barrier). In Figs. 2(e)–2(h) we also plot the velocities of particles by arrows. These figures show how neck develops with time: before touching, the shape deformation of the projectile and target already occurs; then after touching the neck begins to be formed and nucleons transfer through the neck; with time evolution the neck grows further and the vibration motion between the target-like part and the projectile-like part may occur; finally the compound system is formed. To describe this neck development quantitatively, in

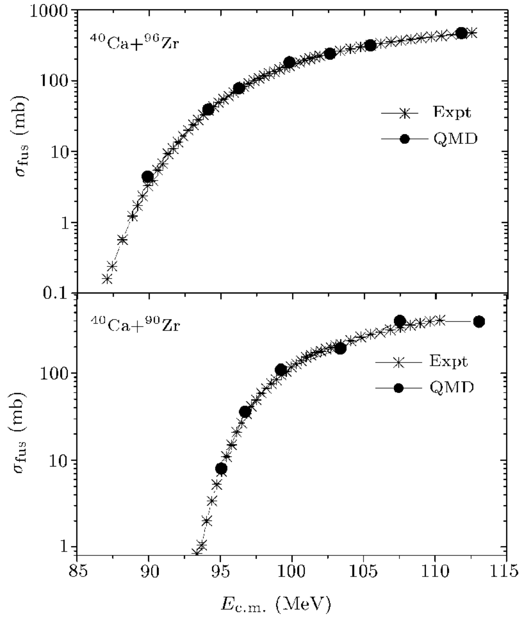

Fig. 1. Fusion cross sections for ^{40}Ca+^{90,96}Zr. The solid curves denote the results of this work and the crossed curves denote the experimental data taken from Ref. [14].

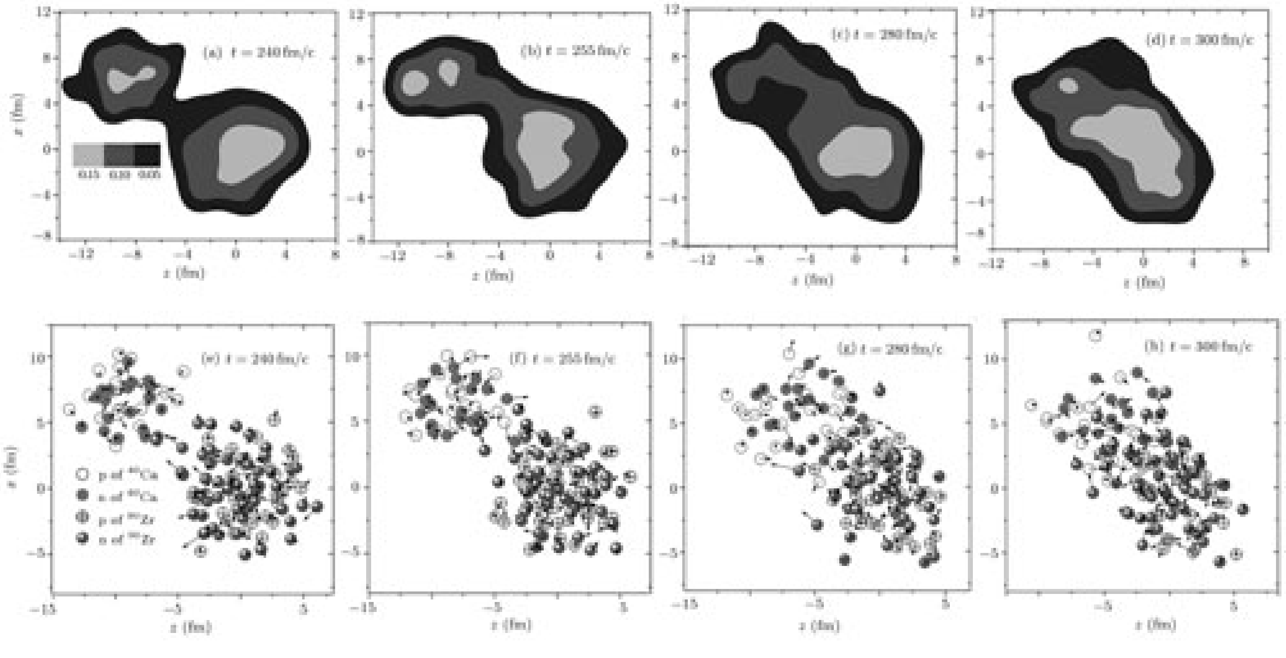

Fig. 2. Contour plots of the density distributions at different time [(a)–(d)] and time-dependent distributions of nucleons [(e)–2(h)] for the fusion ^{40}Ca+^{90}Zr at impact parameter $b = 6$ fm and incident energy $E_{\rm c.m.} = 108$ MeV.

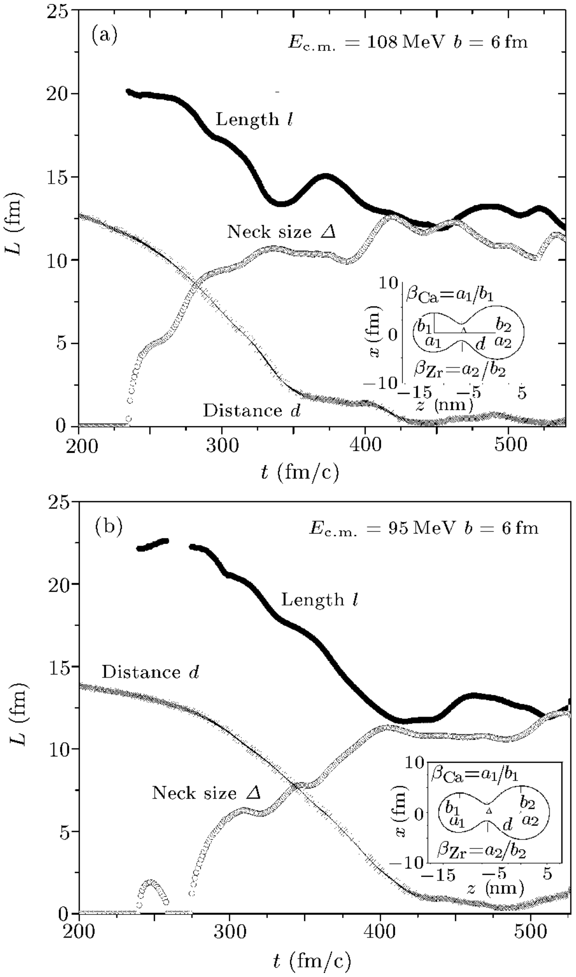

Fig. 3. Time evolution of the neck size, distance between the centres of the projectile and the target, and length of the composite system for fusion ^{40}Ca+^{90}Zr at the impact parameter $b = 6$ fm with incident energies of (a) 108 MeV and (b) 95 MeV. Inserts: definition of the distance d between the centres of the projectile and target, the neck size Δ and the length of the composite system after touching $l = a_1 + d + a_2$.

Figs. 3(a) and 3(b) we show the time evolution of the neck size, the distance between the centres of the projectile and the target, and the length of the composite system, for the fusion process of ^{40}Ca+^{90}Zr at the incident energies 108 MeV (above Coulomb barrier) and 95 MeV (below Coulomb barrier) and the impact parameter $b = 6$ fm. Here the definition of the distance d between the centres of the projectile and the target, the neck size Δ and the length of the composite system after touching $l = a_1 + d + a_2$ are given in the inserts of Figs. 3(a) and 3(b). The time step is 1 fm/c. From Figs. 3(a) and 3(b), one can see that after touching the neck size first increases by jumps and then approaches to a saturation value of the diameter of the compound systems. The jumps reflect the surface oscillation of the neck part of the composite system during the fusion process. Both the distance between the centres the projectile and the target and the length of the total system decrease with time, and eventually the length of total system and the neck size both approach to the diameter of the compound system. From Fig. 3(a) we can obtain the characteristic time of neck growth, which is about 125 fm/c for the fusion reactions of ^{40}Ca+^{90}Zr at incident energy of 108 MeV and impact parameter $b = 6$ fm. In the case of the incident energy of 95 MeV, two nuclei can retain the touching configuration for about 35 fm/c accompanying an oscillation of the relative motion of two nuclei and then the neck grows rapidly. The characteristic time of the neck growth in this case is about 150 fm/c, which is longer than that in the case of incident energy above the barrier (incident energy 108 MeV). The oscillation of neck size in the fusing system at the touching configuration might be one of the characteristics for sub-barrier fusions.

After the neck is formed, the nucleon transfer starts. As an example, in Fig. 4(a) we show the early stage of neck formation for an event of trajectories of particles in reaction ^{40}Ca+^{96}Zr at incident energy of $E_{\rm c.m.} = 108$ MeV and impact parameter of $b = 6$ fm. All neutrons and protons in the system are denoted by different symbols. The motion of two typical neutrons located at target initially is described by trajectories 1 and 2, which end at the projectile and the neck region, respectively. From the figure one can see that the main contribution to neck formation at the early

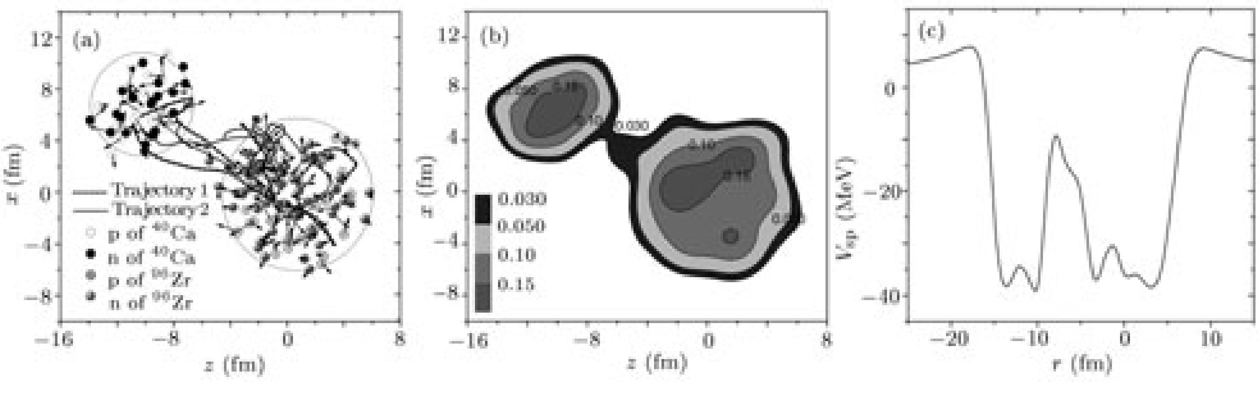

Fig. 4. Early stage of neck formation for an event of trajectories of particles (a), the corresponding contour plot of density (b), and the single-particle potential of the composite system (c), in the reaction ^{40}Ca+^{96}Zr at the incident energy $E_{\rm c.m.} = 108$ MeV and impact parameter $b = 6$ fm. The barrier appears inside the single-particle potential.

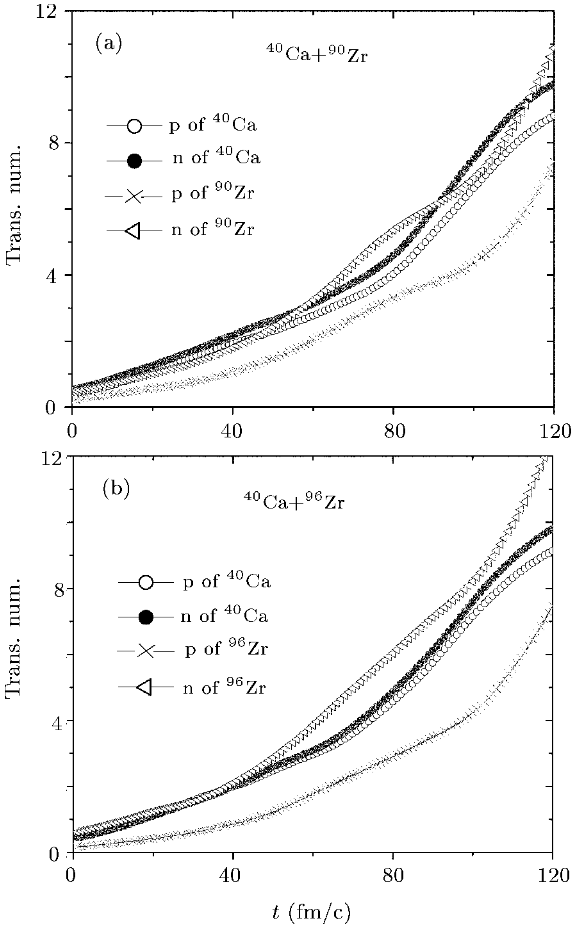

Fig. 5. Time evolution of nucleon transfer for reaction ^{40}Ca+^{90}Zr (a) and neutron-rich (target) reaction ^{40}Ca+^{96}Zr (b) at $E_{\rm c.m.}$ = 108 MeV and b = 6 fm. The time starts from touching configuration and time step is taken to be 1 fm/c.

stage comes from neutrons of neutron-rich target ^{96}Zr. Furthermore, we draw the corresponding contour plot of density and the single-particle potential of the composite system in Figs. 4(b) and Fig. 4(c). The barrier appearing inside the single-particle potential, as shown in Fig. 4(c), depends on the neck size. The single particle potential is calculated by

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

where $V(\boldsymbol{r}-\boldsymbol{r}')$ is the effective nucleon–nucleon interaction and $\rho(\boldsymbol{r}')$ is the density. The inner barrier of the single-particle potential plays a role of preventing nucleons moving from the projectile to target or vice versa. At the early stage of the neck development, the barrier inside the potential is quite high, as shown in Fig. 4(c), most of the nucleons of the projectile and the target are restricted in their individual potential well. With the development of the neck, the inner potential barrier decreases and the common nucleons increase. For quantitatively describing the nucleon transfer through the neck, we first define a neck section which locates at the border of two touching nuclei and is perpendicular to the connection line between two centres of the projectile and the target. Since in the ImQMD model, the coordinate and momentum of each nucleon at each time step are recorded, we can count the number of the nucleons which are transferred through the neck section. Figures 5(a) and 5(b) show the time evolution of the number of the nucleons transferred for reactions ^{40}Ca+^{90}Zr and ^{40}Ca+^{96}Zr at $E_{\rm c.m.}$ = 108 MeV and b = 6 fm. The time starts from the touching point and the time step is 1 fm/c. From these figures we can find that the number of transferred nucleons increases with time (i.e. with development of the neck) and the neutron transfer is easier than protons, even for the ^{40}Ca which has the same number of neutrons and protons. For the neutron-rich target reaction ^{40}Ca+^{96}Zr, the excess neutrons in the target make the neutron transfer stronger than that in the non-neutron-rich reaction of ^{40}Ca+^{90}Zr.

In summary, we have studied the neck development and nucleon transfer in fusion reactions of ^{40}Ca+^{90,96}Zr microscopically by means of our improved QMD model. We have found that for the fusion reactions at the energies lower than barrier, the fusion system can stay at touching configuration for a certain time accompanying an oscillation of the relative motion of two nuclei, and then the neck starts to develop and nucleon transfer through the neck begins simultaneously, finally the compound system forms with the increasing neck size and nucleon transfer. While for the fusion reactions above the barrier, the neck develops relatively faster. The general picture of the neck development and nucleon transfer in fusion reactions given in this work is not very sensitive to the parameters of potential. The further quantitative study about the influence of potential parameters on fusion dynamics is in progress.

References

[1] Zagrebaev V I 2001 *Phys. Rev.* C **64** 034606-1-13

[2] Adamian G G, Antonenko N V, Diaz-Torres A and Sheid W 2000 *Nucl. Phys.* A **671** 233

[3] Shen Caiwan, Kosenko G and Abe Y 2002 *Phys. Rev.* C **66** 061602(R)-1-5

[4] Maruyama Toshiki, Bonasera A, Papa M and Chiba S 2002 *Eur. Phys. J.* A **14** 191

[5] Kondratyev V N and Iwamoto A 1998 *Phys. Lett.* B **423** 1

[6] Wu Xizhen, Depta K, Hermann R, Maruhn J A, Greiner W 1985 *Nuovo Cimento* A **87**, 309

[7] Davees K T R, Sierk A J and Nix J R 1976 *Phys. Rev.* C **13** 2385

[8] Aritomo Y, Wada T, Ohta M and Abe Y 1999 *Phys. Rev.* C **59** 796

[9] Adamjan G G, Antonenko N V, Scheid W and Volkov V V 1997 *Nucl. Phys.* A **627** 361

[10] Wang Ning, Li Zhuxia and Wu Xizhen 2002 *Phys. Rev.* C **65** 064608

[11] Wang N, Wu X Z and Li Z X 2003 *Phys. Rev.* C **67** 024604-1-9

[12] Möller P, Nix J R, Myers W D and Swiatescki W J 1995 *At. Data Nucl. Data* **59** 185

[13] Massimo P, Toshiki M and Aldo B 2001 *Phys. Rev.* C **64** 024612

[14] Timmers H et al 1998 *Nucl. Phys.* A **633** 421